Nathan Splinter, Manager of Energy and Sustainability

APEX Design Solutions
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Kingston, ON

Queen's Facilities
207 Stuart Street
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April 19, 2024

RE: Innovative Building Design – NetZero Materials and Approaches

Dear Mr. Splinter,

Please find attached Apex Design Solutions final copy of NetZero residence design report for Queen's University. This document contains comprehensive details and strategic design parameters, integral to our pursuit of a sustainable, energy-efficient, and environmentally conscious student residence.

This final report represents our commitment to delivering a NetZero student residence that aligns with the sustainability goals of Queen's University. Your feedback has been invaluable, and we eagerly anticipate further collaboration to bring this project to life!

Sincerely,

Ethan Phillip, Euan Brydie, Reid Thompson, Steven Vandenbogaard

APEX
YOUR PROJECT - ELEVATED

Innovative Building Design – **NetZero** Materials and Approaches

CIVL 460 Draft Final Report

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Reid Thompson | 20235655, Steven Vandenbogaard | 20102407

Presented to: Nathan Splinter (Queen’s University Facilities)

April 19th, 2024

Our signatures below attest that this submission is our original work. This report was designed for use by Queen’s Facilities and shall not be used in any other case. Further, this report is a draft and is subject to change as the project progresses. Following professional engineering practice, we bear the burden of proof for original work. We have read the Policy on Academic Integrity posted on the Civil Engineering departmental web site (www.civil.queensu.ca/undergraduate) and confirm that this work is in accordance with the Policy.

Ethan Phillip	**Euan Brydie**	**Reid Thompson**	**Steven Vandenbogaard**

Executive Summary

The mission of the APEX team is to develop a NetZero emissions residence building that aligns with the objectives specified by Queen's University Facilities Group. This design involves a detailed approach, encompassing innovative design methods, sustainable material selection and cost – effectiveness. The projects' primary objective is to reduce the university's carbon footprint through a new NetZero residence design, with deliverables including engineering drawings, a virtual CAD model, a detailed business case, and a final design report.

The scope includes thorough research, assessment of building strategies, appropriate location selection, cost estimation, embodied carbon analysis, and innovative design methods. The superstructure and substructure of the building, including a simplified structural analysis and interior floor plans, are key areas of focus. Success metrics include meeting embodied carbon targets, ensuring a NetZero design, and assessing feasibility within allocated resources and the limited project timeline.

The background research phase focused on sustainable materials, with engineered wood products such as Cross-Laminated Timber (CLT) identified as potential structural members due to their low carbon footprint and superior strength-to-weight ratios. Additionally, case studies on the Brock Commons Residence, Wood Innovation and Design Centre, UBC's Earth Sciences Building, and a costing case study have been conducted to further develop an understanding of mass timber design. Key stakeholders and constraints of this project have been addressed within the report.

A detailed analysis of potential design alternatives has been conducted, including Two-Way CLT Panels, column and beam systems, elevator and stair shafts, foundation types, substructure materials, and the site location. Each of these design alternatives have been evaluated based on factors such as environmental impact, cost-effectiveness, feasibility, constructability, and alignment with sustainability goals. To generate a conceptual design, informed decision-making was employed. The team used weighted evaluation matrices to determine the location, gravity load-bearing systems, structural elements, stair and elevator shaft designs, and the building's shape and dimensions. Additionally, careful consideration was given to the selection of the superstructure and substructure materials, ensuring alignment with sustainability goals.

This document considers comprehensive load analyses and structural design strategies to meet NetZero standards while adhering to the National Building Code of Canada (NBCC). The gravity load analysis, conducted according to NBCC Section 4.1, used conservative estimates for dead and live loads based on the building's use of lightweight glulam, setting dead loads at 1.35 kPa for floors and 3.25 kPa for the roof, and live loads at 4.8 kPa and 1.0 kPa, respectively, ensuring the structure's integrity and sustainability focus.

The snow load analysis, in line with NBCC Section 4.1.6, determined a snow load of 2.08 kPa, considering the roof's flat design and regional climatic conditions. Additionally, live load reduction was applied for tributary areas greater than 20 m², ensuring efficient structural optimization and simplifying construction processes.

The project's superstructure featured glulam columns and beams, designed for optimal structural efficiency and sustainability. Using CSA O86-19 and the 2020 Canadian Wood Design Manual, a dual-column strategy was employed, reducing material costs. The design process took advantage of Douglas-Fir for its strength and cost-effectiveness, where calculations for the compressive resistance of elements were streamlined through excel, considering the self-weights of glulam components.

SAP2000 was used in the structural analysis, particularly for simulating wind loads and evaluating responses of the foundation. Douglas-fir wood defined the material properties for the SAP2000 model, which featured fixed supports at the basement level to simulate the building's reaction to multidirectional forces. This decision facilitated the analysis of wind loading scenarios and the integration of cross-bracing to enhance lateral stability.

The foundation design featured reinforced concrete for its compatibility with Canadian construction standards and the geological conditions, using isolated footings to minimize concrete use and embodied carbon. Future geological assessments are planned to verify the foundation's design and environmental sustainability further.

The embodied carbon for the selected design was modelled using software from OneCLick LCA. The embodied carbon of the design was assessed, revealing total emissions of 4,076 tonnes CO2e and categorizing it as a Category C emitter. The use of mass timber and inclusion of solar panels resulted in a carbon valuation of 2.08 million kg CO2e and a 34% increase in embodied carbon, respectively.

The project's material cost analysis estimated costs at $3,625,152.89, including adjustments for market conditions and the sustainability of materials, specifically glulam and ECOPact concrete. This estimation covers essential materials for achieving the NetZero goal, excluding labor and indirect costs, providing a detailed financial overview for constructing a sustainable residence at Queen’s University.

In conclusion, the APEX team’s approach to the NetZero residence project at Queen’s University highlights a commitment to sustainability, supported by detailed design and understanding of engineering principles. By leveraging sustainable materials, advance design techniques, and comprehensive structural analyses, the project aligns with the sustainability objectives outlined by the university. The projects thorough embodied carbon analysis, adherence to NBCC and detailed cost analysis demonstrate APEX’s dedication to reducing the buildings carbon footprint.

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1.0 Project Mission Statement

APEX's mission is to provide the client with a NetZero emission building design that will align with Queen's University's climate objectives. The primary objective is to create a residence building that will integrate innovative green materials and carbon negating solutions, all while maintaining a defendable and cost-effective approach.

2.0 Introduction

The construction industry is one of the largest contributing industries to the emission of greenhouse gases (GHG). Cement is a common construction material, but on its own it accounts for three percent of GHG emissions globally (Ritchi and Roser 2020a). This is significant considering that the entire airline industry accounts for just 1.9% of global GHG emissions (Ritchi and Roser 2020b). Furthermore, energy use in residential buildings contributes to 10.9% of global emissions, and the buildings and construction sector accounts for a significant 36% of global emissions (World Green Building Council 2023).

The concept of a NetZero emissions building is one that produces, or procures, enough carbon-free renewable energy to meet building operations energy consumption annually (Architecture 2030 2016). Designing buildings to be NetZero emissions will help mitigate climate change and has become an emphasis by governments across the world. In 2021, investments in building energy efficiency increased by 16% to USD 237 billion. Currently, there are 500 NetZero commercial buildings and 2000 NetZero homes around the world. According to a report by the World Green Building Council, every building on the planet must be NetZero carbon by 2050 to keep global warming below 2 degrees Celsius, the limit enshrined in the Paris Agreement (World Green Building Council 2023). In the coming two decades, it is projected that the world's cities will see the construction or reconstruction of approximately 900 billion square feet of building space. This expansion is driven by the need to accommodate roughly 1.1 billion new urban residents (Architecture 2030 2016)

Although the need for NetZero buildings is vital, developers will not cooperate if the designs are cost prohibitive; therefore, engineers must produce NetZero designs that are also cost-effective.

NetZero buildings involve innovative solutions for the materials used and to produce energy. Carbon-releasing materials, such as concrete, are generally avoided where possible and carbon-sequestering materials, such as timber, are often used. Designs emphasize a reliance on renewables and effective resource management. Natural sources of light, heat, and ventilation are often maximized to reduce energy waste (Infogrid 2022).

In 2016, Queen's University adopted a new Climate Action Plan which outlined strategies for incorporating sustainability principles across the campus environment. A key component of Queen's University's GHG reduction strategy includes designing with sustainability as a key focus for any future building projects. A mandate has been established to reduce the carbon emissions profile of existing buildings and any new projects. This strategy incorporates and applies to university residences, given that residence buildings on campus are currently a major emissions source. A new residence design template must be established so that future residence buildings are built in accordance with the plan's target of achieving NetZero status by 2040.

3.0 Scope

The project scope as delivered by Queen's Facilities group is centered on creating a new residence building that can achieve a NetZero or Negative Carbon status. Meeting this objective will need to be determined through research, selection, and assessment of currently available and emerging building strategies. The design parameters include providing an overall estimate of the cost of the new residence building and the embodied carbon of the selected materials. Innovative design methods and creative approaches to improve energy efficiency over existing designs are to be evaluated. An appropriate location for the new residence will need to be assessed and selected. Additionally, the dimensions of the building, as in the floorplate and the height of the building, need to be chosen.

The project focus will be on the superstructure and substructure of the building, including a complete structural assessment, with more emphasis on the superstructure. The superstructure consists of the structural system above the finished grade of the foundation. These include the beams, columns, lateral load bearing elements, and shafts. The substructure consists of the footings and the foundation of the building. Each superstructure elements will be designed from calculated loads from a gravity load analysis, following Section 4 of the National Building Code. The superstructure components will be designed in accordance with Section 7 of CSA O86. The substructure includes the foundation and any footings for the building.

The innovative new design will follow a similar pattern to the recently completed Endaayaan – Tkanónsote residence building as a base case to compare multiple design points, including total emissions, materials used, and budget. Data from previous Queen's energy and/or carbon emissions research studies are advised to be reviewed and their outcomes expressed in the overall design assessment.

Placement on interior furnishings and sub-trade elements, such as plumbing, electrical, and HVAC will not be included, yet should be considered for future developments of the design.

The client recommends a building height target of four stories, given the height of adjacent buildings near the proposed site and the typical height of recently constructed residence buildings at Queen's University. A 3D render of the building has been requested if time and resource availability permits doing so. The final design must be submitted in a comprehensive report detailing the project outcomes and recommendations to Queen's Facilities before April 19th, 2024.

4.0 Project Objectives

In the pursuit of creating a NetZero carbon emission residence design, the project is driven by a commitment to sustainability and the reduction of carbon footprints. To accomplish the objectives, the team will deliver a comprehensive package comprised of a virtual model, a full business case, and a final report. The success of this project hinges on the satisfaction of the client, with a primary focus on the final design report and presentation as the main deliverables. The implemented design's success will be measured by several critical factors. Firstly, the implemented solution must effectively achieve the specified embodied carbon targets, ensuring that the design achieves a NetZero or negative carbon status. Additionally, the feasibility of implementing these goals within the allocated resources and timeframe is an important consideration. The success of the project is not merely confined to immediate outcomes but extends to the lasting impact of sustained carbon reduction efforts across future generations.

Through diligent monitoring and strategic reduction of embodied carbon in new construction, the project aims to enable Queen's to significantly lower its overall carbon emissions. In doing so, the project will contribute to the collective effort to mitigate the impact of climate change, aligning the teams’ objectives with the larger goal of creating a sustainable and environmentally responsible future.

List of Objectives:

- Research sustainable methods of construction.
- Research costs associated with sustainable construction.
- Select computer modelling software.
- Select an appropriate location for the residence.
- Design shape and dimensions of the residence.
- Design gravity load bearing system.
- Design superstructure of the residence
- Design stair and elevator shafts.
- Design substructure of the residence
- Model performance of the superstructure against various loading conditions using SAP2000
- Model performance of the substructure using SkyCiv.
- Design the façade of the building.
- Create 3D render of the building using SketchUp.
- Perform life cycle embodied carbon assessment.
- Perform cost analysis of designed materials.
- Compare the embodied carbon and cost analysis to the performance of Endaayaan – Tkanónsote.
- Highlight risks associated with construction.

5.0 Background Research

To help accomplish a NetZero design for the project, research on material options, existing case studies, and modelling software was conducted.

5.1 Superstructure Materials

Selecting structural materials for a NetZero building hinges on the materials durability, low carbon footprint, affordability, and accessibility to meet sustainability objectives effectively.

Wood has emerged as a sustainable and environmentally responsible choice for structural building materials within the construction industry. Wood within the construction industry can be found in various engineered forms such as mass timber, cross-laminated timber (CLT), glulam, laminated veneer lumber, (LVL) and parallel strand lumber (PSL). These products offer versatility and design flexibility while significantly reducing the carbon footprint of buildings.

CLT is a form of mass timber that is a composite wood panel crafted by arranging and bonding multiple layers of dimensional lumber, with each layer perpendicular to the one below it. CLT panels are commonly comprised of three, five, or seven layers (Wood-Works 2023.). The dimensions of these CLT panels are generally only limited to transportation constraints, yet they typically span up to 40 feet in length and up to 8 feet in width. These CLT panels are often applied in constructing floors, walls, and roofs (Wood-Works 2023.).

Glulam, short for glued laminated timber, is a composite material created by bonding together selected layers of solid-sawn lumber, specifically chosen, and arranged to optimize structural strength and aesthetic appeal. This versatile engineered wood product is primarily found as a support, commonly serving as the backbone for beams and columns (Wood-Works 2023.). Additionally, glulam’s flexibility allows the possibility of creating curved sections, allowing for innovative and architecturally distinctive designs in construction projects (Wood-Works 2023).

LVL is constructed by layering thin sheets of veneer in parallel orientation and then securing them using moisture-resistant adhesives. This engineered wood finds extensive applications in both residential and commercial construction, primarily as load-bearing beams and headers due to its strength and dimensional stability. Additionally, the moisture-resistant adhesives used in the manufacturing process provide protection against moisture related issues such as warping, swelling or decay (Wood-Works 2023).

PSL is a structural composite lumber produced through the bonding of wood strands under controlled heat and pressure. Its excellent strength and versatility make it an excellent choice for applications such as load-bearing beams and columns, especially in the context of post and beam construction (Wood-Works 2023). Furthermore, PSL can effectively be used for creating extended, unobstructed spans when incorporated into substantial sections, making it suitable for both residential and commercial building projects (Wood-Works 2023).

Mass timber behaves very differently than light wood frame buildings when exposed to fire. Large timber elements develop a char layer that insulates the wood beneath. Mass timber elements can therefore be engineered to achieve fire-resistance ratings by accounting for this char layer during design, allowing the timber to be left exposed. These elements can also be encapsulated in drywall or a similar material to achieve the required fire-resistance rating if the exposed timber aesthetic is not critical to the project. Additionally, Mass timber and CLT haven proven to be more cost effective than other building materials such as concrete and steel.

Hybrid mass timber designs have gained widespread recognition for their ability to combine the natural aesthetic appeal of wood with the structural strength of steel. Steel's role in these designs is two dimensional, serving both structural and aesthetic purposes. It excels in areas of highly concentrated forces, including connections, braces, columns, and trusses, offering the necessary load-bearing capabilities. In cases of long spans and seismic activity, steel becomes indispensable, providing the required resilience and ductility (Malczyk and Mpidi Bita 2021). However, integrating steel into timber systems demands thoughtful consideration of moisture and thermal effects. (Malczyk and Mpidi Bita 2021). Wood's sensitivity to moisture requires the inclusion of expansion joints and field-adjustable details, while steel's thermal expansion necessitates the careful placement of expansion joints (Wood-Works 2017). Furthermore, these hybrid-timber systems offer cost efficiencies by reducing foundation expenses and enhance seismic performance. By increasing the proportion of wood, they also contribute to a lower carbon footprint, aligning with sustainable construction practices (Malczyk and Mpidi Bita 2021).

5.2 Substructure Materials

The large majority of building foundations are created using reinforced concrete, as it is a strong material that is able to withstand large compressive and tensile forces, while combatting corrosion from the soil or other sources. However, depending on the existing site conditions a large quantity of concrete can sometimes be required for foundation construction and the production of concrete is detrimental to the natural environment in terms of GHG emissions (Princeton University 2020). Therefore, in order to support the loads of the NetZero residence building properly, while reducing the residence's embodied carbon value, environmentally friendly concrete mixes with reduced embodied carbon will be incorporated.

To help reduce the embodied carbon of the foundation, ECOPact, a Lafarge product available at scale in Ontario, will be considered as a traditional concrete substitute. ECOPact is a low-carbon concrete product range that can reduce the embodied carbon of the foundation by up to 90%, while offering the same performance as traditional concrete (Lafarge Canada 2023). The ECOPact product range is available in three blends, as shown Figure 1.

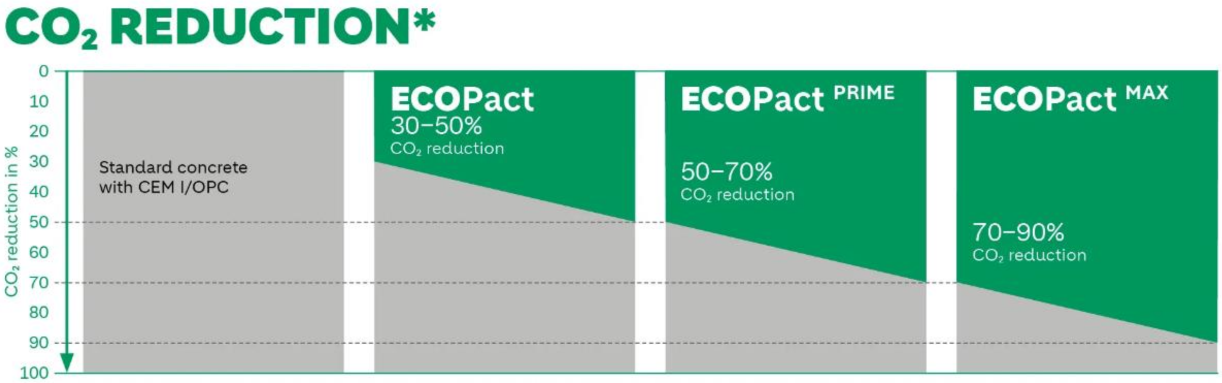

FIGURE 1: LAFARGE ECOPACT CO2 REDUCTION SCHEMATIC (LAFARGE CANADA 2023)

5.3 Case Studies

Having knowledge of existing NetZero and mass timber designs will aid in the design of this building. Understanding why current designs use specific materials for certain purposes is essential when beginning to design the structure for this project. It is important to note that North American codes typically allow a height of up to six storeys for mass timber buildings.

However, with the emergence of low-carbon designs, the 2020 Canadian National Building Code (NBCC) allows the construction of wood buildings up to 12 storeys (Canada 2022). The NBCC will be discussed in the constraints section of the report. The following case studies highlight similarities and differences in existing mass-timber designs that strive for NetZero emissions.

5.3.1 Brock Commons Residence, Vancouver, BC

- 18 storeys
- 53 metres tall
- 404 beds
- $51.5 million
- $248.9 per square foot

FIGURE 2: CONSTRUCTION OF THE BROCK COMMONS BUILDING (WOOD-WORKS 2017)

This mass-timber hybrid design utilizes concrete for the foundation, ground floor, second-floor slab, and stair and elevator cores. The superstructure is composed of CLT panel floor assemblies supported on GLT and PSL columns with steel connections (Wood-Works 2017). The concrete cores improve the seismic performance of the building, as they support the transferred lateral loads form the CLT floor panel (Naturally Wood 2018). For fire protection, the tops of the CLT slabs are covered with concrete topping, which also serves well for acoustic purposes.

The building’s emissions from operational energy and water consumption are estimated to account for 84% of the total global warming potential (GWP), with the embodied GHG in the building’s materials contributing the remaining 16%. The building structure is responsible for almost half of the building material related GWP impacts (Naturally Wood 2018). Figure 3 display the GWP impacts by building element and material.

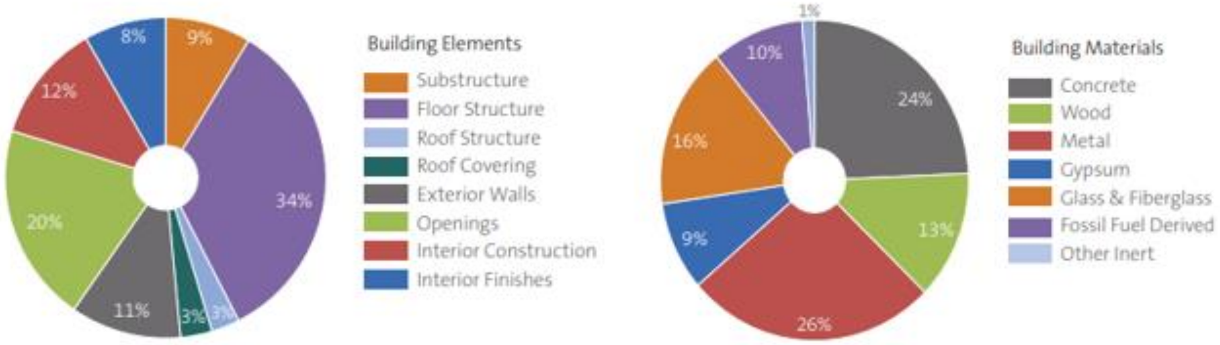

FIGURE 3: GWP OF THE BROCK COMMONS BUILDING DESIGN BY BUILDING ELEMENT AND BY BUILDING MATERIAL (NATURALLY WOOD 2018)

The success of the design lead to many lessons being learned. It was remarked that the detailed virtual design and construction model enhanced the level of detail in coordination and minimized unexpected issues during fabrication and construction (Naturally Wood 2018). Additionally, the importance of the interrelated water, fire, and acoustic performance of the building was noted. Another key takeaway was that the performance of the other materials in addition to the mass timber defined the limits of the design (Naturally Wood 2018).

5.3.2 Wood Innovation and Design Centre (WIDC), Prince George, BC

- Six storeys
- 29.5 metres tall
- $25 million
- $490 per square foot

FIGURE 4: WIDC BUILDING IN BRITISH COLUMBIA (WOOD-WORKS N.D.)

This design includes concrete only in the first level floor slab. It utilizes glulam beams which transfer loads to glulam columns, using 2-millimetre to 16-millimetre glues-in rods and stainless-steel washer plates to secure the post and beam superstructure. This allows the columns to run continuously from the foundation to the roof. Interestingly, this design includes CLT panels comprising the walls, stair, and elevator core (Wood-Works n.d.). The use of timber alone is enough to resist the lateral loads for this design. Semi-rigid fibreglass and acoustic ceiling hangers are used to help insulate the ceilings. For fire protection, the design followed the methodology set out in the Canadian CLT Handbook in the chapter "Fire performance of cross-laminated timber assemblies" (FPInnovations 2019). This included the use of a ULC-listed intumescent coating, a treatment that expands in fire to provide a degree of fire protection.

Lessons were learnt from this design predominantly due to the fast-track schedule of the project. It was noted that some of the timber work that was done on site could have been done more efficiently in the factory, with the installation of the connectors being highlighted as a cause of slower work (Wood-Works 2023). The importance of precise prefabrication of structural elements was stressed as an area of high importance for future projects. Additionally, an emphasis was placed on ensuring the precise location of the vertical wood members on the first level to prevent cumulative errors (Wood-Works 2023) .

5.3.3 University of British Colombia Earth Sciences Building, Vancouver, British Columbia

- 6 storeys
- $48.7 million
- $276.8 per square foot

FIGURE 5: UNIVERSITY OF BRITISH COLUMBIA EARTH SCIENCES BUILDING (ARCH DAILY 2023)

Glulam, CLT, and LSL are predominantly features in this design. Diagonal glulam beam columns at the end walls of each storey provide lateral resistance from seismic loads (Naturally Wood n.d.). The building features a composite flooring system composed of LSL and concrete, offering a lighter alternative to solid concrete while also delivering exceptional sound-absorbing qualities. Additionally, the roof and canopies of the building are crafted using CLT (Naturally Wood 2016a)

Each ton of dry wood product offsets between 1.8 and 2.0 tonnes of CO_2, which means the wood materials that went into the design will sequester about 1,094 tonnes of carbon dioxide (Thinkwood 2017).

On the eastern side, the building showcases vertical laminated glass fins that are translucent and positioned at an angle to effectively manage glare. As for the southern and western facades, they incorporate external horizontal shading elements and interior blinds to precisely manage both light levels and heat absorption (Thinkwood 2023).

5.3.4 Costing Case Study

A valuable way to analyze the projected cost of the project is analyzing the cost performance of other designs. Hanscomb Limited, in collaboration with the National Research Council of Canada (NRCC), conducted a case study to provide a realistic allocation of direct and indirect construction costs, including annual building maintenance costs (“Encapsulated Mass Timber Construction - Cost Comparison Canada” 2017).

This cost-benefit analysis compares the possibilities of an unprotected mass timber design, an encapsulated mass timber design, a traditional concrete design, and a steel design. An encapsulated mass timber design is one similar to a standard mass timber design yet protected with a double layer of Type X gypsum board.

The modeled buildings follow a similar structural design to the Brock Commons building previously discussed. The four proposed models consist of the same common elements to keep things consistent yet vary in their structural and encapsulation elements. Each of the designs consists of the following:

The Mass Timber Design (Building 1)

- Foundation – cast-in-place concrete spread footings and piers.
- Elevator & Stair Cores – cast-in-place concrete structure.
- Podium – slab on grade, L1 columns, L2 floor slab – cast-in-place concrete structure.
- Superstructure – hybrid structure. CLT floor slabs c/w glulam columns and steel connectors
- Assumes low-intensity green roof (shrubs & wild grasses) in some areas. Assumes roof amenity for residential building model.

The Encapsulated Mass Timber (Building 2)

- Foundation – cast-in-place concrete spread footings and piers.
- Elevator & Stair Cores – cast-in-place concrete structure.
- Podium – slab on grade, L1 columns, L2 floor slab – cast-in-place concrete structure.
- Superstructure – hybrid structure. CLT floor slabs c/w glulam columns and steel connectors.
- Encapsulated Superstructure – all vertical and horizontal structural wood elements encapsulated with 2 layers of 16mm type X gypsum wallboard.
- Assume low-intensity green roof (shrubs & wild grasses) in some areas. Assume roof amenity for residential building model.

The Concrete Building (Building 3)

- Foundation – cast-in-place concrete spread footings and piers.
- Elevator & Stair Cores – cast-in-place concrete structure.
- Podium & Superstructure – cast-in-place concrete structure.
- Assume low-intensity green roof (shrubs & wild grasses) in some areas. Consider roof amenity for residential building model.

The Steel Building (Building 4)

- Foundation – cast-in-place concrete spread footings and piers.
- Elevator & Stair Cores – cast-in-place concrete structure.
- Podium – slab on grade, L1 columns, L2 floor slab – cast-in-place concrete structure.
- Superstructure – standard steel construction.
- Assume low-intensity green roof (shrubs & wild grasses) in some areas. Assume roof amenity for residential building model.

To provide a more accurate cost comparison, the four designs will be compared on a square meter basis. Table 1 summarizes a cost comparison of each building type on a square meter basis.

TABLE 1: COST COMPARISON OF NRCC CASE STUDY BUILDING TYPES ON A SQUARE METER BASIS.

	Building 1 ($/m^2)	**Building 2 ($/m^2)**	**Building 3 ($/m^2)**	**Building 4 ($/m^2)**
Common Elements	2628.71	2628.71	2628.71	2628.71
Structural Elements	289.35	289.35	365.125	637.92
Encapsulation Elements	0	221.90	0	Included
Total Construction Estimate	**2918.06**	**3139.61**	**2993.84**	**3266.63**

As seen above, it is evident that the mass timber design (Building 1) is the most cost-efficient design. This is because mass timber not only keeps initial construction costs to a minimum, but the construction process is accelerated due to the materials prefabricated nature. The concrete design arose as the second cheapest option, primarily due to its higher material costs, alongside the labor-intensive nature of concrete construction. Following closely is the encapsulated mass timber design, while providing additional fire protection and aesthetic enhancements, introduces higher costs associated with the encapsulation materials. Finally, the steel design ranked as the least cost-effective option, with higher expenses linked to the materials cost partnered with potentially longer construction times. Within the case study, there was not a significant difference in the cost of maintenance between any of the design options.

5.4 Modeling/Software

Modeling a design can help smoothen the design process and aid in the construction plan of the building. It allows all parties to have the same visual model of the building in very high level of detail. A virtual model often serves primarily as a design-assist tool to assess decisions and aid in coordination of system layouts. Due to the required precision of prefabrication when working with mass timber products, models help design teams place and size the penetrations and appropriate clearances in each product. Furthermore, virtual models are utilized for quantity takeoffs of materials through the design phase. This can aid in the selection process of materials, as numerous designs can be modelled and the quantities of materials, such as timber, can be extracted and evaluated. This would prove beneficial for any design that values a low-carbon design.

Using a model for analysis is common practice and helps serve as a main function in the design phase of buildings. Revit 2023, by Autodesk, allows designers to work seamlessly between a physical model and analysis software. Existing physical geometry can be leveraged in 2D and 3D views as context to the analytical model (Reddick 2022). The analytical model is associated to the physical model but is independent. This could prove useful for quick structural analysis not needing a full model. Figure 6 displays the visual association between the physical model viewport and the analytical model viewport (Reddick 2022).

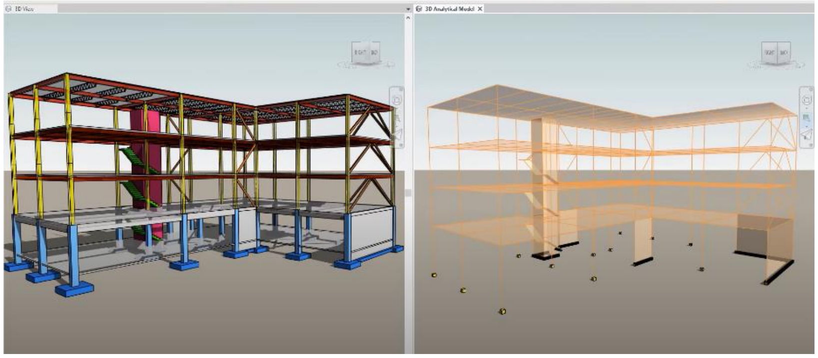

FIGURE 6: PHYSICAL MODEL AND ANALYTICAL MODEL VIEWPORT IN REVIT 2023 (*REVIT 2023: NEW WORKFLOW FOR STRUCTURAL ANALYSIS* 2022)

3DEXPERIENCE CATIA (V6) by Dassault Systems is a modeling software that is widely considered to be more complicated than Revit. The design of the Brock Commons building utilized 3DEXPERIENCE CATIA in tandem with AutoCAD by Autodesk (Naturally Wood 2016b). 3DEXPERIENCE is known for creating a common infrastructure model that is compatible for collaboration across all disciplines. This software is beneficial for combining design, engineering, manufacturing, and project management in real time. 3DEXPERIENCE is known for creating a common infrastructure model that is compatible for collaboration across all disciplines. This software is beneficial for combining design, engineering, manufacturing, and project management in real time. It proved useful in the construction of the Brock Commons building by allowing the design team to assess the constructability of the components and connections between the columns and the floor assemblies (Naturally Wood 2016b). Furthermore, it proved beneficial for construction planning as a model simulation of the installation sequence was developed from the 3D model, which was utilized by the construction team as an overview of the assembly of the construction (Naturally Wood 2016b).

If technical abilities and time constrain a project, then the use of software such as ETABS or SAP 2000 could be explored. These applications could be used to perform finite element analysis of a simplified model of the design. This would allow for the quick structural analysis of the building and still help speed up the design process, allowing the design team to test different types of materials and placements of structural elements. The difference between the two applications is that ETABS is special purpose software and SAP2000 is general purpose. ETABS is used for building systems, having necessary tools for building systems, as well as help in geometry formation of buildings (The Engineering Community 2023). SAP2000 allows the user to model any kind of geometry and so analysis and design. SAP2000 is often used for smaller structures, or portions of larger structures, however it lacks the simplicity that ETABS has of discretizing the structure into macroscopic elements (The Engineering Community 2023).

5.5 Mass Timber Fire Safety

Fire safety is often a concern when considering using mass timber as a structural element in a building. A quick google search will say that mass timber is fire safe. As timber products catch fire, they create a char layer which burns off while keeping the center of the structure intact and still structurally effective (McLain and Breneman 2021). Figure 7 displays the before and aftereffects of this phenomenon on a glulam column.

FIGURE 7: BEFORE AND AFTER EFFECTS OF THE CHAR LAYER FOR A GLULAM COLUMN (MCLAIN AND BRENEMAN 2021).

Although it is often listed as being fire safe, mass timber differs from concrete and steel, as it itself is fuel for the fire. Therefore, even though the timber structural elements may withstand the fire, they will enlarge the intensity of the fire for its duration (McLain and Breneman 2021). This has ramifications for the safety of the occupants of a mass timber building during a fire. Instead of exiting the building with concrete slabs above their heads, the occupants would be exiting the building with timber slabs above their heads that are lit up in flames. Additionally, the external fire on the building will be larger than for a concrete or steel building, which will increase the risk of that fire spreading to surrounding buildings. It is information like this that is often not included in the brochures of the companies that are selling mass timber products.

With that said, it is possible to build a mass timber building that meets an adequate level of safety, but it comes with constraints. Designers must make proper assessments of the building, as it is important to design mass timber buildings that address the specific hazards that the building presents. In some cases, timber floor slabs are encapsulated with gypsum boards and occasionally have a concrete topping to increase the fire resistance of the flooring (Thinkwood 2017).

5.6 Costing Case Study

A valuable way to analyze the projected cost of the project is analyzing the cost performance of other designs. Hanscomb Limited, in collaboration with the National Research Council of Canada (NRCC), conducted a case study to provide a realistic allocation of direct and indirect construction costs, including annual building maintenance costs ("Encapsulated Mass Timber Construction - Cost Comparison Canada" 2017).

This cost-benefit analysis compares the possibilities of an unprotected mass timber design, an encapsulated mass timber design, a traditional concrete design, and a steel design. An encapsulated mass timber design is one similar to a standard mass timber design yet protected with a double layer of Type X gypsum board.

The modeled buildings follow a similar structural design to the Brock Commons building previously discussed. The four proposed models consist of the same common elements to keep things consistent yet vary in their structural and encapsulation elements. Each of the designs consists of the following:

The Mass Timber Design (Building 1)

- Foundation – cast-in-place concrete spread footings and piers.
- Elevator & Stair Cores – cast-in-place concrete structure.
- Podium – slab on grade, L1 columns, L2 floor slab – cast-in-place concrete structure.
- Superstructure – hybrid structure. CLT floor slabs c/w glulam columns and steel connectors

- Assumes low-intensity green roof (shrubs & wild grasses) in some areas. Assumes roof amenity for residential building model.

The Encapsulated Mass Timber (Building 2)

- Foundation – cast-in-place concrete spread footings and piers.
- Elevator & Stair Cores – cast-in-place concrete structure.
- Podium – slab on grade, L1 columns, L2 floor slab – cast-in-place concrete structure.
- Superstructure – hybrid structure. CLT floor slabs c/w glulam columns and steel connectors.
- Encapsulated Superstructure – all vertical and horizontal structural wood elements encapsulated with 2 layers of 16mm type X gypsum wallboard.
- Assume low-intensity green roof (shrubs & wild grasses) in some areas. Assume roof amenity for residential building model.

The Concrete Building (Building 3)

- Foundation – cast-in-place concrete spread footings and piers.
- Elevator & Stair Cores – cast-in-place concrete structure.
- Podium & Superstructure – cast-in-place concrete structure.
- Assume low-intensity green roof (shrubs & wild grasses) in some areas. Consider roof amenity for residential building model.

The Steel Building (Building 4)

- Foundation – cast-in-place concrete spread footings and piers.
- Elevator & Stair Cores – cast-in-place concrete structure.
- Podium – slab on grade, L1 columns, L2 floor slab – cast-in-place concrete structure.
- Superstructure – standard steel construction.
- Assume low-intensity green roof (shrubs & wild grasses) in some areas. Assume roof amenity for residential building model.

To provide a more accurate cost comparison, the four designs will be compared on a square meter basis. Table 2 summarizes a cost comparison of each building type on a square meter basis.

TABLE 2: COST COMPARISON OF NRCC CASE STUDY BUILDING TYPES ON A SQUARE METER BASIS.

	Building 1 ($/m²)	**Building 2 ($/m²)**	**Building 3 ($/m²)**	**Building 4 ($/m²)**
Common Elements	2628.71	2628.71	2628.71	2628.71
Structural Elements	289.35	289.35	365.125	637.92
Encapsulation Elements	0	221.90	0	Included
Total Construction Estimate	**2918.06**	**3139.61**	**2993.84**	**3266.63**

As seen above, it is evident that the mass timber design (Building 1) is the most cost-efficient design. This is because mass timber not only keeps initial construction costs to a minimum, but the construction process is accelerated due to the materials prefabricated nature. The concrete design arose as the second cheapest option, primarily due to its higher material costs, alongside the labor-intensive nature of concrete construction. Following closely is the encapsulated mass timber design, while providing additional fire protection and aesthetic enhancements, introduces higher costs associated with the encapsulation materials. Finally, the steel design ranked as the least cost-effective option, with higher expenses linked to the materials cost partnered with potentially longer construction times. Within the case study, there was not a significant difference in the cost of maintenance between any of the design options.

5.7 Base Case

The client has requested the comparison of the completed NetZero building design to a base case building design. The design of the Endaayaan – Tkanónsote residence building, which opened in 2022, on Queen’s University campus will be used as a base case for this project. Performance parameters of the final design will be compared to the base case to assess the overall success of the design. The main parameters include the carbon performance and the cost of the design. This comparison allows the client to judge the advantages and disadvantages of building a NetZero building on the Queen’s University campus instead of repeating a similar design to the Endaayaan – Tkanónsote residence building. The comparison between the base case and the design of the proposed building will be considered throughout the project and conducted in detail in Section

11.0 and Section 12.7. The carbon footprint assessment for the Endaayan – Tkanónsote building can be seen in Appendix VII. The cost analysis for the Endaayan – Tkanónsote building can be found below in Appendix VIII.

6.0 Stakeholders

A project of this magnitude must consider the effects and consequences it will have on a variety of different communities and organizations.

6.1 Queen's University

As the NetZero residence is designed for the Queen's University campus, the university itself can be considered one of the main stakeholders of the entire project. The residence will be built on the Queen's University campus, operated, and maintained by Queen's University staff, and occupied by future Queen's University students. Therefore, the successful design of a NetZero residence building will have a direct impact on Queen's University. The proposed design also must follow Queen's building standards, to align with the goals of the university (Queen's University Facilities 2023a). A subgroup of Queen's that has an increased stake in this project is Queen's Facilities. This group oversees the operation and maintenance of all Queen's buildings, as well as energy and emissions of the university. On top of this, they are spearheading the university's conservation efforts through Queen's' Climate Action Plan (CAP) (Queen's University 2016), which is set towards the goal of becoming carbon-neutral by 2040 (Queen's University Facilities 2023b). Queen's University Facilities is the client for this project, and as such are an essential stakeholder of the NetZero residence design.

6.2 City of Kingston

While the NetZero residence building will be located on the Queen's University campus, the university must comply with any related bylaws imposed by the City of Kingston, including building permits, inspections, zoning bylaws and occupancy permits, etc. (City of Kingston 2023). An in-depth residence design that follows the City of Kingston's recommendations will be a crucial part of making the NetZero residence design a reality. Should the NetZero residence evolve from the design phase into the construction phase, staff from the university and the City of Kingston will be working closely with each other to ensure that construction unfolds according to plan, and thus will be affected by this project's outcome.

6.3 Future Tenants

The future tenants of the NetZero residence will be the main beneficiaries of this project's completion, as they will be living and working within the building. The design choices that are made now will have an immense impact on the lives of the tenants and their quality of life.

6.4 Provincial/Federal Government

The design and construction of the NetZero residence must comply with all of the relevant statements in the current version of the National Building Code of Canada (NBCC) (Canada 2022). Alongside this, the design must comply with Ontario's provincial building code (Ontario 2023a), which is part of the Building Code Act (BCA) (Ontario 2023b). For a building on the Queen's University campus, the Ontario building code will govern. Should the NetZero residence design not comply with the governing code and fail to make the proper repairs, then fines and investigations will ensue from the provincial or federal governments, giving them a stake in the outcome of this project.

Another act that needs to be considered throughout the project timeline is the Canadian Environmental Protection Act (CEPA) (Canada 2023). The CEPA is an act that is intended to prevent pollution, protect the Canadian environment, and support sustainable development (Canada 2021). The CEPA governs many new and existing substances that are produced in Canada or imported for commercial use, and whether these substances pose a risk to human health or the natural environment (Canada 2009). The NetZero residence design will have to comply with the CEPA, specifically the materials used for the design and what they are composed of.

The Accessibility for Ontarians with Disabilities Act (AODA) (Ontario 2016a) is another provincial act that will have a major impact on the design of the NetZero residence building. The goal of the AODA is to remove all barriers and difficulties for those with disabilities, so they can live their lives independently. As part of the AODA, the Integrated Accessibility Standards Regulation (IASR) (Ontario 2016b) introduced five standards:

1. Customer Service
2. Design of Public Spaces
3. Employment
4. Information and Communication
5. Transportation

The second standard, Design of Public Spaces, is in charge of the design of physical features in public space (Queen's University 2023). While this standard, along with the rest of the AODA does not directly affect the design of buildings, it does cover items such as on and off-street parking, waiting areas and service counters, as well as exterior travel paths which include stairs and ramps to buildings. All of these topics must be considered when designing a new residence building. The remaining four standards will have an effect on the residence building, but to a lesser extent. As mentioned previously, the AODA and underlying regulations do not affect the design of buildings, however the Ontario building code has included certain design requirements for accessibility, which apply to all new buildings or buildings under extensive renovations (Ontario 2021). These design requirements include:

1. Barrier-free access paths
2. Fire safety devices
3. Public washrooms
4. Access to pools and saunas
5. Seating in public spaces

The design of the NetZero residence building must follow these design requirements for accessibility in order to create a space that can accommodate people of all abilities.

6.5 Indigenous Communities

The Queen's University campus is located on traditional Anishinaabe and Haudenosaunee lands, and as such the NetZero residence will be built on these lands. Therefore, representatives from these peoples must be consulted with throughout the entire design and construction process. There are various ways that indigenous communities can be included in the design process, such as designing spaces within the residence building dedicated to indigenous culture, giving the residence an indigenous name (Rideout 2023), or even employing indigenous people to aid in the design process of the building. Indigenous groups getting the opportunity to aid in the design process of a Queen's University residence building will vastly improve the relationship between Queen's and indigenous groups and will highlight the university's dedication to reconciliation.

6.6 Contractors and Subcontractors

While the scope of this project is focused around creating a viable NetZero design, contractors and subcontractors that would build the residence will be a stakeholder of the project as the final design needs to be feasibly constructable, with workable materials, a realistic timeline, and safe working conditions. Another consideration would be whether the contractors are familiar with the materials and technology that will be used for the residence, as the contractor's abilities must be placed in consideration to build the residence efficiently. It may also be the case that the contractor will require specific certifications or training to build the residence, depending on the method of construction and materials. This could affect the team's ability to find a suitable contractor, as there may not be a company in the area that is able to complete a project of this scale. If there are not any contractors in the area that are able to complete the work, then a contractor from elsewhere the proper abilities and certifications will need to be brought in, potentially causing another host of issues such as budget, lodging for the workers, scheduling issues, etc.

7.0 Constraints

In the design of a NetZero carbon emission student residence, numerous constraints and considerations demand thoughtful consideration and innovative problem solving.

7.1 Cost and Budget

Establishing a budget is essential for this project, giving the client a comparison of overall price in comparison to a non-NetZero build. This budget should consider sustainable material costs, energy-efficient technologies, and costs of labor. Additionally, this budget should provide leeway for any fluctuations in material and construction costs. A contingency fund will be set in place as unforeseen challenges or changes in the project scope can arise during the construction phase. While the overall cost and budget should be taken into close consideration, the importance is placed on maintaining the sustainability factor of the building. If the cost were to rise, this shouldn't prevent the design from being feasible.

7.2 NetZero Carbon Design

Implementing the necessary energy-efficient technologies and renewable energy systems can lead to a significant increase in upfront construction costs. Incorporating state of the art energy efficient technologies, procuring renewable energy systems, and utilizing sustainable construction materials often come at a premium when compared to a conventional approach to building. NetZero design often involves the use of innovative technologies, some of which are still in their preliminary stages of development. Assessing the reliability and availability of these technologies is crucial to mitigate risks to the project's success. It is important to consider the energy sources of the design. Selecting renewable energy sources such as solar panels, wind turbines, or geothermal systems could be constrained by factors such as available space, local climate, and initial costs. Finding the right balance between achieving carbon neutrality and managing these limitations is a complex task. Moreover, sustaining a NetZero carbon building throughout its lifecycle demands ongoing investment in maintenance and operational expertise. This ongoing investment could also include the potential for upgrades in products as technology advances and becomes more efficient. Not only does the operation and maintenance require financial resources, yet also a commitment to prolonged monitoring. This prolonged monitoring will be completed at the request of the client, Queen's Facilities.

7.3 Building Code

Designing this residence on Queen's University's campus in Kingston, Ontario, requires an understanding of local building codes and regulations that may serve as potential constraints. Understanding of both the Ontario Building Code (OBC) and the National Building Code of Canada (NBCC), which influence construction standards, is required (Canada 2022). The OBC serves as Ontario's primary regulatory system, highlighting structural design, fire safety, accessibility standards, and specific energy requirements (Ontario 2023b). An understanding of both the Ontario Building Code (OBC) and the National Building Code of Canada (NBCC), which influence construction standards, is required (Canada 2022). Additionally, local zoning bylaws and environmental regulations are often in place to preserve Kingston's natural beauty. These local bylaws can dictate land use, building height, and environmental protection measures. To add to this, Queen's University has their own set of building requirements, which are implemented on all new construction on campus. Working in close compliance with all these requirements will help to lead to an effective and successful design.

7.4 Design Manuals and Standards

The design of the structural members will be in accordance with Section 7 of the Canadian Standards Association (CSA) O86-19, which provides rational approaches for structural design checks for engineered wood structures (Canadian Standards Association Group 2019). The Canadian Wood Council represents the Canadian wood products industry through a national federation of associations (FPInnovations 2019). This project will consider the 2020 Canadian Wood Council Wood Design Manual for the design of glulam structural members. This design manual aids in the design of typical engineered wooden products in accordance with Part 4 of the 2020 NBCC and the entirety of the CSA O86-19 (Canadian Standards Association Group 2019).

7.5 Time

Designing a NetZero carbon student residence by a team of four students, all with demanding course schedules, poses a considerable time constraint. With a limited period to complete the project of eight months, efficient time management will prove crucial in the success of the design. To ensure progress and satisfy the clients' expectations, the team will establish a well-structured schedule that accommodates the availability of team members, the project manager (TA), and the client. Regular team meetings will be organized twice a week to facilitate collaboration and effective decision making. These meetings will help to serve as checkpoints for reviewing progress, sharing insight, and addressing any challenges in a prompt manner. Additionally, the use of technology and collaboration tools will help to streamline communication, allowing us to maximize productivity within this constrained period of time.

7.6 Technical Proficiency

The technical proficiency of a team of undergraduate engineering students may introduce certain constraints to the project. While they provide fresh perspectives and innovative ideas, they may lack the depth of experience and expertise that experienced engineers possess. This constraint could potentially lead to a steeper learning curve, requiring additional time in researching and understanding complex sustainability technologies. The team has a limited knowledge base and experience in using advanced engineering modelling tools such as Revit or AutoCAD. This constraint could potentially affect the efficiency in drafting detailed plans and models, leading to longer periods of time spent on this portion of the project. However, having a willingness to acquire new skills and familiarity with digital technology may help to mitigate the effects of this constraint. Balancing academic commitments with the demands of the project may limit the time and focus put towards creating detailed models and/or design calculations.

7.7 Physical Space

The physical space allocated for the design may pose constraints. The parcel of the residence on Queen’s University’s Campus, will be located on Stuart St, adjacent to McLaughlin Hall, refer section 9.1 Decision Making, Location, for a detailed breakdown of the site. The specific site’s characteristics, such as its surroundings, topography, and existing structures, will play a significant role in dictating the design parameters. Adhering to these spatial constraints while accommodating the NetZero goals will require innovative solutions to optimize space. The shape and size of the residence have been determined (see decision making for further explanation), ensuring complete adherence to all local zoning regulations. We note that these constraints may serve as an opportunity to heighten boundaries of sustainable design within a defined space.

7.8 Material Procurement

Material procurement will undoubtedly become a significant constraint in the design. It heavily relies on the availability of sustainable building materials within the local supply network. If specific eco-friendly materials are not readily available from local sources, it may require longer lead times and the possibility for additional costs in transportation and organization. Furthermore, the logistical appropriateness of these materials is crucial, as some sustainable options may not align with construction methods or requirements of the selected location. This could potentially lead to an added layer of complexity within the material procurement process.

8.0 Design Alternatives

Alternatives were collected to start the decision-making process for elements of the building design.

8.1 Structural Design Alternatives

8.1.1 Two-Way CLT Panels

Mass timber construction presents multiple alternatives to the load bearing floor system. CLT panels carry loads in both directions due to their cross lamination and because of this, CLT panels can be used as two-way slabs. This has allowed engineers to utilize CLT panels in the load bearing system in a manner that negates the need for beams ("Glulam Handbook Volume 1" 2013). Designs that only include CLT panels and no beams have been proven to reduce the cost and increase the constructability of the design (Naturally Wood 2018). A design that utilized the two-way effect of CLT beams is the design of the Brock Commons building in Vancouver, British Columbia. A graphic of the design can be seen A graphic of the design can be seen in Figure 8.

FIGURE 8: COLUMN AND TWO-WAY CLT PANEL SYSTEM IN THE BROCK COMMONS BUILDING (BROCK COMMONS)

When timber slabs span over columns, it is critical that the compressive forces from the columns do not transfer into the slabs. This could cause shear failure of the slabs and could result in fatalities. This design would adopt a similar connection design as used in the Brock Commons building, as explored in Section 5.3.1. To ensure that the compressive forces transfer from column to column, a round hollow steel structure spans from the top of the column to the top of the slab height. The columns connect to the hollow structure via a steel plate that connects to the column through epoxied steel threaded rods (Wood-Works 2017). This connection design is structurally safe, while allowing a seamless aesthetic from column to floor. Figure 9 and Figure 10 display this connection.

FIGURE 9: COLUMN TO COLUMN CONNECTION FOR BROCK COMMONS BUILDING (NATURALLY WOOD 2018)

FIGURE 10: CROSS-SECTION OF THE COLUMN TO COLUMN CONNECTION IN THE BROCK COMMONS BUILDING (NATURALLY WOOD 2016B)

It should be noted that this floor system requires collaboration between the engineers, the contractors, and the manufacturers to ensure that the panel-to-column connections are adequate.

Although appearing simple, this type of system requires complex analysis, restrained panel dimensions, and a restrained column layout. The design of a two-way CLT panel is dependent on the dimensions of the panel, which constraints the column layout, consequently affecting the floor plan of the building. A regular two-way panel system consists of approximately rectangular panels that support primarily uniform gravity loading (FPInnovations 2019). According to Section 3.5.4 of the *Canadian CLT Handbook*, to act as a two-way panel, the ratio of the longer to the shorter span, center-to-center of the supports must not be greater than 2.0 (FPInnovations 2019). Additionally, the column offsets must not be greater than 20% of the span from either axis between the centerlines of successive columns (FPInnovations 2019). These geometric limitations must be considered when choosing to use a two-way CLT panel system. Additionally, the Canadian CLT Handbook notes that the calculation of bending moments and deflections for two-way panels is quite complex. Often the complexities of the design outweigh the benefits of the two-way action and a one-way system results in a more conservative solution (FPInnovations 2019).

8.1.2 Column and Beam

A more conventional approach to a mass timber gravity load bearing system is the use of a column and beam system. The system is comprised of beams spanning from column to column with a decking system on top of the beams. An image of this load bearing system can be seen in Figure 11.

FIGURE 11: COLUMN AND BEAM SYSTEM (“GLULAM HANDBOOK VOLUME 1” 2013)

Typically, glulam is the preferred material for both the columns and the beams and CLT is used for the floor panels (Mirski et al. 2021). Glulam is commonly stronger than and has a greater stiffness than comparably sized dimensional lumber (Mirski et al. 2021). This design reduces the need for precise manufacturing of mass timber products; however, it increases the time of construction when compared to using a system composed of just columns and CLT panels. This is because there are more elements that must be connected for each floor.

8.1.3 Continuous Column Design vs. Continuous Beam Design

This project will consider two options when using a column and beam system, whether to have continuous columns, or to have continuous beams. A design with continuous columns requires the beams to be attached to the sides of the columns. This results in a series of one span fixed support beams. Depending on the height of the building, a continuous column design can consist of more than one column, as there are manufacturing limits to the height of glulam columns. Additionally, there are limits to the slenderness of glulam columns, which is a parameter that relies on the height of the columns, as set out by the Wood Design Manual (Canadian Wood Council 2020). A design with continuous beams involves beams spanning the width of the building, interrupting the columns. As compressive loads increase from the top of building to the bottom of the building, having discontinuous columns allows for better optimization of column dimensions from floor to floor. If the span of the beam is long, having a continuous beam can cost more than having multiple single span beams (“Glulam Handbook Volume 1” 2013). Additionally, most glulam beams have higher tension capacities on the bottom of the cross-section. This is done to optimize the required strength of the beam against positive bending, which results in high tension forces at the bottom of the beam. So, to use continuous glulam beams, the engineer must ensure that the beam is manufactured to resist moments in both positive and negative bending, since continuous beams undergo both types of bending. This can increase the cost and lead time of the product.

This project will consider two options for glulam column to beam connections. One option is to utilize notches in the column and have beams connected through partially threaded screws. This connection can be seen in Figure 12.

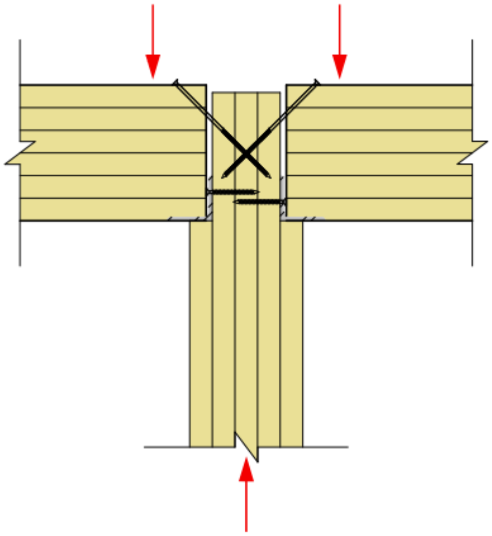

FIGURE 12: BEAM TO COLUMN SCREWED CONNECTION (WOODWORKS 2021)

This design is aesthetically pleasing, as views from inside the building do not show any steel in the connection. However, this connection is constrained by the perpendicular-to-grain strength of the beam. Additionally, this connection could require an increase in optimal column dimensions to achieve adequate bearing strength (WoodWorks 2021). This means that this connection could require the building's columns to be larger than they must be to carry its compressive loads. Since this connection rests on the top of a column, it could not be chosen for a continuous column design.(WoodWorks 2021).

An alternate connection design involves the use of steel bearing plates with bolts fixing the two beams to the column. This connection is shown in Figure 13.

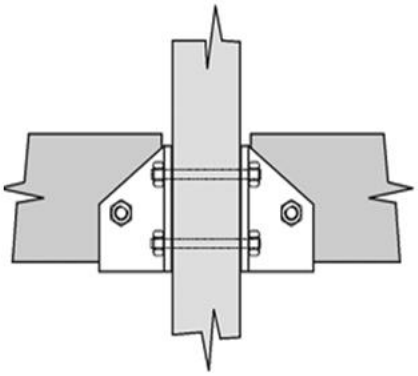

FIGURE 13: BEAM TO COLUMN CONNECTION USING STEEL BEARING PLATES (WOODWORKS 2021)

This design is dependent on the perpendicular-to-grain bearing capacity of the beam at the bearing plate. Aesthetically, this connection is less desired due to the exposed steel connection. Since this connection does not rest on the top of a column, it is a viable option for a continuous column design.

8.1.4 Elevator and Stair Shafts

This design will consider concrete or CLT elevator and stair shafts. Concrete is the industry norm for elevator shafts. It is readily available, and contractors are familiar with constructing concrete shafts. However, a concrete elevator shaft will negatively affect the NetZero carbon performance of the design. Replacing a concrete shaft with a CLT shaft would have a significant impact on the carbon performance of the building. Due to the panelized design, CLT shafts take only hours to days for installation, when concrete shafts can take up to a month (Henjum et al. 2021). Compared to concrete designs, a CLT design requires fewer inspections and involves less trades to complete its construction. However, it is critical to detail the CLT shaft to meet minimum code requirements and to impact the ease of construction. Therefore, it is important that the engineers, contractors, and manufacturers work collaboratively when choosing a CLT design for elevator and stair shafts.

8.2 Substructure Design Alternatives

8.2.1 Foundation Types

The loads from the main structure of the residence building will need to be transferred to the ground surface via a foundation system. There are two main classes of foundations to select from, deep foundations and shallow foundations. Shallow foundations are a suitable choice when the surface soil has sufficient load bearing capacity. Deep foundation may be required in cases where the surface soils are weaker, and deeper soil or bedrock needs to be accessed for the required foundation strength (Budhu 2011). There are various forms of shallow foundations, which include:

- Strip footings
- Isolated footings
- Combined footings
- Cantilevered footings
- Raft foundations

For deep foundations, piles foundations or caissons are most commonly used. Piles make use of materials such as steel and wood, and are driven into the ground. Caissons, also referred to as bored piles or drilled shafts, are when a shaft is drilled into the soil, and then filled with concrete and steel reinforcement (Budhu 2011).

8.3 Location Design Alternatives

In terms of the location of the residence building, multiple areas on the Queen's campus were proposed, according to part two, chapter nine of the Queen's University Campus Master Plan (Queen's University Facilities 2021). This chapter of the master plan splits up the campus into different precincts, ranging from precinct one to precinct five for the main campus, and designates certain areas for potential development. The master plan also provides valuable information such as minimum and maximum floor area and potential land uses. Three locations were selected for evaluation from these precincts: area 1D, area 4C, and the area just south of area 2A. These sites can be seen in Figure 14: Highlighted plan view of site 1D (Queen's University Facilities 2021)., Figure 15, and Figure 16.

Figure 14: Highlighted plan view of site 1D (Queen's University Facilities 2021).

Figure 15: Highlighted plan view of site 4C (Queen's University Facilities 2021).

Figure 16: Plan view of third potential location, between site 2A and 4A (Queen's University Facilities 2021).

While this third location mentioned was not officially designated by the master plan, the client recommended it as a potential area for a new residence during a bi-weekly client meeting and was therefore considered a viable choice.

8.3.1 Area 1D

Area 1D is located in the north-east corner of the Queen's campus, between the corners of Clergy St W and Division St, and Clergy St W and Barrie St. It is north of Dupuis Hall and east of the Athletic Recreation Centre (ARC). There are currently seven occupied buildings on the site that would need to be demolished in order to make use of this site. The permitted uses of this site include a new residence building, as well as an administrative building. The maximum gross floor area for this location is 10613 m^2, ample space for a new residence building.

8.3.2 Area 4C

Area 4C is located on the south side of Stuart St, with Leggett Hall to the west and McLaughlin Hall to the east of the site. Multiple buildings are located on the site, including the LaSalle building, a portion of the University Club building, and 140 Stuart St. The Film Studies building seen in Figure 15 has already been demolished as of the writing of this report. According to the Campus Master Plan, the permitted uses for this site are academic uses, student life spaces, and below grade parking. Student residence is not mentioned as a permitted use; however, this does not mean that the site cannot be reevaluated in the future for use as a student residence. The max gross floor area for site 4C is 16097 m^2.

8.3.3 Third area

The third area is located on Albert St between areas 2A to the north and 4A to the south across Queen's Cresent. As mentioned previously, this location is not a designated area for development in the Campus Master Plan, however this location was highlighted during a client meeting discussing potential residence locations. In order to prepare this plot of land for construction, multiple occupied houses would have to be demolished. Currently, as seen in Figure 16, there are house located in this area that are not owned by Queen's University. Therefore, the university would have to acquire this land and property in order to construct a residence at this location. While not ideal, the client has expressed during a previous meeting that this land can be acquired if needed.

9.0 Decision Making

As the project has progressed from the initiation phase to the design and development phase, decisions have been made to create the preliminary design concept. Choices such as the ideal location of the residence, shape of the building, materials and methods used for superstructure and substructure construction, and dimensions of the building were evaluated and decided upon.

9.1 Location

To determine which of the three previously mentioned location options would be ideal, a weighted evaluation matrix was used. The following criteria were considered when creating the matrix:

- Proximity to other student residences
- Proximity to dining halls/food hubs
- Availability/suitability for residential development

- Size of parcel/available development space
- Construction access/disturbance
- Existing conditions/Site preparations

The selection criteria were weighted on a scale of one to five, with one being the lowest weighting, considered fairly unimportant, and five being the highest weighting, considered extremely important. A one to five scale was used to grade the site alternatives for each criterion, with a one being the lowest grade, and a five being the highest grade. A site alternative receiving a one would mean that it does not fit the criterion well at all, and a five would mean that it fits the criterion extremely well. Table 3 shows the weighted evaluation matrix of the site alternatives.

TABLE 3: WEIGHTED EVALUATION MATRIX FOR LOCATION OPTIONS

		Site Alternatives		
Criteria	**Rank**	Albert	Lasalle/Film	Clergy/Division
Proximity to other student residences	4	5	5	1
Proximity to Dining halls/Food hubs	5	5	4	2
Availability/suitability for residential development	3	2	2	4
Size of parcel/available development space	4	1	5	3
Construction access/disturbance	5	3	2	5
Existing conditions/Site Preparations	2	4	3	4
Total:	/	78	82	71

As can be seen in Table 3, site 4C, the area containing the LaSalle building and the Film Studies building, scored the highest and as such was chosen as the ideal residence location moving forward.

9.2 Gravity Load Bearing System

To decide on a gravity load bearing system, the two-way CLT panel design and the column-and-beam design were evaluated against criteria relating to stakeholder needs. Each criterion was assigned a weight, from one to five, as to how important the criterion is to achieving an effective design. The criteria for this evaluation included:

- Cost
- Ease of construction
- Carbon performance
- Design simplicity
- Procurement/Lead time

The cost of the system was given a weight of 4, as this system will compose a significant amount of the cost of the building design and cost is important for the stakeholders. The ease of construction was given a 3, as it will affect the time of construction, but it was not deemed to be more important than a 3, relative to the other criteria. The carbon performance of the system was given a 5 since the success of this design is reliant on the carbon performance of the design. The design simplicity was given a 4. This is because it impacts the time of design and the feasibility of the design, especially given the teams limited structural design experience with two-way systems acting as beams. The procurement/lead time was given a weighting of 4, because it impacts cost and feasibility of design. The weighted evaluation matrix can be seen in Table 4.

TABLE 4: WEIGHTED EVALUATION MATRIX FOR GRAVITY LOAD BEARING SYSTEM ALTERNATIVES

Gravity Load Bearing System Alternatives			
Criteria	Weight	Two-way CLT panel	Column-and-Beam
Cost	4	4	3
Ease of construction	3	5	3
Carbon performance	5	4	4
Design simplicity	4	1	4
Procurement/Lead time	4	2	4
Total:	-	63	**73**

The column and beam system outperformed the two-way panel system when evaluated through the aforementioned criteria and it was chosen for the design of the building's gravity load bearing system. Due to the lack of need for beams, the two-way panel system would be more cost effective, and it would be easier for the contractors to construct. However, the complexity of the two-way panel design would not only be challenging for structural analysis, but it would require the columns to be closely spaced in a grid pattern. This would alter the room dimensions and could result in a wider building than needed, given the standard dimensions of residence rooms at Queen's University. This is not favorable for the project as the proposed design is to be compared to the Endaayaan – Tkanónsote building at Queen's University; therefore, it would be ideal to mimic the current dimensions of the Queen's residence building. Another reason why the column and beam system outperformed the two-way panel system is because the two-way panel system requires precise manufacturing, and this increases lead time.

9.3 Continuous Beams vs. Continuous Columns

With the gravity load bearing system decided upon, the decision to use a continuous beam, or a continuous column design was determined through an evaluation of the two options. The criteria from the evaluation of the gravity load bearing system were used, with the same weights assigned to each criterion. The weighted evaluation matrix can be seen in Table 5.

TABLE 5: WEIGHTED EVALUATION MATRIX FOR CONTINUOUS BEAM DESIGN VS. CONTINUOUS COLUMN DESIGN

Continuous Beam vs. Continuous Columns			
Criteria	Weight	Continuous Beam	Continuous Column
Cost	4	3	4
Ease of construction	3	4	4
Carbon performance	5	4	4
Design simplicity	4	3	4
Procurement/Lead time	4	3	4
Total:	-	68	**80**

The continuous column design outperformed the continuous beam design in the evaluation matrix and was chosen for this project. A design that uses continuous beams could cost more, as the beams have long spans and must be manufactured to resist bending in both directions. This generally costs more than using smaller span beams that are optimized for positive bending (APA Wood 2017). Since continuous beams undergo both positive and negative bending, this makes the design of the beams more challenging. Additionally, due to the simplicity of the continuous column design, the simply supported beams would be easier to procure, with less lead time. This is due to the availability of smaller span and positive bending resistant glulam beams (APA Wood 2017).

It should be noted that since a continuous column design has been chosen, the connection design option to have the beams screwed into the top of the column, as seen in Figure 12, is not feasible, as previously explained. Therefore, the connection design seen in Figure 13 was chosen for the beam to column connections.

9.4 Stair and Elevator Shafts

The elevator shaft design was determined through an evaluation between a concrete design and a CLT design. The criteria from the evaluation of the gravity load bearing system were used, with the same weights assigned to each criterion. The weighted evaluation matrix can be seen below in Table 6.

TABLE 6: WEIGHTED EVALUATION MATRIX FOR ELEVATOR AND STAIR SHAFT DESIGN

Stair and Elevator Shaft Design			
Criteria	Weight	Concrete	CLT
Cost	4	3	4
Ease of construction	3	2	5
Carbon performance	5	1	5
Design simplicity	4	4	2
Procurement/Lead time	4	4	2
Total:	-	55	**72**

The CLT shaft design outperformed the concrete design in the evaluation matrix and was chosen for the project. Although a concrete shaft results in a simpler design and easier procurement, the needed volume on concrete for the design would be detrimental to the zero-carbon aspect of the building. The panelized CLT shaft design is easier to construct and will reduce the time of construction. A CLT shaft is cheaper than a concrete shaft (Henjum et al. 2021). Additionally, the use of CLT for an elevator shaft is innovative, which makes the project more effective, helping to satisfy one of the stakeholder's needs of innovation.

9.5 Shape

Once the ideal location was determined, the proposed shape of the NetZero residence building was determined. As the recently completed Endaayaan – Tkanónsote residence building is being used as a base case for comparison in terms of embodied carbon, it was decided by the team to model the shape of the proposed NetZero residence building similar to that of the Endaayaan – Tkanónsote residence building.

The Endaayaan – Tkanónsote residence is made up of multiple rectangular sections that wrap around a large courtyard, with an opening to said courtyard south of the main entrance. Two pre-existing houses were also incorporated into the Endaayaan – Tkanónsote residence design and shape. The NetZero residence building will take a similar shape, making use of rectangular sections that wrap around a central courtyard, with an opening on the west side of the building. This opening will be two storeys high, with a walkway connecting the wings of the building for the remaining storeys. There will also be an archway entrance to the courtyard from the front of the building, which faces Stuart Street. This archway will work similarly to the west courtyard entrance, where the opening is only for the first two storeys, and a walkway connecting the remaining storeys.

Other building shapes were considered, including a rectangle, square, and an L-shape. These options had advantages compared to the chosen shape, mainly ease of structural design and analysis and space considerations. However, it was determined that in order to make the comparison between the NetZero residence and the Endaayaan – Tkanónsote residence as accurate as possible, a similar shape should be used.

9.6 Dimensions

The dimensioning of the proposed residence building was another topic that was considered, as the dimensions of the building dictate the capacity and height of the building. The overall building dimensions were determined based on the space of the chosen location as well as the previously determined shape of the building. Dimensions of interior features such as rooms, hallways, stairwells, etc., were determined through a comparison with the Endaayaan – Tkanónsote residence. Using the interior dimensions of the Endaayaan – Tkanónsote residence as a basis for the dimensions of the proposed residence allows the embodied carbon comparison to be completed more accurately, as the embodied carbon could be compared per unit or per floor. This will prove to be a valuable metric to determine the overall success of the project.

9.7 Substructure Materials

A comparison between the traditional concrete mix and Lafarge's ECOPact concrete mix was conducted to determine which mix would provide the most benefits for the NetZero residence building. This comparison was done using a weighted evaluation matrix. Criteria used for the evaluation include:

- Cost
- Availability
- Embodied Carbon
- Constructability

As with previous evaluation matrices, a scale of one to five was used for both the weighting and the score of each alternative. For the scoring, five is the highest grade and 1 is the lowest.

TABLE 7: WEIGHTED EVALUATION MATRIX FOR CONCRETE MIX OPTIONS

Concrete mixes			
Criteria	Weight	Traditional mix	ECOPact mix
Cost	5	4	2
Availability	4	5	5
Embodied Carbon	5	1	4
Constructability	2	4	4
Total:	-	53	58

From Table 7, it can be seen that the ECOPact concrete mix is the ideal foundation material for the NetZero residence, as it reduces the embodied carbon of the concrete, aiding in the efforts to make this residence building net-zero.

9.8 Foundation Types

As mentioned previously, there are two main foundation types that could be utilized for the NetZero residence: shallow foundations or deep foundations. To determine which foundation type would be ideal for the residence, the soil profile of Kingston and the surrounding area was consulted. In general, the depth of soil to limestone bedrock is only a few metres in the Kingston area, and as such a deep foundation solution will not apply. Therefore, a shallow foundation solution is the only feasible choice for the Endaayaan – Tkanónsote residence.

10.0 Proposed Design

10.1 Floorplan and Location

An established floorplate was built based on the available space of site 4C and the selected shape. The preliminary design dimensions are 80 m on the North face, 45 m on the South Face, 45 m on the East face, and 32.75 m on the West face, as shown in Figure 17 below.

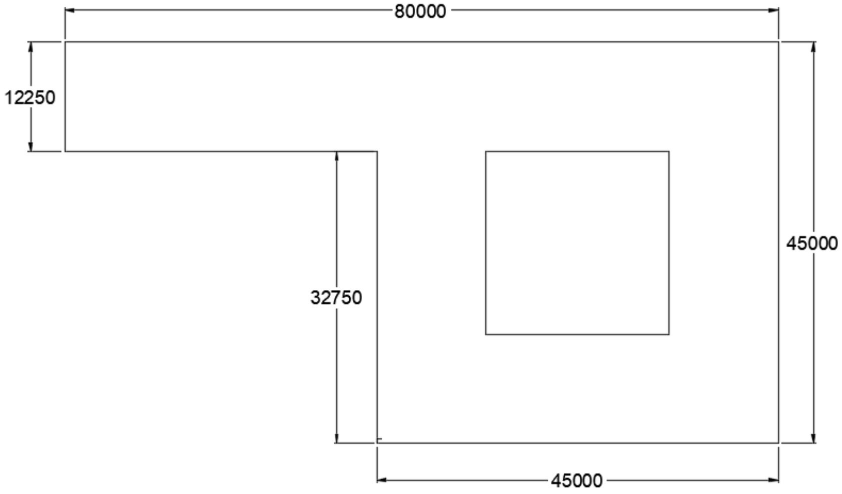

FIGURE 17: PRELIMINARY DESIGN DIMENSIONS

The selected design is located North of King Street W. between Leggett Hall and McLaughlin Hall. This space is currently occupied by two buildings including the Lasalle Building and 140 Stuart Street. Both buildings are owned and operated by Queen’s University, which eliminates the need for any form of property acquisition. The 2014 Queen’s campus master plan recommended demolishing up to 2/3 of The University Club. After consultation with the client, it was decided that this building should be preserved if possible. Demolition of the existing site is currently outside of the scope of this project and will need to be reviewed separately before moving forward with building the new innovative residence.

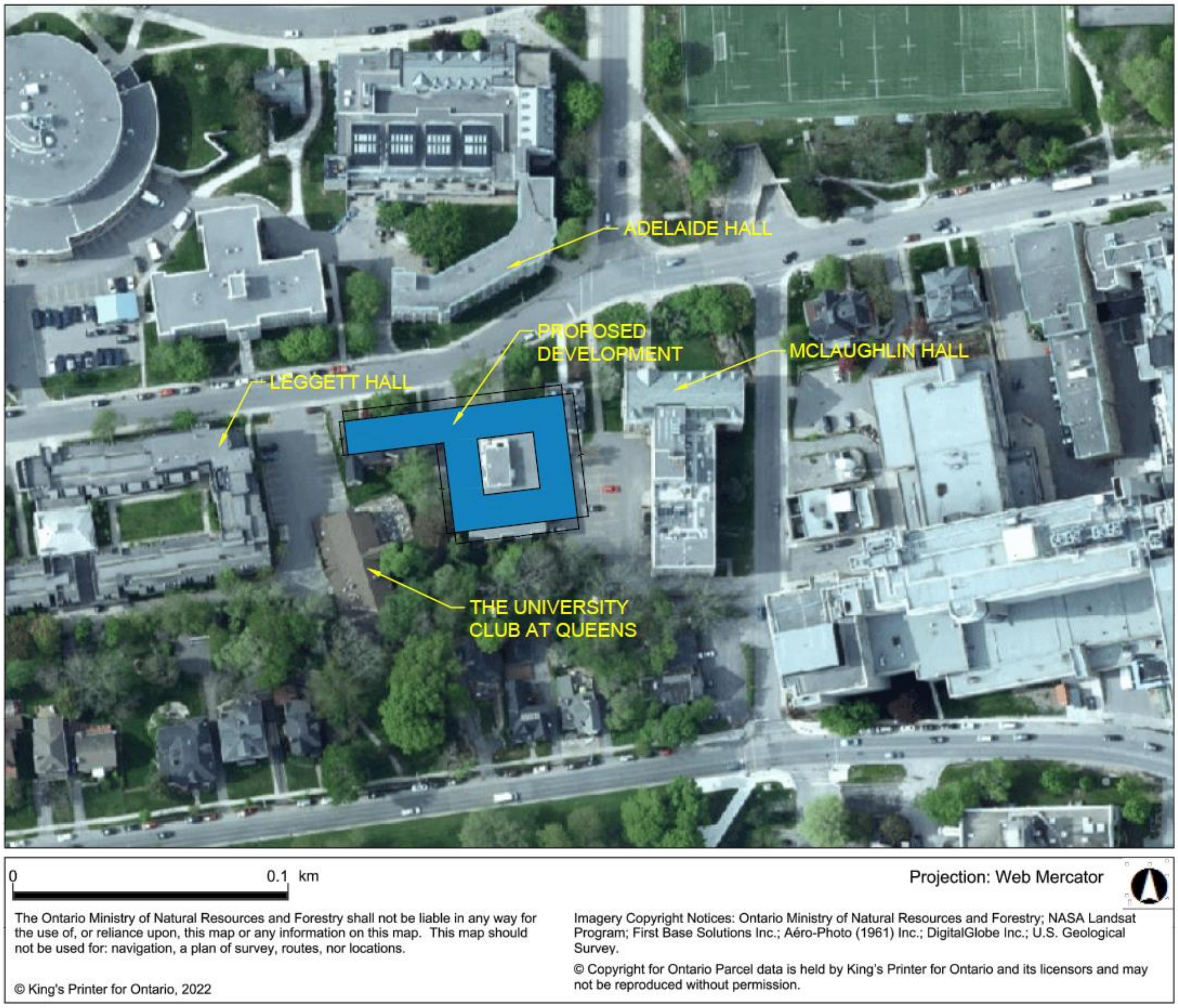

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Figure 18: Key Plan Of Site Showing Approximate Building Location

The selected shape yields a useable floor area of 1730 m^2. Scaling this result to the planned four storeys and basement results in a gross residential floor area of 8,650 m^2. This space will be primarily allocated towards combined single plus residence rooms, in accordance with the typical design of Queen's residence buildings constructed within the last 10 years. A single plus residence unit is composed of two single occupancy residence rooms with a shared washroom. An example layout of an upper-level floorplan can be viewed below in Figure 19.

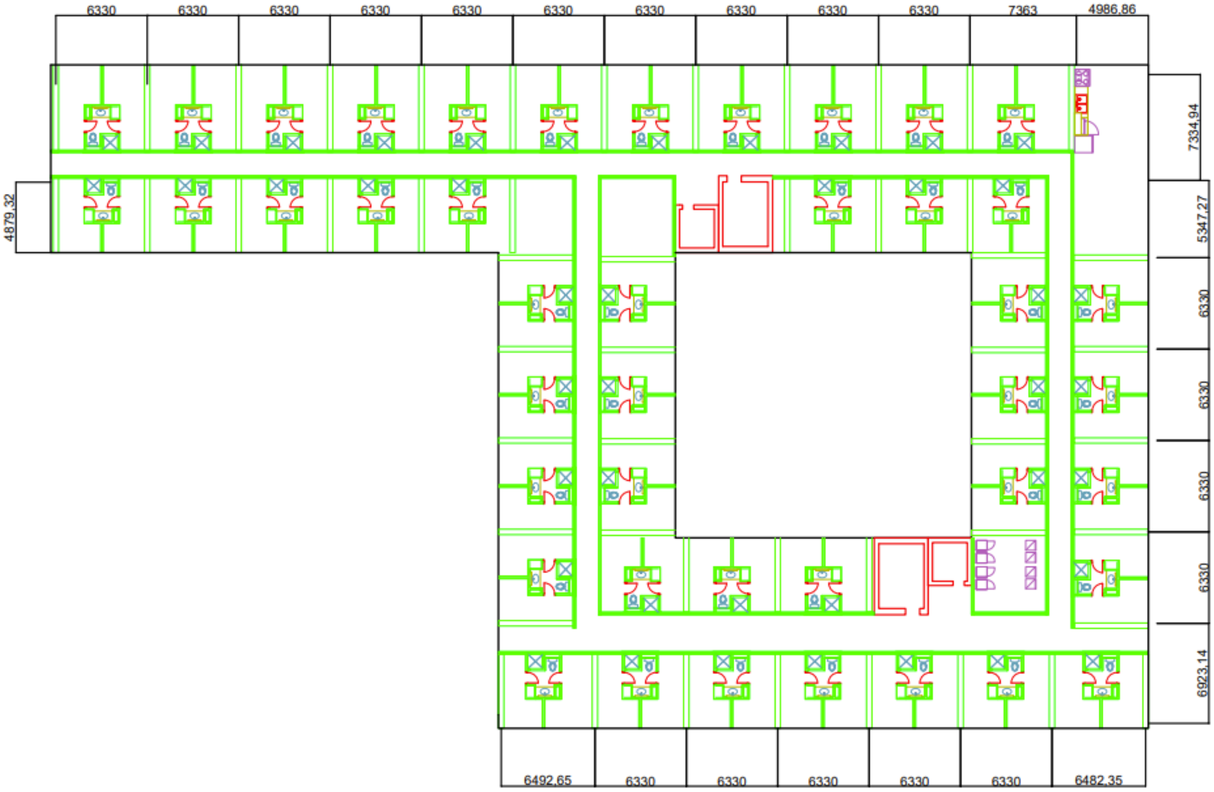


FIGURE 19: UPPER-LEVEL CAD FLOOR PLAN FOR BUILDING DESIGN

The current upper-level floorplan supports up to 42 units or 84 individual rooms. The first floor and basement will have a smaller allotment of units (36) given the space required for an entrance lobby. This results in a scaled five-floor preliminary design with a capacity of 396 beds. Other notable interior elements include laundry rooms, stairwells, elevator shafts, and common rooms. Each floor will be equipped with one common room, which serves as a communal gathering place for residents.

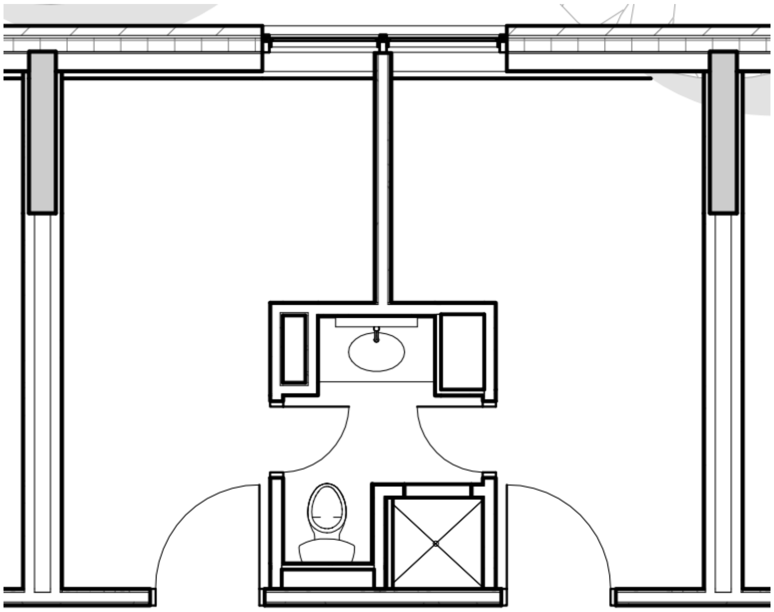


FIGURE 20: LAYOUT OF QUEEN'S "SINGLE PLUS" RESIDENCE UNIT (QUEEN'S UNIVERSITY 2024)

10.2 Innovative Design Elements for Further Consideration

The completed design concept incorporates innovative strategies to reduce its carbon profile to NetZero while ensuring that the livability of the residential space is maximized. These design innovations require further exploration and evaluation to ensure that they match the client needs and project requirements before they can be fully incorporated into the final design.

These innovations include but are not limited to environmentally friendly products such as hemp insulation, engineered wood cladding, solar energy generation, high efficiency interior light and plumbing fixtures, geothermal temperature management, and maximized natural lighting. As the design progresses beyond the current level of completion, these innovations should be assessed for feasibility and if deemed appropriate, included in the final building template.

- Hemp Natural Insulation
- Engineered Recycled Wood Cladding
- Building Integrated Photovoltaics (Solar)
- Combined Solar/Green Roof
- AI Optimized Lighting and HVAC Systems

10.3 Gravity Load Bearing System

10.3.1 Gravity Load Analysis

A gravity load analysis was necessary to determine the compressive forces that the columns had to resist. The load analysis was conducted in accordance with Section 4.1. of the NBCC (Canada 2022). The dead load for a structural member, from Section 4.1.4.1. of the NBCC, was considered to be the following:

- Weight of the member.
- Weight of partitions (cannot be less than 1 kPa).
- Weight of all construction materials in building that be permanently supported by the member.
- Weight of permanent equipment.

Without a detailed estimate of the partitions and permanent equipment for the building, the dead load used for the Endayaan-Tknasote design was taken. This was chosen based on the assumption that the building will be used for the same purpose as the Endaayaan – Tkanónsote building; therefore, having similar dead loads. This choice was conservative, as the self-weight of concrete, which was used for the Endaayaan – Tkanónsote building, is about 4-5 times greater than the self-weight of glulam (APA Wood 2017). The dead load for each floor was 1.35 kPa and the dead load for the roof was 3.25 kPa. In accordance with Table 4.1.5.3., the live load for each floor was 4.8 kPa and the live load for the roof was 1.0 kPa (Canada 2022).

The importance category of the building had to be concluded, with reference to Table 4.1.2.1. of the NBCC. Since the building does not provide a greater degree of safety to human life than a normal importance category building, the gravity load analysis was conducted using a normal importance category.

10.3.2 Snow Load

The snow load was calculated in accordance with Section 4.1.6. of the NBCC (Canada 2022). The building was assumed to be flat and not include an upper roof. The design ground snow load (S_s) and the design rain load (S_r) were taken from the climatic information tables in Appendix C of the NBCC. The snow load calculations can be seen in Appendix I. The snow load value was calculated to be 2.08 kPa.

The gravity loads that were used in the gravity load analysis are summarized in Table 8:

TABLE 8: SUMMARY OF GRAVITY LOADS IN KPA.

	Roof	Floor
LL	1.0	4.8
$DL_{superimposed}$	3.25	1.35
SL	2.08	-

10.3.3 Live Load Reduction Factor (LLRF)

The NBCC allows a reduction of the live load for tributary areas (TA) that are greater than 20 m^2 (Canada 2022). The tributary area of a column represents the area of the floor that the column must take the load from. According to section 4.1.5.8.c, the LLRF for an element with a tributary area between 20 m^2 and 80 m^2 is as follows:

$$LLRF = 0.3 + \sqrt{\frac{9.8}{B}} \leq 1.0,$$

where B is the tributary area. Due to the large number of columns in this building, it was determined that the column design would be divided into three categories, based on tributary widths. Columns were divided into the following categories: having a tributary area between 26.2 m^2 and 41.15 m^2, between 16.9 m^2 and 26.2 m^2, and under 16.9 m^2. These three thresholds categorize the tributary areas throughout the building well, based on the geometry of the floorplan layout. Ideally, each 75 columns would be optimized based on their tributary areas; however, this is unrealistic for such a large number of columns and would make procurement and construction more challenging. In the industry of structural design, it is common to even use just one dimension for columns throughout a residential floor (Jayachandran 2009). Figure 21 depicts the column designation throughout the floor layout.

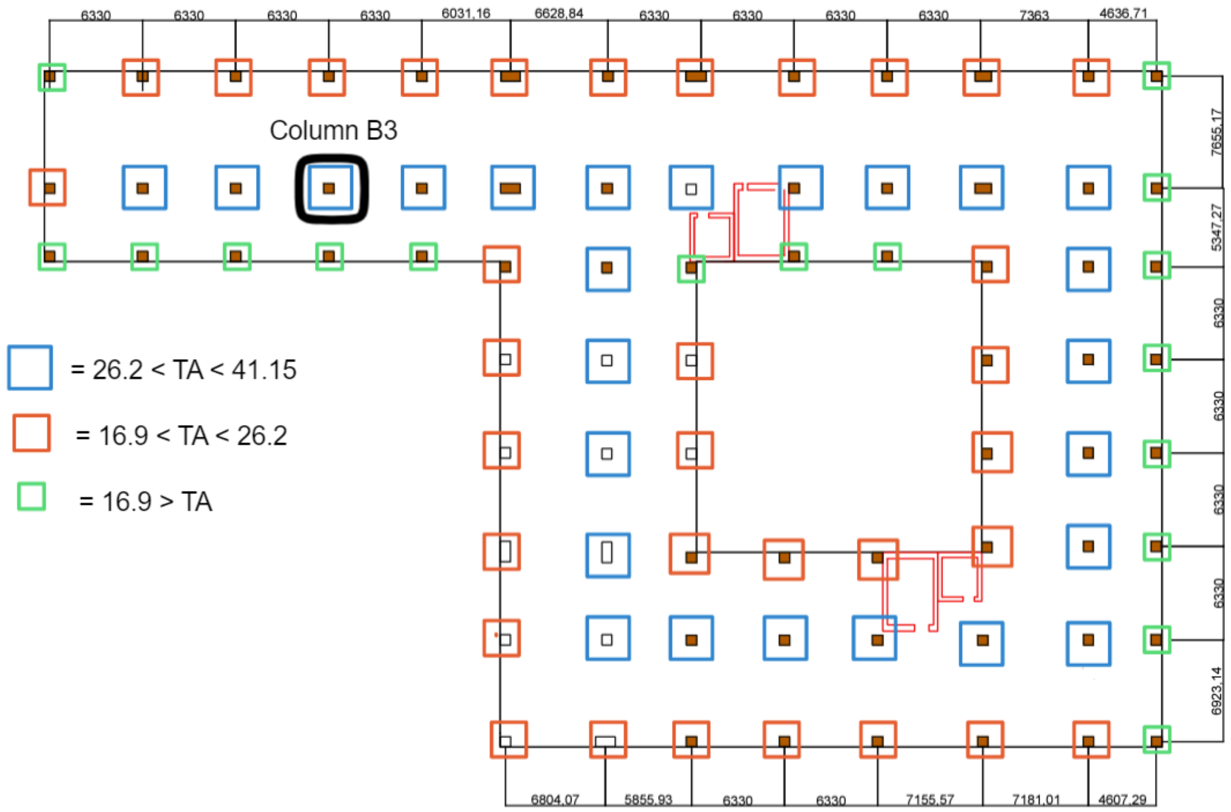


FIGURE 21: COLUMN LAYOUT DISPLAYING TRIBUTARY AREA IN M^2 DESIGNATIONS FOR EACH COLUMN.

An Excel spreadsheet was created to calculate the compressive forces of a column given a tributary width. This allowed the analysis of the compressive loads of each column to be conducted. A sample calculation for column B3 can be seen in Appendix II.

Table 9 displays the compressive forces for each tributary area category for each of the 5 floors.

TABLE 9: DESIGN COMPRESSIVE FORCES FOR EACH TRIBUTARY AREA CATEGORY

Column	**TA = 41.15 m^2**	**TA = 26.2 m^2**	**TA = 16.9 m^2**
4th Floor	336.7	214.4	138.3
3rd Floor	639.6	430.6	288.5
2nd Floor	857.8	579.1	438.7
1st Floor	1062.1	716.6	588.9
Basement	1259.2	848.3	739.1

10.3.4 Glulam Column Design

With the design compressive forces from Table 9, the glulam columns were designed, following the 2020 Canadian Wood Design Manual and the Canadian Standards Association (CSA) O86-19 (Canadian Wood Council 2020). As previously stated in Section 9.3, a continuous column design was used for the building. The design consisted of two columns, with one 10 m column spanning the basement, first floor, and second floor, and a 6 m column spanning the top two floors. This was determined to reduce the cost of the materials and of procurement. Utilizing two columns instead of a single, 16-meter expanse allows for a reduction in the total glulam volume required for each floor. This design efficiency arises because the upper floors are supported by a 6-meter column that can be less substantial in thickness than its 10-meter counterpart below. This differentiation is feasible due to the decreasing design compressive forces from the bottom to the top of the building.

Table 7.1 from CSA O86 shows two options for the type of timber to be used for glulam columns: Spruce-Pine, or Douglas-Fir-Larch (Canadian Standards Association Group 2019). Since Douglas-Fir-Larch is the stronger of the two and is available in Ontario, it was used for the design of the columns. The following assumptions were made for the design of the columns:

- The columns are in pure axial compression.
- The timber is in dry service condition.
- The timber was not treated.

In accordance with CSA O86 Section 7.5.8, an Excel spreadsheet was created to calculate the compressive resistance of any input dimension of column. This allowed for an efficient design process to come upon the most optimized design for each column. With compressive forces for each floor for the three categories of tributary areas, as seen in Table 9, the column selection tables in the Canadian Wood Design Manual were used to select an initial design. From there, the design was changed, based on its compressive resistance output from the spreadsheet, until the most optimized design was concluded. It should be noted that only the common dimensions given in CSA O86 were considered during the design process.

In addition to the compressive forces listed in Table 9, the dead loads from the self-weights of the glulam beams and columns had to be taken into consideration. This is because the dead load values that were used to get the listed compressive forces were the superimposed dead loads, which do not include the self-weight of the columns themselves and of the glulam beams. This step was taken after an initial design of the beams, since the rough volume of the beams had to be known. To get a load in kPa for the self-weight of the beams, the total volume of the beams was converted into a weight, using a density of 530 kg/m^3 (The Engineering ToolBox 2018). The calculation of the dead load from the beams can be seen below:

$$DL_{sw\ of\ beams} = Total\ Volume * \rho_{douglasfir} * \frac{1}{Total\ Area\ of\ Floor} * \frac{0.009807kN}{kg}$$

$$DL_{sw\ of\ beams} = 779.1\ m^3 * 530\frac{kg}{m^3} * \frac{1}{2035.9\ m^2} * \frac{0.009807kN}{kg} = 0.398\ kPa.$$

Additionally, the dead load from the self-weight of the columns had to be considered. This was conservatively done, by assuming that the largest chosen column was used for the self-weight of every column. A sample calculation of the dead load for the top floor, in kN, from a singular column can be seen below:

$$DL_{sw\ of\ column} = b * d * L * \rho_{douglasfir} * \frac{0.009807kN}{kg}$$

$$DL_{sw\ of\ column} = 0.315\ m * 0.304\ m * 3.0\ m * 530\frac{kg}{m^3} * \frac{0.009807kN}{kg} = 1.87\ kN.$$

During the design process, square columns were desired over more rectangular columns. This is because they perform better in lateral movement due to similar moments of inertias in each axis. Additionally, the columns have beams attached to them from both directions, so avoiding having thin sides to the column will mitigate issues with connections.

The key properties for the compressive resistance calculations for a glulam column are the elastic modulus and the compressive strength of the timber. These values were taken from Table 7.2 in CSA O86 showing 16 c-E Douglas Fir-Larch glulam having an elastic modulus of 12400 MPa and a compressive strength of 30.2 MPa (Canadian Standards Association Group 2019). A sample calculation of the compressive resistance of column B3 for the 10 m column, as seen in Figure 21, is displayed in APPENDIX. These calculations follow Section 7.5.8 of the CSA O86.

Table 10 displays the column designs for the three tributary area categories.

TABLE 10: GLULAM COLUMN DESIGN SUMMARY

TA (m^2)	# of columns	Width (mm)	Depth (mm)	Length (mm)
40.1	25	315	304	10000
	25	215	228	6000
26.2	33	265	266	10000
	33	175	190	6000
16.9	17	265	266	10000
	17	175	152	6000

10.3.5 Glulam Beam Design

The layout for the glulam beams on each floor consists of larger beams spanning the width of the building from column-to-column, and smaller glulam beams, acting like joists, spanning the opposite direction. Figure 22 displays this layout on one section of the building, with the design replicating this layout for the entire floorplate.

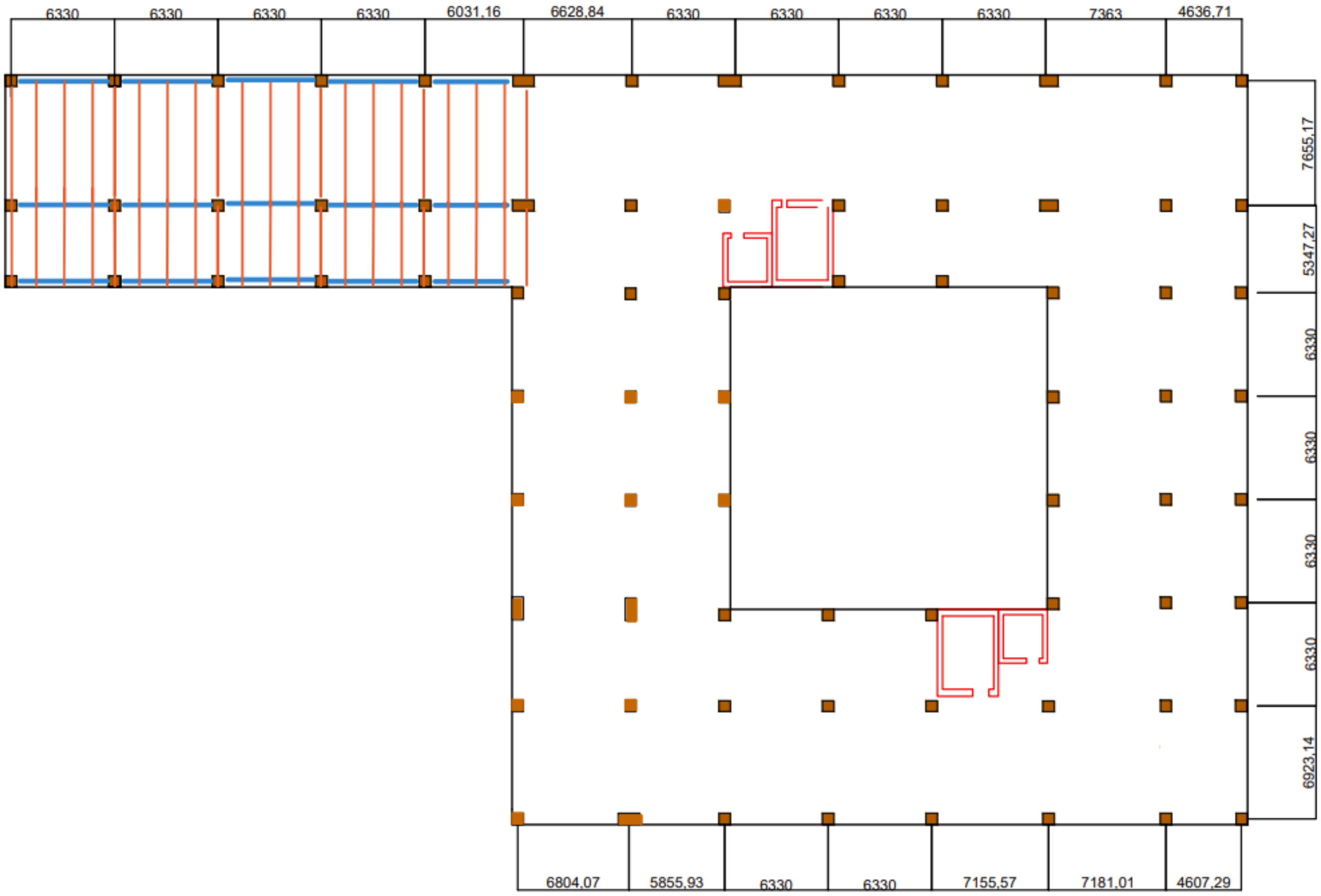


FIGURE 22: BEAM LAYOUT DISPLAYED ON ONE SECTION OF THE FLOOR LAYOUT.

With the columns in the building having followed a continuous column design, the beams; therefore, followed a single span design. This allowed each beam to be analyzed as a single span, simply supported beam. It was assumed that the load path to each beam could be analyzed as a uniformly distributed load. The uniformly distributed loads for each beam were a product of the tributary width (TW) of the beam and the loading in kPa on the floor. The tributary width of a beam represents the total adjacent width of the floor that the beam must take the load from.

Similarly to the design of the columns, the beams were broken down into categories to better strike a balance between optimization of materials and feasibility of procurement and construction. The key factors in the resistance of a beam are the length of the beam and the tributary width of the beam. Therefore, categories were made based on these parameters, and can be seen in Table 11. Figure 23 displays the placement of the beams in each category throughout the floor layout.

TABLE 11: CATEGORIES OF BEAMS FOR DESIGN BY LENGTH AND TW.

Length (mm)	TW (mm)
7363	6660
7363	3828
6330	6500
6330	3682
4640	6530

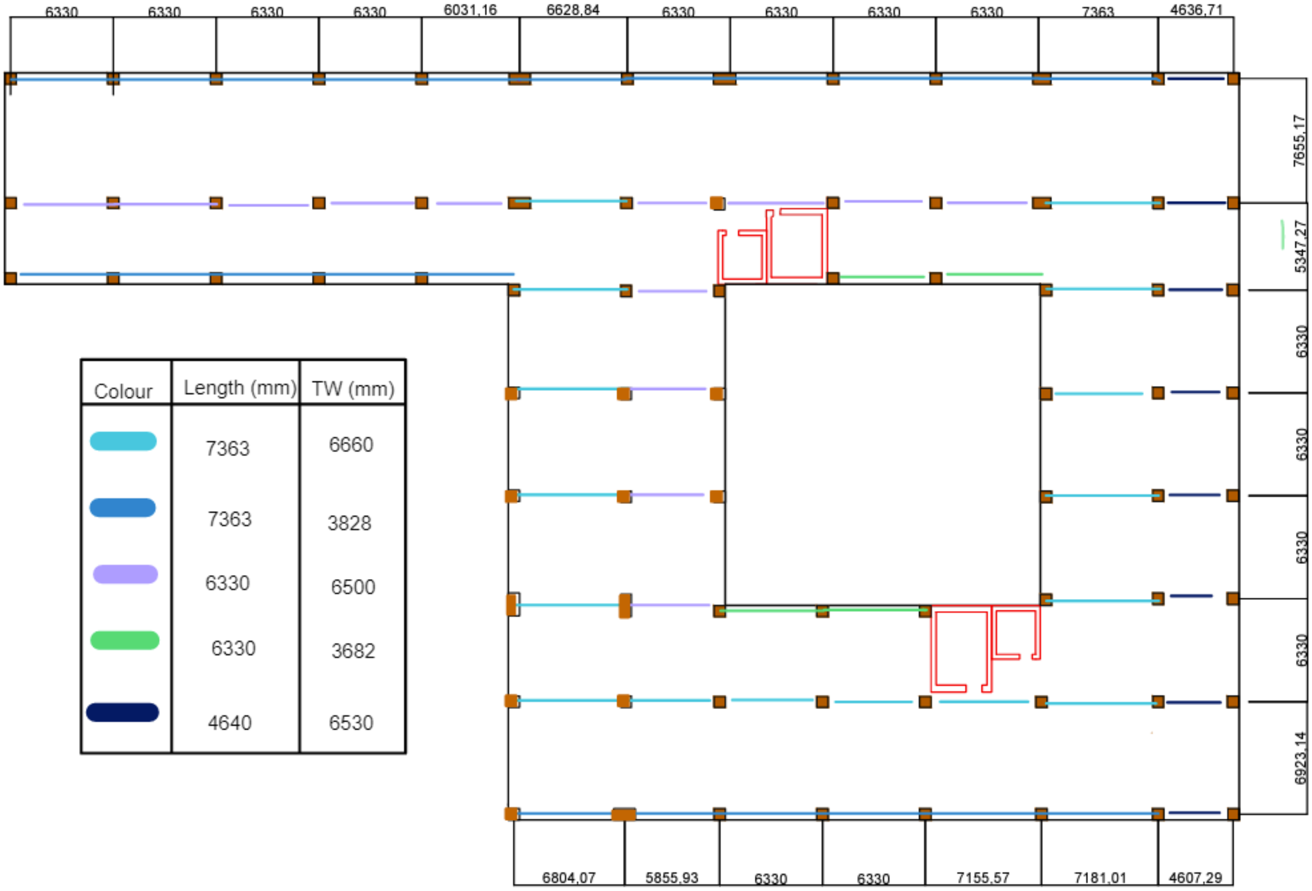


FIGURE 23: FLOOR LAYOUT SHOWING LOCATION AND CATEGORY OF EACH BEAM.

For the smaller beams, or joists, a similar approach was taken, as the joists were categorized according to their lengths. The three lengths of joists that were designed were 7655 mm, 6330 mm, and 5347 mm. The spacing of the joists was decided to be 1.25 m, as it allowed for the members to not be large compared to the perpendicular beams and it was a distance that allowed for close to a whole number of joists to be placed along each section. Figure 24 displays the sections for each category of joist.

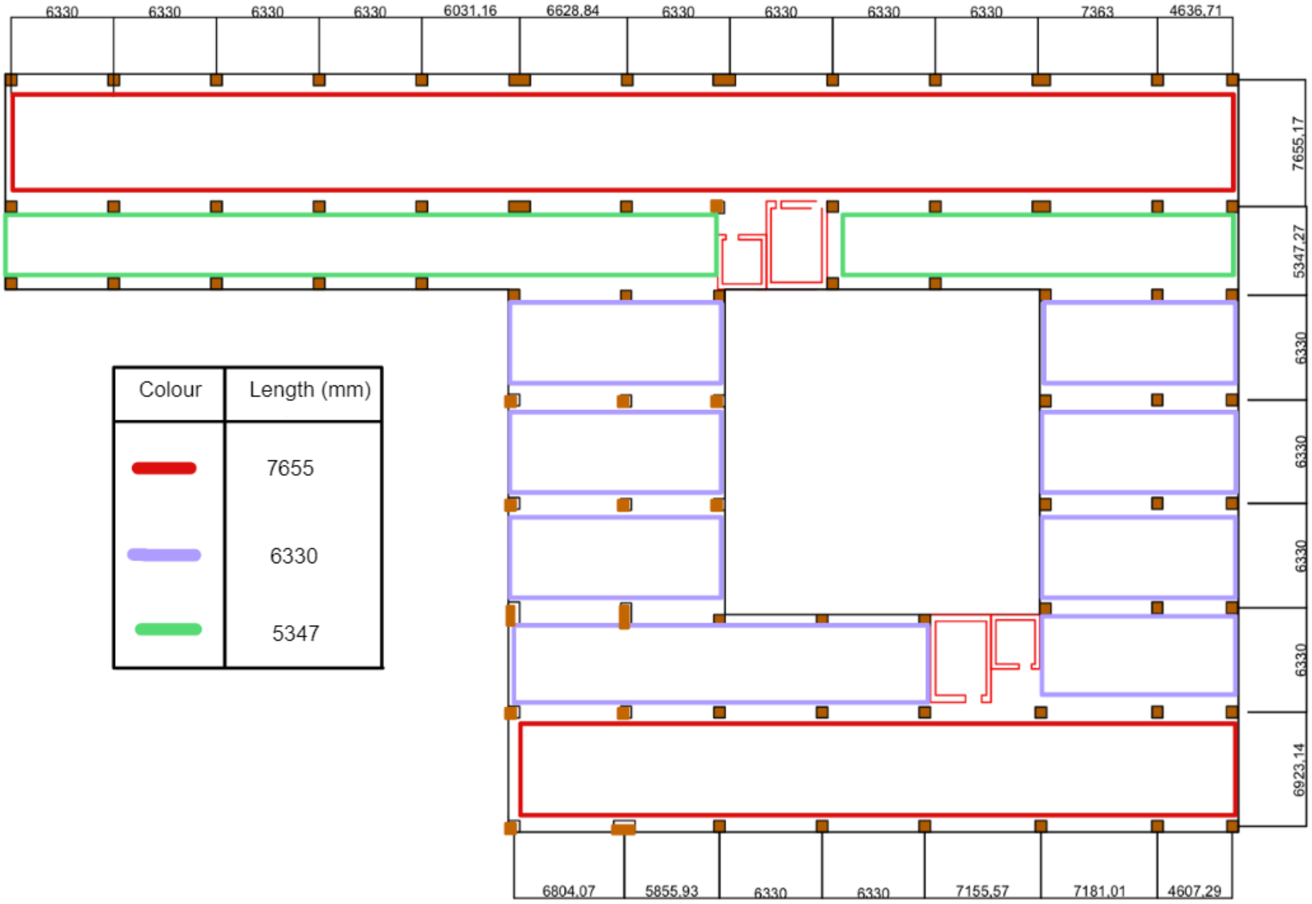


FIGURE 24: FLOOR LAYOUT SHOWING LOCATION AND CATEGORY OF EACH JOIST.

From Table 7.1 in CSA O86, the timber that was chosen for the glulam columns was 24f-E Douglas Fir (Canadian Standards Association Group 2019). The 24f-E grade is the strongest of the options listed in CSA 086 and it is available in Ontario. The 24f-E grade is cheaper than the 24f-EX grade, and since the design involves simple, single span beams that do not experience negative bending, the 24f-E grade wood is just as effective as the 24f-EX grade counterpart, which has equal resistance on the top and bottom fibers (Canadian Standards Association Group 2019).

In accordance with CSA O86 Section 7.5.6, an Excel spreadsheet was created to calculate the bending moment resistance of any input dimension of beam. This allowed for an efficient design process to come upon the most optimized design for each beam. During the design process, it was assumed that flexural failure of the beams would govern; therefore, the beams were designed for flexure and then checked for other failure mechanisms.

The loads on each floor, as seen in Table 8, were converted into a maximum bending moment for each beam to obtain a factored bending moment that the beam had to resist. A sample calculation can be seen below, for a beam on the third floor, with a length of 7363 mm and a tributary width of 6660 mm:

$$M_f = \frac{wL^2}{8}$$

$$w = (1.5L + 1.25D) * TW = \big(1.5(4.8\ kPa) + 1.25(1.35\ kPa)\big) * 6.660\ m = 59.19\ kN/m$$

$$M_f = \frac{(59.19)(7.363)^2}{8} = 401.1\ kNm.$$

With a calculated factored moment, the beam selection tables in the Canadian Wood Design Manual were used to select an initial design. From there, the design was changed, based on its bending moment resistance output from the spreadsheet, until the most optimized design was concluded.

The calculated factored bending moment did not include the self-weight of the beam. Once an initial design was chosen for a beam, the bending moment due to the weight of that respective beam was added to the overall factored bending moment, to ensure that the design could also resist its own weight. It should be noted that only the common dimensions given in CSA O86 were considered during the design process.

The key properties for the bending moment resistance calculations for a glulam column are the elastic modulus and the bending moment strength of the timber. These values were taken from

Table 7.2 in CSA O86 showing 16 c-E Douglas Fir-Larch glulam having an elastic modulus of 12800 MPa and a compressive strength of 30.6 MPa (Canadian Standards Association Group 2019). A sample calculation of the bending moment resistance of a beam on the third floor, with a length of 7363 mm and a tributary width of 6660 mm is displayed in Appendix IV. These calculations follow Section 7.5.8 of the CSA O86.

Although it was assumed that the flexural strength of the beam was the governing failure mechanism for the design, each design was also tested in shear and in deflection to ensure that this assumption was correct. A sample calculation for the shear resistance of a beam on the third floor, with a length of 7363 mm and a tributary width of 6660 mm is displayed in Appendix V. These calculations follow Section 7.5.7 of the CSA O86.

A sample calculation for the deflection of a beam on the third floor, with a length of 7363 mm and a tributary width of 6660 mm is displayed in Appendix VI. These calculations follow the Canadian Wood Design Manual and Section 5.41 of the CSA O86. The shear and deflection calculations showed that the glulam beams governed in flexural failure for each beam.

Table 12 displays the five different designs for the glulam beams for each floor including the roof.

TABLE 12: SUMMARY OF THE FIVE DESIGNS FOR THE GLULAM BEAMS ON EACH FLOOR INCLUDING THE ROOF.

Type	Length (mm)	Width (mm)	Depth (mm)	# per floor
D.Fir-L 24 f-E	4640	215	418	22
D.Fir-L 24 f-E	6330	215	418	16
D.Fir-L 24 f-E	7363	215	532	12
D.Fir-L 24 f-E	6330	265	494	4
D.Fir-L 24 f-E	7363	265	608	8

Table 13 displays the three different designs for the glulam joists for each floor including the roof.

TABLE 13: SUMMARY OF THE THREE DESIGNS FOR THE GLULAM JOISTS ON EACH FLOOR INCLUDING THE ROOF.

Type	**Length (mm)**	**Width (mm)**	**Depth (mm)**	**# per floor**
D.Fir-L 24 f-E	5350	175	266	53
D.Fir-L 24 f-E	6330	175	304	86
D.Fir-L 24 f-E	7600	175	380	92

10.4 Lateral loads and SAP2000 Analysis

As part of the technical analysis, SAP2000 was used to create an accurate model of the structure. This was done in order to simulate the structure's response to wind loading. The SAP2000 model was also used to aid in the substructure design process, by providing the bending moment values that would be acting at the foundation of the structure. SAP2000 is software that is meant for the design, modeling, and analysis of complex structures that would be impossible to design manually. The software can produce a variety of outputs such as axial forces, moments, shear forces, and deflections of structural members (Computers and Structures, Inc. 2024), which is all essential information that engineers need in order to determine whether a structure will function as intended and whether it will meet the governing codes and regulations.

The SAP2000 model was constructed using the material properties of Douglas-fir wood, as it is commonly used for construction purposes due to its high availability in the area, along with its reliable strength and relatively low price (The Wood Database 2024). Douglas-fir wood is also a valid choice for the structure's main building material as it can be converted to glulam quite easily (Buckland Timber 2024). In order to simulate the foundations supporting the structure, the lower ends of the basement level have been assigned as fixed supports, which will resist vertical, horizontal, and moment loading. Another minor simplification that was made was to treat the basement level of the structure as a regular storey rather than it being embedded in the soil and experiencing soil pressure, as the soil profile and water table level of the area are unknown. Because of this simplification, the ground floor of the building is shown as the second storey in the model. In terms of lateral loading resistance, the frames that make up the structural model have been treated as moment-resisting frames, as no moment releases have been assigned to the frame elements or joints. This specification allows the frames to resist lateral loading. The two elevator shafts and stairwells within the building will also aid in resisting lateral loads, since they will act as shear walls, a common practice for larger buildings (Fox Blocks 2024). The shear walls have not been added to the SAP2000 model, since there is no specific option to design shear walls in SAP2000, and a workaround would need to be found. As such, it can be assumed that any forces and moments from wind acting on the structure could be reduced, since there will be shear walls in the completed building able to resist lateral loading.

With the goal of simplifying the loading cases and combinations acting on the structure during analysis, no superimposed dead load was considered. The dead load acting on the structure is purely the self-weight of the structural members. The wind loading was determined using SAP2000's load case system, which made use of the appropriate clauses from NBCC 2020 to assign the proper amount of load for the structure (Canada 2022). The software created 12 different wind loading cases, which correspond to different wind directions. Live load was determined through the use of Table 4.1.5.3. in the NBCC 2020, which provides uniformly distributed live load values for areas of floor or roof (Canada 2022). From this table, a live load of 4.8 kPa was selected for the floors of the structure, and a live load of 1 kPa for the roof. The snow load was calculated by hand using clause 4.1.6.2. in the NBCC 2020 (Canada 2022) which produced a value of 2.08 kPa, and was then added to the SAP2000 model. While all of the appropriate loads were applied to the SAP2000 model, the analysis was only conducted for the wind load, since calculating accurate wind loads by hand for a structure of this shape and size would be highly complicated. The gravity loads (dead, live, snow) were also previously calculated manually, and were used for the design of the structural members. The gravity loading from SAP2000 was not used for design because the axial force and moment values it created in the members was far too large to be a reasonable approximation, indicating that an error was made somewhere in the process of the SAP2000 modeling and analysis. Once the analysis was completed, the structural members were studied to find the members that were experiencing the largest wind loads, and the values that were being produced. This process was done for all 12 wind load cases to understand how changing the wind direction would affect the structure.

The results can be seen in Table 14. Note that positive values are in tension, while negative values are in compression.

TABLE 14: RESULTS TABLE FROM SAP2000 ANALYSIS OF WIND LOADS.

Load Case	Largest Axial Force (Columns) (kN)	Largest Axial Force (Beams) (kN)	Largest Moment Not at Foundation (kNm)	Largest Moment at Foundation (kNm)	Largest Shear Force (Columns) (kN)	Largest Shear Force (Beams) (kN)
1	-43.03	12.88	67.06	51.44	-31.15	-23.90
2	120.19	-21.24	83.28	13.38	13.70	-37.25
3	-40.05	8.07	60.06	46.00	-22.40	16.98
4	-31.12	11.25	49.97	37.86	-21.80	12.40
5	58.19	-21.49	-62.07	4.86	2.10	-15.71
6	132.91	-47.14	-48.71	-36.57	22.91	-42.14
7	-77.00	36.28	80.47	54.07	-33.64	31.20
8	103.30	-32.37	-75.08	43.59	-27.07	-26.44
9	-101.45	40.32	-99.70	62.00	-31.62	37.02
10	-49.32	14.14	-40.85	80.20	-18.48	15.05
11	59.49	-11.21	47.07	98.22	-22.73	-16.70
12	121.21	-37.39	89.58	45.50	-27.57	-33.45

From Table 14, it can be seen that the axial forces caused by wind loading were generally higher in the columns rather than the beams, with the largest column axial force of 132.91 kN being produced in load case 6. This load case coincidentally produces the largest beam axial force of -47.14 kN. The moments acting at the foundation were separated from the moments acting on the other structural members since the largest moment acting at the foundation will be used for the substructure design. The largest moment not acting on the foundation is -99.7 kNm, produced in case 9. The largest moment acting on the foundation is 98.22 kN, from case 11. Since it is the largest value, it will be used to design the foundation, along with the compressive axial force created by gravity loads. With shear, the forces between columns and beams are quite similar in range, with the largest column shear force being -33.64 kN, and the largest beam shear force being -42.14 kN.

Based on the axial loads, moments, and shear forces caused by wind loading, it was determined that the use of moment resisting frames within the structure as well as the shear walls created by the elevator shafts and stairwells would be sufficient to resist the lateral loading acting against the structure. An image of the SAP2000 model can be seen in Figure 25 below.

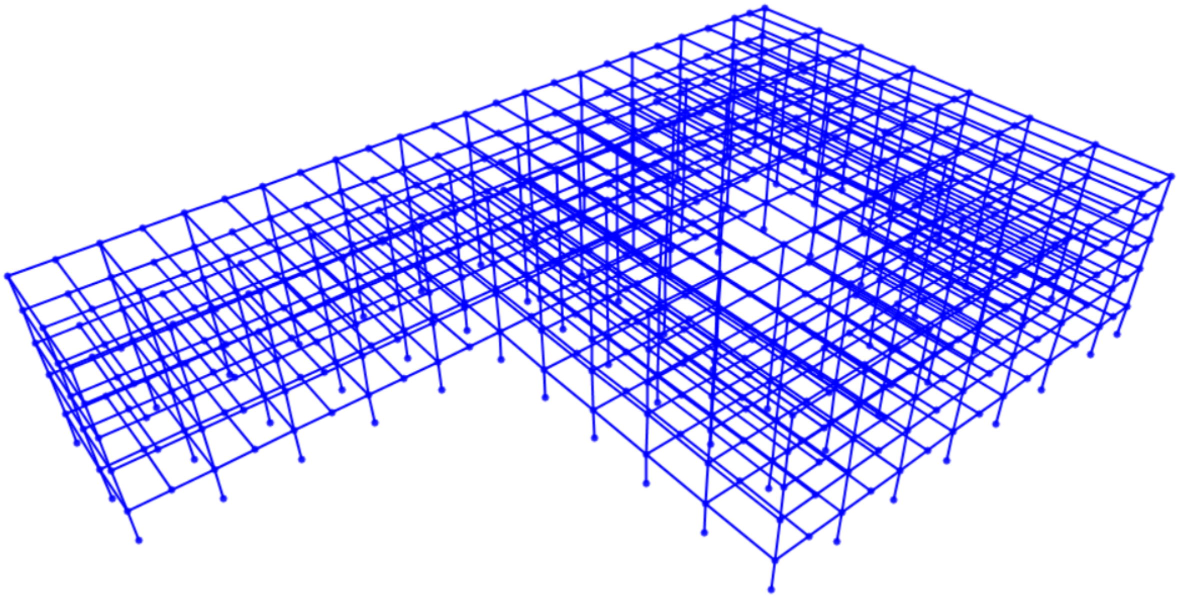


FIGURE 25: 3D VIEW OF THE SAP2000 MODEL USED FOR LATERAL LOAD ANALYSIS.

10.5 Flooring System

A case study was previously researched concerning the WIDC building in Prince George, British Columbia (Wood-Works 2023). This building was researched as it was a successful example of a mass timber building that makes use of a beam and column style of structural design, which has been implemented for the NetZero residence design as well. Furthermore, the flooring system that was implemented at the WIDC building was an innovative solution that did not make use of traditional building materials, as other flooring systems do (Wood-Works 2023). As such, it makes sense to emulate design elements of the WIDC building, especially the flooring system. The WIDC building flooring system makes use of two parallel CLT panels that are connected together with HSK connection plates, epoxy glue, and foam in order to create a composite system that is both strong and elastic, as both CLT panels act together. This flooring system method leaves gaps between the upper and lower CLT panels for simple spacing and installation of utilities and other services. Acoustic subflooring was also installed at the WIDC building to provide insulation and noise suppression (Wood-Works 2023). This is a comprehensive flooring system that would be a viable solution for the NetZero residence building. Very few modifications would need to be made to the installation process as well as the list of materials needed in order to implement it for the NetZero residence. An image of the WIDC building floor system can be seen in Figure 26.

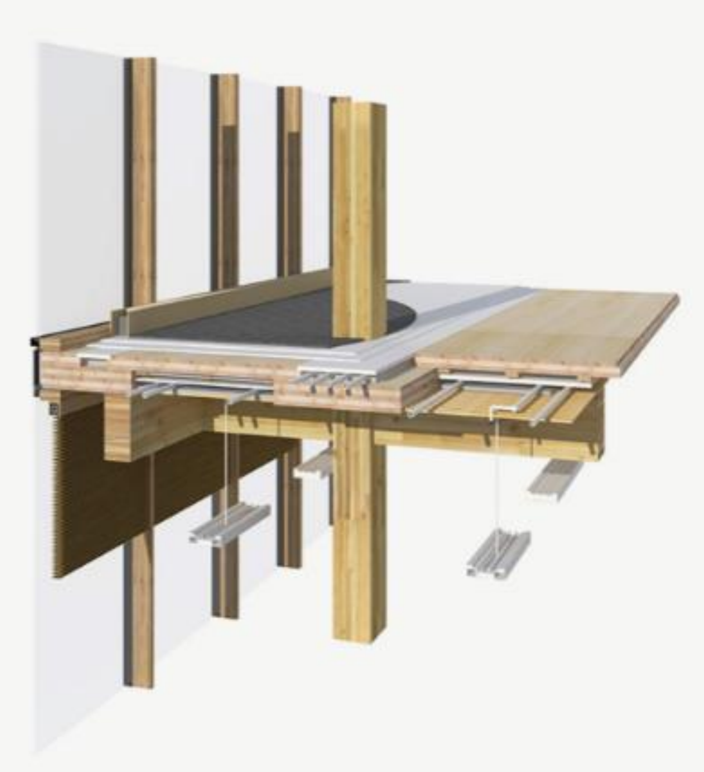


FIGURE 26: STRUCTURAL ELEMENTS IN THE FLOOR SYSTEM IN THE WIDC (MICHAEL GREEN ARCHITECTURE 2014)

10.6 Façade and 3D Model

A 3D model of the building was created using SketchUp in order to provide the client with a more aesthetically pleasing visual representation of what the final product could look like. Note that the following 3D model is a concept and does not represent a confirmed visual of the NetZero residence building once completed, as changes can still be made to the design. The façade of the model was created as an emulation of the façade from the Brock Commons building (Wood-Works 2017), which makes use of black cladding and wood paneling to create a modern and appealing façade, as shown in Section 5.3.1. Different angles of the 3D model can be seen in Figure 27, Figure 28, and Figure 29.

FIGURE 27: FRONT VIEW OF 3D MODEL.

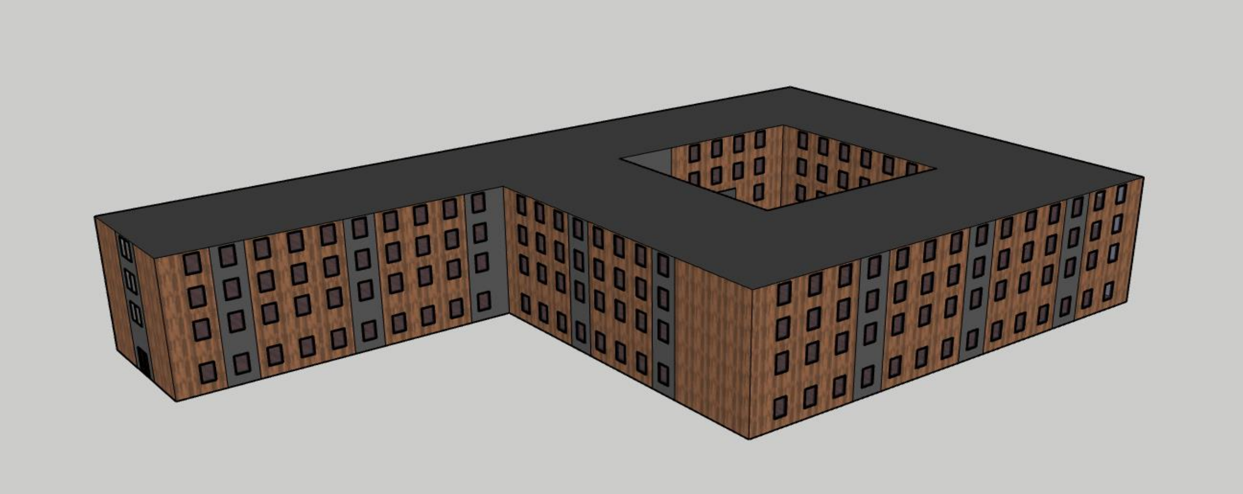


FIGURE 28: REAR LEFT VIEW OF 3D MODEL.

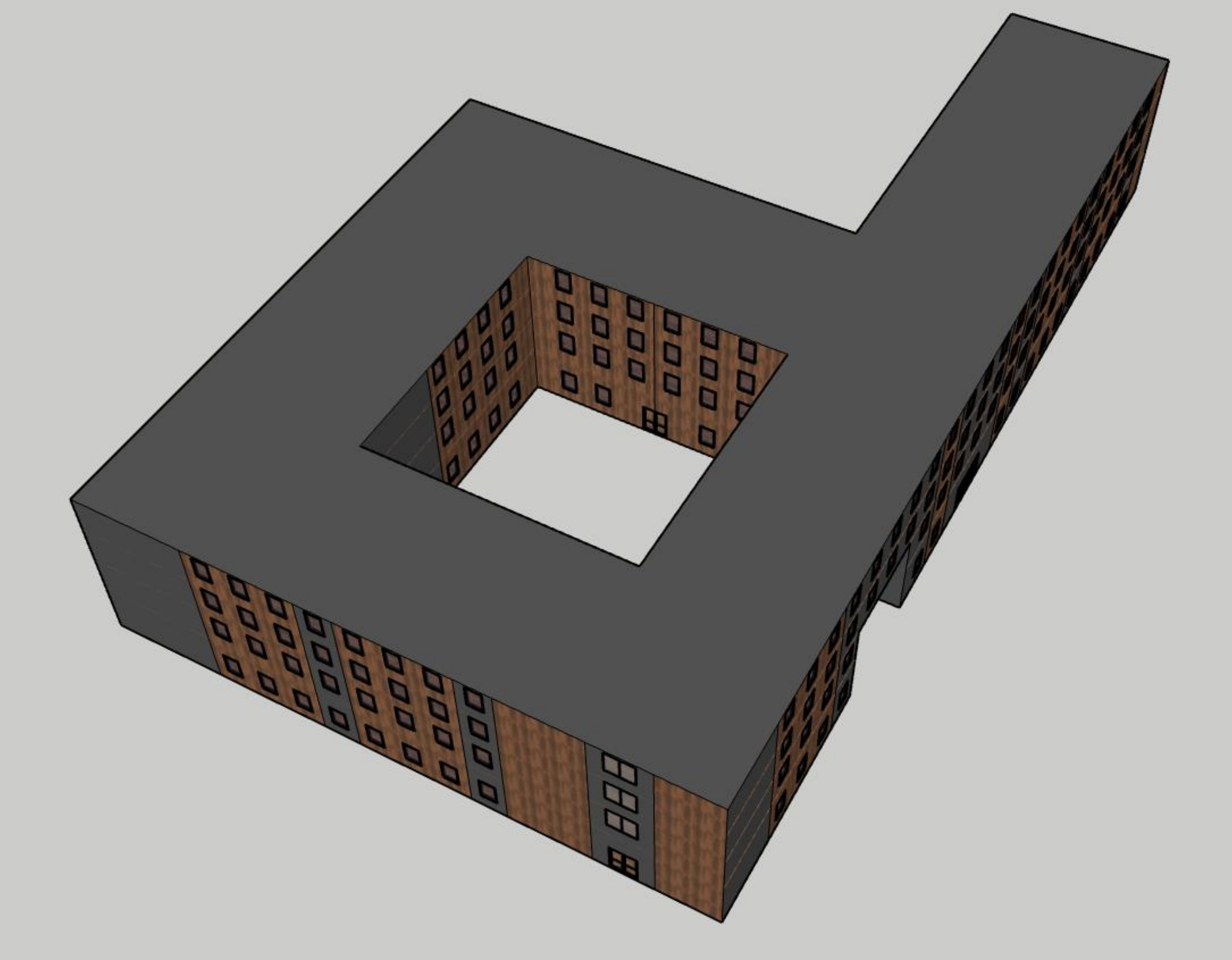


FIGURE 29: ANGLED TOP VIEW OF 3D MODEL, SHOWING COURTYARD.

10.7 Substructure Design

Reinforced concrete was selected as the building material for the substructure components as this is the only material that the Canadian Foundation Manual and accompanying design guidelines currently account for.

The city of Kingston is underlined by an expansive layer of limestone bedrock. This bedrock is covered by a thin layer of till, averaging 2-3 m in most areas (Gillespie et al. 1966). Given the shallow depth to high strength bedrock, the most practical and feasible solution for the building's foundation is a shallow design. There are various modes of shallow foundation styles that could be made to work for the design, as shown in Figure 30 below. The mode of shallow foundation that was assessed and selected after the design loads and column placement were finalised is isolated footings. This footing style is optimal for the proposed column configuration and bedrock conditions. In many cases larger spread footings or combined style footings may be required for a building when a larger surface area of engagement is required to distribute the loading across a larger area of weaker soils. Placing the footings directly on bedrock enables the isolated footing profiles which greatly reduces concrete use and by extension, the embodied carbon of the foundation system. Isolated footings are more straightforward to design and analyse compared to other footing types which aligns well with the team's current competency levels.

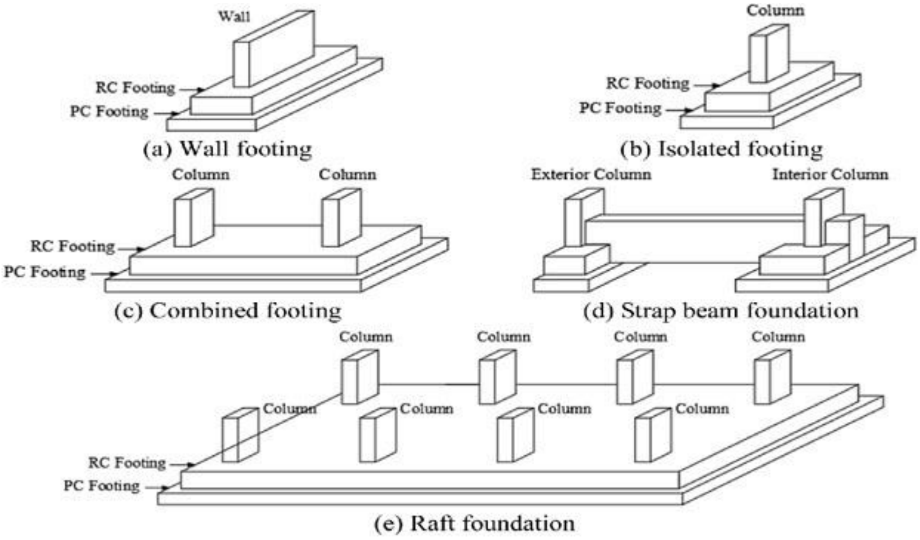


FIGURE 30: SHALLOW FOUNDATION TYPES AND SKETCHES (CANADIAN GEOTECHNICAL SOCIETY 2006)

The software package utilised in order to ensure an accurate and complete foundation design was SkyCiv Foundation Design Beta. The model uses a multi-dimensional assessment profile and directly incorporates the Canadian guidelines for concrete materials and methods of construction (CSA A23.1). Foundation Design Beta combines the structural assessment of the footings with the geotechnical analysis, while factoring in multi-dimensional loading scenarios. Computing this form of analysis by hand calculations would be unrealistic due to the quantity of time and technical expertise that would be required. A factor of safety of 2 is applied for overturning resistance and 1.5 for sliding resistance. Groundwater effects were not considered due to the configuration on bedrock and that the foundations are located within the basement system rather than in a backfilled scenario where the column of groundwater above the footing would apply a vertical pressure on it. The foundation is located is a seismically stable zone and on bedrock, which eliminates the risk of soil liquefaction. The risks of loss of strength due to excess pore water pressures or groundwater level changes are also averted by placing the foundation directly on bedrock.

The loading parameters were obtained from the SAAP2000 model and incorporate the most critical of 12 assessed loading cases with varying snow, wind, and earthquake loading simulations. It was found that the critical loading case results in a base column load of 5640.8 kN of axial force and 99.8 kNm of rotational force. The foundation modelling software accounts for the self weight of the concrete in the footing by adding an equivalent load to the applied column loading. Figure 31 shows the model in SkyCiv and Figure 32 displays the results from the test on the model.

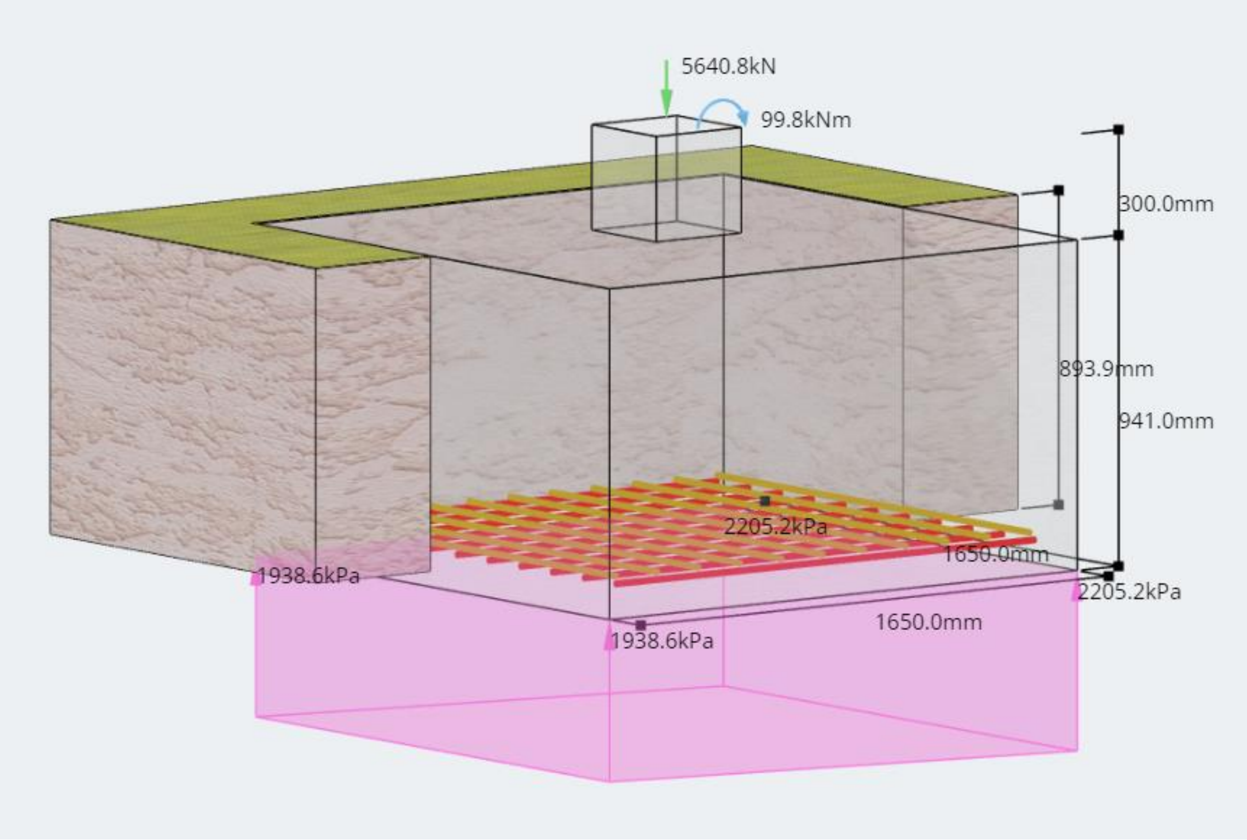
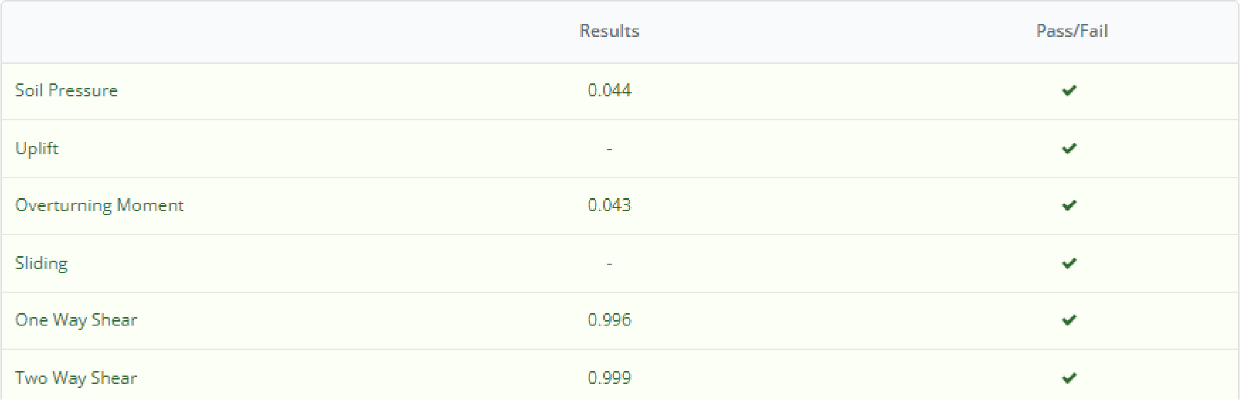


FIGURE 31: FOUNDATION MODEL SHOWING FOOTING LAYOUT AND TEST RESULTS



	Results	Pass/Fail
Soil Pressure	0.044	✓
Uplift	-	✓
Overturning Moment	0.043	✓
Sliding	-	✓
One Way Shear	0.996	✓
Two Way Shear	0.999	✓

FIGURE 32: FOUNDATION MODEL VERIFICATION TABLE

Inputting these values in the foundation design software and running multiple iterations yielded an optimized footing template. Featuring a square base of width 1.65 m and a depth of 0.94 m, each footing encompasses a space of 2.56 m^3. The foundation design passes all of the relevant CSA A23 checks including bearing pressure, uplift, overturning, sliding, one way shear, and two-way shear. The reinforcement layout to achieve the optimized design includes longitudinal and transverse 20M bars running along the bottom of the footing, with a spacing of 150 mm and a cover of 75 mm. Each footing will require a steel length of 36.3 m. Cumulatively, the total materials required for the 75 individual column foundations includes 192 m^3 of concrete and 2723 m of 20M reinforcing bar.

The floor slab for the basement of the proposed building will lie at grade with the top of the foundations for the columns. The slab follows the guidelines set in section 9.39 of the Ontario Building Code, which specifies a minimum slab depth of 125mm and 200 mm spaced 10M rebar (Ontario 2008). Given these specifications, a slab depth of 150 mm was specified with longitudinal 10M reinforcement at 200 mm spacing. The total materials required for the basement slab includes 274 m^3 of concrete and 18310 m of 10M reinforcing bar. These values were computed based on the gross area found by subtracting the column footings from the overall floor area.

It is assumed based on standard values from the Canadian Foundation Manual, and must be verified, that limestone of minimum strength 50 MPa exists at the site prior to further detailed design and construction (Canadian Geotechnical Society 2006). Standard values of compressive strength for native limestone range from 50 - 100 MPa (CFM). Other relevant parameters will also need to be confirmed including site geometry, soil stratigraphy, groundwater levels, bedrock depth, and bedrock strength. Any discontinuities in the bedrock that could affect the structural integrity of the foundation, including shears, faults, and joints will need to be assessed. These parameters can be obtained through field investigations and laboratory material assessments. Borehole sampling can be utilised to verify the depth to bedrock across the site and to collect rock core samples for further assessment. Bedrock samples will need to be extracted through rock core sampling. These samples will need to be evaluated for discontinuities such as fractures, joints, and faults, all of which reduce the effective bearing capacity of the rock (Canadian Geotechnical Society 2006).

The basement exterior wall foundations that bear the weight of the wall will be strip footings and ensure the wall has sufficient overturning capacity to retain the adjacent soil. The exterior walls and associated footings will need to be designed to ensure sufficient watertightness and structural capacity (Canadian Geotechnical Society 2006). These elements were not included in this preliminary design due to project timeframe limitations.

11.0 Life Cycle Embodied Carbon Assessment

As the Canadian regulatory mood towards embodied carbon and environmental protection continues to adjust in the face of climate change, the need to proactively create low carbon designs continues to grow. A preliminary assessment of the embodied carbon for this project will enable a further understand the significant components contributing to carbon and where changes can be made to future buildings.

Carbon Connected, an undergraduate consulting team, commissioned a study in 2022 to provide Queen's University with an evaluation of the approaches and modelling tools for embodied carbon (Anderson et al. 2022). These comprehensive learnings have enabled the University to better understand the technical background for how to assess projects to determine their embodied carbon and associated environmental impacts. The design team recommended that the University employ the software package OneClick LCA, a dynamic modelling tool that can assess the material choices and embodied carbon of a given project (Anderson et al. 2022).

OneClick LCA offers a Student Trial Edition of their carbon footprint and life cycle assessment programs, which were used to compute the embodied carbon of the proposed residence design. The life cycle carbon assessment was completed, with a focus on the embodied carbon of the building materials. The assessment incorporates the environmental impact of the materials including transportation to the site from their estimated storage or production facilities. Estimated material wastage values during construction are incorporated into the assessment via OneClick LCA's extensive material and building methods library.

To reduce the overall embodied carbon of the building the size of the structural elements was optimized to reduce unnecessary section profiles where possible while maintaining appropriate design factors of safety. The mass/recycled timber structural, floor, and cladding components provide significant biogenic carbon sequestration. Results from the life cycle carbon assessment pegged the sequestered carbon in the building at just over 2.08 M kg CO2e, a significant value considering the total environmental impact of construction activities is assessed as 4.07 M kg CO2e.

In accordance with the commitments established in the Greening Government Strategy, the Canadian Government established a standard on the Embodied Carbon in Construction. The standard provides guidance on the disclosure and reduction of embodied carbon in major construction projects and took effect in December, 2022. The standard applies to all projects with a value greater than $5 million, and as such the proposed design is subjected to the standard. In terms of the specific project application, the standard restricts the ready-mix concrete that can be used by mandating that the mix contains 10% less GHG emissions compared to the regional baseline mix of an equivalent strength (Environment and Climate Change Canada 2022). In this instance the proposed design exceeds the standard by utilizing ECOPact, which provides a baseline reduction in embodied carbon of 30% (Lafarge Canada 2023).

A variety of design assumptions were necessary for the completion of the life cycle carbon assessment, as many common building components were not selected within the scope of this project in creating a preliminary design. It was assumed that the interior of the residence building will have walls that are lined with gypsum board. Gypsum board is a very common wall lining product due to its ease of installation and availability (Canadian Home Inspection Services 2021a). It was assumed that the flat roof system will be composed of an asphalt core and waterproofing membrane, as both of these elements are essential to a functional flat roof (Canadian Home Inspection Services 2021b). It was assumed that an abrasion resistant vinyl tile flooring system or equivalent will be used on all of the floors. An aluminum core wall system was assumed to be used for the interior partition walls. These provide addition fire resistance properties and are evenly distributed throughout the building interior. The construction activities includes the demolition of the Lasalle Building and 140 Stuart Street.

The results show a total carbon dioxide equivalent emissions for the project as 4076 tonnes CO2e. Assessing the carbon impact on a distributed area metric shows that the building design is considered as a category C emitter compared to other comparable designs, as shown in Figure 33 below.

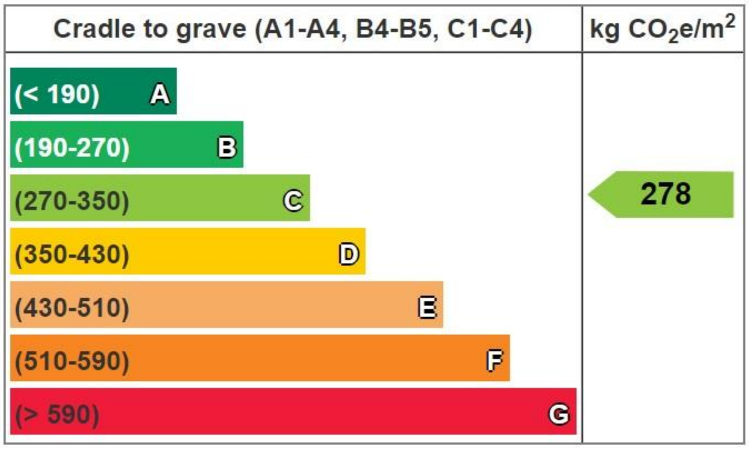


FIGURE 33: EMBODIED CARBON BENCHMARK (ONECLICK LCA)

A bubble chart has been generated to provide an easy to visualize breakdown of the contributions to the lifecycle impact. Each building material is represented either separately or within a relevant product category. The scale of the carbon contribution from each material can be noted from the relative size of the material bubble. The results show that the largest contributor to the project carbon is from the rooftop solar panel units, generating 23% (320 tonnes CO2e) of the environmental impact of the building. The next largest contributors are the wall and flooring systems, as shown in Figure 34 below.

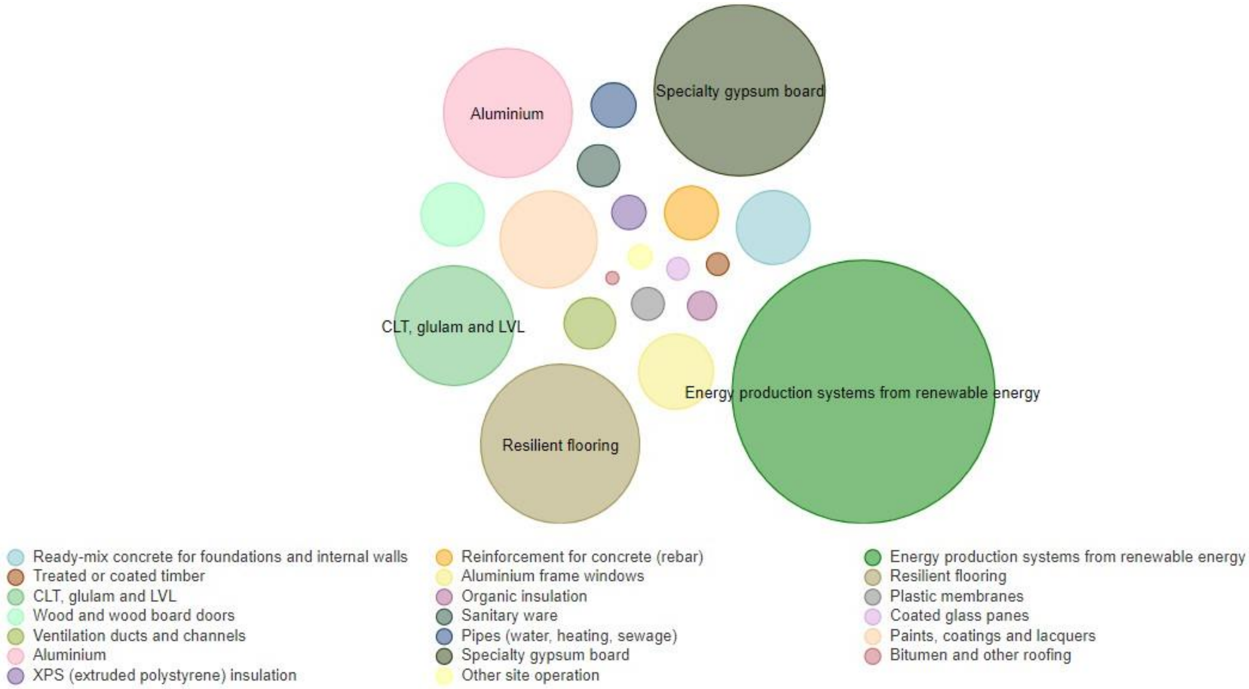


FIGURE 34: MATERIAL RELATIVE CO2E IMPACTS (ONECLICK LCA)

The service life of the building was assessed on a 100-year timeline, with the options provided by OneClick LCA as 50, 100, and 150 years. Currently the oldest Queen’s residence is Ban Righ Hall, which has been operating for 99 years (Queen’s University 2024). The life cycle assessment incorporates the estimated lifespan of various building materials and computes the environmental impact of replacing these materials at the end of their service lives via building renovations. It should be noted that the replacement and renovation of the building over the 100-year lifespan contributes 44% of the overall embodied carbon, as shown in Figure 35 below. The reference service life and Initial CO2e contribution on the major CO2e contributing building materials is provided in Table 15 below.

FIGURE 35: EMBODIED CARBON BY LIFE-CYCLE STAGE (ONECLICK LCA)

TABLE 15: SIGNIFICANT EMBODIED CARBON COMPONENTS AND ASSOCIATED SERVICE LIVES

Building Material	Design Service Life	Initial CO2e Contribution (%)
Rooftop Solar Panels	20 Years	40%
Interior Drywall	40 Years	16%
Resilient Vinyl Flooring	25 Years	14%
Aluminum Sandwich Walls	100 Years	8%
CLT Floor Pannels	100 Years	4%
Interior Paint	10 Years	5%

Certain elements were not incorporated in the carbon assessment due to difficulty in obtaining information on the specific components. These include the elevator units, electrical components, stair units, trim and other finishing elements, room furnishings, and mechanical HVAC equipment. Construction mobilization activities and building end of life deconstruction activities were not included in this assessment. Water and electricity use during construction activities were not included due to challenges in finding relevant baseline values from similar scale projects. This preliminary assessment may contain inaccuracies due to the estimations and assumptions that were used to generate the results and will require verification as the design progresses into further stages of finalizing the building materials and construction approach.

Comparing the results of this assessment to the recently constructed Endaayaan – Tkanónsote residence shows that the carbon performance of the proposed design is similar but slightly lower. Footprint consulting’s post-construction report on the completed Endaayaan – Tkanónsote residence lists the building as having a total environmental impact of 2.97 M kg CO2e, and a distributed impact of 271.4 kg CO2e/m^2 (Michayluk 2023). While the results are similar and both buildings would be listed as category C emitters based on their environmental impacts, the target of creating a residence design with a lower embodied carbon has not been met with the current design configuration.

Singular design decisions can have a major impact on the embodied carbon of the building. Removing the rooftop solar panels increases the carbon performance of the proposed design to 183 kg CO2e/m^2, a 34% improvement in the environmental impact. This single change increases the building to a Category A emissions rating. Further assessment will be required to assess the impacts of alternative energy generation methods and to confirm the layout and quantities of construction materials.

12.0 Cost Analysis

This report delivers a detailed cost analysis of the NetZero residence project at Queen's University, focusing on the financial aspects of constructing a sustainable living space. By examining material costs, adjusting for scale, and considering market conditions, it aims to provide an informed estimation of the project's financial requirements.

12.1 Costing Scope

The cost analysis for the NetZero residence at Queen's University is specifically constrained to the elements designed specifically by the project team, focusing on material costs for the components necessary to achieving NetZero standards. The analysis considers the impact of market variability on material costs, highlighting how fluctuation in readily available supply can affect the budget. Acknowledging these fluctuations can aid in preparation for potential in the project's financial planning. While this cost analysis offers a detailed breakdown of these direct construction costs, it acknowledges the presence of numerous additional costs associated with the construction of this project. These elements include, but are not limited to, labor, transportation, and indirect expenses. While these costs are crucial to the overall project budget, they are outside the primary scope of this analysis. This focussed approach to the cost analysis, allows the team to provide a more clear and detailed estimation of the costs specifically necessary to achieve a NetZero design.

12.2 Limitations

This cost analysis, while through in its focus on direct material costs, is bound by several limitations that must be acknowledged to develop a full comprehension of the scope and implications of this financial overview. Firstly, the analysis is specifically constrained to the elements that were designed in this document, focusing primarily on the costs of materials necessary for the project's sustainability goals. This focus inherently excludes several significant expenses that would be crucial to the project's completion later on.

A notable challenge encountered was the inability to gather direct quotes for the glulam elements. This difficulty arose primarily due to time constraints, limiting the team to have extensive negotiations with local suppliers and manufacturers. Additionally, the theoretical nature of this NetZero residence design served as a barrier to receiving direct quotes. Local manufacturers, assessing the projects requirements, were hesitant to provide a quote as they believed that the effort involved in quoting this project would not be justified by the potential for actual construction, making it not worth their time and resources.

A key component for the project's sustainable structure is glulam elements including columns, beams, and joists. Initially, through conversation with professional engineers within the industry, the cost of glulam was estimated at $1,500 per cubic meter. This estimation was taken from industry standards and insights from professionals with experience in similar projects. Using this cost as a baseline for the analysis, it is recognized that variability within construction projects is inherent, thus a scaling factor was applied to this initial estimate. This 30% increase, adjusting the cost to $1,950 per cubic meter, was done in consideration of several factors that could impact the final cost. The variability in the dimensions of the structural elements was a factor that would influence the price of the elements. Larger or more complexly shaped glulam beams and columns might require more material, specialized fabrication process, leading to increases in cost. Additionally, the specific type of glulam required for the residence was a key consideration in applying the scaling factor. Not all glulam is created equally; variations in wood type, grade, and manufacturing processes can affect both the performance and the price. For a project aiming towards NetZero standards, selecting glulam elements that offer the best balance of strength and sustainability. With this premium in quality, comes a premium in price, leading to costs on the higher end of the price spectrum. This scaling factor was an adjustment based on an understanding of the complexities and specific requirements of the project.

12.3 Gross Floor Area

A description of the gross floor areas and their respective floor levels can be found below in Table 16.

TABLE 16: GROSS FLOOR AREA

Gross Floor Area	
Description	**M²**
Basement	1730
Level 1	1730
Level 2	1730
Level 3	1730
Level 4	1730
Total Gross Floor Area	**8650**

12.4 Construction Cost Estimate Summary

Table 17 presents a concise comparison of estimated costs for new construction, site development, and demolition for the 8650 m² residence development. This assessment reflects the unit costs from the 2019 cost assessment for the Endaayaan – Tkanónsote residence, with an 18.9% increase applied to these previous unit costs to account for the affects of inflation. It should be noted that this construction cost estimate is exclusive of the NetZero elements, rather an estimate on pricing based on the size of the development.

TABLE 17: CONSTRUCTION COST ESTIMATE SUMMARY

Construction Cost Estimate Summary			
Element	**Area (m^2)**	**Unit Cost (\$/m^2)**	**Cost (\$)**
New Construction	8650	2647.02	22,896,700.90
Site Development	2482	328.60	815,464.86
Demolition & Alterations	NA		400,000
Total Construction Cost (excluding allowances)			**24,112,165**

12.5 Elemental Costing

In calculating the cost of the superstructure for the building, a detailed assessment was made of the glulam elements required, including, columns, beams, and joists. The columns were specified as Douglas Fir, grade L 16 c- E, while the beams and joists were comprised of Douglas Fir, grade 24 f-E. The unit pricing for the glulam was determined by referencing a general industry standard, which was established through consultations with professional engineers who have a proficient understanding of the construction market within Kingston, Ontario. Direct quotes for these materials were unobtainable due to timeline constraints and general reluctance from manufacturers to provide estimates for a conceptual design of this nature. To estimate the total cost for each glulam element, the total volume was calculated by multiplying the number of each element by their respective dimensions. This total volume was the multiplied by the assumed unit cost of $1,500 per cubic meter, deriving a total cost for each type of structural component.

12.5.1 Glulam Columns

Seen below in Table 18 is a comprehensive breakdown of the costs associated with the glulam columns. As illustrated, the analysis includes various dimensions and quantities of Douglas Fir, grade 16 c-E, to derive the total volume and subsequent cost for each column specification. Calculations are based on the assumed unit cost of $1,500 per cubic meter, factoring in the length, width, and depth of each column. The detailed costing cumulates to a total cost of $108,552.30 for the glulam columns required for this design.

TABLE 18: COST ANALYSIS OF GLULAM COLUMNS

Glulam Columns							
Material	**# of Columns**	**Width B (m)**	**Depth D (m)**	**Length L (m)**	**Total Volume (m^3)**	**\$/m^3**	**Cost (\$)**
D. Fir - L 16 c-E	25	0.315	0.304	10	23.94	1500	35,910.00
D. Fir - L 16 c-E	25	0.215	0.19	6	6.12	1500	9,191.25
D. Fir - L 16 c-E	33	0.265	0.266	10	23.26	1500	34,892.55
D. Fir - L 16 c-E	33	0.175	0.19	6	6.58	1500	9,875.25
D. Fir - L 16 c-E	17	0.215	0.266	10	9.72	1500	14,583.45
D. Fir - L 16 c-E	17	0.175	0.152	6	2.71	1500	4,069.8
Total Cost (\$)							**108,522.30**

12.5.2 Glulam Beams

Table 19 displays a detailed costing for the pricing of glulam beams required in this design. The table specifies various dimensions and quantities of Douglas Fir, grade 24 f-E, alongside a detailed breakdown of the number of specific beams needed on each floor and their respective net quantities. Additionally, the individual dimensions of each element are displayed, with a total volume calculated. After applying the unit cost of $1,500 per cubic meter to the respective total volumes, a cumulative cost of the glulam beams was found to be $370,686.39.

TABLE 19: COST ANALYSIS OF GLULAM BEAMS

Glulam Beams								
Material	**# of Beams /Floor**	**Net # of Beams**	**Width B (m)**	**Depth H (m)**	**Length L(m)**	**Total Volume (m^3)**	**$/$m^3$**	**Cost ($)**
D. Fir - L 24 f-E	22	132	0.215	0.418	4.64	55.04	1500	82,565.37
D. Fir - L 24 f-E	16	96	0.215	0.418	6.33	54.61	1500	81,918.30
D. Fir - L 24 f-E	12	72	0.215	0.532	7.363	60.64	1500	90,955.43
D. Fir - L 24 f-E	4	24	0.265	0.494	6.33	19.89	1500	29,831.77
D. Fir - L 24 f-E	8	48	0.265	0.608	7.363	56.94	1500	85,415.51
Total Cost ($)								**370,686.39**

12.5.3 Glulam Joists

Table 20 details the costing for the glulam joists specified for the design, comprising of various dimensions and quantities of Douglas Fir, grade 24 f-E. The table the total number of joists required for each element, along with individual width, depth, and length measurements. Through calculating the total volume and applying the unit cost of $1,500 per cubic meter, the total cost of the glulam joists was found to be $797,913.62.

TABLE 20: COST ANALYSIS OF GLULAM JOISTS

Glulam Joists							
Type	**# of Joists**	**Width B (m)**	**Depth D (m)**	**Length L (m)**	**Total Volume (m^3)**	**$/$m^3$**	**Cost ($)**
D. Fir - L 24 f-E	318	0.175	0.266	5.35	79.20	1500	118,793.27
D. Fir - L 24 f-E	516	0.175	0.304	6.33	173.77	1500	260,649.14
D. Fir - L 24 f-E	552	0.175	0.38	7.6	278.98	1500	418,471.20
Total Cost ($)							**797,913.62**

12.5.4 Glulam Elements Costing Summary

Seen below in Table 21 is a summary of the costs of each glulam element, supported by a total cost of all glulam elements required for this design. This total sum was found to be $1,277,122.31.

TABLE 21: SUMMARY TABLE OF GLULAM ELEMENTAL COSTING

Summary Table	
Glulam Element	**Cost ($)**
Columns (D. Fir - L 16 c-E)	108,522.30
Beams (D. Fir - L 24 f-E)	370,686.39
Joists (D. Fir - L 24 f-E)	797,913.62
Total Cost	**1,277,122.31**

As previously stated, there is a level of uncertainty in preliminary costing estimates due to factors such as variation in the dimensions of the structural elements and their respective grades of timber. Understanding this, a 30% buffer has been applied to the initial costing results. This conservative approach ensures a more realistic costing projection, accommodating potential deviations from the estimated costs. This decision to incorporate this 30% buffer aligns with the Class D cost analysis specifications used in the estimation of the Endaayaan – Tkanónsote residence, which recommends a similar allowance for early-stage estimates. As a result, the unit cost for glulam has been adjusted to $1,950 per cubic meter, providing a more reliable costing estimate. The application of this buffer can be seen below in Table 22 with a final cost of glulam elements coming to $1,660,259.31.

TABLE 22: SUMMARY OF GLULAM ELEMENTAL COSTING WITH 30% BUFFER.

Summary Table	
Glulam Element	**Cost ($)**
Columns (D. Fir-L 16 c-E)	141,079.00
Beams (D. Fir - L 24 f-E)	481,892.31
Joists (D. Fir - L 24 f-E)	1,037,288.00
Total Cost	**1,660,259.31**

12.5.5 CLT Elevator Shaft

The costing of the CLT elevator system was determined by referencing the costs from the Endaayaan – Tkanónsote residence project and adapting them to current market conditions. It was established through research that a CLT elevator shaft typically includes 70-75% of the cost of a conventional elevator shaft (McOlson 2023). To accurately reflect current day expenses, the initial cost of $133,333.33 from the Endaayaan – Tkanónsote residence's cost analysis was updated to account an inflation rate of 18.9% since 2019. This adjusted figure represents the current standard figure for a conventional elevator system. Conservatively, the lower end of the percentage range, 70%, was applied to this inflation-adjusted cost to derive the final estimation for the CLT elevator systems. This approach presented a total cost of $221,199.99 for the two required CLT elevator systems.

12.5.6 Steel Reinforcement

The cost estimation for the steel reinforcement required in the project was calculated based on the specific needs for foundational support. A total of 2723 meters of 20M bar and 18310 meters of 10M bar was required for this design. The materials were sources from Vieira Concrete Supplies, taking the high end of the pricing range, with the cost of a 6 – meter 10M bar listed at $9.94 and a 6 – meter 20M bar at $27.90. To determine the total number of bars required, the total meterage for each bar type was divided by the length of each individual bar, yielding 454 bars of 20 M and 3052 bars of 10M. A detailed breakdown of the steel reinforcement costing can be seen below in Table 23, with a total cost of $43,003.48.

TABLE 23: COST ANALYSIS OF STEEL REINFORCEMENT

Steel Reinforcement Costs				
Steel Reinforcement Type	**Length Required (m)**	**Cost per 6-meter bar**	**Number of Bars**	**Cost ($)**
10M	18310	9.94	3052	30,336.88
20M	2723	27.9	454	12,665.46
Total Cost				**43,003.48**

12.5.7 Concrete Foundation

In order to reach the sustainability goals of this project, ECOPact concrete sourced by LaFarge Canada will be used. The base unit cost for standard concrete is specified by Canada's Building Material Guide as $250 per cubic meter (CBM 2024). For the required volume of 466 cubic meters, the initial material cost computes to $116,500. However, it is an industry standard practice to apply a premium for environmentally sustainable materials due to their complexities. Low carbon concrete mixes like ECOPact typically have a 10-30% premium in price due to their enhance properties (Wright 2020).

In conservative estimates, the upper limit of this range, 30%, has been applied to the unit cost, adjust the cost per cubic meter to 325$. This increased unit cost results in a total cost for the concrete foundation material to be $151,450.

12.6 Total Elemental Costing, Net Zero Residence

A detailed breakdown of the total elemental quantities and their respective costings can be seen below in Table 24, with a total material cost of $2,488,054.86 for the elements that the team has designed.

Table 24: Cost Analysis Summary of the Total Elemental Costing

Total Elemental Costing, Net Zero Residence		
Substructure	**Quantity**	**Element Cost ($)**
Concrete Foundation	466 m^3	151,450
Steel Reinforcement	21033 m^2	43,003.48
Basement Excavation	5493.6 m^3	302,148
Total Substructure Cost		**496,601.48**
Superstructure	**Quantity**	**Element Cost ($)**
Glulam Columns	72.35 m^3	141,079
Glulam Beams	247.12 m^3	370,686.39
Glulam Joists	531.94 m^3	1,037,288.00
CLT Elevator Shaft	2 units	221,199.99
CLT Stair Shaft	2 units	221,199.99
Total Superstructure Cost		**1,701,082.37**
Total Cost (Substructure + Superstructure)		**2,488,054.86**

12.7 Costing Comparison

The material cost comparison between the Endaayaan – Tkanónsote and NetZero residences, detailed in Table 25, displays variations in construction elements and cost associated with these different methods. The Endaayaan – Tkanónsote residence consists of a total material cost of $1,977,801.65, encompassing concrete for both the superstructure and substructure, steel reinforcement, basement excavation, and combined costs for elevators and stairs. In contrast, the NetZero residence materials totals to $2,488,054.86, with costs stemming from the concrete used in the substructure, glulam elements for the superstructure, steel reinforcement, basement excavation, and combined costs for the CLT elevator and stair systems. The significant cost contributor for the NetZero residence is glulam, accounting for $1,549,053 of the total expenditure.

Table 25: Cost Comparison of Material Costs for the NetZero Residence and Endaayaan – Tkanónsote Residence

Endaayaan – Tkanónsote			**NetZero Residence**		
Element	**Quantity**	**Cost ($)**	**Element**	**Quantity**	**Cost ($)**
Concrete (Superstructure and Substructure)	2859 m^3	514,620.00	Concrete (Substructure)	466 m^3	151,450.00
			Glulam (Superstructure)	851.49 m^3	1,549,053.00
Steel Reinforcement	225,905 kg	677,715.00	Steel Reinforcement	21033 m^2	43,003.48
Basement Excavation	2160 m^3	118,800.00	Basement Excavation	5493.6 m^3	302,148.00
Elevator/Stairs	5 units	666,666.65	Elevator/Stairs	4 units	442,399.98
Total Cost		**1,977,801.65**	**Total Cost**		**2,488,054.86**

Direct comparison is constrained by the different quantities and types of materials used, reflective of each project's unique designs. The NetZero residence with its sustainability focus, includes elements specifically chosen to reduce the carbon footprint, such as ECOPact concrete, which is much more expensive that standard options used in the Endaayaan – Tkanónsote residence. Additionally, the cost per unit for similar materials may have increased over time as they are subject to inflation.

Labor costs are a significant factor in construction projects and can vary widely based upon methods and materials of construction. Reinforced concrete construction typically involves complex formwork, site-specific rebar fabrication, extensive material transportation due to its weight, and the need for highly skilled labor for on-site concrete finishing. These processes are labor intensive and time consuming, which can lead to increased labor costs. On the contrary, mass timber construction with materials like glulam often benefits from off-site prefabrication, which allows for a more efficient process, including less on-site labor. The installation of mass timber elements is generally faster, requiring a smaller crew with different skill sets compared to those needed for concrete construction, potentially lowering the overall labor costs.

In the context of this NetZero design, it is important to consider that while upfront the material costs of mass timber may be higher, the potential for reduced labor costs due to quicker and more efficient installation could potentially offset some of these expenses. A detailed analysis of labor costs, considering the specific requirements of the project's design, local market condition, and the types of labor required, will be crucial for a complete financial comparison of the two buildings.

13.0 Risk Assessment

Constructing a five-storey tall mass timber building in Ontario presents several unique risks, primarily due to the material's properties and local regulations. Mass timber poses fire risk concerns, particularly during the construction phase before fire protection measures are fully implemented. Ontario's building codes and fire safety standards are stringent, requiring comprehensive planning to mitigate these risks through fire-resistant design and construction practices (Ontario 2008). Additionally, the region's climate can introduce challenges related to moisture management, necessitating careful design and material treatment to prevent decay and maintain structural integrity. Compliance with local building codes and standards is paramount, as is collaboration with authorities to ensure the safety and durability of the structure. The relative novelty of mass timber construction at such a scale may also pose logistical and engineering challenges, requiring specialized expertise to navigate successfully.

14.0 Conclusions

The innovative design for a new NetZero residence building at Queen's University was complete, in accordance with the stakeholders' needs. The location for the building was decided to be on the south side of Stuart St, with Leggett Hall to the west and McLaughlin Hall to the east of the site. The building was chosen to be five-storeys tall, including a basement. The shape of the building was chosen to optimize the occupancy for the area of the site and to allow for natural lighting in the building. The building has an occupancy capacity of 396 residents, with the three upper floors having an occupancy capacity of 84 residents each.

The design makes use of a glulam column and beam gravity load bearing system. Structurally, the building has a continuous column design, allowing for single-span beams to make up each floor. The design innovatively consists of CLT elevator and stair shafts, which reduce the cost and installation time of the shafts when compared to concrete shafts (Henjum et al. 2021).

The substructure was designed according to a SAP2000 analysis of the building, allowing axial forces, lateral forces, and moments to be used in the design of a foundation. The substructure design utilized ECOPact concrete, which reduces the carbon emissions from the foundation by approximately 30% when compared to normal concrete (Lafarge Canada 2023).

The carbon performance results from the OneClick LCA show that the embodied carbon of the building materials is comparable to the Endayaan residence, when including rooftop solar panels as an alternative energy production method. The total carbon dioxide equivalent emissions for the project is 4076 tonnes CO2e. Assessing the carbon impact on a distributed area metric shows that the building design is considered as a category C emitter compared to other comparable designs. Removing the rooftop solar panels improves the design to a category A emitter. Using low carbon building materials such as mass timber and low-carbon concrete enabled a sequestered carbon valuation of 2.08 M kg CO2e. Further assessment will be required to verify the carbon performance post-construction, as was done for the Endayaan residence.

The final material cost for the NetZero residence project is detailed at $2,488,054.86, as per the focused cost analysis on materials relevant to NetZero Design. This report, while comprehensive in the material scope, excludes cost of labor and additional overhead costs. A comparative summary presented in Table 24 shows the cost differential between the Endayaan and NetZero residences, highlighting the increased cost implications of sustainable material choices in the NetZero project.

15.0 Recommendations

As it currently stands, the NetZero residence building design has progressed well. The location of the residence has been determined, the shape, size, and capacity of the building have all been established, and a floor plan demonstrating the interior layout has been created. In terms of technical design, the structural design has been completed for both gravity and lateral loads, along with the foundation design, the costing estimate for the materials needed, and the carbon emission analysis of the building. However, should this project continue, more work would still need to be done. The utilities needed to operate and maintain the building, including electricity, water, and HVAC, have not yet been considered and would need to be designed. Energy production/carbon reduction methods, such as the addition of solar panels or a green roof have not been adequately researched for implementation in the design, however they were both considered and would ideally be a part of the final design to aid in the NetZero effort. In addition to this, a more detailed cost estimate would need to be conducted, as the current cost estimate only covers the construction materials. The new estimate would need to include details about the cost of furnishings, partitions, utility implementation, etc. This estimate would provide the client with more insight into whether the NetZero residence design is beneficial compared to conventional building construction. Another recommendation for the continuation of this project would be to create a construction plan for the NetZero residence, as that would be the next logical step in the project after the design work is completed.

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16.0 Appendix I – Snow Load Calculation

$$S = I_s(S_s(C_bC_wC_sC_a) + S_r) \qquad (4.1.6.2.1.)$$

$$C_w = 1.0 \qquad (4.1.6.2.3.)$$

$$C_b = 0.8\ for\ l_c \leq (\frac{70}{C_w^2}) \qquad (4.1.6.2.2.a.i)$$

$$l_c = 2w - \frac{w^2}{L} = 2(13) - \frac{(13)^2}{76} = 23.8\ m$$

$$l_c \leq \left(\frac{70}{1^2}\right)\ \therefore C_b = 0.8 \qquad (4.1.6.2.1.)$$

$$C_s = 1.0 \qquad (4.1.6.2.5.a)$$

$$C_a = 1.0 \qquad (4.1.6.2.8.)$$

$$S = (1.0)\Big((2.1)\big(0.8(1.0)(1.0)(1.0)\big) + 0.4\Big) = 2.08\ kPa$$

17.0 Appendix II – LLRF Sample Calculation

Column B3 has a tributary area of 41.15 m^2.

17.1.1 Roof:

$$Roof\ with\ a\ \min LL\ of\ 1\ kPa\ \therefore\ no\ LLRF \qquad (4.1.5.8.a)$$

17.1.2 Basement, 1st, 2nd, and 3rd Floor:

Factored loading for floors (Case 2):

$$1.25D + 1.5L \qquad \text{(Table 4.1.3.2.-A)}$$

$$D_{floor} = 1.25 * (1.35) = 1.6875\ kPa$$

$$L_{floor} = 1.5 * (4.8) = 7.2\ kPa$$

Factored loading for roof (Case 3):

$$1.25D + 1.5S + 1.0L \qquad \text{(Table 4.1.3.2.-A)}$$

$$D_{roof} = 1.25 * (3.25) = 4.0625\ kPa$$

$$S_{roof} = 1.5 * (2.08) = 3.12\ kPa$$

$$L_{roof} = 1.0 * (1.0) = 1.0\ kPa$$

Table 26: LLRF for the columns on each floor, where TA is the tributary area and B is the allowable tributary area for LLRF calculations.

Column	Loads Supported	TA (m^2)	B (m^2)	LLRF
4th Floor	Roof	41.15	-	-
3rd Floor	Roof + 1 Floor	82.3	41.15	0.78
2nd Floor	Roof + 2 Floors	123.45	82.3	0.64
1st Floor	Roof + 3 Floors	164.6	123.45	0.58
Basement	Roof + 4 Floors	205.75	164.6	0.54

3rd Floor column:

$$LLRF = 0.3 + \sqrt{\frac{9.8}{41.15}} = 0.78801 < 1.0 \therefore ok \tag{4.1.5.8.c}$$

Table 27: The cumulative compressive superimposed dead load (DL) for column B3 for each floor.

Superimposed Dead Load			
Column	TA (m^2)	**DL (kPa)**	**Cumulative DL (kN)**
4th Floor	41.15	4.0625	167.17
3rd Floor	41.15	1.6875	236.61
2nd Floor	41.15	1.6875	306.05
1st Floor	41.15	1.6875	375.49
Basement	41.15	1.6875	444.93

TABLE 28: THE CUMULATIVE COMPRESSIVE LIVE LOAD (LL) FOR COLUMN B3 FOR EACH FLOOR.

Roof Live Load			
Column	TA (m²)	**LL (kPa)**	**Cumulative LL (kN)**
4th Floor	41.15	1	41.15
3rd Floor	41.15	0	41.15
2nd Floor	41.15	0	41.15
1st Floor	41.15	0	41.15
Basement	41.15	0	41.15

TABLE 29: THE CUMULATIVE COMPRESSIVE SNOW LOAD (SL) FOR COLUMN B3 FOR EACH FLOOR.

Snow Load			
Column	TA (m²)	**SL (kPa)**	**Cumulative SL (kN)**
4th Floor	41.15	3.12	128.38
3rd Floor	41.15	0	128.38
2nd Floor	41.15	0	128.38
1st Floor	41.15	0	128.38
Basement	41.15	0	128.38

TABLE 30: THE CUMULATIVE REDUCED COMPRESSIVE LIVE LOAD (LL) FOR COLUMN B3 FOR EACH FLOOR.

Floor Live Load with LLRF					
Column	TA (m²)	**SL (kPa)**	**Cumulative SL (kN)**	**LLRF**	**Reduced LL (kN)**
4th Floor	41.15	3.12	128.388	-	-
3rd Floor	41.15	0	128.388	0.788009	233.471402
2nd Floor	41.15	0	128.388	0.645075	382.245465
1st Floor	41.15	0	128.388	0.581752	517.084726
Basement	41.15	0	128.388	0.544005	644.710804

Combining the loads from Table 27 to Table 30, the compressive force (Cf) for the columns at each floor can be determined:

Table 31: The compressive forces (Cf) for column B3 for each floor.

Compressive Force (Cf) at Ultimate Limit States (ULS)	
Column	**Cf (kN)**
4th Floor	336.71
3rd Floor	639.62
2nd Floor	857.84
1st Floor	1062.12
Basement	1259.18

18.0 Appendix III – Glulam Column Sample Calculation

The chosen dimensions were 315 mm by 304 mm for this 10 m tall column.

Modification Factors:

$$K_D = 1.0 \qquad \text{(Table 5.1)}$$

$$K_H = 1.0 \qquad \text{(5.3.5)}$$

$$K_{SC} = 1.0 \qquad \text{(5.3.3)}$$

$$K_T = 1.0 \qquad \text{(5.3.4)}$$

$$K_{SE} = 1.0 \qquad \text{(5.4.1)}$$

$$P_r = \emptyset F_c A K_{Zcg} K_C \qquad \text{(7.5.8.5)}$$

$$F_c = f_c(K_D K_H K_{SC} K_T) \qquad \text{(7.5.8.5)}$$

$$F_c = 30.2(1 * 1 * 1 * 1) = 30.2\ Mpa$$

$$C_c = \max\left(C_{c_x} = \frac{L_{eff,x}}{b}, C_{c_y} = \frac{L_{eff,y}}{d}\right) \qquad \text{(7.5.8.2)}$$

$$C_c = \max\left(C_{c_x} = \frac{4}{0.315}, C_{c_y} = \frac{4}{0.304}\right) = 13.16$$

$$E_{05} = 0.87E = 0.87(12400) = 10788\ Mpa$$

$$K_{Zcg} = 0.68(Z)^{-0.13} = 0.68(0.315 * 0.304 * 10)^{-0.13} = 0.6838\ m^3$$

$$K_C = \left[1 + \frac{F_c K_{Zcg} C_c^3}{35 E_{05} K_{SE} K_T}\right]^{-1} \qquad \text{(7.5.8.6)}$$

$$K_C = \left[1 + \frac{(30.2)(0.6838)(13.16)^3}{35(10788)(1)(1)}\right]^{-1} = 0.8892$$

$$\therefore P_r = 0.8(30.2)(95760)(0.6838)(0.8879) = 1406.8\ kN$$

18.1 Resistance Check:

From Table 26, the maximum factored compressive force for this bottom column is 1259.18 kN, but this does not take the dead load of the beams and of the column into account. Sample calculations for the dead loads of the beams and columns can be seen in SECTION. The additional factored load from the beams and the column can be seen below:

$$1.25 * (DL_{beams} + DL_{column}) = 1.25 * (82.3 + 9.95) = 115.3\ kN.$$

Therefore, the factored resistance check for this column can be seen below:

$$[C_f = (1259.18 + 115.3)] < [P_r = 1406.8\ kN] \quad \therefore OK.$$

19.0 Appendix IV – Flexural Resistance Sample Calculation

The chosen dimensions were 265 mm by 608 mm for this 7363 mm long beam.

Modification Factors:

$$K_D = 1.0 \qquad \text{(Table 5.1)}$$

$$K_H = 1.0 \qquad \text{(5.3.5)}$$

$$K_T = 1.0 \qquad \text{(5.3.4)}$$

$$K_{SE} = 1.0 \qquad \text{(7.4.4)}$$

$$K_{Sb} = 1.0 \qquad \text{(7.4.4)}$$

$$K_X = 1.0 \qquad \text{(7.5.6.5.2)}$$

According to clause 7.5.6.5.3, M_r is equal to the lesser of M_{r1} and M_{r2}.

$$M_{r1} = \emptyset F_b S K_X K_{Zbg} \qquad \text{(7.5.6.5.1)}$$

$$M_{r2} = \emptyset F_b S K_X K_L \qquad \text{(7.5.6.5.1)}$$

Where:

$$\emptyset = 0.9 \qquad \text{(7.5.6.5.1)}$$

$$F_b = f_b(K_D K_H K_{Sb} K_T) \qquad \text{(7.5.6.5.1)}$$

$$F_b = 30.6(1 * 1 * 1 * 1) = 30.6\ Mpa$$

$$K_{Zbg} = \left(\frac{130}{b}\right)^{\frac{1}{10}} \left(\frac{610}{d}\right)^{\frac{1}{10}} \left(\frac{9100}{L}\right)^{\frac{1}{10}} \leq 1.3 \qquad \text{(7.5.6.5.1)}$$

$$K_{Zbg} = \left(\frac{130}{265}\right)^{\frac{1}{10}} \left(\frac{610}{608}\right)^{\frac{1}{10}} \left(\frac{9100}{7363}\right)^{\frac{1}{10}} > 1.3\ \therefore = 1.3$$

$$S = \frac{bd^2}{6} = \frac{(265)(608)^2}{2} = 16.327 * 10^6\ mm^3 \qquad \text{(7.5.6.5.1)}$$

$$When\ C_b \leq 10, K_L = 1.0 \qquad \text{(7.5.6.4.4.a)}$$

$$C_b = \sqrt{\frac{L_e d}{b^2}} \quad (7.5.6.4.3)$$

$$L_e = 1.92L = 1.92(7.363) = 14.137 \quad (7.5.6.4.3)$$

$$C_b = \sqrt{\frac{(14.137)(0.608)}{(0.265)^2}} = 0.350 \ \therefore K_L = 1.0$$

$$M_{r1} = (0.9)(30.6)(16.327 * 10^6)(1.0)(1.3) = 584.53\ kNm$$

$$M_{r2} = (0.9)(30.6)(16.327 * 10^6)(1.0)(1.0) = 449.64\ kNm$$

$$\therefore M_r = 449.64\ kNm$$

19.1 Resistance Check:

As seen in SECTION, the factored bending moment for this beam is 401.1 kNm, but this does not account for the dead load from the self-weight of the beam. The additional factored load from the beam can be seen below:

$$w_{self-weight} = d * b * \lambda_{material} = (0.608\ m)(0.265\ m) * 5.194 \frac{kN}{m^3} = 0.8369 \frac{kN}{m}$$

$$M_{self-weight} = \frac{w_{self-weight} * L^2}{8} = \frac{(0.8369)(7.363)^2}{8} = 5.671\ kNm.$$

Therefore, the factored resistance check for this column can be seen below:

$$M_f = 401.1\ kNm + 5.671\ kNm = 406.77\ kNm.$$

Since the moment resistance of the beam is greater than the factored moment of 406.77 kNm, the design passes in flexure.

20.0 Appendix V – Shear Resistance Sample Calculation

The chosen dimensions were 265 mm by 608 mm for this 7363 mm long beam.

Modification Factors:

$$K_D = 1.0 \qquad \text{(Table 5.1)}$$

$$K_H = 1.0 \qquad \text{(5.3.5)}$$

$$K_T = 1.0 \qquad \text{(5.3.4)}$$

$$K_{Sv} = 1.0 \qquad \text{(7.4.4)}$$

$$W_r = \emptyset F_v 0.48 A_g C_v Z^{-0.18} \qquad \text{(7.5.7.3.a)}$$

Where: $\emptyset = 0.9$ (7.5.7.3.b)

$$F_v = f_v(K_D K_H K_{Sv} K_T) \qquad \text{(7.5.7.3.b)}$$

Where: $f_v = 2.0\ MPa$ (Table 7.2)

$$F_v = (2.0)(1*1*1*1) = 2.0\ MPa$$

$$A_g = bd = (265)(608) = 161120\ mm^2$$

$$Z = bdL = (0.265)(0.608)(7.363) = 1.186\ m^3$$

$$C_v = 3.69 \qquad \text{(Table 7.8)}$$

$$W_r = 0.9(2.0)0.48(161120)(3.69)(1.186)^{-0.18} = 498.14\ kN$$

20.1 Resistance Check:

$$W_f = w_f L$$

$$w_f = (1.5L + 1.25D) * TW + w_{self-weight}$$

$$w_f = \big(1.5(4.8\ kPa) + 1.25(1.35\ kPa)\big) * 6.660\ m + 0.8369\frac{kN}{m} = 60.03\ kN/m$$

$$W_f = \left(60.03\frac{kN}{m}\right) * (7.363\ kN) = 441.98\ kN$$

$$(W_r = 498.14\ kN) > \ (W_f = 441.98\ kN) \quad \therefore OK$$

Since the shear resistance of the beam is greater than the factored overall shear of, the design passes in shear.

21.0 Appendix VI – Deflection Sample Calculation

According to section 5.4.2 of the CSA O86, the deflection of a member under the loads for serviceability limit states shall not exceed 1/180 of the span of the member (Canadian Standards Association Group 2019). Serviceability limit states means that the loads in Table 8 are not factored for the calculations. The dead loads are not included in defection checks, according to section 5.4.2 of the CSA O86.

$$\Delta = \frac{WL^3}{E_S I} K_\Delta \qquad \text{(Wood Design Manual)}$$

$$E_S = E(K_{SE}K_T) = 12800(1)(1) = 12800\ MPa \qquad (5.4.1)$$

$$I = \frac{bd^3}{12} = \frac{(265)(608)^3}{12} = 4.9634 * 10^9\ mm^4$$

$$W = 4.8\ kPa(6.33\ m) = 30.384\ kN/m$$

$$K_\Delta = 0.013 \qquad \text{(Wood Design Manual)}$$

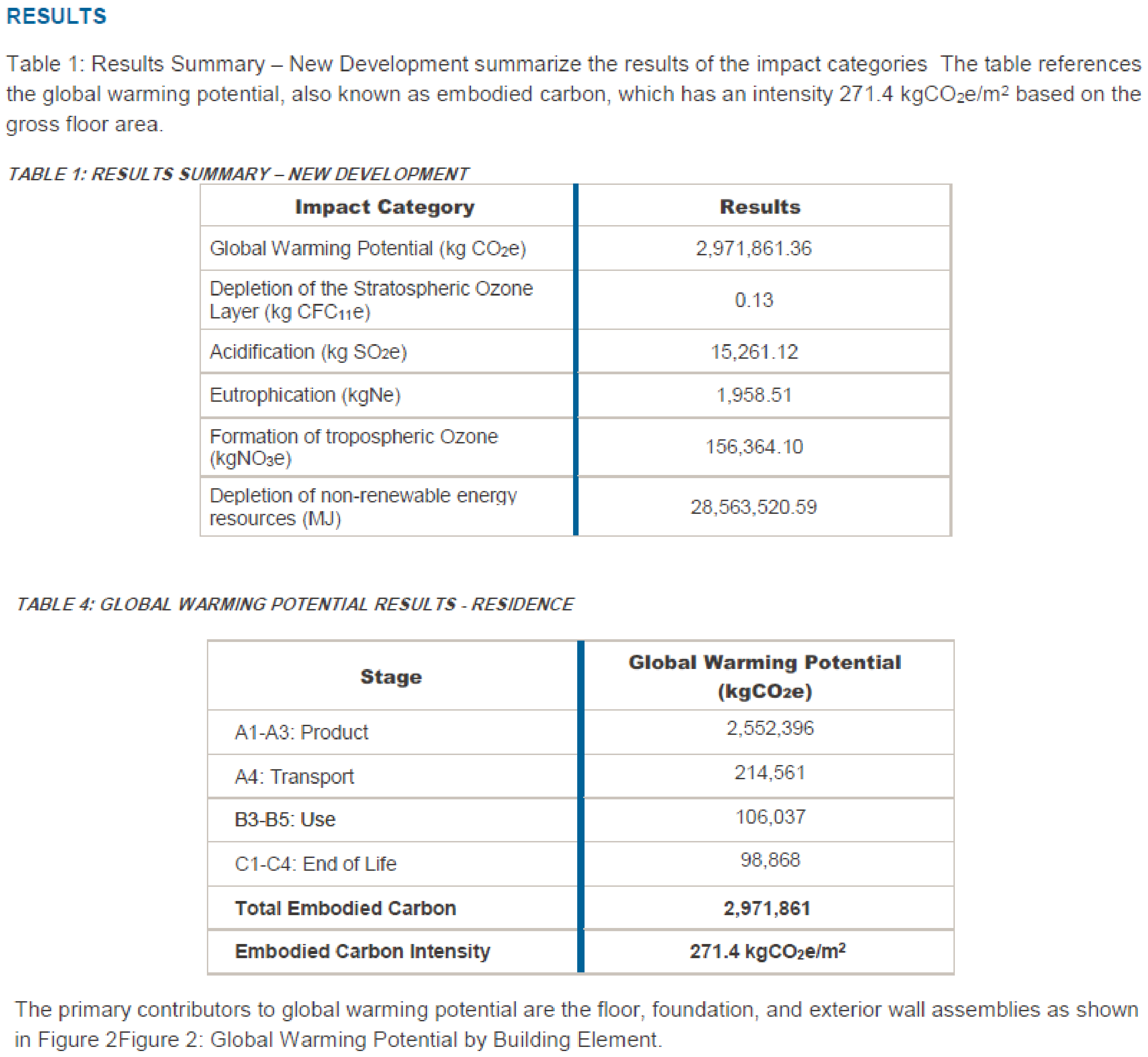
$$\Delta = \frac{(30.384)(7.363)^3}{(12000000)(4.9634 * 10^{-3})}(0.013) = 0.002647\ m$$

21.1 Check:

$$(\Delta = 0.002647\ ) > \left(\frac{L}{180} = \frac{7.363m}{180} = 0.0409\ m\right) \therefore OK$$

22.0 Appendix VII – Footprint Endaayaan Carbon Assessment

Attached here are key elements of the post-construction life cycle assessment report conducted by Footprint for the Endaayaan -Tkanónsote residence (Michayluk 2023).



RESULTS

Table 1: Results Summary – New Development summarize the results of the impact categories The table references the global warming potential, also known as embodied carbon, which has an intensity 271.4 $kgCO_2e/m^2$ based on the gross floor area.

TABLE 1: RESULTS SUMMARY – NEW DEVELOPMENT

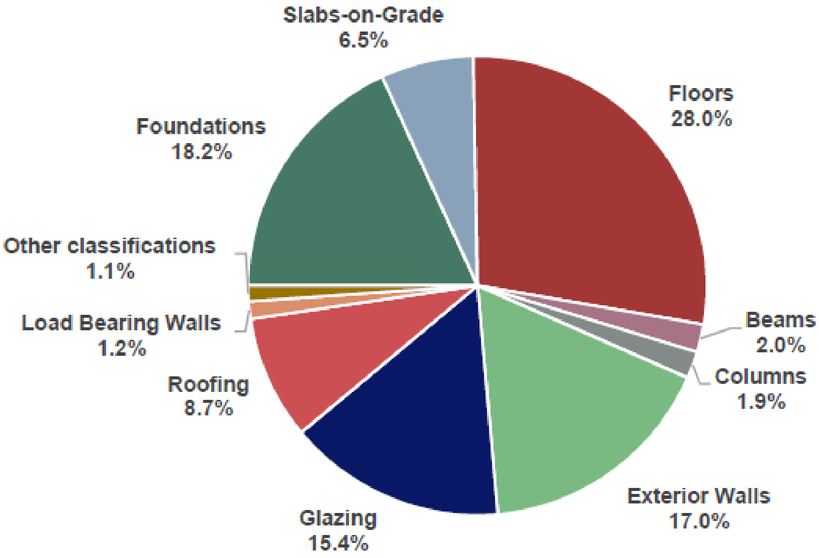
Impact Category	**Results**
Global Warming Potential (kg CO_2e)	2,971,861.36
Depletion of the Stratospheric Ozone Layer (kg $CFC_{11}e$)	0.13
Acidification (kg SO_2e)	15,261.12
Eutrophication (kgNe)	1,958.51
Formation of tropospheric Ozone ($kgNO_3e$)	156,364.10
Depletion of non-renewable energy resources (MJ)	28,563,520.59

TABLE 4: GLOBAL WARMING POTENTIAL RESULTS - RESIDENCE

Stage	**Global Warming Potential ($kgCO_2e$)**
A1-A3: Product	2,552,396
A4: Transport	214,561
B3-B5: Use	106,037
C1-C4: End of Life	98,868
Total Embodied Carbon	**2,971,861**
Embodied Carbon Intensity	**271.4 $kgCO_2e/m^2$**

The primary contributors to global warming potential are the floor, foundation, and exterior wall assemblies as shown in Figure 2Figure 2: Global Warming Potential by Building Element.

FIGURE 2: GLOBAL WARMING POTENTIAL BY BUILDING ELEMENT



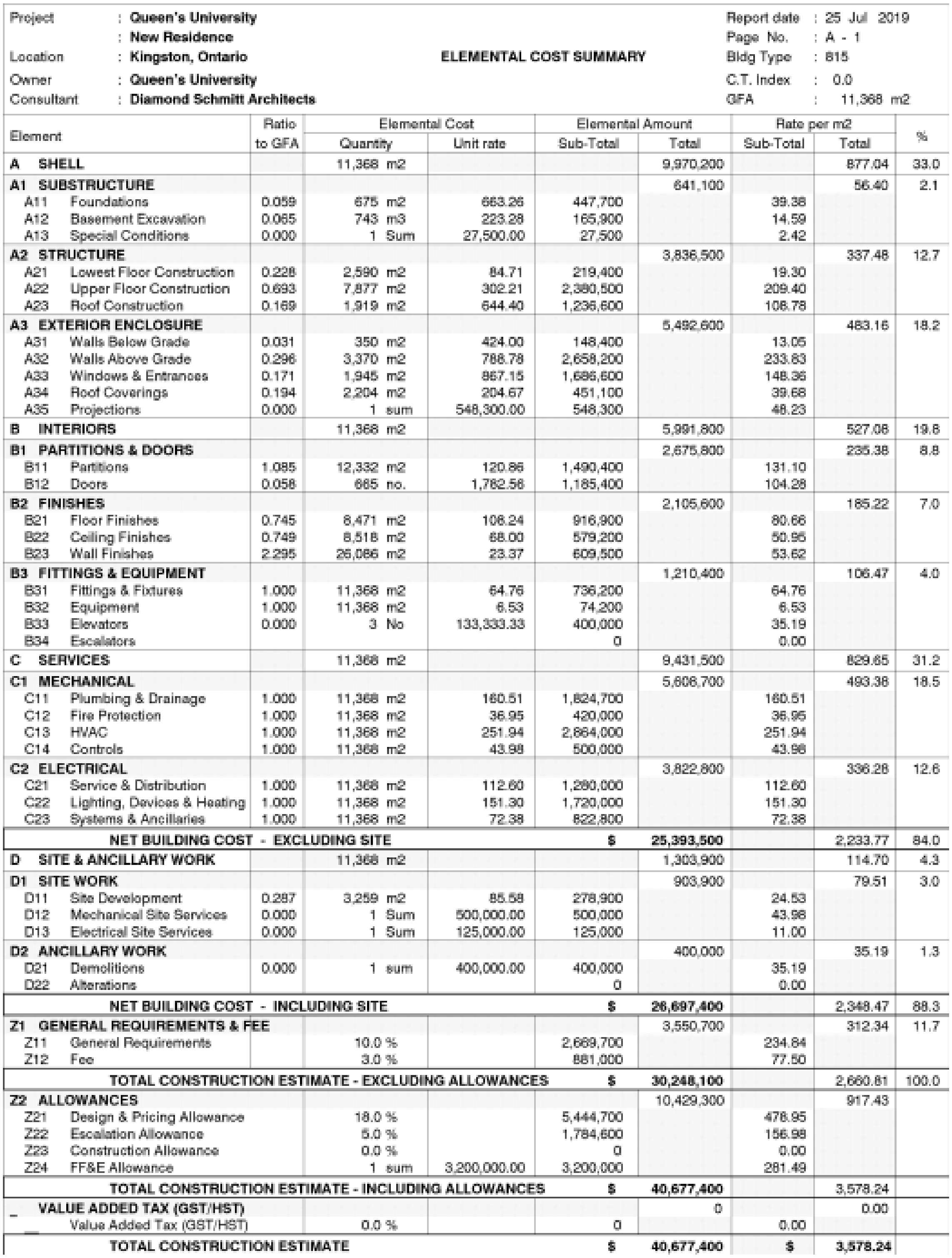
The following tables provide the full life cycle assessment results for the proposed design.

TABLE 7: PROPOSED LCA RESULTS BY STAGE

Result Category	**Global Warming (kg CO2e)**	**Ozone Depletion (kg CFC11e)**	**Acidification (kg SO2e)**	**Eutrophication (kg Ne)**	**Formation of Tropospheric Ozone (kg O3e)**	**Depletion of Non-renewable Energy (MJ)**
A1-A3: Construction Materials	2,552,396	0.06	11,142	1,544	145,359	24,114,203
A4: Transportation to site	214,561	0.05	369	149	5,242	3,301,298
B3-B5: Maintenance and Material Replacement	106,037	0.01	399	202	4,987	1,014,323
C1-C4: Deconstruction	98,868	0.01	3,351	64	776	133,696
TOTAL	**2,971,861**	**0.13**	**15,261**	**1,959**	**156,364**	**28,563,521**

23.0 Appendix VIII – Cost Analysis Endaayaan – Tkanónsote

Attached here is an elemental cost summary for the Endaayaan – Tkanónsote residence. These costs are inclusive of material and labour costs.



Project : **Queen's University**
: **New Residence**
Location : **Kingston, Ontario**
Owner : **Queen's University**
Consultant : **Diamond Schmitt Architects**

ELEMENTAL COST SUMMARY

Report date : 25 Jul 2019
Page No. : A - 1
Bldg Type : 815
C.T. Index : 0.0
GFA : 11,368 m2

Element	Ratio to GFA	Elemental Cost		Elemental Amount		Rate per m2		%
		Quantity	Unit rate	Sub-Total	Total	Sub-Total	Total	
A SHELL		11,368 m2			9,970,200		877.04	33.0
A1 SUBSTRUCTURE					641,100		56.40	2.1
A11 Foundations	0.059	675 m2	663.26	447,700		39.38		
A12 Basement Excavation	0.065	743 m3	223.28	165,900		14.59		
A13 Special Conditions	0.000	1 Sum	27,500.00	27,500		2.42		
A2 STRUCTURE					3,836,500		337.48	12.7
A21 Lowest Floor Construction	0.228	2,590 m2	84.71	219,400		19.30		
A22 Upper Floor Construction	0.693	7,877 m2	302.21	2,380,500		209.40		
A23 Roof Construction	0.169	1,919 m2	644.40	1,236,600		108.78		
A3 EXTERIOR ENCLOSURE					5,492,600		483.16	18.2
A31 Walls Below Grade	0.031	350 m2	424.00	148,400		13.05		
A32 Walls Above Grade	0.296	3,370 m2	788.78	2,658,200		233.83		
A33 Windows & Entrances	0.171	1,945 m2	867.15	1,686,600		148.36		
A34 Roof Coverings	0.194	2,204 m2	204.67	451,100		39.68		
A35 Projections	0.000	1 sum	548,300.00	548,300		48.23		
B INTERIORS		11,368 m2			5,991,800		527.08	19.8
B1 PARTITIONS & DOORS					2,675,800		235.38	8.8
B11 Partitions	1.085	12,332 m2	120.86	1,490,400		131.10		
B12 Doors	0.058	665 no.	1,782.56	1,185,400		104.28		
B2 FINISHES					2,105,600		185.22	7.0
B21 Floor Finishes	0.745	8,471 m2	108.24	916,900		80.66		
B22 Ceiling Finishes	0.749	8,518 m2	68.00	579,200		50.95		
B23 Wall Finishes	2.295	26,086 m2	23.37	609,500		53.62		
B3 FITTINGS & EQUIPMENT					1,210,400		106.47	4.0
B31 Fittings & Fixtures	1.000	11,368 m2	64.76	736,200		64.76		
B32 Equipment	1.000	11,368 m2	6.53	74,200		6.53		
B33 Elevators	0.000	3 No	133,333.33	400,000		35.19		
B34 Escalators				0		0.00		
C SERVICES		11,368 m2			9,431,500		829.65	31.2
C1 MECHANICAL					5,608,700		493.38	18.5
C11 Plumbing & Drainage	1.000	11,368 m2	160.51	1,824,700		160.51		
C12 Fire Protection	1.000	11,368 m2	36.95	420,000		36.95		
C13 HVAC	1.000	11,368 m2	251.94	2,864,000		251.94		
C14 Controls	1.000	11,368 m2	43.98	500,000		43.98		
C2 ELECTRICAL					3,822,800		336.28	12.6
C21 Service & Distribution	1.000	11,368 m2	112.60	1,280,000		112.60		
C22 Lighting, Devices & Heating	1.000	11,368 m2	151.30	1,720,000		151.30		
C23 Systems & Ancillaries	1.000	11,368 m2	72.38	822,800		72.38		
NET BUILDING COST - EXCLUDING SITE				**$**	**25,393,500**		2,233.77	84.0
D SITE & ANCILLARY WORK		11,368 m2			1,303,900		114.70	4.3
D1 SITE WORK					903,900		79.51	3.0
D11 Site Development	0.287	3,259 m2	85.58	278,900		24.53		
D12 Mechanical Site Services	0.000	1 Sum	500,000.00	500,000		43.98		
D13 Electrical Site Services	0.000	1 Sum	125,000.00	125,000		11.00		
D2 ANCILLARY WORK					400,000		35.19	1.3
D21 Demolitions	0.000	1 sum	400,000.00	400,000		35.19		
D22 Alterations				0		0.00		
NET BUILDING COST - INCLUDING SITE				**$**	**26,697,400**		2,348.47	88.3
Z1 GENERAL REQUIREMENTS & FEE					3,550,700		312.34	11.7
Z11 General Requirements		10.0 %		2,669,700		234.84		
Z12 Fee		3.0 %		881,000		77.50		
TOTAL CONSTRUCTION ESTIMATE - EXCLUDING ALLOWANCES				**$**	**30,248,100**		2,660.81	100.0
Z2 ALLOWANCES					10,429,300		917.43	
Z21 Design & Pricing Allowance		18.0 %		5,444,700		478.95		
Z22 Escalation Allowance		5.0 %		1,784,600		156.98		
Z23 Construction Allowance		0.0 %		0		0.00		
Z24 FF&E Allowance		1 sum	3,200,000.00	3,200,000		281.49		
TOTAL CONSTRUCTION ESTIMATE - INCLUDING ALLOWANCES				**$**	**40,677,400**		3,578.24	
_ VALUE ADDED TAX (GST/HST)					0		0.00	
__ Value Added Tax (GST/HST)		0.0 %		0		0.00		
TOTAL CONSTRUCTION ESTIMATE				**$**	**40,677,400**	**$**	**3,578.24**	

24.0 Appendix IX – Team Roles

APEX's undergraduate Civil Engineering design team was responsible for managing the project in its entirety, with support from the client and other stakeholders. Each team member had assigned responsibility for various project components, as matched to their skill set and experience. A collaborative effort ensured that tasks and deliverable subcomponents were provided with an appropriate level of review and verification from the entire team. This plan was subject to change as the project progressed, and any significant changes were communicated in a timely manner to the client and any relevant stakeholders.

The team brought a combined 5+ years of design and consulting experience in diverse civil engineering environments. A strong technical and soft skills background from undergraduate applied science courses ensured that the group was well equipped to provide the client with a clear and concise solution.

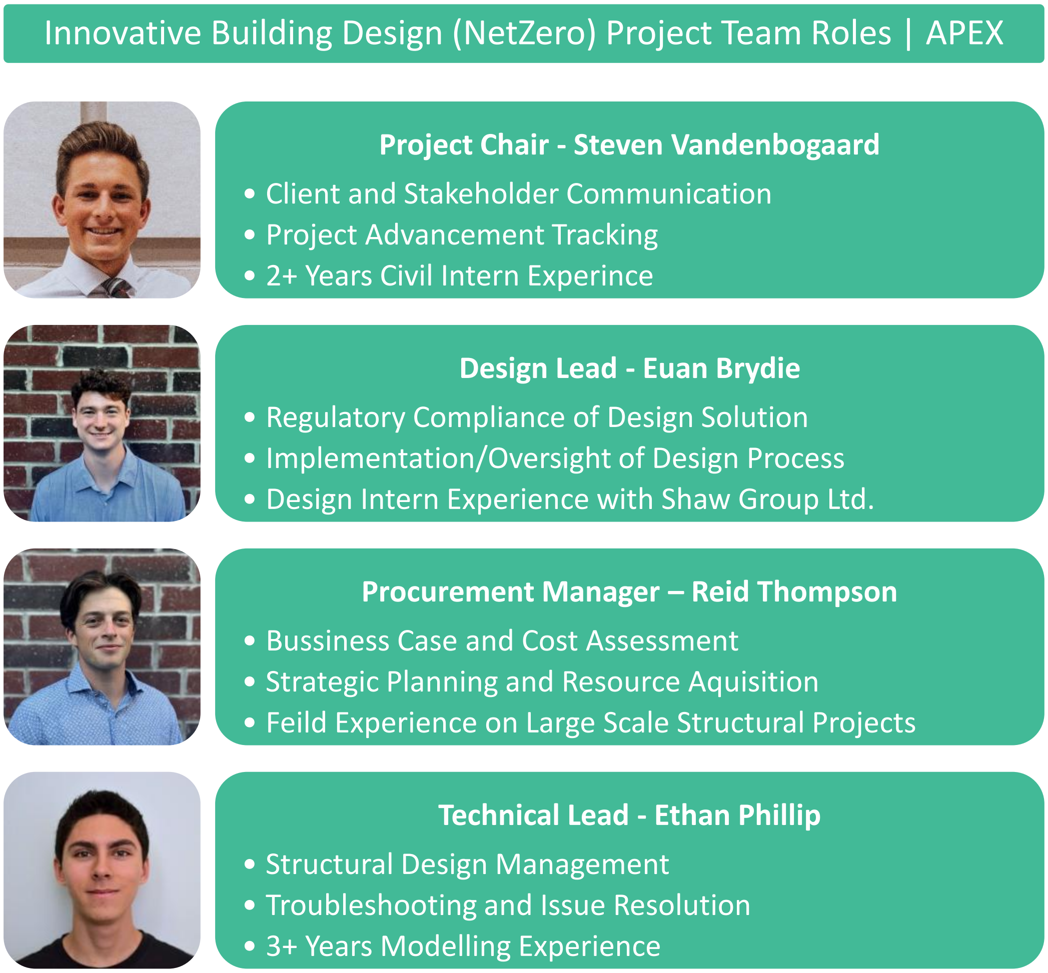
Steven's role as Project Chair was one that naturally suited his personality and desire for success. In this position, he was responsible for tracking the progress of key project deliverables. Establishing a clear line of communication with the client and stakeholders provided project stability throughout the duration of the project. Steven had experience coordinating medium-scale projects through MTO Eastern Region and EXP.

Euan supported the team as the Design Lead. He was responsible for directing the design process to ensure that the proper engineering process was utilized and that all regulatory requirements were met. Experience with Shaw Group’s precast concrete department and DesignPoint Engineering had provided him with a wealth of professional experience. His passion for engineering design suited him well for this role and in successfully meeting the client’s needs.

Reid served the team as Procurement Manager and was responsible for strategic planning. He also assisted the team with material data acquisition/analysis and oversaw the cost assessment of the design solution. Specifically, Reid was in charge of the final cost estimation of the design, using RSMeans as a sufficient cost estimation tool to aid his analysis. As a field and laboratory technician with Metro Testing + Engineering, he oversaw the construction of substantial structural projects, including Vancouver Island's largest concrete pour. Additionally, he held an assistant manager role at W&J W Wilsons.

Ethan, the Senior Technical Administrator for the project, managed the structural modelling of the superstructure components. His prior experience with software SAP2000 ensured that the new innovative design could be accurately assessed with a structural CAD model. Ethan was well-suited for this role as expressed by his extensive site experience, which included structural rehabilitation projects with the Town of Newmarket.

A graphic overview of the team and each member's project responsibilities is provided in Figure 36.



Innovative Building Design (NetZero) Project Team Roles | APEX

Project Chair - Steven Vandenbogaard

- Client and Stakeholder Communication
- Project Advancement Tracking
- 2+ Years Civil Intern Experince

Design Lead - Euan Brydie

- Regulatory Compliance of Design Solution
- Implementation/Oversight of Design Process
- Design Intern Experience with Shaw Group Ltd.

Procurement Manager – Reid Thompson

- Bussiness Case and Cost Assessment
- Strategic Planning and Resource Aquisition
- Feild Experience on Large Scale Structural Projects

Technical Lead - Ethan Phillip

- Structural Design Management
- Troubleshooting and Issue Resolution
- 3+ Years Modelling Experience

FIGURE 36: PROJECT TEAM ROLES

25.0 Appendix X – Team Dynamics

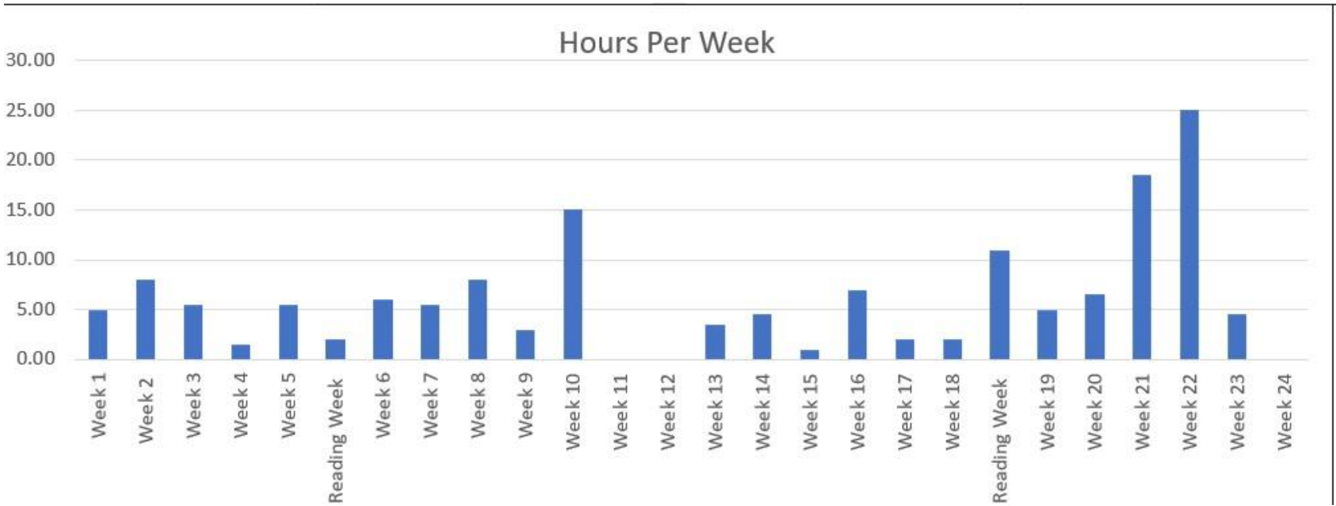
The team consisted of Euan Brydie, Ethan Phillip, Reid Thompson, and Steven Vandenbogaard.

The team worked well together throughout the course of this project. Two team meetings were conducted each week, alongside a weekly meeting with the project manager and bi-weekly meetings with the client. Team members attended all the meetings that they could and collaborated effectively during the team meetings. Each team member contributed during the meetings and final decisions were always a product of collaboration. The established roles from the start of the project held true to the end of the project, with team members ensuring to keep each other up to date with any individual work that they have done.

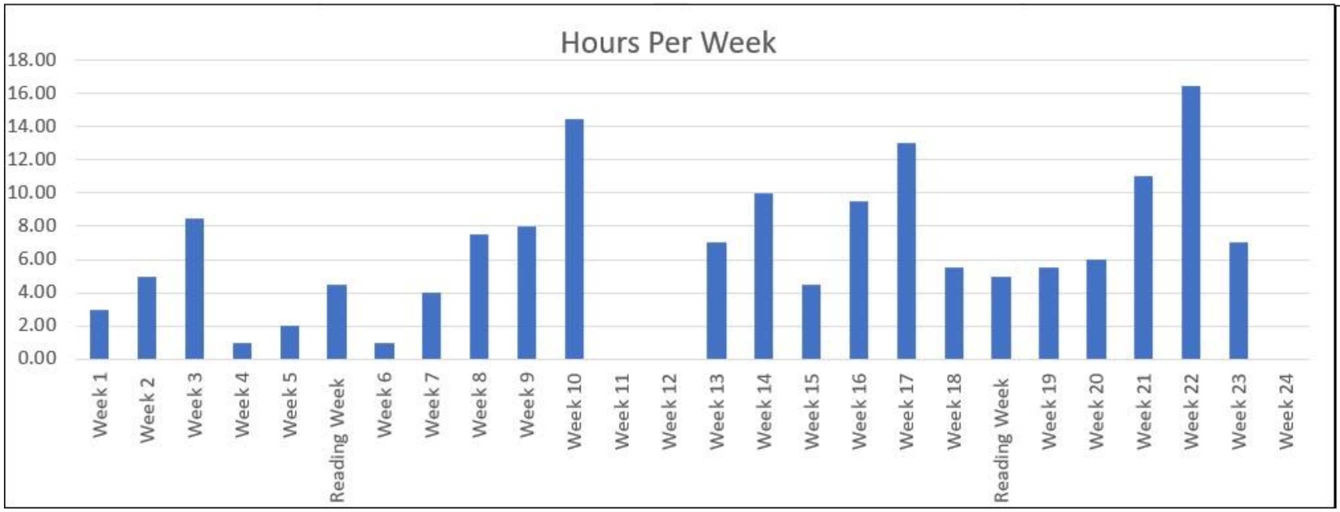
One of the biggest challenges during the project had to do with the large scope of the project. The scope was narrowed down from the beginning of the project, but it was still sometimes unclear how much detail each objective was to be completed in due to the size of the scope. In terms of group dynamics, this created some uncertainty between what each group member was working on, and when they would be finished an individual piece of work. This affected the project schedule, as, for example, at the start of the project, it took much longer to complete the initial objectives of the report before the structural design could have commenced. This would lead to the group member responsible for the modelling portion of the project having to be delayed, waiting for the structural design to be complete, which in turn delayed the ensuing objectives of the project. However, the group maintained good communication to overcome these types of setbacks to still produce a final design. Additionally, the project schedule was constantly updated and allowed for flexibility in objective completion dates, while still allowing for a complete design to be delivered on time. An attached file with the submission of this report displays the project schedule in the forms of a Gantt Chart.

26.0 Appendix XI – Hours Logged

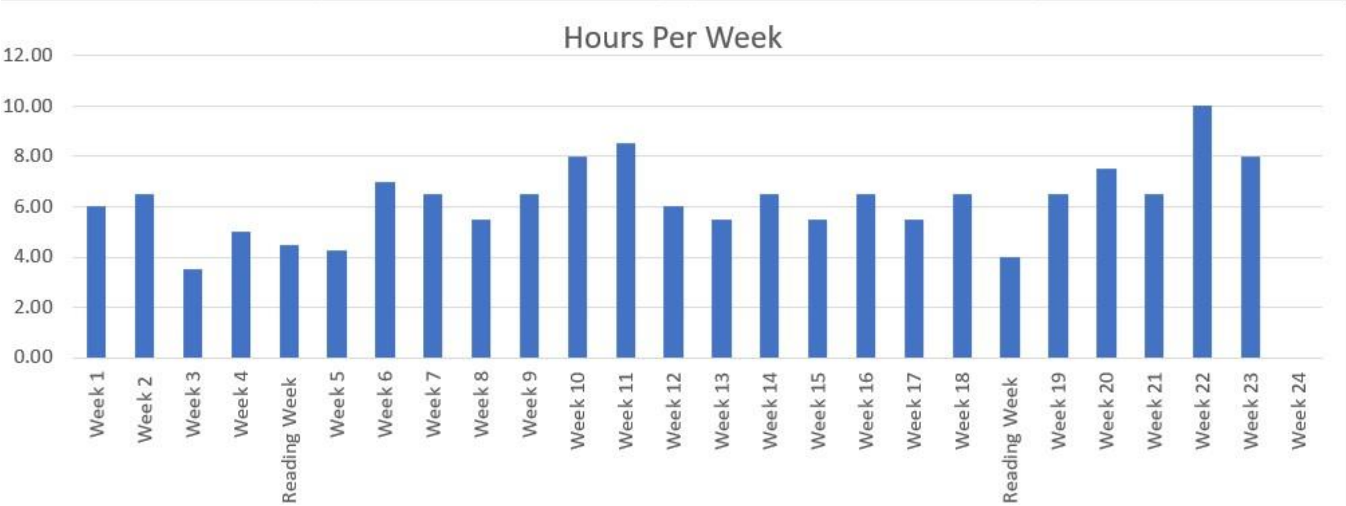
Ethan Phillip: (155.5 Hours)



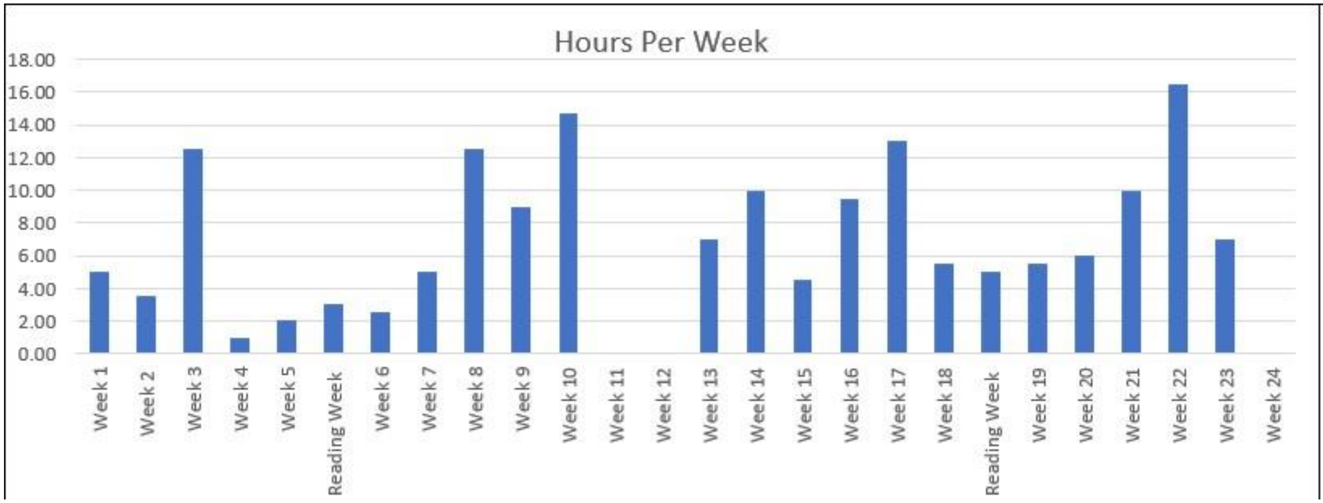
Reid Thompson: (159.5 Hours)



Steven Vandenbogaard: (156.25 Hours)



Euan Brydie: (170.25 Hours)



27.0 Appendix XII – Client Meeting Minutes

Date	**Key Points**
September 19, 2023	• Team introduction to client. • Client presentation of scope to the team.
October 5, 2023	• Team presented initial work plan with current scope. • Client recommended possible site locations. • Client added substructure design to the scope.
October 19, 2023	• Team presented key points from discussion with Dr. Woods about structural design approach. • Team presented possible locations to client with an evaluation of the options. • The client gave the team carbon performance data of the base case.
November 2, 2023	• Presented site location decision with detailed evaluation. • Team presented possible shapes of the building to the client. • Client liked the shape that was ultimately decided upon. • Team presented the created structural analysis tables to client.
November 16, 2023	• Team presented proposed floor plan to client. The client liked how the design modeled the dimensions based off the base case. • The team presented updates on the progress report write up to which the client was pleased with.

December 7, 2023	• The team presented some of the innovative materials that were considered for the design to the client. The client liked the idea of using a CLT elevator shaft but wanted to know the feasibility of this. The client liked the idea of using ECOpact concrete, but said to consider the associated challenges with procurement and cost.
January 10, 2024	• The team delivered a 15-minute presentation on their progress to the client as well as other invited professionals.
January 25, 2024	• The client requested a summary of materials when possible to investigate outsourcing a cost consultant to get a detailed cost estimate. • The client requested a portion of the final deliverable to be aimed towards addressing the safety of using mass timber as a structural product.
February 8, 2024	• The team showed the client the structural design that was conducted. The client liked the progress that the team was making. The client requested for a portion of the final deliverable to address the construction time of mass timber designs as well as the life span of these types of buildings. Requested to have the deliverable addressed for decision makers and business leaders.
March 7, 2024	• The client liked the progress that the team was making, but requested the team to consider putting a bike storage room in

	the basement, as opposed to in the main floor.
March 28, 2024	- The team delivered a 20-minute presentation to the client and other invited professionals, presenting the final product from the project.