UNIVERSITY OF CALGARY

Design Investigation of Container-based Residential Buildings for Improved Energy and Environmental Performance: Integrated Life Cycle Perspective

by

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Abstract

Container-based residential buildings (CBRB) can attain low-energy and low-environmental impacts through systematic envelope design and material selections focused on life cycle perspective. Critical influences for the upcycling of shipping containers into modular buildings include its module-like geometry, which allows for stacking as building blocks, and other environmental benefits of avoided impacts/credits associated with recycling such products. This thesis takes an integrated life cycle perspective to investigate the effects of selected envelope design parameters on the overall building performance (i.e., energy, environmental, and economic) of CBRBs as summarized: 1) building materials and envelope configurations, 2) detached and row housing design, and 3) apartments (i.e., multistorey and layout). Calgary, Canada (AB, Latitude 51°N), is chosen as the study pilot location. The research begins with a selection of building envelope design parameters, followed by energy performance analysis. The second part of the study focuses on environmental life cycle impact assessment, life cycle cost analysis of selected scenarios, and the interpretation of results to report potential environmental impacts and design implications. Other building envelope aspects such as thermal bridging analysis and achieving improved airtightness are excluded from the thesis. However, methods of construction to eliminate thermal bridging effects and ensure continuous insulation and airtightness in container buildings should be covered in future research, to ensure that high energy efficiency such as analyzed in the thesis can be reached. The integrated approach aims to enrich the thesis and provide a comprehensive understanding of the impact of various design decisions undertaken to realize low-energy and low-impact container-based residential buildings. The thesis proposes design recommendations for improved energy and environmental performance of container-based buildings. It contributes to advancing scientific knowledge in developing single and multi-unit CBRB by addressing some challenges associated with its application in attaining high performance.

Keywords: *building material, envelope design, layouts, energy performance, multi-unit residential building, building simulation and modeling, modular housing, life cycle assessment, shipping container, environmental impact, life cycle costing, integrated building performance*

Preface

Chapter 5 of this thesis has two peer-reviewed journal publications as its contribution:

- "Dara, C., Hachem-Vermette, C., & Assefa, G. (2019). Life cycle assessment and life cycle costing of container-based single-family housing in Canada: A case study. *Building and Environment*, *163*, 106332." https://doi.org/10.1016/j.buildenv.2019.106332.
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- "Dara, C., & Hachem-Vermette, C. (2019). Evaluation of low-impact modular housing using energy optimization and life cycle analysis. *Energy, Ecology and Environment*, *4*(6), 286-299." https://doi.org/10.1007/s40974-019-00135-4.
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A portion of Chapter 3 covers a co-authored paper with permission from Hachem et al. (2018).

- Hachem-vermette, C., Dara, C., & Kane, R. (2018). Towards net zero energy modular housing: a case study. *Modular and Offsite Construction (MOC) Summit Proceedings*.

The rest completed thesis is original, accepted or unpublished independent work by the author, Chinyere Dara.

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Dedication

Dedicated to the memory of my father
Sir David O. Dara

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List of Symbols, Abbreviations and Nomenclature

Symbols

Eq. (1). LCC = I + E + OM&R

where:

LCC = Total LCC in present-value dollars

I = Present-value investment costs

E = Present-value energy costs (electricity)

Eq. (2). *single present value (SPV)*

$$X = \frac{F_t \times 1}{(1+d)^t}$$

Where: F_t = Future cash amount occurring at the end of the year t, d = 6% discount rate

The single present value (SPV) factor is used to calculate the present value, of a future cash amount occurring at the end of the year, t F_t given a discount rate, d.

Eq. (3). *uniform present value (UPV)*

$$Y = A_o \times \frac{(1+d)^n - 1}{d(1+d)^n}$$

Eq. (4). *non-uniform recurring cost*

$$Z = A_o \frac{(1+e)}{1+d} \left[1 - \frac{(1+e)}{(d-e)}^{n}\right]$$

The UPV factor is used to calculate the PV recurring annual amounts that change from year to year at a constant escalation rate, e over n years given d.

Abbreviations and Acronyms

ACH	Air Change per Hour
AR	Aspect ratio
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIPV	Building Integrated Photovoltaic
CBS	Container-Based Structures
CMHC	Canada Mortgage and Housing Corporation
COP	Coefficient of Performance of Heat Pump
C-Can	Container Can
CC	Container Code
CU	Container-based Unit
CBRB	Container-based residential building
CWEC	CWEC – Canadian Weather for Energy Calculations
DHW	Domestic Hot Water
DOE	Department of energy
EUI	Energy use intensity
GHG	Greenhouse gas emissions
GSD	Goal and scope definition
FU	Functional unit
HVAC	Heating, Ventilating and Air Conditioning
HRV	Heat recovery ventilation
IC	Improved Container
ISO	International Organization for Standardization
IEA	International Energy Agency
KgT	Kilogram tonnes
LCIA	Life cycle impact assessment
LCA	Environmental life cycle assessment
LCC	Life cycle costing
LCCA	Life cycle cost analysis

LCI	Life cycle inventory
LCEA	Life cycle energy analysis
MJ	Mega Joules
MURB	Multi-unit residential building
NECB	National energy code for buildings
NEI	Net energy intensity
NZEB	Net- Zero Energy Buildings
NZC	Net Zero-energy Container
PV	Photovoltaics
RSI	Thermal Resistance (R-value)
SHGC	Solar Heat Gain Coefficient
SETAC	Society of Environmental Toxicology and Chemistry
TED	Thermal energy demand
U-value	Thermal transmittance
WWR	Window to wall ratio

Chapter 1 Introduction

This chapter provides an introductory discussion for the thesis. It sets the background study of the research context, summarizes the research problems and gaps, and presents the research purpose and objectives. Next, it presents a discussion of relevant literature surrounding the different topics and themes within the thesis to inform the research study. The rest of the chapter outlines the thesis organization and flow.

1.1 Background

Off-site prefabrication traces back to the 16th century British colonization period, characterized by the exportation of panelized systems for temporary shelters from Britain to other colonized countries (Smith, 2009). By the mid-1620s, the importation of prefabricated modular wooden houses became popular, influenced by the need for shelters in host nations (Boafo et al., 2016; T. Ganiron & Almarwae, 2014; Smith, 2009). Before the industrial revolution peak in the 1800s, prefabricated timber remained the primary material for building construction (O'Neill & Organ, 2016). During the industrial revolution, technological advancement brought other building materials such as steel and iron to the limelight as a feature of the urbanscape. While the demands for affordable housing immediately after the World Wars caused modular construction popularity, the post-war period, however, reports a decline in demand due to market perception as temporary and sub-standard structures (Canada Mortgage and Housing Corporation, 2013).

Today, prefabrication and modular construction methods play a crucial role in the design and construction of sustainable buildings (Antonio Dumas et al., 2014; T. U. Ganiron, 2016). Recent research studies report a gradual yet progressive shift from conventional on-site construction to factory-built and modular systems (British Columbia Housing, 2014; Monahan & Powell, 2011). Disadvantages of on-site construction include increased volume of solid wastes to landfills from processing, damaged or unused building materials, as well as a high rate of death of construction workers (Karthik et al., 2020). The modular method of construction, as a form of prefabrication, has few advantages, such as cost efficiency, timely construction, construction efficiency, improved energy performance, and the possibility for material recycle and reuse (Canada Mortgage and Housing Corporation, 2016; Ganiron & Almarwae, 2014; Knaack et al., 2012; Lim et al., 2013; O’Neill & Organ, 2016; Piroozfar et al., 2012; Salama et al., 2018). For instance, Canada Mortgage and Housing Corporation (CMHC 2016) indicates that off-site factory-built results in about 55% reduction in building cost and up to 43% reduction in carbon dioxide (CO_2) emissions compared to on-site built homes. Other advantages relate to efficiency in project scheduling and safety in handling building products (Ferdous et al., 2019; Karthik et al., 2020; Li et al., 2018; Ramaji & Memari, 2016).

While there is a strong evidence on benefits of modular construction to offer sustainable construction, gaps still exist in the procedures and construction processes to effectively maximize these potentials (Al-Hussein & Manrique, JD, Mah, 2009). Few disadvantages of modular construction methods include negative perception and market acceptability, lack of knowledgeable personnel, transportation and site limitations, lack of past successful applications, and considerable higher initial investment cost to run modular services (British Columbia Housing, 2014; Kamali & Hewage, 2017; O’Connor et al., 2016; Salama et al., 2018). Besides, transportation of modular units from plants to construction sites for assemblage can also present a challenge to construction efficiency (British Columbia Housing, 2014). For example, there is a possibility that modules might be damaged while on transit and difficulties in procuring trucks for large modules. Modular construction also requires accurate planning and excessive coordination during the project process (O’Connor et al., 2016).

1.2 Research Problem and Gaps

Adaptive reuse of shipping containers in building construction is gradually gaining recognition as a form of modular construction. Research studies point to the potential of achieving affordable, durable, fire-resistant, energy-efficient modular buildings employing container-based construction (Bernardo et al., 2013; T. Ganiron & Almarwae, 2014; Lim et al., 2013; Robinson et al., 2011; Slawik, H., Bergmann, J., Buchmeier, M., & Tinney, 2010). The key influencer of the adaptive reuse of shipping containers into modular buildings is the overarching environmental benefits and credits associated with the upcycling of such products. For instance, up to 3,700 kg of steel can be recovered through potential upcycling, a standard 40-foot container module. Nevertheless, research on the utilization of container envelopes in energy-efficient buildings is still at its early stage in North America.

Notable challenges of attaining high energy efficiency in container-based structures (CBS) in cold climate regions, particularly Canada, include high thermal conductivity and acoustic constraint inherent as a steel product (Alemdağ & Aydin, 2015; Elrayies, 2017; Islam et al., 2016; Peña & Schuzer, 2012; Sadineni et al., 2011; Tanyer et al., 2018). For this reason, there is a higher rate of envelope heat transfer between the interior and exterior environment and higher chances of noise propagation within the interior spaces. Such challenges require critical considerations in designing an energy-efficient container-based envelope. One way to mitigate these design constraints is by selecting insulation material with high thermal properties and acoustic barriers to help regulate heat flow and moisture movement within the envelope (Alemdağ & Aydin, 2015; Hachem-Vermette, 2018; Peña & Schuzer, 2012).

Case studies on improving the thermal performance of CBS present a bias in meeting the requirements as a permanent structure, designed as either temporary shelters or single-unit demonstration homes (Alemdağ & Aydin, 2015; Elrayies, 2017; Giriunas et al., 2012; Peña & Schuzer, 2012). While improving energy efficiency in such buildings has attracted significant attention, notably, none of these studies provide an in-depth investigation on the systematic design and improving the container envelopes to achieve high energy efficiency in a multi-unit complex (Alemdağ & Aydin, 2015; Peña & Schuzer, 2012). Despite the need to expand this research area, there is no consolidated research on evaluating modular CBS's energy performance beyond single-unit houses (e.g. stacked or multi-units) in Canada elsewhere.

There is no guarantee in realizing the overall benefits of designing for the high energy performance of CBS. There is also no guarantee that they cannot. One way to ensure an environmentally responsive design is to conduct an integrated building performance analysis at the early design stage focused mainly on envelope design and building material assessment. That said, this study is necessary and desirable to explore the effects of envelope design parameters on energy performance for various classifications of container-based residential buildings, including single-detached, row houses and apartments. It also makes a case to reduce building operational energy (i.e. annual energy consumption) and increase electricity generation through systematic envelope design exploring passive and active solar principles.

Despite the need to improve energy efficiency and reduce operational energy use in buildings, this action sometimes results in a counterproductive effect leading to an increase in embodied energy (Paleari et al., 2016). Thus, the need for holistic life cycle assessment (LCA) of all energy uses in buildings, from production, construction, operation and end-of-life (Ramesh et al., 2010; Stazi et al., 2012). Adaptive reuse or upcycling of container boxes into modular units can perhaps mitigate potential embodied impact (i.e., energy and carbon emissions) associated with the manufacturing of conventional building materials. However, there is little extant research into the investigation of environmental life cycle assessment to ascertain these environmental benefits, including sensitivity analysis to account for avoided environmental impacts through product reuse. Similar research on systematic life cycle assessment of recycled products proved beneficial in accounting for LCA of products with multiple life cycle chain (K. Allacker et al., 2014; Karen Allacker et al., 2017; Koffler & Finkbeiner, 2018; Zink et al., 2018).

Researchers interested in CBS argue that upcycling shipping containers present its own environmental benefits. While the adaptive reuse of containers into habitable structures may offer economic and environmental benefits; it is however, difficult to quantify the level of its potentials without a rigorous life cycle assessment and life cycle cost analysis, including sensitivity analysis. Limited research on this subject matter has focused primarily on assessing life cycle energy and greenhouse gas emissions (A. Atmaca & Atmaca, 2015; N. Atmaca, 2017; Islam et al., 2015, 2016). While Islam et al. (2016) provide a comprehensive life cycle analysis in the Australian context, the study did not provide a systematic analysis of container reuse in buildings. Instead, it assumes a 100% environmental credit for reusing the products in building construction. Modeling the LCA of a container-based structure as a secondary product requires an understanding of existing approaches to deal with the allocation of environmental burdens and credits due to avoided environmental impacts (i.e., virgin material production or recycling) to different product life cycle chains. The lack of a singular approach in allocating environmental burdens relating to LCA of products with more than one life cycle (e.g., primary and secondary) will likely necessitate a multivariate construct (K. Allacker et al., 2014; Karen Allacker et al., 2017; Boguski et al., 1994; Ekvall, 2000; Koffler & Finkbeiner, 2018). Such research findings will sustain the viability of container-based modular housing, particularly for its mass adoption.

The goal of presenting these criticisms is not necessarily to diminish the contribution of existing studies on CBS. Of course, as much as the existing literature contributes to the advancement of practice, these studies must represent all environmental LCA impact categories to prove acclaimed environmental benefits. Conducting LCA for CBS analysis - much less for energy and carbon emissions – can present problems when it assumes the place of overall environmental impacts. There is also the fact that literature supporting research on CBS originates from temporary shelter or demonstration projects rather than permanent structures. In other words, there is still plenty of room for scholarly attempts for evidence-based research for acceptability in the construction market. For example, more comparative analysis using conventional structural systems as benchmarks can present more quantifiable and objective research findings. A compelling demonstration of this is argued by (Islam et al., 2016), stating the need for comparative life cycle assessment comparing modular container structures to stick-built.

1.3 Research Purpose and Objectives

The primary objective of this research is to develop envelope design guidelines for low-energy and low-environmental impact container-based residential buildings (i.e., single and multi-units) to support its progression in the building industry. A low-energy building is referred to as in this thesis as buildings that demands less operational and life cycle energy than a conventional building designed according to the national building codes and standards. This aims to achieve between 25% -50% improvement in building’s energy and environmental performance (Department of Energy (DOE), 2015; Lockhart, 2020). Other research objectives are summarized as follows:

1. Identify key envelope design parameters and components to increase energy performance and reduce life cycle environmental impacts
2. Quantify life cycle impacts of the selected design parameters on energy, environmental, and economics aspects, and compare their performance to lightwood frame house using a case study
3. Explore the effects of building geometry on the energy performance of multistorey apartments and layouts.

1.4 Literature Review: Integrated Building Performance Analysis

The literature review includes three main parts – energy-efficient buildings, environmental life cycle assessment, and life cycle costing. The first section provides a general introduction to energy-efficient buildings, passive and active solar strategies for high envelope performance. The rest outlines the life cycle impact assessments and life cycle cost analysis, as studied in the literature, and the effects of building systems design and material selections on embodied energy and carbon emissions.

1.4.1 Building Energy Efficiency and Solar Energy Generation

The first step for improving building performance is to design an energy-efficient envelope (Thun, G. & Velikov, 2013). The building envelope is the “outer skin” of the building that sets the boundary between the interior and exterior conditions of the environment (FPInnovations, 2014; Rodriguez-Ubinas et al., 2014; Sadineni et al., 2011). Building envelope improvement aims to reduce annual building energy consumption by implementing energy-efficient design strategies at the early design stage. Such building design relies first on passive solar design to reduce heating and cooling loads and the use of high-efficiency appliances, lighting, domestic hot water (DHW), and auxiliary heat supply. A holistic solar-powered design involves the systematic integration of passive solar principles and active solar systems to improve the overall energy performance (Ochoa & Capeluto, 2008; Sadineni et al., 2011). Active systems include mechanical and other active solar systems (Sadineni et al., 2011).

Passive House (Passivhaus) standard is the most rigorous voluntary-based standard that allows for the design and construction of high-energy efficient buildings targeted at reducing operational energy demands (Chiras, 2002; PassiveHouse, 2017; Stevanović, 2013). Every passive house design target 90% fewer energy demands for heating and cooling demands than conventional buildings. The goal is to capture and utilize free solar energy from sunlight to improve thermal performance without mechanical systems (Stevanović, 2013). Passive design strategies include optimal building orientation, utilizing high-performance thermal insulation and window assemblies, shading controls to control excessive solar heat gain, incorporating thermal mass and advanced phase change materials (PCMs) for thermal storage and regulations (Chiras, 2002; Dara & Hachem-Vermette, 2019; Hachem-Vermette, 2018; Pacheco et al., 2012; PassiveHouse, 2017; Stevanović, 2013; Xiao et al., 2009; Zhou et al., 2012).

Key design strategies and integrated steps for improving the energy efficiency of container-based structures are summarized below.

Building Orientation. Building orientation is considered the first and critical parameter in passive solar design (Li Liu et al., 2017). It influences the amount of useful direct solar heat gain and daylight received by the building (Li Liu et al., 2017; Tokbolat et al., 2013). For optimal passive design, the general rule is that the most extended building must follow full south orientation, aligning its long axis with east and west facades (Rodriguez-Ubinas et al., 2014; Tokbolat et al., 2013). This, of course, applies to the northern hemisphere, having the largest facade equatorial facing south. The interior space arrangement can take advantage of the optimal south orientation by placing the public areas and most frequently used spaces (e.g. living area) towards the south façade to maximize solar heat gain during the winter period warm up the interior spaces without overheating (Chiras, 2002). In contrast, a west orientation with short-facing south facades will lead to building overheating during the cooling season and reduce heat gain during the heating season.

Building Envelope Control Layers: Insulation, Air and Vapour Barrier. Layers help control moisture, vapour, and air movement within the building envelope and protect materials prone to moisture from condensation, such as steel containers,. Uncontrolled air leakage allows for moisture movement resulting in severe deterioration of the building envelope and material components. The impact of air leakage in the building includes condensation, increased energy consumption for space heating and cooling, health-related problems due to mould, poor indoor air quality and possible building failure (Lisa M. Tucker, 2015; Stephenson, 2018). Condensation occurs when there is a substantial difference in temperature between the inside and the outside environment. For instance, when water vapour escaping through a wall envelope contacts a cold surface, such as insulation, it condenses and dampens the material.

To prevent condensation from forming within building envelope assemblies, materials that act as vapour barriers (vapour retarders), including certain types of insulation, must be located within the assembly so that moisture moving from the inside to the outside does not condense and accumulate within the assembly (Chiras, 2002; FPInnovations, 2014). If required, a vapour retarder should be installed on the warmer side of the wall, which is towards the inside in cold climates (Lisa M. Tucker, 2015). A similar placement applies to insulation materials (closer to the surface of heat entry) of the interior envelope (Chiras, 2002; Elrayies, 2017; Sadineni et al., 2011). An air barrier helps reduce air leakage in buildings. The National Building Code of Canada stipulates that the building envelope must be designed and constructed with a continuous air barrier system comprised of air barrier assemblies to control air leakage into or out of the conditioned space (National Research Council Canada, 2015a). The air barrier system must be capable of resisting wind loads.

Insulation Materials: The simplest and most effective way to enhance the thermal performance of buildings is by improving the insulation value. The R-value or RSI, thermal resistivity, measures the level of a material's resistance to heat flow. An excellent insulating material should be low in thermal conductivity and have a high thermal resistance value to slow down heat transfer through it (Sadineni et al., 2011). Attaining improved thermal performance of steel structures (e.g. shipping container) with high thermal conductivity and low thermal resistivity can be challenging, especially in cold climate regions (Alemdağ & Aydin, 2015; Elrayies, 2017; Islam et al., 2016; Sadineni et al., 2011; Tanyer et al., 2018). Spray foam insulation, which prevents corrosion and mould, is often used as a wall insulation material for container steel structures (Elrayies, 2017). Using spray foam ensures a smooth and seamless barrier, characterized by its high R-value (thermal resistance) against heat flow. Pena and Schuzer (2012) suggest using closed-cell polyurethane spray foam with a high R-value as insulation to provide extra sealing to openings against moisture. PassiveHouse design guidelines aim at very high insulation, R-40 to R-60 for walls, R-50 to R-90 for roofs, and R-30 to 50 as sub-slab insulation (Straube, 2009).

A*irtightness Performance.* Many research studies argue the importance of improving airtightness to reduce building energy loads (Antretter et al., 2007; Hachem-Vermette et al., 2018; PassiveHouse, 2017; Sfakianaki et al., 2008; Sherman, M. H., Wilson, D. J., & Kiel, 1986; Tanyer et al., 2018; Younes et al., 2012). Air leakage or air infiltration refers to an unintended inflow of air into and out of a building, typically through cracks or openings caused by wind or stack effect (Fennell & Haehnel, 2005; Sfakianaki et al., 2008; Tanyer et al., 2018). Air leakage through the building envelope occurs due to differential air pressure from inside to outside. When the air pressure is more significant inside than outside, air will flow outwards through any holes or cracks in the building envelope, carrying with it any water vapour it contains. This process is called "exfiltration." The reverse, called "infiltration," is when the air pressure outside is more significant than inside, and air will flow in through holes and cracks (Stephenson, 2018).

Tanyer et al.'s (2018) study on the impact of airtightness performance of container-based houses on energy efficiency shows that sealing interior surface junctions can improve building performance (up to 10% reduction in annual energy consumption). Most airtightness testing and inspection show 1.5 air change per hour or less at 50 Pascals (Pa) pressure differential for residential buildings (FPInnovations, 2014). The airtightness levels of 1.5 ACH@50 Pa are achievable for the Canadian R2000 standard program with some effort (Straube, 2009). This value is proven by a blower test for existing buildings. The 50 Pa pressure (ACH50) air change rate is the air leakage rate at a differential pressure of 50 Pa divided by the building volume and defines the length of time required to completely change the volume of air in the dwelling (1/h). PassiveHouse design guide suggests an airtight enclosure of 0.6 air changes per hour at 50 Pa pressure (ACH50), verifiable with a pressure test such as blower door equipment (PassiveHouse, 2017). In other words, the allowable air change cannot exceed 0.6 times the room's volume per hour and the pressure differential is limited to 50 Pascals. Straube (2009) argues that an airtightness level lower than 0.6 ACH@50 is only achievable in custom homes designed with simple geometric patterns in North America. However, the actual value of ACH50 is only verifiable during blower-door test measurement.

Thermal Mass. Thermal energy storage capacity is an important parameter that affects performance of lightweight structures (Rodriguez-Ubinas et al., 2014). The thermal mass of a material is its ability to absorb and store heat energy and then release the heat afterwards into surrounding spaces when the temperature drops below mass temperature (Chiras, 2002; Sadineni et al., 2011). A large surface of concrete floor finish with high heat capacity is an excellent example of building thermal mass. When a dark-coloured concrete slab is strategically placed in the house to absorb direct sunlight and heat from south glazing, it should be sized "in relation" to available direct solar glazing. For adequate heat gain distribution, the PassiveHouse standard requires additional mass added when glazing exceeds 7% (Chiras, 2002). For buildings with a low window-to-wall ratio (WWR), incorporating massing to floor areas does not necessarily influence energy performance (Sadineni et al., 2011).

Window Size and Assembly. Glazing can act as solar collectors in a passive house. For instance, windows play a vital role in providing daylight illumination levels and enhancing the comfort level of the occupants (FPInnovations, 2014; Stevanović, 2013). Despite these crucial roles, window glazing is considered the weakest thermal control because glass materials have a low insulating value compared to other building components. Chiras (2002) argues that glazing is a significant source of heat loss in a highly insulated, airtight envelope, resulting in about 50% heat loss. For passive solar design, south glazing is encouraged with minimum north, west and east glazing in the northern hemisphere. To avoid summer overheating and reverse the increase in cooling loads, studies suggest WWR of the south façade should not exceed 40% in a single-detached house and 20% in apartment buildings (Beckett & Hachem, 2017; Hachem-Vermette et al., 2018; Hachem et al., 2014a). However, the above parameters are not considered the optimal or most functional for all building types. These may vary based on the combined effects of other envelope parameters studied, such as integrating solar shading controls and building orientation.

Low-e, triple-paned glass with argon-filled air, designed with a high solar heat gain coefficient (SHGC), offers better thermal performance (Hachem-Vermette, 2018). While most high SHGC assembly applications lead to higher cooling loads, careful integration of solar shading controls can help reduce the cooling loads in summer and allow solar heat gain in the winter months. Besides, a low-emissivity coating should be used on glazed surfaces to further retard heat loss or gain by blocking long-wavelength infrared radiation or heat transmission.

Solar Shading Controls. When attempting to mitigate excessive heat gains in the building, designers often implement shading control strategies, such as overhangs, vertical fins, and interior blinds. Studies suggest that passive shading of building facades can help control the amount of solar radiation received by the building and reduces cooling loads (Dave et al., 2014; Pacheco et al., 2012). Interior blinds are generally suitable for all façades. Horizontal overhangs are best for south-facing exteriors to reduce the solar gain at intermediate sun positions, while vertical fins are ideal for west and east facades.

Phase change materials (PCMs). Incorporating PCMs into the building envelope (e.g. microencapsulated PCM with 30% paraffin wax in gypsum board) increases the thermal capacity of the building material (Tabares-Velasco et al., 2012). The use of PCM in buildings benefits lightweight structures such as steel containers with low thermal mass by improving the its envelope ability to store heat while regulating indoor temperature (Al-Saadi & Zhai, 2013; Soares et al., 2013; Tabares-Velasco et al., 2012; Xiao et al., 2009; Zhou et al., 2012). The "phase change process" usually starts during the daytime when PCM absorbing heat which then melts with increasing solar heat gain from surroundings. The process is reversed at night when the PCM solidifies and releases the stored heat back into the building interior as outdoor temperature falls. Therefore, preventing indoor overheating during summer while providing heating for cold winter nights.

Building Integrated Photovoltaic Systems. The most straightforward solar electricity generation application integrates solar photovoltaic (PV) systems on the south-facing area of a building roof system. While this can generate enough electricity required to attain a net-zero energy status of a single-detached container house, depending on the design of the roof tilt angle. However, it may not apply to apartment buildings with less roof surface area compared to exterior wall surface area (Hachem et al., 2012, 2014b). According to Hachem et al. (2014) roof-mounted PV can only generate 19% of its required energy consumption in a 12-storey building. Therefore, to maximize electricity generation for such building types, façade energy generation is encouraged. For instance, PVs are easily integrated with external solar shading devices to increase energy generation. Other design strategies include the use of folded-plate roof design to enhance the roof's potential to integrate PV systems, which provides up to 97% of total energy consumption in a three-storey apartment (Hachem et al., 2014b). This roof design refers to the roof's shape, composed of triangular plates with various orientations, not necessarily the structural system. Building-integrated photovoltaic and thermal systems (BIPV/T) can also displace electricity needed for hot water, space heating and cooling (Athienitis, 2011). For example, the EcoTerra house uses solar-heated air generated by the BIPV/T for clothing drying, preheat of domestic hot water, and active heating ventilated concrete slab utilized in the basement as thermal mass (Canada Mortgage and Housing Corporation, 2017).

1.4.2 Environmental Life Cycle Assessment of Recycled Products

Life cycle assessment (LCA) is defined as a broad methodology for the quantitative evaluation of material use, energy flows and environmental impacts of products (Sharma et al., 2011). The whole LCA covers all life cycle phases – from the cradle to the grave – including product extraction, manufacturing, construction, operation, use and end-of-life (Stazi et al., 2012). This thesis considers the life cycle assessment of container-based structure as a secondary upcycled product, which requires an understanding of existing approaches to allocating environmental burdens and credits to different product life cycles.

Scholars of life cycle assessment theories agree that transferring environmental burdens among products in multiple life cycle inventory advances the quantitative analysis of recycled products. However, a dichotomy still exists in discourse concerning what life cycle chain is ideal in light of ever-changing product use. The lack of consensus on a standardized approach in modeling end of life (EoL) of recycled products regarding environmental impacts and credits due to avoided impacts remains a crucial challenge to the appropriate modeling of such products

(Karen Allacker et al., 2017). Thus, the careful design of system boundary becomes the starting point for such LCA study (Carbon Leadership Forum, 2018; Curran, 1996).

In quantifying products' environmental footprints within multiple life cycles, the system boundaries should accommodate End of Life (EoL) modeling (Karen Allacker et al., 2017). So far, the two levels of assessments are system-level or product-based assessments. The system-level assessment considers all product life cycles or product chains (both primary and secondary product life cycles). In contrast, the product-based assessment is limited to a single product, either primary or secondary product life cycle. Karen Allacker et al. (2017) point out that double-dipping in reporting environmental burdens and recycling credits amongst product life cycles flaws this approach.

A summary of the LCA modeling considerations at the system level are:

1. Should full burdens of virgin material production and recycling impacts be assigned to the primary product's life cycle? Or
2. Should the burdens of virgin production and recycling impact from primary products be transferred to the secondary product? Or
3. Should the burdens of virgin production and recycling impacts be allocated in full to both products or shared amongst the two products?

Another issue raised by Koffler & Finkbeiner (2018) is the credible calculation of the appropriate recycling credit in open-loop and closed-loop situations. In an open-loop system, material from one product system gets recycled into another useful product system (Karen Allacker et al., 2017; Ekvall, 2000). In this system, the secondary product need not be recycled again but disposed of at the end of life (Boguski et al., 1994). In contrast, the closed-loop system considers material from one product system recycled back into the same product chain, which can be recycled multiple times. Some misconceptions exist that recycled material displaces the same product virgin production, reducing the associated environmental effects. While this might be true for some products, Zink et al. (2018) argue that secondary product reuse may displace virgin production of materials other than its inherent material. Therefore, it is crucial to evaluate other environmental effects of energy use and environmental burdens associated with product recycling processing using life cycle inventory techniques (Boguski et al., 1994).

When considering approaches to EoL in general, there is no question that all approaches are different in terms of allocating environmental burdens associated with primary material production between the first and the subsequent product life cycle. No approach is complete as the specific product situation under analysis determines what needs to be covered or considered (Curran, 1996). While there are few approaches available, discussions around LCA of recycled products have focused mainly on two broad approaches: (i) end of life (EoL) recycling, also know as avoided burden approach, and (ii) recycled content approach, also known as the cut-off method (Bontempi, 2017; Koffler & Finkbeiner, 2018; Koffler & Florin, 2013; Nicholson et al., 2009; Vadenbo et al., 2017). Frischknecht (2010) and Kofflerand Florin (2013) also report that the above two approaches dominate discussions on LCA of recycled metal products (as identified in this thesis): recycled content approach and the avoided burden approach. The recycled content approach allocates all primary material production burdens to the first life cycle in allocating burdens. No environmental impacts from primary material production go to a secondary product. The avoided burden approach allocates the full burden of EoL recycling in the first life cycle and much burdens associated with primary material production to the subsequent life cycle.

While research on approaches in modeling LCA of recycled products has produced mixed results, some stakeholders demonstrated their promise in delivering a more acceptable approach. For example, in 2007, seventeen international metal associations officially endorsed the avoided burden approach as a recommended practice for metal recycling in LCA (Koffler & Finkbeiner, 2018). Literature review suggests that most approaches are developed based on leading stakeholders and pressing environmental concerns of the product (Frischknecht, 2000). Contrary to this, most international life cycle organizations and researchers support the 50/50 equal distribution method of reporting environmental footprints relating to the allocation of burdens, including the Society of Environmental Toxicology and Chemistry (SETAC) Europe and the European Commission Directorate-General Environment (DG EC) (K. Allacker et al., 2014; Karen Allacker et al., 2017; Kotaji et al., 2003). Nevertheless, sensitivity analysis modeling all possible approaches based on product life cycle situations is preferred.

1.4.3 Assessing Embodied Impact in Buildings

Greenhouse gas (GHG) emissions and other pollutants are continuously produced and released back into the surrounding environment throughout the building life cycle. These emissions mostly occur at the use stage during building operations (Dara et al., 2019; Ramesh et al., 2010). Without limiting the importance of designing high-performance buildings to reduce operational energy and environmental impacts significantly, it is important to note that integrating these technologies often leads to increased embodied impacts in such buildings. For example, studies on life cycle impacts of net-zero energy buildings found the pre-use stages (i.e. raw material extraction, manufacturing, and construction) as having the most life cycle environmental impacts (Faludi et al., 2012; Paleari et al., 2016). Thus, the need for an in-depth understanding of the cumulative environmental impacts of products and material technologies applied in building designs. Recent observations show a reverse trend in reporting life cycle assessment (LCA) of buildings, which brings the need to account for embodied related impacts (i.e. material, energy, and carbon emissions) to the forefront of tackling building life cycle environmental impacts. This paradigm shift further increases the need to explore advanced building materials with less embodied impacts and the adaptive reuse of sustainable products in buildings.

Building materials present an incredible opportunity for reducing embodied impacts in buildings. Embodied carbon commonly refers to Global Warming Potentials (GWP) contributions from materials and energy utilization during the manufacturing, construction, and maintenance of buildings (Carbon Leadership Forum, 2019). While LCA studies on embodied effects can assess other environmental impact categories, GWP is often the focus of most LCA studies. One reason is that embodied carbon emissions currently account for about 11% of global GHG emissions and 28% of global building sector emissions (International Energy Agency (IEA), 2019). Similarly, embodied energy comprises energy for initial building construction and recurrent energy required to manufacture and replace building materials across the building life span (Crawford & Stephan, 2013).

Embodied effects associated with building materials occur at the different life cycle stages, from raw material extraction to manufacturing, transportation, construction process, use, and end-of-life disposal (Canada Green Building Council (CaGBC), 2020). At the use phase, embodied impacts occur during building maintenance and material replacements. The adaptive reuse of sustainable recycled/upcycled materials in building construction further presents an opportunity to replace initial embodied effects intended to produce new materials and products (Assefa & Ambler, 2017; Zink et al., 2018). Careful selection of low-impact materials with sustainable attributes such as longer life span and re-usability can mitigate upfront carbon emissions during the production and construction phases. This sustainable approach provides an opportunity to offset GHG emissions from other building materials. It creates the possibility of attaining low impact designs or/and zero-carbon status in buildings.

1.4.4 Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) evaluates the economic performance of buildings to: (i) determine the cost-efficient option that would result in the best investment decisions, and (ii) benefits of envelope upgrades in terms of energy cost savings. The LCC calculation considers the following steps: establish main assumptions and parameters, estimate costs and times of occurrence for each building system, discount future costs to present value, and compute and compare LCC (Fuller & Petersen, 1996). The building-related costs considered in a study include the sum of initial investment costs, capital replacement costs, energy costs, and non-energy operation, maintenance, and repair costs for a defined study life span. Comparative cost analysis helps determine the cost-efficient option that would result in the best investment decisions and explain the life cycle cost benefits of energy performance improvements and material selection choices between building systems.

1.5 Application of Shipping Container in Buildings

Prefabrication is the production of building elements, components or modules under factory-controlled conditions and then transport to the building location for final assemblage. According to British Columbia Housing (2014), prefabricated and modular systems represent up to 12.5% of all single-detached housing in Canada. Under the umbrella, off-site prefabrication, there are two main types; panelized and modular systems, which are also applicable to standard building materials (e.g. timber, concrete and steel).

- In panelized systems, prefabricated components are pre-engineered at the factory and shipped to the building location for assembly on-site. Structural insulated panels and precast concrete panels are typical examples of these.
- Modular or volumetric systems involve the production of three-dimensional modular units in controlled factory conditions before transport to the site. Volumetric construction sometimes demands the assemblage of large building modules and units on-site rather than an off-site factory location.

- The hybrid system is a more recent prefabrication form and combines volumetric modules as an exterior envelope while maintaining panelized systems as interior partitions (Venables & Courtney, 2004).

Research on prefabrication and modular architecture has seen significant progress in recent years. The container-based structure is one of such innovations (Sun et al., 2017). According to (Berbesz & Szefer, 2018), container-based structure is first conceived by Phillip C. Clark in 1989 as an innovation to convert a steel shipping container into a habitable space. A shipping container usually consists of a steel frame, walls, roof, floor (plywood or steel), doors and corner castings corrugated and insulated into an envelope (see Figure 1.1).

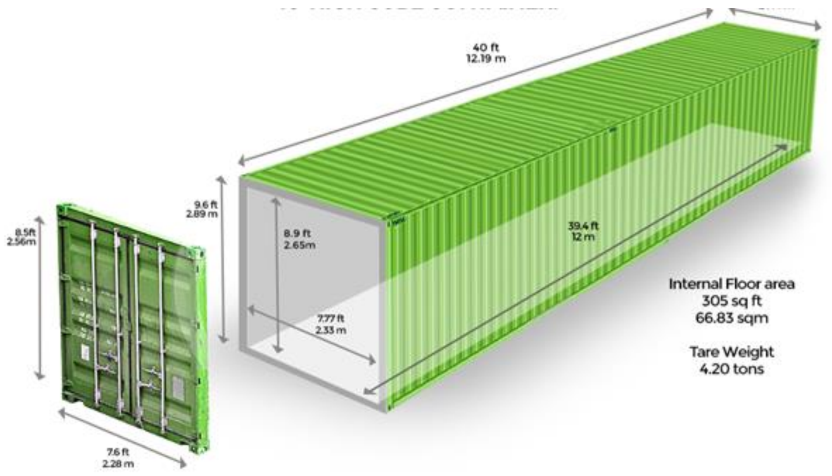


Figure 1.1 Image of 40 foot (12.2 m), High Cube Container Can (Containers – Smartbox.com, 2018).

A shipping container freight is often designed with either wooden or steel flooring. A key concern with adaptive re-use of shipping containers into habitable permanent structures is the decision to retain or remove the original wooden plywood floorboard treated with potentially harmful pesticides. While these chemicals are used to prevent damage to goods by the insects on wood products during the long travels, they could be dangerous to humans when converting shipping containers into a house. Considering the associated environmental impacts, this thesis recommends the existing wooden floor be either removed or washed properly before installing a top floor finish. For any shipping container to be re-used in housing, it is required to pass the safety or health inspection test as well as meet the same requirements and restrictions as permanent buildings in Canada. This thesis, however, utilizes the steel floor design without associated environmental impacts from the treatment of wood products (Hapag-Lloyd, 2016).

Container boxes are universally applicable to modular construction methods. The most common standards by International Organization for Standardization (ISO) shipping containers are of two commercial lengths: 6.06 m (20-Foot) and 12.2 m (40-Foot) (Grębowski & Kałdunek, 2017; Hong, 2017). While the above sizes are considered standard for international freight, the 53-Foot high cube shipping container is the largest storage containers are perfect for commercial, industrial and rural storage applications. The 53-ft containers are primarily for domestic over the road and rail services, and not utilized for international shipping. The shorter length box of 3.05 m (10-Foot) provides an alternative for smaller units, eliminating the need to cut more extended modules. Table 1.1 presents a summary of the dimensions of most freight container sizes from modular construction. Shipping containers have a standard width of 2.44 m wide and are often 2.59 m high regular height. However, the high cube containers (HC) of 2.90 m high, and 2.48m wide on the exterior are most suitable for modular housing. They provide more headroom for integrating building services such as electrical ducting works (Bernardo et al., 2013).

Table 1.1 Container Sizes for Modular Construction

	53 FOOT (16.15m) HIGH CUBE	**40 FOOT (12.2 m) HIGH CUBE**	**40 FOOT (12.2 m) STANDARD**	**20 FOOT (6.06 m) STANDARD**	**10 FOOT (3.05 m) STANDARD**
Description	largest mass-produced container most effective for increased building height	Longest and most effective for increased building height	Longest with moderate height	Standard, and most commonly found	The alternative for smaller units or lengths
Length	16.15 m	12.2 m	12.2 m	6.06 m	3.05 m
Width	2.48 m	2.44 m	2.44 m	2.44 m	2.44 m
Height	2.90 m	2.90 m	2.59 m	2.59 m	2.59 m

The hallmark of container-based structures ties to the delivery of post-disaster shelters as temporary homes for vulnerable populations to withstand exposure to harsh climatic conditions, and presently, to the global use in providing decent housing needs from residential to rental commercial and public spaces (Berbesz & Szefer, 2018; British Columbia Housing, 2014; Kamali & Hewage, 2016, 2017). Arguably, container structures are considerably more suitable for multiple complexes stacked as building blocks than panelized systems. At the construction factory, approximately 100% of the container envelope is upcycled and reused during modular construction (Antonio Dumas et al., 2014). Moreover, CBSs do not only present advantages based on steel inherent properties as an offshoot. They also provide timely construction, up to 75 to 150 units within a month, as well as high structural strength and sturdy to withstand loads and harsh climatic conditions (Alemdağ & Aydin, 2015; Berbesz & Szefer, 2018; Bernardo et al., 2013; A. Dumas et al., 2012; Antonio Dumas et al., 2014; T. U. Ganiron, 2016; Grębowski & Kałdunek, 2017; Islam et al., 2015; Lim et al., 2013; Robinson et al., 2011; Tanyer et al., 2018). In addition to size constraints with width containers reduced to interior envelope design, significant drawbacks to its global application include:

- possible corrosion by moisture if exposed to harsh weather conditions,
- high thermal conductivity of steel to increase in heat transfer between the indoor/outdoor temperature,
- interior noise propagation, and
- building permit restrictions in some provinces and countries (Elrayies, 2017; Lim et al., 2013).

1.5.1 Canadian Context: Availability and Application

There is evidence of the upcycling of freight shipping containers in Canada into other uses, especially by the agricultural sector for inter-province transportation of goods, mobile food supplies and micro-farming. Nevertheless, a significant number of “un-used” container cans continue to occupy cubic metres of virgin land at its main seaports and elsewhere (Economics, 2017). At the moment, thousands of empty containers are un-used in shipyards around Canada, including at the Port of Vancouver, which handles over 50% of container importations (2.7 million 20-foot-equivalent units) per annum (Bonney, 2013). Canada relies on importing goods from Asia which increases greenhouse gas (GHG) emissions from freights transportation.

Canadian housing and building sector can benefit from year-round modular construction development by converting abandoned container cans and repurposing to inhabitable living spaces away from harsh winter snow and weather. Action plans to repurpose containers have commenced as a way to promote affordable housing. The allocation of ten million dollars (10,000,000 CDN) Alberta Rural Development Network (ARDN) by the Government of Canada through the National Housing Strategy’s Affordable Housing Innovation Fund is an expression of this (Alberta Rural Development Network, 2019). Allocated funds will deliver eight affordable, energy-efficient container-based housing to create up to 467 rental units over the next two years in Alberta. The first project, a net-zero energy YWCA Banff Courtyard Project, comprises 33-unit, three-storey rental apartments for residents with housing challenges. All these projects are designed and built as permanent structures for the cold climate of Canada.

1.5.2 Case Studies of Container-based Buildings

As noted in the background study, a growing number of container-based projects exist in different locations in the world. This sub-section presents successful case studies examples of detached and apartment residential buildings based on secondary literature analysis (websites and documentaries). Some of the most advanced countries in the design and application of container-based projects include Amsterdam, Japan, United States, United Kingdom, and Canada. In general, these projects adapt upcycled shipping containers into sustainable buildings. While these case studies offer a starting point and perhaps inspirational studies for this thesis, none of the reported projects provides an in-depth explanation of the design methodology adopted to achieve the desired sustainable outcomes and milestones. Energy efficiency, economic benefits, environmental impacts, material resource efficiency are discussed using different case studies below and remain the critical building performance parameters and strategies studied in this thesis. The case study examples discussed below are all intended for permanent residency:

Drivelines Studios - Johannesburg (South Africa). Drivelines Studios is a mixed-use development (i.e., residential and commercial retail) with a total building area of 6,968 m^2. Figure 1.2 presents images of the (seven) 7-storeys multi-family apartment that combines frontal rental outlets and a private courtyard for residents with planted areas and a pool on the ground floor level (ArchDaily, 2018). The rest of the floors comprises 100 units of studio apartments of varying sizes, between 40 and 60 square meters per unit (Berbesz & Szefer, 2018). The social intention is to revitalize the city downtown with active urban living, thereby creating a sustainable urban community for its surrounding neighbourhood (LOT-EK, 2017).

Drivelines Studios is an example of an on-site container construction and embraces the triangular geometry of the site. It achieves its V-shaped geometry by combining 140 upcycled shipping containers with a free-access galleria view of the inner yard (Berbesz & Szefer, 2018). The building façade pattern is a straight flush view and adopts the exterior unpainted container panels, stacked and cut on-site to generate units, then cut diagonally to create large windows for each unit. The building derives its concept from the billboard design of two separate volumes hinged at the narrow triangular lot end, framing the open interior courtyards as a social community space. For instance, the inner courtyard shares an open circulation concept enclosed by staircases connecting all levels, an elevator tower, and three service units (ArchDaily, 2018). Although there is no mention of integrating energy-efficient measures in the Drivelines Studios development, Berbesz & Szefer (2018) reports that each unit design allows for the incorporation of sustainability features, e.g. solar panels, rainwater-based systems. In terms of affordability, the studio apartments offer an attractive rent of is 4,900 Rand (399 CAD) per month, 50% less rental than an average 45 m^2 furnished studio apartment in Johannesburg city hub area (Expatistan, 2020).

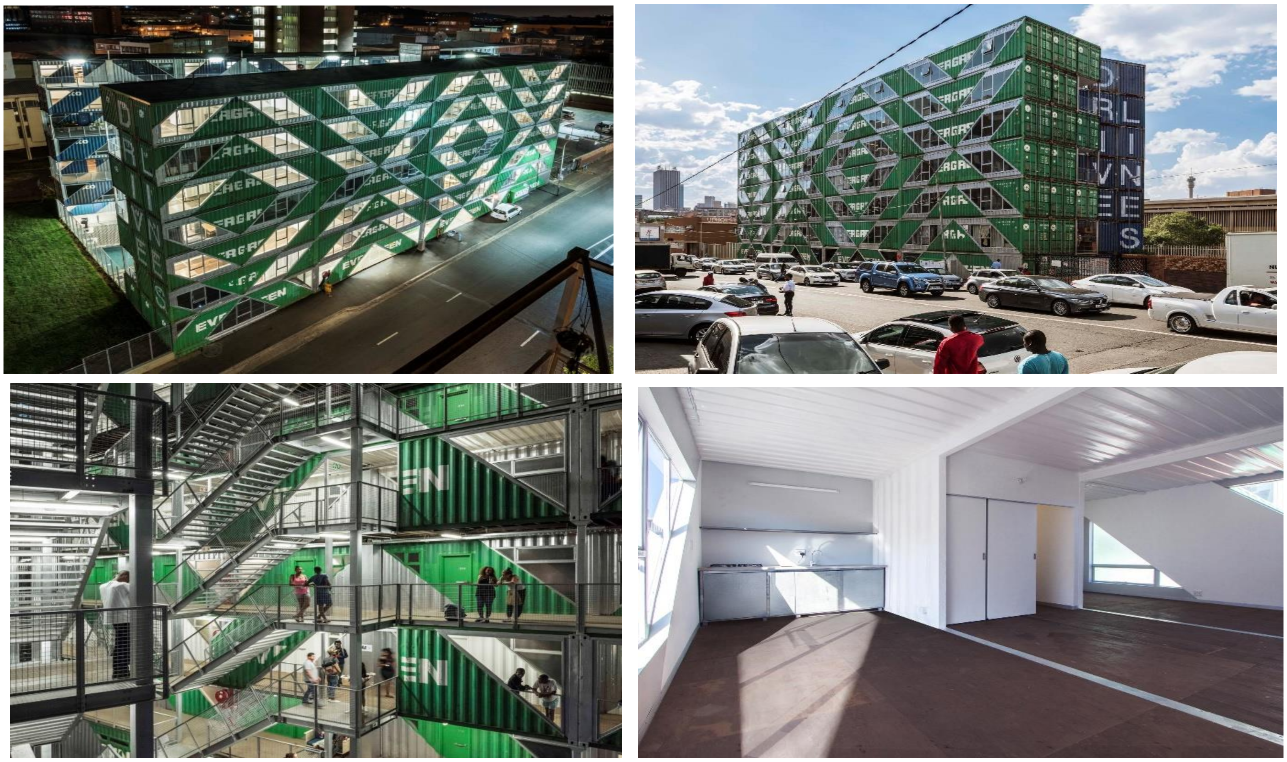


Figure 1.2 Drivelines Studios – Johannesburg (LOT-EK, 2017).

Zigloo Domestique - City of Vancouver (Canada). Zigloo Domestique is an example of a DIY (do-it-yourself) design (see Figure 1.3 for illustrations of floor plans and three-dimensional drawings). Zigloo is a 3-storey single-family detached house initially built in 2006 as Canada’s first shipping container home. The total building area is about 2000 ft^2 (186 m2) and includes 180 m^2 perimeter house and 7.4 m^2 accessory studio (Zigloo.ca, 2019). The homeowner, an architect (Keith Dewey), designed and developed Zigloo using (8) eight C-Cans of 20-foot (6.0 m) standard size, which are strategically modified to include windows and sliding deck doors. The building layout creates an open floor plan with a linear arrangement of C-Cans creating a rigid rectilinear form but carefully blended with a curved roof concept. The main floor comprises three-bedroom, two bathrooms, with an open kitchen and dining area, while the basement floor contains a large open rec room, a bathroom, and a laundry room (Inhabitat, 2007b). Zigloo's container home design integrates energy efficiency measures such as a solar-powered hot water system, on-demand in-floor heating system, soy-based spray foam insulation, and integrated passive and natural ventilation used for building cooling in the warm summer months (Inhabitat, 2007b). Other environmental sustainability strategies include a built-in green roof with a grey-water reclamation system and recycled shipping containers as the main structure (Houseporn.ca, 2016).

Figure 1.3 Zigloo Domestique - City of Vancouver (Zigloo.ca, 2019).

Carroll House, Brooklyn - New York (United States). Carroll House, Figure 1.4, is a single-family residence with a total building area of 464.5152 m^2. The Carrol house utilizes 21 brown C-Cans stacked and cut diagonally along the top and bottom, generating a monolithic volume within the urban fabric of its surroundings (ArchDaily, 2017). The exterior building envelope features large glass doors to create access to all levels, offering sufficient daylight and natural ventilation into the interior spaces (LOT-EK, 2016). C-cans are stacked in ununiform patterns to create a dynamic façade look while resting on a concrete base. For example, the concepts showcased the slicing off of sections from the lower back of the building volume, cut at an angle downwards from front to back. Rather than discard the leftover pieces, the project resorts to material conservation by flipping over sectional cut-offs and placing them on top of the higher stack to maximize building volume (LOT-EK, 2016). Removing portions from the bottom of the structure allows for access to a below-grade entrance, sloped driveway. The container assembly optimizes material usage by recombining and reusing all leftovers generated by the diagonal cut (ArchDaily, 2017).

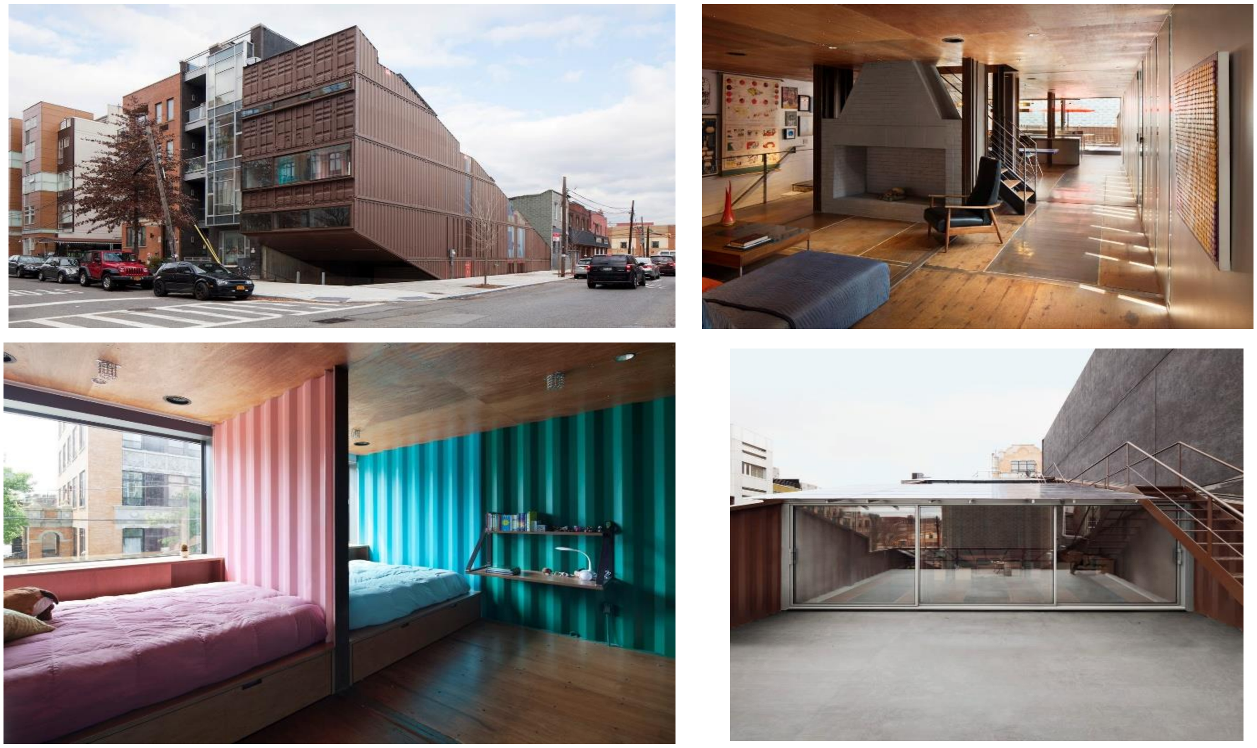


Figure 1.4 Carroll House, Brooklyn - New York (ArchDaily, 2017).

YWCA Banff Courtyard Project - Alberta (Canada). The net-zero container-based multi-unit building is a demonstration project and the first of its kind aimed at repurposing sea containers to tackle the affordable housing crisis in rural areas of Canada. Funded in part by the provincial government and the federal government’s National Housing Strategy Initiative, it proposes eight energy-efficient modular buildings to create up to 467 affordable rental units in Alberta (Alberta Rural Development Network, 2019). The YWCA Banff Courtyard Project being the pilot project is designated for 33 self-contained units and four (4) barrier-free units to accommodate accessibility needs (YWCA Banff, 2018). The goal is to create robust social connectivity and active living to improve tenants' physical and mental well-being (Elford, 2019).

The proposed study employs energy-efficient measures to include: the use of high-performance windows, integrated roof-mounted solar photovoltaic systems to generate enough electricity for the complex (Elford, 2019). Its target is to create a net-zero building by generating enough electricity on-site to balance annual energy consumptions, thereby reducing building operating energy costs. As part of the sustainability strategies, the YWCA Banff Courtyard Project also adheres to the WELL Building Standard, a global rating system, to enhance tenants' quality of life. The WELL Building Standard set criteria for improving air and water quality, green space, efficient building materials and high-quality cleaning supplies amongst the project focus (YWCA Banff, 2018).

Figure 1.5 YWCA Banff Courtyard Project - Alberta
(Elford, 2019).

Keetwonen 1000 Shipping Container Housing Complex – Amsterdam. Keetwonen student complex is the first and largest container-based housing project serving as a functional and comfortable space. Keetwonen, designed by TempoHousing in Amsterdam, is a 1,000 units dorm accommodation constructed from repurposed shipping containers. The residence sits on a 31020 m^2 building area. The C-cans are stacked vertically on top of each other and horizontally side by side, complete the complex of 1,034 modules (Tempohousing, 2019).

Although first conceived as temporary housing (i.e., for five years) to help meet huge affordable housing challenges students face, Keetwonen container-based residence has survived over a decade and still counts in good maintenance as its finish meets the high building standards in Europe for permanent housing. The building consists of 6 blocks of varying sizes with close internal courtyards for social integration. In addition to the environmental benefits of re-using surplus recycled containers, the project integrates a roof-top rainwater drainage system, which provides heat dispersal and insulation for the container units beneath (Inhabitat, 2007a).

Figure 1.6 Keetwonen 1000 Shipping Container Housing Complex – Amsterdam (Tempohousing, 2019).

1.5.3 Discussion of the Case Studies

These case studies suggest that shipping containers are not only boxes for cargo transport or emergency housing but also beneficial to sustainable building construction. Table 1.2 provides a summary of the main features of each of the case studies. Most of the case examples focus on sustainability features, such as energy-efficient measures or rainwater harvesting. The case study deductions include findings on environmental impacts and material wastes reduction, building envelope design, energy efficiency and performance, and role of stakeholders and government in affordable housing projects as discussed below:

Table 1.2 Summary of Case Studies

Shipping Container Project	**Project Description**	**Sustainable Design Strategies**	**Building Concept and Geometry**
South Africa - Drivelines Studios 	**Type:** Studio apartments and front store retail spaces **Year:** 2017 **Area:** 6,968 m^2 **Architects:** LOT-EK **No of cans:** 140 upcycled standard containers	Energy-efficient measures are not provided. The project focused on the social aspect of revitalizing urban living—affordable unit rental of 4900 RAND per month (CAD 398.74).	V-shaped triangular geometry
Canada - Zigloo Domestique 	**Type:** Detached house **Year:** Constructed 2006 **Area:** 186 m^2 **Architect:** Owner, Keith Dewey. **No of cans:** 8 boxes of the 20-foot standard containers	Zigloo is designed as an energy-efficient container house. Design strategies include soy-based spray foam insulation, hot water on demand, a heated floor system, a green roof, and the use of various numerous recycled materials.	Rectilinear form softened by a curved vaulted roof.
United States - Carroll House 	**Type:** Single-family residence **Year:** 2016 **Area:** 465m^2 **Architect:** LOT-EK **No of cans:** 21 modules of recycled steel containers	Material resource efficiency by recombining leftovers and creatively re-used on the pent floor. Large windows on the façade.	Rectangular shaped with diagonal cut-off sections.
Canada – The Courtyard Project: YWCA's net-zero building 	**Type:** Multi-unit residential building **Year:** 2019 **Area:** 465m^2 **Architect:** YWCA Banff **No of cans:** not provided	Proposed to meet net-zero energy status through on-site roof-mounted PV generation. High energy efficiency with energy-efficient windows. Social connectivity and well being of tenants. Rental rates 20% below market rates.	A rectangular building with a courtyard design concept. Barrier-free units.

Amsterdam – Keetwonen housing complex 	**Type:** Studio apartments (6 blocks) **Year:** 2006 **Area:** 31020 m^2 **Architect:** TempoHousing **No of cans:** 1,034 40-foot standard containers	Integrated roof-top rainwater drainage while providing heat dispersal and insulation for the containers beneath. Courtyards for social connection.	Rectilinear blocks with close off internal courtyards.

Environmental Impacts and Material Wastes Reduction. In all of the presented case studies, the justification for using upcycled steel containers relates to associated environmental benefits. These include environmental credits for avoided embodied energy and carbon dioxide (CO_2) emissions at the production phase, minimal use of conventional building materials, and alleviating container abandonment at ports of destinations and reduced construction waste to landfills. In some of the projects, such as in the Amsterdam, Keetwonen housing complex and the United States - Carroll House, the container modules are utilized 100% with zero waste and cut-offs. As an example, the Carroll House case study, rather than discard the leftover pieces, resorts to material conservation by re-combining leftover steel panels into an additional unit for the pent floor. Comparing the Carroll house and Keetwonen housing complex layouts to the YWCA Banff Courtyard Project that requires envelope modification emphasizes the need for material improvement during the design stage unanticipated environmental impact through material waste generation. Thus, there is a need to examine how cut-off wastes are handled during off-site manufacturing. The building construction process might affect the whole life cycle environmental impacts of such a building. For the Drivelines Studios, South Africa case study, material waste management was considered in the construction phase by stacking units on-site to create a straight flush façade view and only cutting diagonally to install large windows. There is also an opportunity to reuse material cut-offs in the fabrication of ancillary facilities such as plenum floors for building service distributions and storage units on site.

Building Envelope Design, Energy Efficiency and Performance. Most case studies lean towards maximizing environmental benefits and creating a live-work building with communal spaces for social connection between residents. In general, there is no procedure for how the buildings are insulated, technical aspects of the building constructions, as well as improving energy performance (i.e., balancing energy consumption and generation), other than the mention of the expected net-zero energy status of the YWCA' Courtyard Project (Canada case study). While the above case study considers a few energy-efficient measures and potential energy generation, this project is yet to commence or update not available to the public. The Zigloo, Canada, attempts to integrate energy-efficient measures, applying a passive solar design strategy (e.g., rectangular building layout with long facing south façade, designed with a glazed area for solar capture), which reduced energy consumption for space heating. There is also limited evidence on actual envelope design and construction steps followed in the multi-unit designs. Therefore, evidence of technical design guidelines appears to be a major limitation to advancing its application in the building industry.

Role of Stakeholders and Government in Affordable Housing Projects. Homeowners or clients play an important role in the development of the projects. In some cases, the homeowner is also the building developer (e.g., Zigloo project) and handles the building construction. In the apartment buildings, such as the Amsterdam, Keetwonen housing complex, and Drivelines Studios, affordability was considered in the design stage by maximizing land use for clients (i.e., increased number of units) for urban living, with a reduction in the rental cost. While most apartment buildings portray affordable housing delivery, this perhaps could be an intervention fund from the government or paid subsidy as with YWCA Courtyard Project.

The case studies described above mainly measure reducing environmental impacts in recycling shipping containers as an achievement and providing immediate housing needs for people of need. It should be noted that these qualitative measures are not generally regarded as the only outcomes of the effective application of container-based structures (CBS) to demonstrate actual building performance. This ties to the research gaps explained in the research problem and rationale (see section 1.2) for an integrated building performance analysis to ensure that CBS provides high-performance buildings to match existing building systems in the market. Research on the utilization of container envelopes in energy-efficient buildings is still at its early stage globally. For example, there are yet established studies on post-occupancy evaluations to better understand container-based buildings' actual performance. That said, the case study discussions are limited to the authors' findings based on the studied buildings, and some projects might suggest otherwise.

1.6 Thesis Outline and Organization

This thesis subdivides into seven (7) chapters. Except for the introduction (Chapter 1), methodology (Chapter 2) and concluding chapter (Chapter 7), all other chapters are written in the format of complete research papers published or to be published in international peer-reviewed journals and may not be alternated in any meaningful way during the preparation of this dissertation. It presents a manuscript style, ensuring that Chapters 3 to 6 are self-contained and can be read and understood independently. Chapter 7 provides a synthesis of all research findings to support the design recommendations and thesis conclusion. A brief outline of the thesis chapters forming the main content of this doctoral dissertation include:

Chapter 1. discusses the overall context, background of the study and presents the research purpose and objectives, problem and gaps. It also presents a survey of the pertinent themes and discusses literature surrounding the relevant areas and aspects of the thesis to inform the research objectives. Additionally, the chapter outlines the organization of the thesis and the content of the research studied.

Chapter 2 provides an overview of the research methodology. It describes the general approach applied in each research stage, stating the study assumptions, scope and limitations of each method and research. In addition, it summarizes the modeling and simulation tools and methods employed in the integrated building performance analysis to respond to the research objectives. The study methodology includes parametric design of building envelope and life cycle environmental assessment and design methodology employed in defining modular geometric patterns and layouts of residential buildings and multi-unit design to address some of the challenges of designing low-energy and low impact container-based structures.

Chapter 3 develops the envelope design parameters needed for the optimal model using a 5-bedroom single-detached housing as a case study. This chapter aims for high energy performance and possible net-energy status for the single-detached and row housing design. It concludes with a presentation of research findings (results) on energy performance analysis in terms of the effects of the design parameters on energy demand/consumption for heating and cooling and potential energy potential.

Chapter 4 presents an investigation of modular geometric patterns for multistorey and layout designs. The investigation includes the effects of vertical and horizontal modular expansion on energy performance, balancing energy supply from building-integrated façade photovoltaics with the total energy consumption. Results findings report on potentials for the design of low-zero energy MURBs within container-based research.

Chapter 5 builds on the previous chapter (Chapter 3) with an integrated life cycle approach for the single-family detached case study. It presents a holistic evaluation of the case study, including life cycle cost analysis, while comparing the environmental impacts of both code case and optimal scenarios to conventional lightwood frame houses. Envelope design parameters and building operation energy for the LCA and LCC are derived from the previous study on energy performance analysis (Chapter 3).

Chapter 6 is a detailed analysis of the wall envelope design for potential low-impact design over its life cycle. The chapter presents an in-depth study of the different exterior and adjacent modular wall systems designed for CBS. It summarizes the life cycle embodied effects of building materials for life cycle energy and life cycle global warming potentials

Chapter 7 focuses on developing envelope design guidelines for low-energy and low-impact container-based residential buildings. It summarizes previous chapters' findings and recommends future research work based on Chapters 3, 4, 5, and 6. The chapter also presents design recommendations and guidelines for improved container-based residential buildings.

Chapter 2 Methodology

Chapter 2 provides an overview of the research approach and methodology of this thesis. It discusses the research methods and tools employed to respond to the research objectives and milestones. Next is the discussion of the procedure for modeling and simulation using various tools, the rationale for selecting each application, and the limitations of selected tools. The rest of the chapter defines the overall research scope and limitations of the study.

2.1 Research Approach

This research focuses on integrated building performance-based analysis, combining energy performance analysis, environmental life cycle assessment, and life cycle cost analysis. The primary focus is the effects of envelope design parameters on energy and environmental performance of container-based modular buildings, based on three classifications: 1) building materials and components design, 2) detached and row housing configurations, and 3) modular apartment design (i.e., multistoreys and layouts).

Figure 2.1 presents the research design map. The research investigation centres on energy performance analysis, implementing a set of energy efficiency measures for classifications of container-based residential building types described above. While the simulation methodology considers whole-building analysis, construction details such as eliminating thermal bridging effects are excluded from the current energy performance analysis.

The first stage begins with a selection of passive solar design parameters, followed by the parametric investigation of the building envelope (i.e., building energy modeling). Life cycle impact assessment and life cycle cost analysis are also integral research methodologies to support a more robust exploration of the single-detached house case study and building components analysis. The goal is to enrich the thesis and provide a comprehensive understanding of the impact of various design decisions undertaken to attain low-energy and low-impact outcomes. Architectural aspects of the research approach include the geometric design of multi-units and building materials and components selected for the thesis.

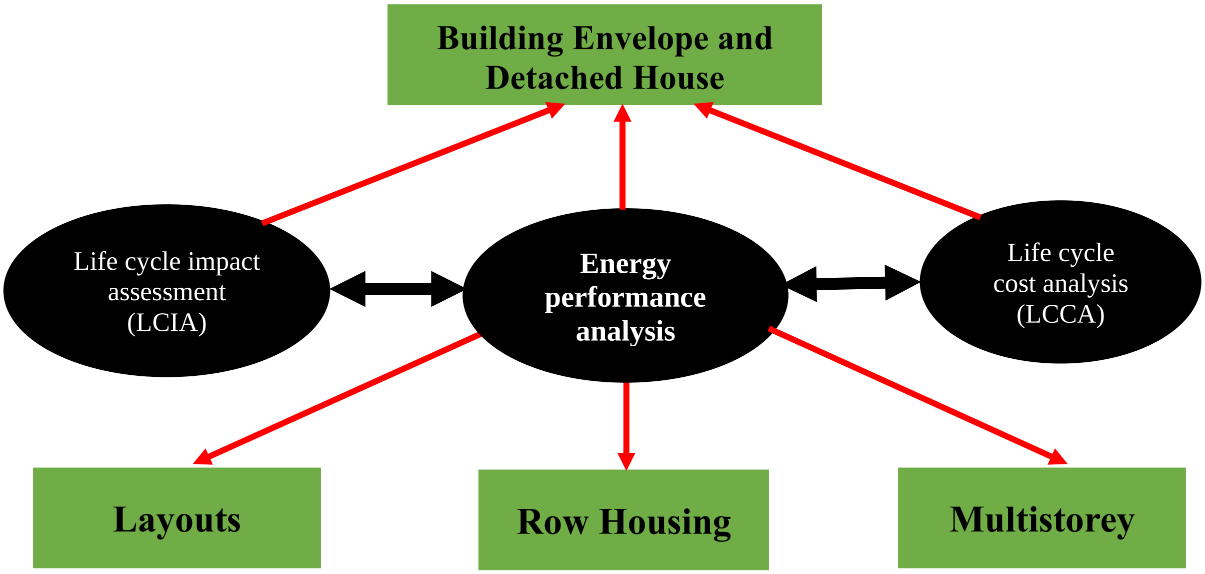


Figure 2.1 Research Map Showing Methods and Workflow

Note: *Black shapes and lines relate to the primary research methods. Green blocks are the different classifications of building scenarios. Red lines relate to the proposed flow of research analysis and important milestones completed.*

2.2 Research Methods and Tools

Figure 2.2 presents research methods and tools used to achieve each of the three research objectives associated with the vital milestones. Methods and tools employed for the whole building performance analysis are best for early design evaluation in the current research trend. This study utilizes two main simulation tools: EnergyPlus for energy simulation and modeling and Athena Impact Estimator for the life cycle impact assessment. The author manually calculates the life cycle cost analysis based on existing formulas for similar building types.

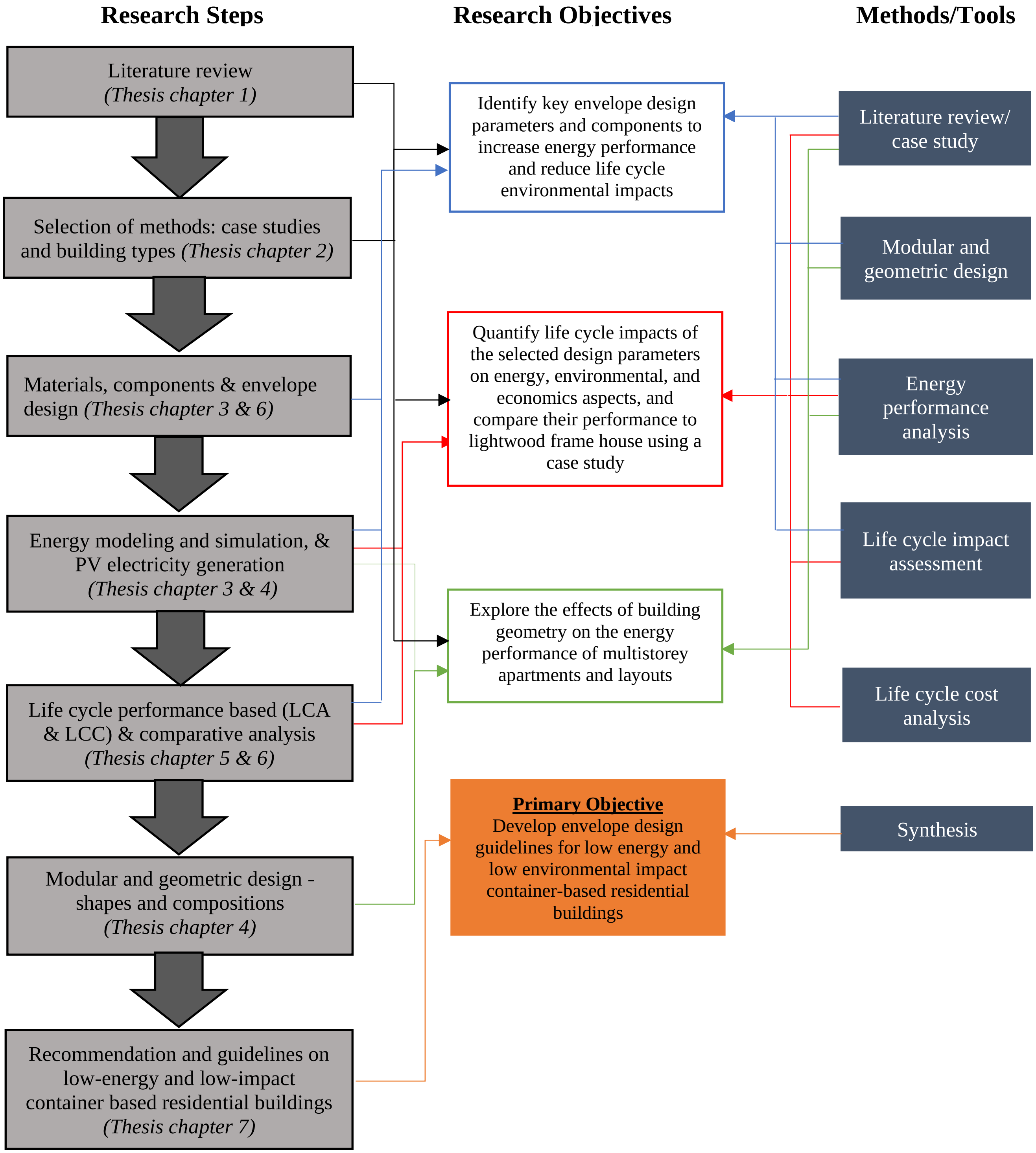


Figure 2.2 Methods and Tools for Specific Research objectives and Related Milestones

Note: Blue lines relate to the first research objective. Red lines relate to the second research objective. Green lines relate to the third research objective. Black lines relate to all three research objectives, while Orange lines relate to the primary thesis objective.

2.2.1 Description of Case Study: Single-Detached House

The case study is a two-storey single-detached container-based house manufactured by Ladacor Advanced Modular System, Inc (Ladacor Advanced Modular System, 2018). Figure 2.3 illustrates the three-dimensional perspective of the case study project. The project applies to Chapter 3, energy performance analysis and Chapter 5, life cycle impact assessment and life cycle cost analysis. Appendix A: Case Study Drawings: Single Detached House provides detail of the working drawing re-used with the permission of the developer, Ladacor. The project is a 5-bedroom container-based detached house designed with a basement (i.e., main and basement floor). Each floor is approximately 119 m^2, and a total of 238 m^2 of building area. The dimension is 12.2 m in length, 9.75 m in width and 2.9 m in height. The main floor modular design is factory-built using four (4) upcycled and then repurposed Intermodal Steel Building Unit (ISBU) container boxes. Two container boxes are attached horizontally as one module, and each module is fabricated together at the factory by removing a side of the container wall. The adjoining wall between two container modules, also known as the "marriage wall," is retained. The basement floor design did not utilize the container modules; instead, it follows the typical basement design building systems and specifications for Canada's residential construction.

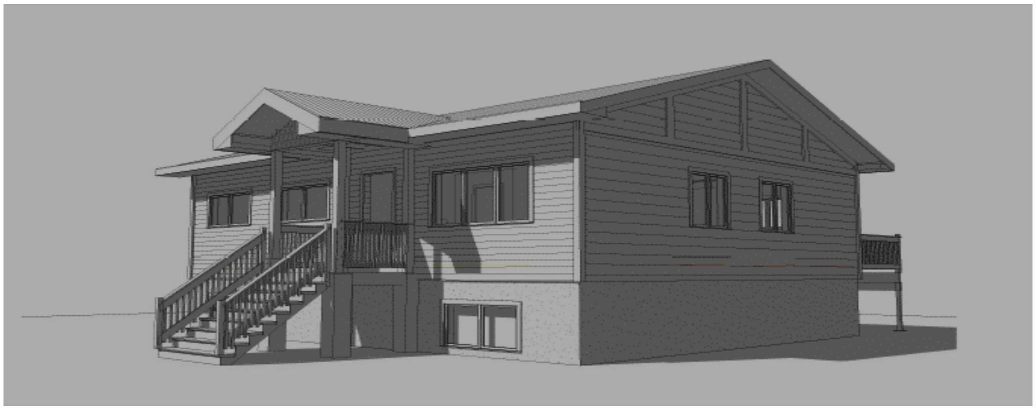


Figure 2.3 Three-dimensional Perspective Single-detached House Case Study Building

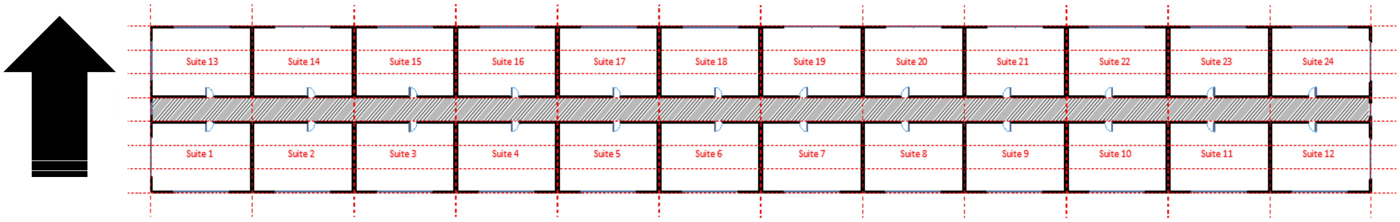
2.2.2 Apartment Modular and Geometric Design

The design of proposed layouts and multistoreys is covered in Chapter 4. Each unit consists of three modules 40-foot (12.2 m) high cube containers. The initial design considers a south-facing building orientation of the rectangular unit module. However, this did not work out for all apartment buildings as the modules needed to be re-arranged to follow desired layouts and storey levels.

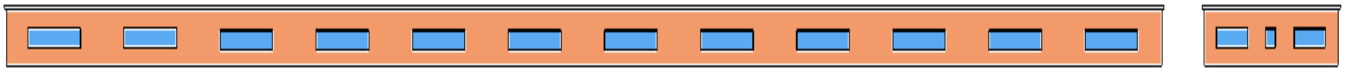
Layout Modular Design. The layout consists of eight-unit apartments per floor and a total floor area of 892 m^2. The study layouts are created by combining modular units and modifying geometric configurations into different shapes and forms. The layouts consist mainly of two wings at mostly south orientation to follow passive design principles. The layouts include rectangular, I – shape (narrow rectangle), square, and U shape (see Figure 2.4). The rectangular layout serves as the reference layout and assumes an optimal south orientation with an elongated east-west axis. Chapter 4 presents the details of research results and findings.

Figure 2.4 Container-based Building Layouts

Multistorey Modular Design. The multistorey employ 24 modular units to create a maximum of a 6-storey apartment by varying floor levels, building heights and aspect ratio per model. The modular design concept starts with a single storey of 24-unit apartments. It transposes into different floor levels (up to 6 storeys) by stacking the modules and varying vertical and horizontal configurations. Each storey design assumes evenly distributed units on both south and north façades divided by a hallway. Graphical illustrations of single-storey apartments and six-storey apartments are represented in Figure 2.5 and Figure 2.6, respectively.

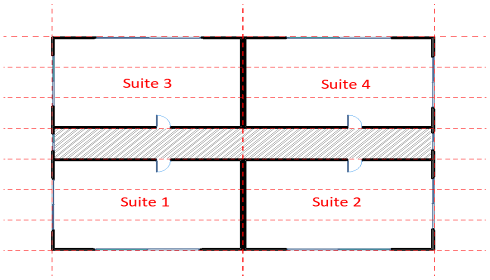


(a) Apartment floor plan

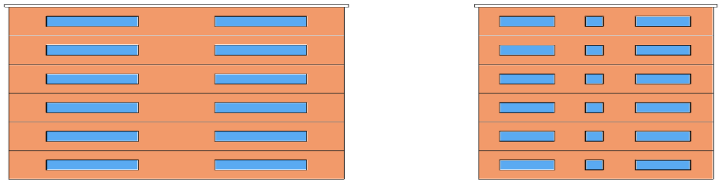


(b) South elevation (c) West elevation

Figure 2.5 Single-storey Apartment



(a) Typical floor plan



(b) South elevation (c) West elevation

Figure 2.6 Six-storey Apartment

2.2.3 Energy Performance Analysis

This section explains research steps taken to investigate the effects of various building envelope design parameters on thermal loads, total building energy consumption, and solar electricity generation. The result variables consider building energy loads/consumption for heating and cooling, domestic hot water, lighting and equipment per dwelling type. The process starts with reference model design (code case) designed using the case study, Ladacor building characteristics. The code envelope characteristics compliances with Alberta Building Code (National Research Council Canada, 2014) standards, the National Building Code of Canada (National Research Council Canada, 2015a), recommended for low-rise housing and small buildings in Canada, and the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) Standard 90.2-2007 – Energy-efficient design of low-rise residential buildings (American Society of Heating Refrigerating and Air-conditioning Engineers Inc (ASHRAE), 2007). Design appliances follow the Energy Code of Canada (National Research Council Canada, 2015b).

The energy simulation and modeling follow a parametric investigation of various envelope compositions, combining the best performing scenarios into different configurations to achieve an improved model. All configurations are subjected to simulations, followed by comparative analysis to assess the effect of various envelope parameters on energy performance relative to a reference case. A summary of these results is presented both for reference and improved case. The row housing and apartment designs assume improved envelope characteristics based on the extensive energy performance analysis of the single-detached house.

Building Integrated Photovoltaics (BIPV) System. For the single-detached house and row houses, a gable roof-mounted PV is designed on the south-facing roof surface at a 22.5° tilt angle as per the original design inclination. The system assumes a photovoltaic efficiency of 18% (Canadian Solar Inc, 2019) and inverter efficiency of 90% (Kapsis & Athienitis, 2015) during the PV simulation analysis in EnergyPlus. While the detached house explores roof-mounted PV systems, apartment designs (e.g. multistorey and layouts) adopt façade integration PV systems on opaque areas of the south, east, and west façades. The basic PV system is assumed to cover 80% of the façade areas, given 20% WWR for all glazed areas. The facade's reduced window area enables a total BIPV area of more than two-thirds of the façade, comparable to most studies on facade energy generation (Hachem-Vermette, 2018; Hachem et al., 2014b). The facade electricity generation favours higher envelope surface area, given the reduced roof area available for roof-mounted systems relative to the total occupied area, in multistorey buildings (Hachem et al., 2012, 2014b).

2.2.4 Environmental Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is chosen as the methodology to assess the life cycle performance of design decisions and material options for the dwelling types discussed in this thesis. The LCA methods are long-term design decision tools to evaluate environmental footprints associated with buildings and products at different life cycle stages (Kotaji et al., 2003). LCA provides a holistic perspective by considering cradle-to-grave of all life cycle stages (i.e., resource extraction, manufacturing, construction, transportation, maintenance, replacement of building materials, building operation, demolition, and disposal) (Islam et al., 2016; Kumar et al., 2015; Marszal & Heiselberg, 2011; Paleari et al., 2016; Ramesh et al., 2010; Sharma et al., 2011; Stazi et al., 2012). This study considers LCA an appropriate tool for evaluating the environmental burdens associated with adaptive re-use of shipping containers in housing, accounting for life cycle environmental impacts as a building system, while reporting on possible environmental credits through avoided impacts as an upcycled or recycled product. Therefore, complements the energy performance study and provides the integrated life cycle perspective as required for this thesis.

This research step follows a generic LCA methodology, a standardized process, according to the International Organization for Standardization (ISO). The LCA framework comprises four (4) distinct steps (phases) according to ISO 14044 standard. It includes: define goals and scope, collect and analyze inventory, perform impact assessment and interpret results (International Organization for Standardization, 2006b). Figure 2.6 illustrates the LCA methodology process.

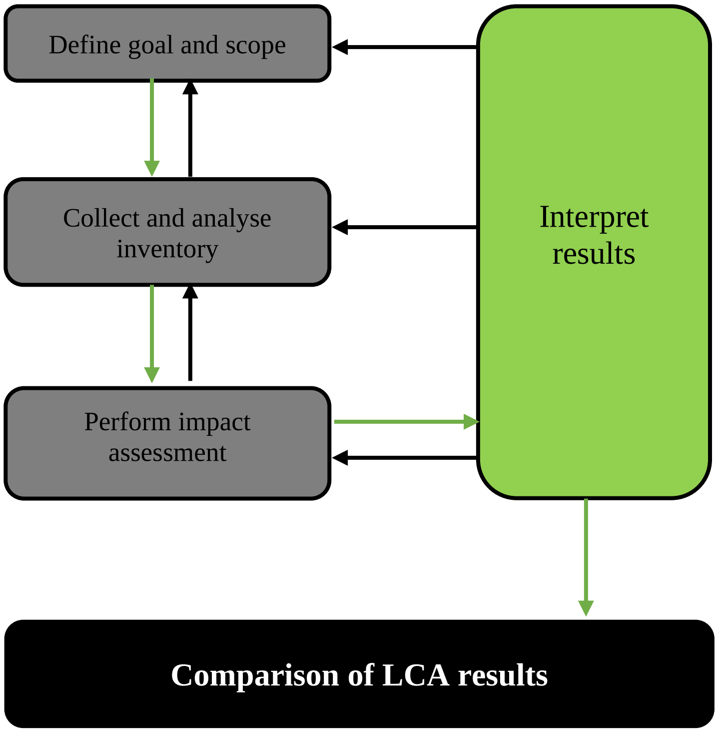


Figure 2.7 Phases of the LCA Process Based on ISO 14044 2006

Define Goal and Scope. The first step to performing an LCA is to establish the goal and scope of the assessment. The main LCA goal for this study is to examine the environmental impacts of container-based residential buildings to aid design decisions on the adaptive re-use of shipping containers by designers. More specific goals are designed based on research objectives as covered in different chapters of the thesis as follows:

- Evaluate building systems and compare life cycle environmental performance of selected case studies (Chapter 5), based on results of the energy performance of chapter 3.
- Evaluate wall design systems and identify building materials and components design options to reduce life cycle embodied impacts (Chapter 6).

This phase also covers functional unit, system boundaries and impact categories considered in the LCA building analysis. Functional equivalence or functional units describe the whole building critical functions under assessment using a set of quantifiable criteria (Carbon Leadership Forum, 2019). Lavagna (2012:81) defines functional equivalence as "the challenge of ensuring that two or more products (or buildings) provide the same level of service." This ensures the evaluation of products with interchangeable and equivalent alternatives for a more rigorous comparative LCA within a given study (Kotaji et al., 2003). Building scale, building characteristics, technical and functional requirements are few examples of objective criteria for whole building LCA, thus ensuring "apples-to-apples" comparisons of buildings (Carbon Leadership Forum, 2020). Other characteristics reported in the thesis are total gross floor area (GFA), building type and purpose, the number of building occupants and life expectancy for equivalent building and product scenarios. The operational energy consumptions of models satisfy functional equivalence based on results from energy performance analysis. The LCA approach in this thesis links to the functional unit identified for each case study. These vary for chapters based on the dwelling type under assessment (e.g. detached house or building component).

The system boundaries consider both cradle-to-grave for building (system-level) assessment and cradle-to-cradle for product level, materials and building components assessment to meet different research objectives. The life cycle scope for Chapter 5, - cradle-to-grave assessment follows the standardized module designations (A1 – C4) (Islam et al., 2016; Kumar et al., 2015; Marszal & Heiselberg, 2011; Paleari et al., 2016; Ramesh et al., 2010; Stazi et al., 2012). It considers the product (A1 – A3), construction (A4 – A5), use and operation (B2, B4 & B6) and end-of-life (C1 – C4) stages, omitting the downstream processes of beyond life. Cradle-to-grave assessment assumes that environmental benefits at end-of-life will not directly influence the container-based units life cycle environmental performance, already assessed as second life cycle situation. The LCA analysis of embodied impact based on materials and components includes building life cycle module (D) as supplementary information accounting for materials benefits and loads beyond the defined system boundary (see chapter 6). This module contains miscellaneous for re-use, recovery and recycling potentials of products. Both assessment levels use the Athena Impact Estimator (IE) for buildings simulation tools (Athena Sustainable Materials Institute, 2016), as shown in Figure 2.8.

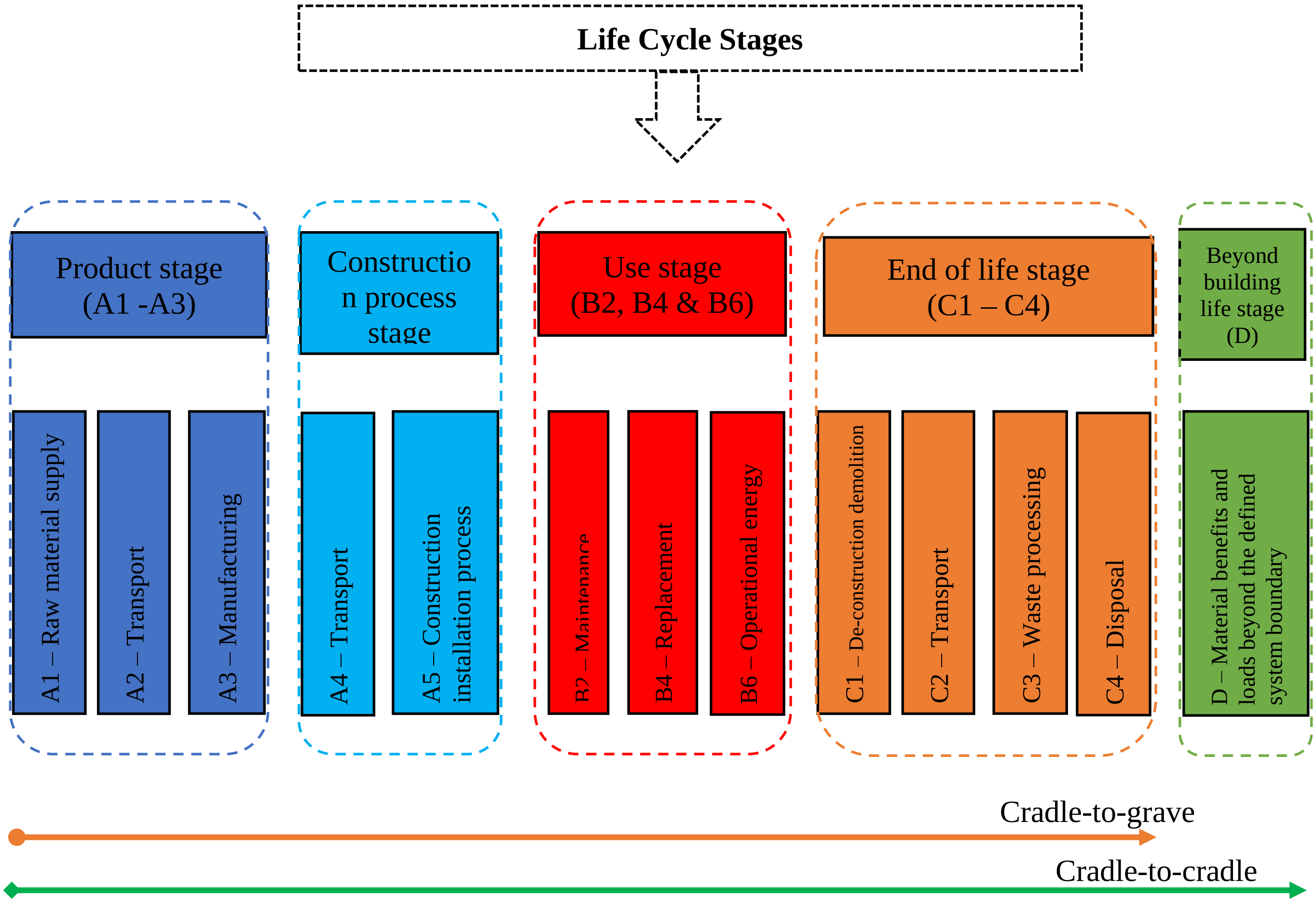


Figure 2.8 Defining System Boundaries (life cycle stages and modules)

Diagram modified based on Athena IE (Athena Sustainable Materials Institute, 2016).

The study uses selected environmental impact categories to determine the data collected in the inventory analysis phase. The thesis considers nine environmental impact categories for environmental LCA. They include global warming potential (GWP), smog potential (SP), primary energy use (PEU), fossil fuel consumption (FFC), acidification potential (AP), human health particulate (HHP), ozone depletion potential (ODP), eutrophication potential (EP), and solid wastes generation (SWG). These indicators are selected to ensure an in-depth life cycle assessment of the case study buildings.

Collect and Analyse Inventory. This second phase covers the collection of data and inventory fed into the LCA. Life cycle inventory (LCI) data collection follows the SETAC (Society of Environmental Toxicology and Chemistry) guidelines recommended for LCA of building and construction (Kotaji et al., 2003). While inventory collection appears to be a challenging task, the Athena IE application provides information on all indicators of LCA activities, including energy consumption, air emissions, waste and land emissions (solid waste generation), water emissions, and embodied effects required to estimate material quantities. This template (i.e., bill of materials) reflects the list of materials, product specifications, and construction systems for each building system to be analyzed.

Athena's life cycle inventory database contains the most detailed construction data in North America, with frequently updated databases on materials, systems and processes (Athena Sustainable Materials Institute, 2014). The Athena LCI database comprises ISO 14040/14044-compliant unit process LCI data (e.g. concrete manufacturing LCI results per m^3 concrete) related to raw materials. It is region sensitive, considering manufacturing technology, transportation and electricity grid differences, and recycled content differences for products produced in various regions and locations, for example, Calgary. For this thesis, the LCI quantitative data is collected at the unit process level using building characteristics and information provided on the building drawings and construction notes. The primary source of data collection comes from the specific building assembly design, which considers information regarding materials types and quantities, mostly occurring at the production stage (modules A1 – A3) (Carbon Leadership Forum, 2018, 2019).

Impact Assessment. Emissions associated with materials and products are typically estimated from computational models using simulation tools or actual measurements (Simonen, 2014). Athena IE pre-determines emissions and generically translates that into environmental impacts by multiplying their masses with characterization factors through the Athena tool built-in data processing engine. Athena IE LCA tool calculates the environmental impacts and organizes the results into different life cycle stages and building assembly, keeping track of materials, scenarios, and impacts. The LCA indicators are as follows:

(1) Energy consumption: The life cycle energy results discuss three (3) primary energy indicators: total primary energy, fossil fuel consumption and non-renewable primary energy. The life cycle energy is assessed in kilowatt-hour (kWh). It sums the total energy consumed during the pre-use (embodied and construction), use (operational energy), and post-use phase over a given life expectancy.

(2) Air emissions: Five life cycle environmental impacts caused by air pollution are evaluated (for e.gs. global warming potential, acidification potential, ozone depletion potential, smog potential, and human health particulate). The results present the environmental impacts in kilograms (kg) as equivalent to the predominant substances contributing to the impact (e.g. CO_2, SO_2). The global warming potential indicator determines the product's climate change impact and the end of life radiation effects due to greenhouse gases. Acid formation potential (ability to form hydrogen ions) calculation provides the acidifying effect of building products and case models' materials. Other critical and potential indicators that cause significant air pollution include ozone depletion potential, smog potential, and human health particulate.

(3) Waste and land emissions: For appropriate analysis of the environmental impacts associated with recyclable products (e.g., container steel), this study assesses the emissions from resource depletion and waste disposal and studied the avoided material impacts and reduction in land and waste emissions through product recycling and re-use. The study considers three indicators: solid waste generation, solid waste to landfill during the disposal phase and resource use.

(4) Water emissions: The water indicator employed in this LCA is simply a summation of all water used in materials within the system boundary. Water emissions and eutrophication potential apply critical volume (M^3/kg eq.) for the life cycle phases.

(5) Embodied effects: This summarises the embodied effects of the building assembly groups (e.g. walls, roofs) in terms of related emissions, waste, energy, and resource use throughout the life cycle phases.

Interpretation of Results. The interpret LCA results simply understand the impact values presented beyond the simple numbers and draw a conclusion based on existing studies or comparisons to standards. This thesis compares study results to similar LCA studies of similar building size, type, and regions (e.g. North America). A combination of comparative and sensitivity analysis of the case study provides validity for the study results (Carbon Leadership Forum, 2018, 2019).

Performing sensitivity analysis of the recycled shipping containers used as part of the building envelope helps identify variables in assessing the recycled containers' actual weighted impacts. Sensitivity analysis reflects few approaches for allocating and distributing environmental burdens and credits between a product with multiple life cycle situations (Karen Allacker et al., 2017; Frischknecht, 2010; Koffler & Finkbeiner, 2018; Nicholson et al., 2009; Vadenbo et al., 2017). Two-product life-cycle situations are considered: (i) primary product life cycle as cargo used for freight transportation and (ii) subsequent product life cycle which is upcycled to a house (see Figure 2.9).

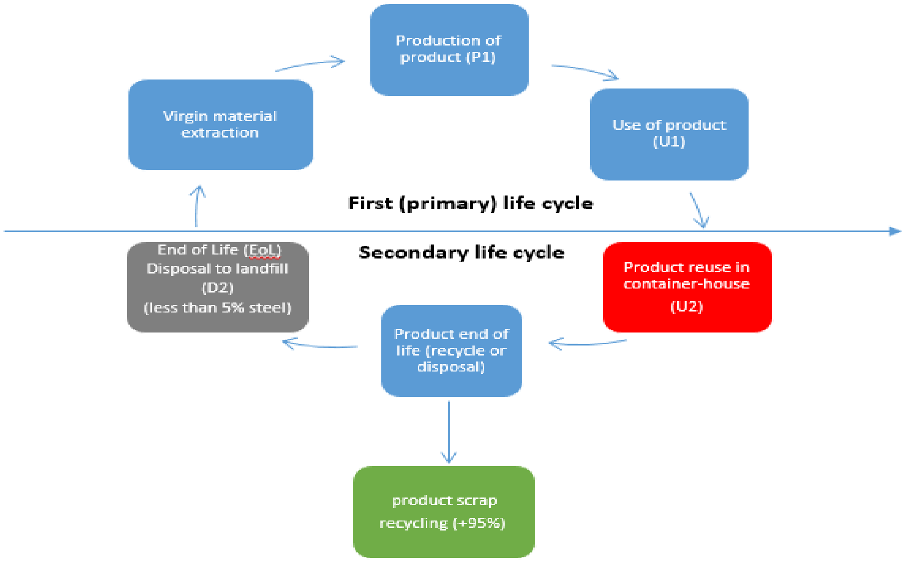


Figure 2.9 Life Cycle Situation of Container-based Structure

2.2.5 Building Life Cycle Cost Analysis

The Life Cycle Costing (LCC) study sums up the initial investment costs, energy costs, non-energy operation, maintenance, and repair costs for 50 years lifespan. The study excludes capital replacement costs, water costs and residual costs.

The total life-cycle cost can be calculated using equation the equation below:

LCC = I + E + OM&R (1)

where: LCC = Total LCC in present-value dollars

I = Present-value investment costs

E = Present-value energy costs (electricity)

OM&R = Present-value non-fuel operating, maintenance, and repair costs.

2.3. Selection of Building Modeling and Simulation Tools

Simulation and modeling tools enable building performance analysis, such as solar analysis, thermal performance, ventilation and airflow analysis, lighting design and life cycle assessment. A high-performance building uses various energy efficiency measures and targets, reducing its energy demand by 50-80% compared to a Code-compliant home (FPInnovations, 2014). One approach to achieving energy efficiency in a building is by employing building simulation and modeling to design, optimize, and analyze building performance during the design phase (Mottahedi et al., 2015).

Advantages of building performance analysis using simulations tools include:

- Designers use it to provide valuable insight to building owners on whole building performance over the building life cycle and thermal performance (Reddy, 2006).
- It provides valuable information that helps designers make better decisions about the characteristics of building envelopes, the life cycle impact of materials, and HVAC systems, etc.
- It provides more value to the occupants with detailed information to reduce building operational costs.

2.3.1 Energy Performance Simulation Tool

EnergPlus: Assumptions, Modeling and Simulation Process. SketchUp/OpenStudio is employed to generate the geometric data for EnergyPlus, with each housing unit modelled as a single conditioned thermal zone for the apartments (Chapter 4). In the case of a single-family case study designed with two floors (e.g. Chapters 3), the modeling process considers separate thermal zones for each floor level. EnergyPlus employs weather data files based on CWEC – Canadian Weather for Energy Calculations hourly weather observations (Weather Network, 2018). Data collected simulate one year, intended explicitly for building energy calculations and includes hourly solar radiation values, wet bulb temperature, wind speed, ambient temperature, cloud cover, and wind direction. The CWEC database simulates the hourly weather conditions for the study location, the Calgary area (AB, 51°N, 114°W, Canada). The simulation engine is designed on an hourly basis for one year (January 1 to December 31), maintaining an indoor air temperature range of 20°C and 24.5°C as heating and cooling set-points. The interior lighting power density assumes high-efficient LEDs provided by the National Energy Code of Canada for each dwelling type (National Research Council Canada, 2015b). The model then calculates thermal loads for heating and cooling demands and other building electricity loads.

Rationale for Selecting EnergyPlus. Although there are various simulation tools available for energy performance analysis of residential buildings, this research selects EnergyPlus 8.5 version (EnergyPlus, 2018) as the simulation tool based on the following reasons:

- It allows for whole building modeling with advanced dynamic energy simulation for aspects of energy consumption and loads.
- It offers open-source designed with North American building material database, geographical location, weather data, and ASHRAE standards database.
- It accepts simulation input data from other sources such as the Google Sketchup plug-in that significantly facilitates the generation of geometric data of complex shapes.
- It attains a considerable level of detailed output reports to facilitate the interpretation and analysis of results.
- It is a text-based program that reads input and writes output to text files.
- It provides a holistic modeling approach by combining passive design and active solar technologies and solar control strategies within one simulation.
- It enables systematic envelope improvement and analysis through group simulation and interpretation of results.

Limitations of Modeling within EnergyPlus. One major challenge of using EnergyPlus in building simulation is the lack of flexibility in modeling building geometry, coordinates and shapes within its platform. However, its capacity to accommodate external plug-ins such as Google Sketchup enables easy modifications to envelope design in SketchUp and export into EnergyPlus as idf file for further simulations. A notable limitation of using simulation tools, including EnergyPlus, is that few assumptions on design parameters such as airtightness might not reflect the actual as-built parameters. This can affect the accuracy of the energy analysis and simulation and often lead to a differential in the actual building performance results compared to a simulated model. Energy modeling results should be accepted as predictive performance until the completion of post-occupancy evaluation on the building. However, actual building performance at the use and operation phase is perhaps controlled by the occupants' daily activities; and can also influence highly energy-efficient building monitored performance.

2.3.2 Environmental Life Cycle Assessment Tool

Athena Impact Estimator: Assumptions, Modeling and Simulation Process. Below are steps to generate a building model in Athena Impact Estimator (IE):

1. Enter a general project description: The general parameters needed are building characteristics, operational energy, project location, building type, and life span.

2. Define the building/assembly structure: Enter the study input for envelope assemblies and materials, including material thicknesses and other specifications. The "selected envelope components" area defines the envelope components for wall, floor, roof, and foundation assemblies.

3. Add window and door openings: In Athena IE, openings (e.g., doors and windows) are modelled as subsets of the wall assembly. In the "add custom wall" menu, the "opening" tab houses specific opening details. Window specifications such as the total number of openings, the total number of openings, frame materials and design, glazing type, and operation (fixed or operable) are within the wall assembly.

4. **Generate results:** The Report menu provides a preview of LCA measures and results as a graph or editable table, compatible with excel or word or pdf formats. Global Warming Potential is one of the most well-known midpoint indicators to measure greenhouse gas emissions' potential environmental impact. It is expressed in terms relative to carbon dioxide's contribution to climate change, usually referred to as CO_2 equivalents. Reports generations cover either assembly group embodied effects or life cycle stages of building.

5. Comparing projects: Athena provides the opportunity for a comparative analysis of different projects. The impact estimator allows for comparing the results of two or more project designs across all LCA measures, which applies to this research.

Rationale for Selecting Athena Impact Estimator. Athena Impact Estimator (IE) for building, version 5.2 (referred to as Athena IE hereafter) for whole building and assembly LCA is employed. Athena Sustainable Materials Institute in Ottawa developed the Athena IE based on the ISO 14,044 standards. While SimaPro allows for robust life cycle assessment, it is most suitable for product-specific LCA rather than whole building LCA. It also requires lots of assumptions to track the dynamics of various building materials across life cycle stages. Athena IE is adopted based on the following reasons:

- It is open-source software designed for regional geographical locations and incorporates data and building systems specific to North America (e.g., Calgary).
- It consists of comprehensive building material systems and building assembly, representing ninety-five percent (95%) of the building stock in North America.
- It provides comprehensive summary measures for selected life cycle stages (cradle to grave) at the whole building or assembly level.
- Adopts the United States Environmental Protection Agency, US EPA TRACI 2.1 method to inform the evaluation of environmental loads and provides the region-specific interpretation of design decisions.
- It enables building reference cases and flexible comparison of alternative building projects in one simulation window to identify the best-performing scenario.

LCA Limitations using Athena IE. Assumptions and uncertainties are inherent to any form of LCA (Athena Sustainable Materials Institute, 2014, 2016). Thus, understanding uncertainties in LCA results is paramount in making informed decisions. Multiple uncertainties exist in LCA results, such as input, parameter, data inventory and model uncertainty (Heijungs & Huijbregts, 2004). Due to methodological choices, literature reviews on LCA uncertainty have focused on life cycle inventory (LCI) and allocation approach (Cherubini et al., 2018; Heijungs & Huijbregts, 2004; Kotaji et al., 2003). Data uncertainty in LCA may occur as a result of design options or choices on data for which no value is available, data for which an inappropriate value is available, and data for which more than one value is available (Funtowicz & Ravetz, 1990; Heijungs & Huijbregts, 2004).

Data availability challenges are reduced in this case study using additional external data sources to quantify product parameters missing in the Athena database. For instance, by substituting missing product data for which no data is available with similar products. While the substitution approach applies to replacing shipping container panels with steel products in the Athena database, few materials such as phase change materials (PCM) used in the design of the improved cases are not inventoried in the analysis. A substitution may be possible by creating individual materials into a component; however, using such an approach may result in an inaccurate estimation of the product impact and too many assumptions.

Athena IE does not estimate building operational energy consumption. However, Athena calculates the total primary energy for the life cycle assessment by converting the input secondary energy into primary energy. For this reason, EnergyPlus software is used to calculate the total building energy consumption for all LCA-related modeling and simulations of this thesis. Making a comparative analysis, as it is in this study, can also lead to uncertainty. To minimize uncertainty based on input parameters and characterization, this study establishes precise functional equivalence. Product options assume equivalence to the broad range of performance characteristics throughout the building's whole life cycle (Carbon Leadership Forum, 2018, 2019). This study also considers comparable building scenarios using the exact size of floor area, envelope design and building height.

Carbon Leadership Forum (2019) suggests that to further conduct a sensitivity analysis on an uncertain variable after identifying sources of uncertainty. To reduce the level of uncertainty associated with conducting LCA for shipping containers, sensitivity analysis is conducted with a range of possible values using different allocation approaches and then evaluating the possible life cycle environmental performance outcomes. A combination of comparative and sensitivity analysis of the studied scenarios provides validity for the study results (Carbon Leadership Forum, 2018, 2019).

2.4 Assumptions, Study Scope and Limitations

This research investigates methods of achieving low energy and environmental performance in container-based dwellings through the implementation of selected energy efficiency measures and maximizing solar potential, as well as environmental life cycle assessments of this method of construction in residential buildings. This thesis considers Calgary, Canada (AB, Latitude 51°N) as its pilot location, representing mid-latitude locations in a northern climate.

In order to complete the energy analysis and life cycle assessments, assumptions were made (refer to sections 2.3.2 and 2.3.2 above). The thesis makes a primary assumption that the case study project, which is considered the starting point of the parametric investigation is designed to the building code characteristics (see 2.2.1 Description of Case Study: Single-Detached House). The energy performance analysis also considers whole building modeling using EnergyPlus simulation engine to analyze energy consumption, thermal loads, and present comparative analysis of selected scenario cases. In the simulations, it is assumed that issues such as thermal bridges are eliminated and high airtightness can be achieved and as such analyzing these aspects is excluded from the thesis. However, methods of construction to eliminate issues of thermal bridges and ensure continuous insulation and airtightness in container buildings should be covered in future research, to ensure that high performance such as analyzed in the thesis can be reached.

The study scope is limited to residential dwellings considering the application of container-based design in detached, row housing and apartment buildings. The scope of economic performance (life cycle cost analysis) in this research is limited to investigating the single-family detached house (see chapter 5). The goal is to establish a benchmark for evaluating modular container-based structures in terms of cost-efficiency compared to typical lightwood frame housing. It is outside the scope of this research to address the life cycle costing of other residential dwellings, including apartments. This thesis offers technical (quantitative) performance-based research. It, therefore, excludes social-related issues associated with the acceptance of shipping container housing as a modular construction type by the building industry. Uncertainty associated with various assumptions is not the focus of this research, however, this thesis recognizes its existence as part of the current study limitations.

The next chapter is the beginning of the core research work, starting with the systematic envelope design and analysis to improve energy performance and possible net-energy status for the single-detached and row houses. The chapter uses the five bedrooms single-detached case study project for the systematic energy analysis with EnergyPlus.

Chapter 3 Impact of Building Envelope Design on Energy Performance of Single-Detached and Row Housing: Case Study

Chapter 3 investigates the use of the container-based structure for residential buildings and determines its potential to achieve low-energy status in Calgary, Canada. It uses a case study (5) five-bedroom house with a finished basement developed by Ladacor Advanced Modular Systems. This chapter explores the effects of improving energy performance through systematic building envelope design for detached and row housing configurations using the case study building characteristics. The research focuses on maximizing passive and active solar energy to reduce overall energy consumption. Part of the research work has been published in a conference proceeding *(Hachem-vermette, C., Dara, C., & Kane, R. 2018)*[1], co-authored with my supervisor and industry partner from Ladacor ltd.

3.1 Envelope Design and Parametric Investigation

This case study is a two-storey detached family house developed by Ladacor Advanced Modular System. As illustrated in Figures 3.1 and 3.2, the model consists of two floors (i.e., first and basement), approximately 119m^2 each, and a total building area of 238m^2. The dimension is 12.2m in length, 9.75 m in width, and 2.9 m in height. Building a roof height of 1.8 m is designed based on a 22.5° tilt angle. The house comprises five bedrooms, two bathrooms, kitchen, and living area**.** The main floor modular design is factory-built using 4 upcycled and then re-purposed Intermodal Steel Building Unit (ISBU) container boxes (Figure 3.1). According to Hapag-Lloyd (2016), high cube general purpose containers designed with non-treated steel floor and corrugated walls are 100% recyclable and more sustainable without the use of chemical treatment. The original container steel floor consists of 0.17m floor height (ground level to interior floor surface), 0.07m container roof thickness, and 2.66m interior dimension (floor to ceiling height) before envelope modifications. Section 3.1.1 discusses container-envelope modifications. Two container boxes are attached horizontally as one module, and each module is fabricated together at the factory by removing a side of the container wall. The adjoining wall

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[1] Hachem-vermette, C., Dara, C., & Kane, R. (2018). Towards net zero energy modular housing: a case study. *Modular and Offsite Construction (MOC) Summit Proceedings*.

between two container modules, also known as the "marriage wall," is retained. The basement floor design did not utilize the container modules; instead, it follows the typical basement design building systems and specifications for Canada's residential constructions (Figure 3.2).

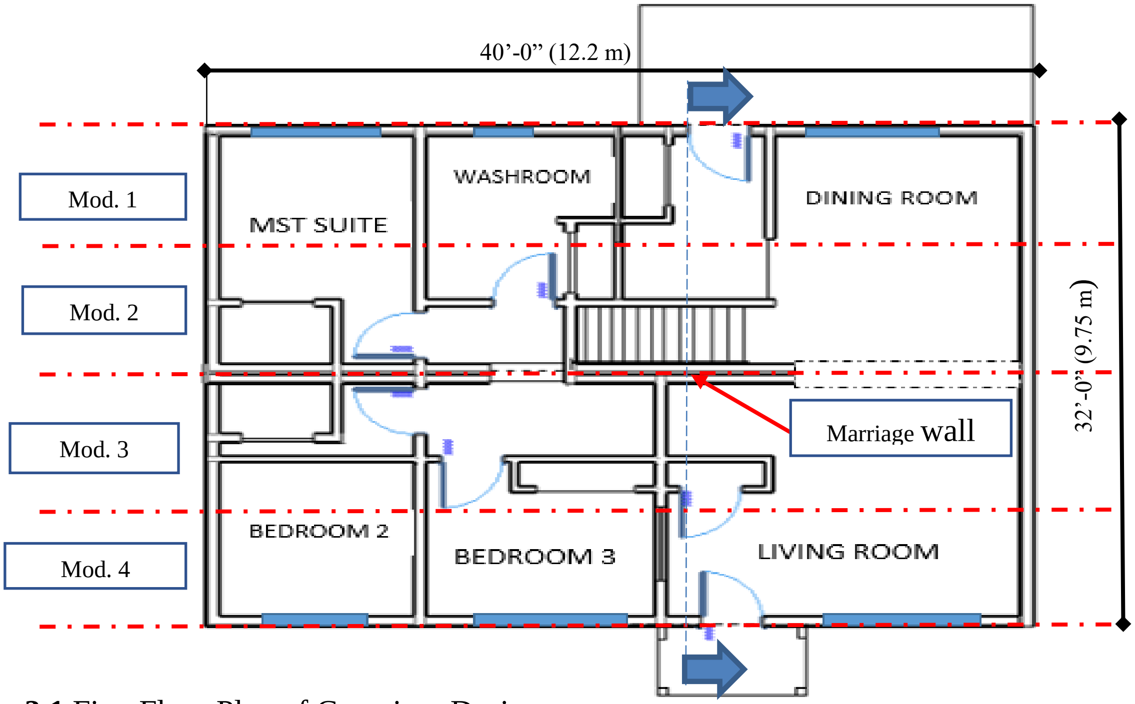


Figure 3.1 First Floor Plan of Container Design

Redrawn by the author with permission from Ladacor Advanced Modular System

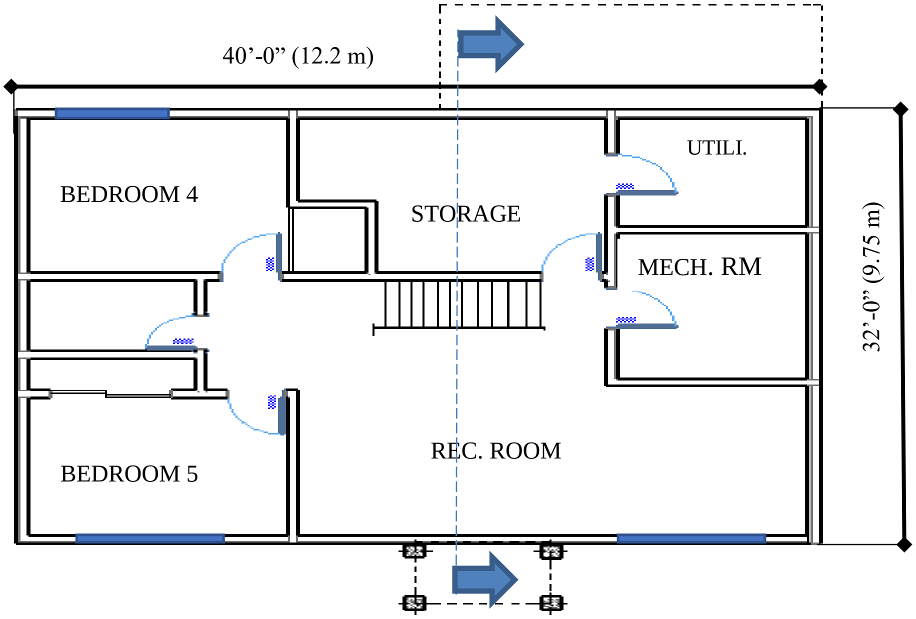


Figure 3.2 Basement Floor Plan Designed with a Concrete Wall

Redrawn by the author with permission from Ladacor Advanced Modular System

3.1.1 Container Building Envelope Connections

The building section (Figure 3.3) cut across the container modules as represented on the floor plans above. The building section provides an overview of building assembly and envelope connections. Additional detailed drawings are provided to elaborate on individual assembly connections, such as floor to wall connections (See Figures 3.4 – 3.8). The red lines on the section drawing represent the container demarcations. The main floor layout shows that side of the container panel is cut off during the re-design and envelope configuration process to allow for a more spacious interior. However, for each container box, one side panel of corrugated steel panel is retained. Steel studs are also introduced to support the wall systems. These studs are insulated for exterior load-bearing walls and uninsulated when used as interior partitions.

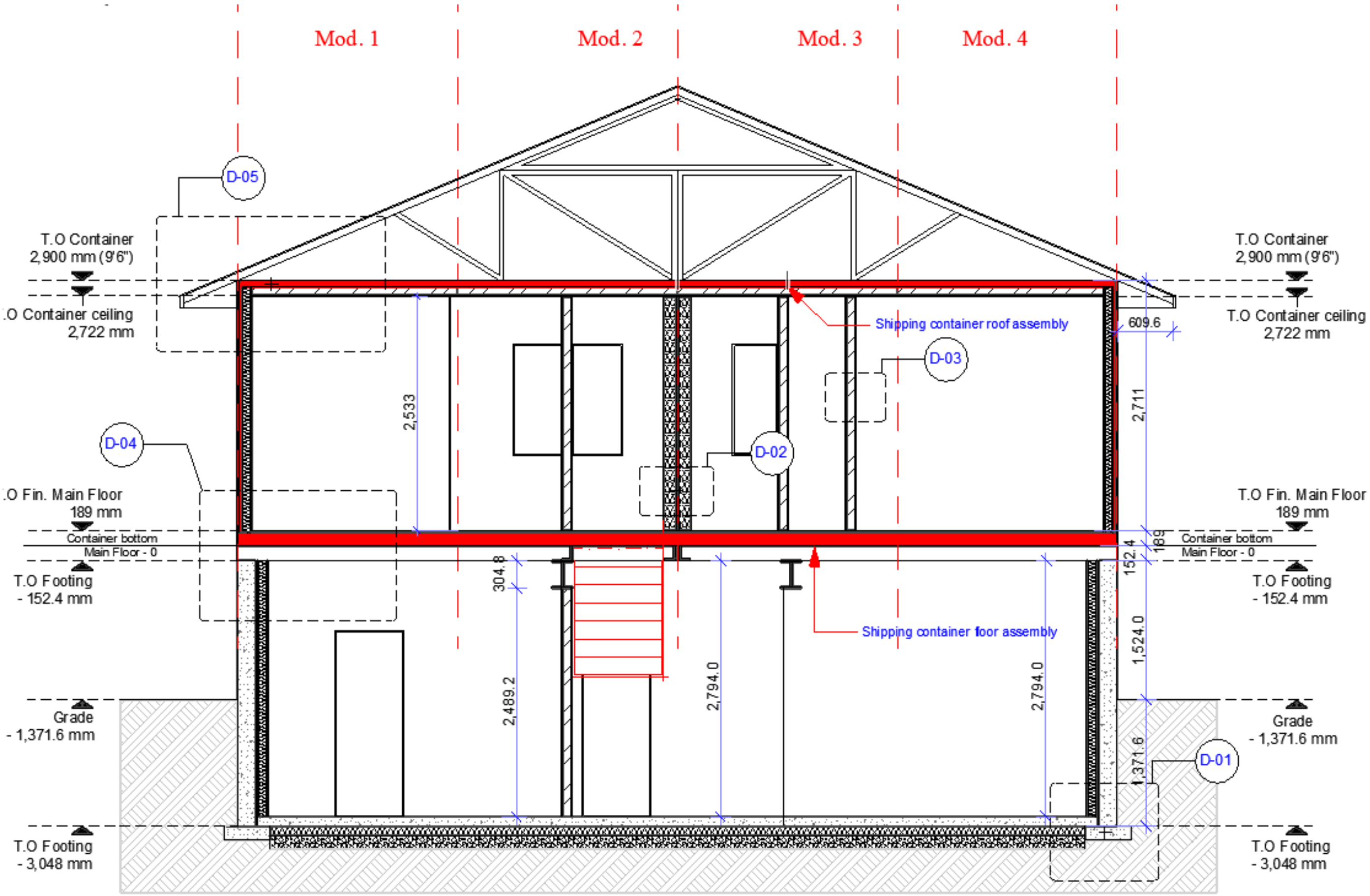


Figure 3.3 Container Building Section showing Connections of Assembly

To ensure a strong thermal boundary, air barrier and exterior sheathing are provided to protect the spray foam insulation against heat loss by reducing envelope heat transfer. Although the basement floor assumes batt insulation to conform with typical code design, spray foam insulation is which prevents corrosion and mould, is often used as a wall insulation material for container steel structures (Elrayies, 2017), and is applied to the main container-based floor. Using spray foam ensures a smooth and seamless barrier, characterized by its high R-value (thermal resistance) against heat flow. Pena and Schuzer (2012) suggest using closed-cell polyurethane spray foam with a high R-value as insulation to provide extra sealing to openings against moisture. Notably, spray foam offers better thermal insulating capacity with reduced thickness compared to batt insulation. If consideration is given to material thickness per performance, typical batt insulation will require more space to accommodate the desired thickness of the improved container model and might be a misfit as container-based buildings are challenged with reduced interior dimensions.

A strategy used in this study to reduce the effects of thermal bridging within the steel studs is by utilizing spray foam insulation that can also resist air movement. Spray foam insulation acts as a thermal bracket that wraps around the steel stud, thereby keeping the steelwork within the building’s insulated envelope, which further reduces the contact area for the high conductive steel material used as a structural element. Additionally, the insulation reduces transverse heat transfer, which takes place through stud flanges. Advanced framing is also deployed in this study to reduce material use and thermal bridging (Ching & Shapiro, 2014; Way & Kendrick, 2008). For example, steel stud spacing is increased from 16-inch (405 mm) of Ladacor case study design to 24-inch (610 mm) allowing for more insulation and less cold contact area. This approach has been successfully applied in similar studies to reduce thermal or cold bridges in steel construction (Kosny, Childs, and Gorgolewski, 2002).

Building Foundation Assembly. The container detached house assumes typical basement design building systems and specifications for Canadian residential constructions based on the Ladacor building characteristics. Figure 3.4 (D-01 of building section) illustrates the concrete foundation wall design on a strip foundation footing. In addition to the concrete foundation wall, 92mm steel wall studs are filled with batt insulation spaced at 600 mm. The basement floor assembly design assumes 100 mm poured concrete slab placed over a rigid insulation board.

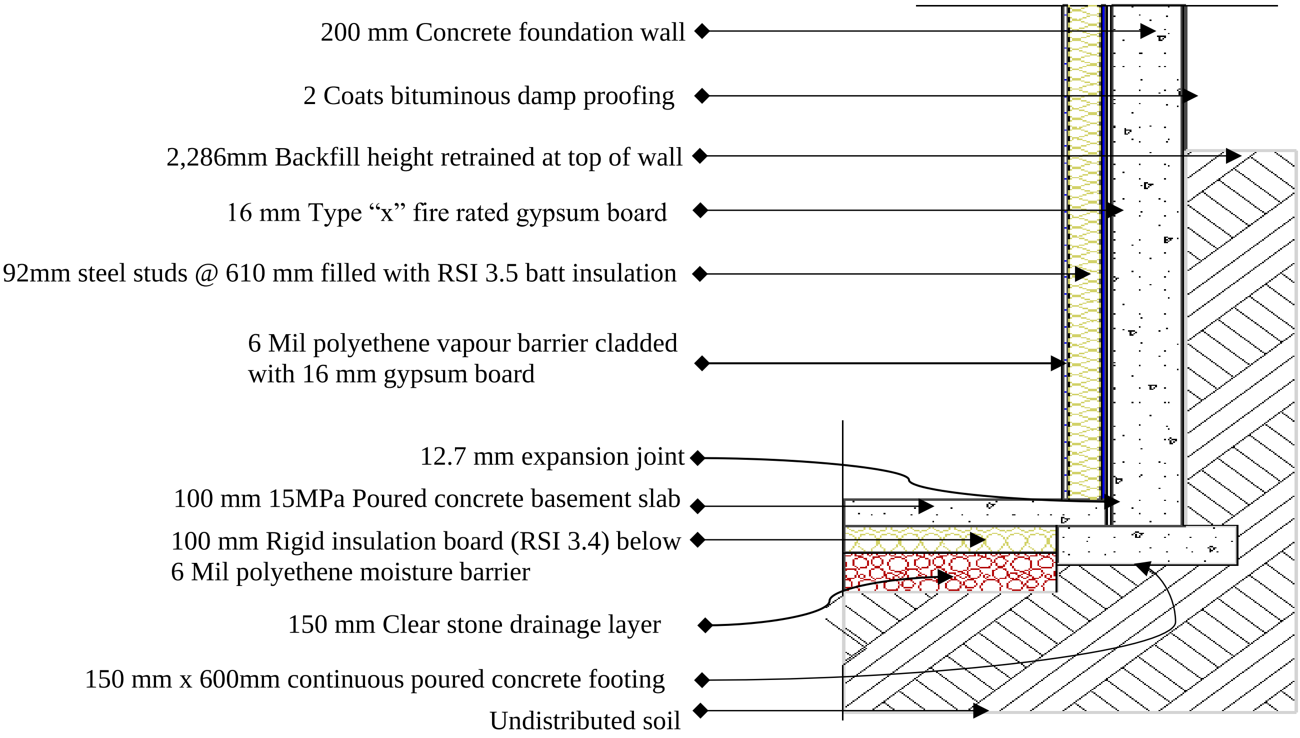


Figure 3.4 D-01 Foundation to Basement Connection Detail

Container Floor Connection to Basement. When stacking the shipping container on the basement foundation, containers are connected to each other to make a module (Fig. 3.5). The container connections are welded to a steel base plate as part of the floor connection. Plenum floor design provides a pathway for building services such as heating systems, and distribution systems. The plenum floor 152mm (6”) unites the container main floor to the basement ceiling. The original container flooring is about 170 mm, corten steel exiting floor. The code design assumes 19 mm floor finish incorporated on top of the original steel floor.

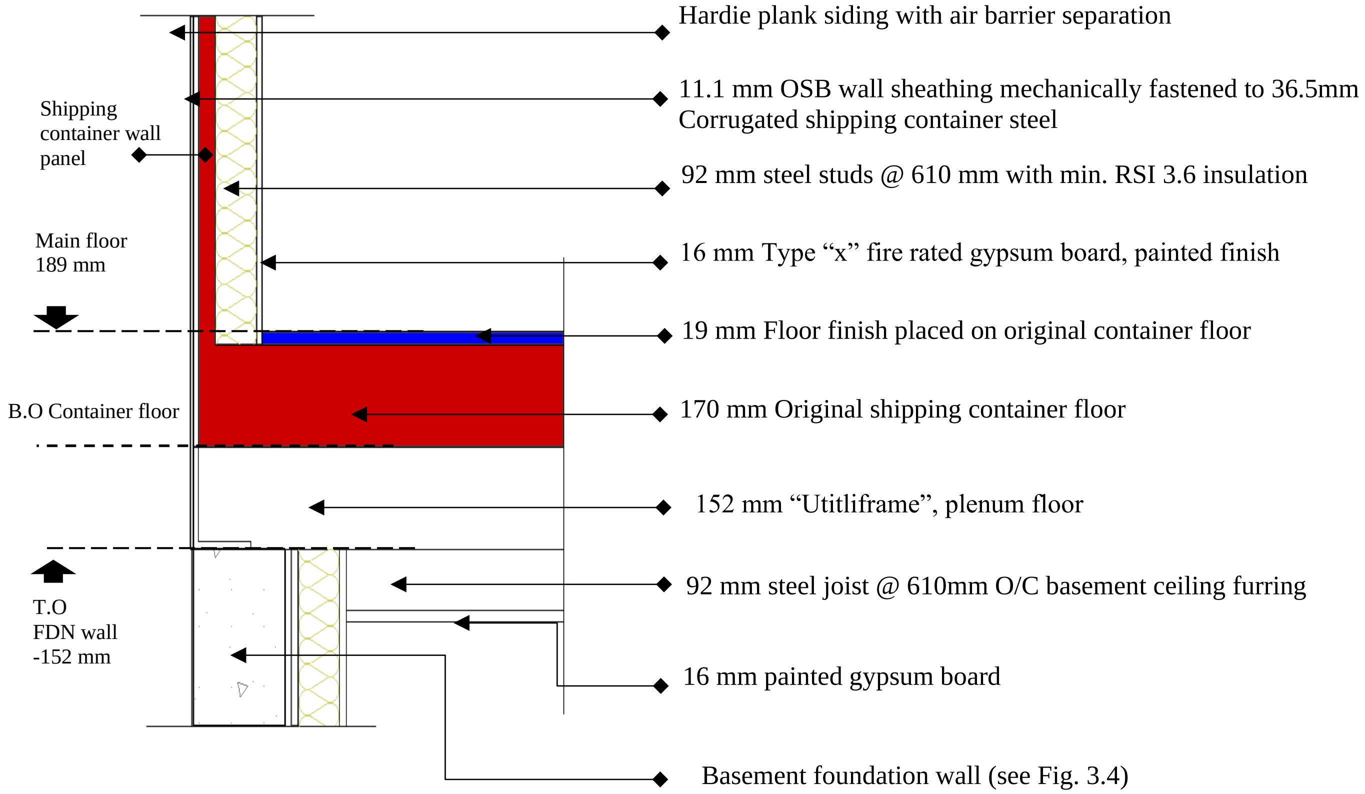


Figure 3.5 D-04 Basement to Main Floor Connection Detailing Wall and Floor
Note: Original shipping container envelope represented in red colouring.

Container Module Connections and Wall Design. The exterior load-bearing walls comprise of original corrugated corten steel side panel in the middle, insulated steel stud finished with a fire-rated gypsum board as interior envelope materials. Oriented strand board (OSB) sheathing and Hardie siding as the exterior finish (Figure 3.5). The OSB sheathing act as a minimal form of insulation and additional rigid layer to improve the thermal boundary of the inner envelope (Ching & Shapiro, 2014). The interior floor to ceiling height of 2.5m is achievable after incorporating envelope re-design and interior finishes. Figure 3.6 illustrates a situation where the two container modules are connected to complete the building envelope (marriage wall).

Air space is provided between the airtight containers. This is important between two heated spaces to allow the circulation of air inside the wall and ventilate humidity through the wall. For this study, the mate connections or marriage wall can either be a permanent welding connection for modules or a joint anchor bolt connection, completed on the building site. For connections with other containers, the temporary anchor bolt connections are fabricated with holes in the lower and upper corners, which can be locked together. Then twist and latch locks are used to fix the containers during the stacking (Shen et al., 2020). The module mate is bolted at the top and bottom steel plates and welded together as a permanent structure if needed. Interior container building walls are designed without the shipping container panel (Figure 3.7). Therefore, the partition walls consist of uninsulated steel studs separated by gypsum boards on both sides of the wall-painted finish. While the spray foam insulation used in the parametric investigation of the improved case acts as a vapour retarder, vapour barriers are also provided at the interior warmer side of the wall (Stephenson, 2011).

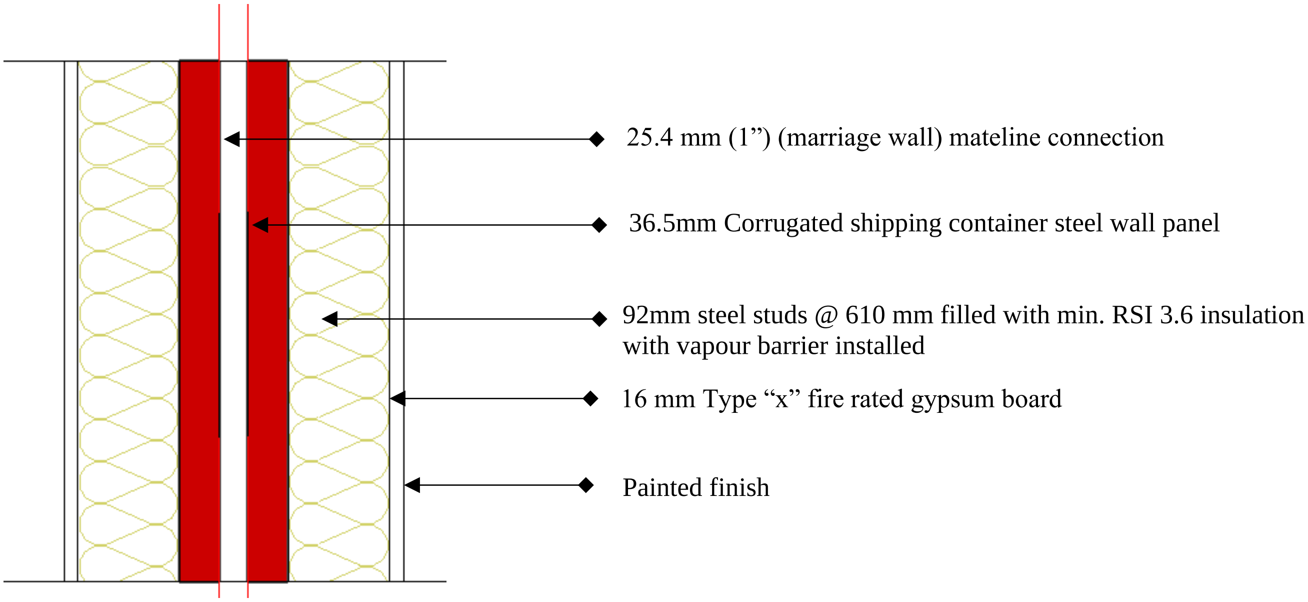


Figure 3.6 D-02 Typical Container Mate Connection (Marriage Wall)

Note: Original shipping container envelope represented in red fills and lines

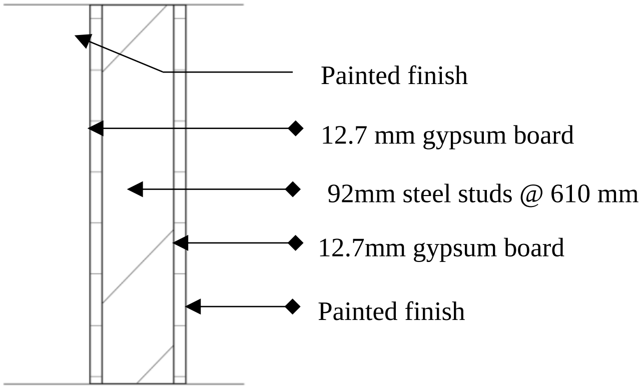


Figure 3.7 D-03 Interior Partition Wall Detail

Container Wall Connection to Typical Roof Assembly. Figure 3.8 presents container building roof section detail. The roof assembly follows a typical design of engineered trusses welded to top and bottom chords. The ceiling of the original shipping container is modified by installing a ceiling joist cladding with a painted gypsum board as the interior envelope finish. The entire roof system is prefabricated at the factory and assembled to the wall envelope on-site. The main structural systems include pre-engineered tilt-up light gauge steel trusses with bracing as per case study manufacturing details (Ladacor design, see Appendix A). To improve energy efficiency, blown-in cellulose insulation is provided. Other roof members are finished following standard roof design requirements in Canada.

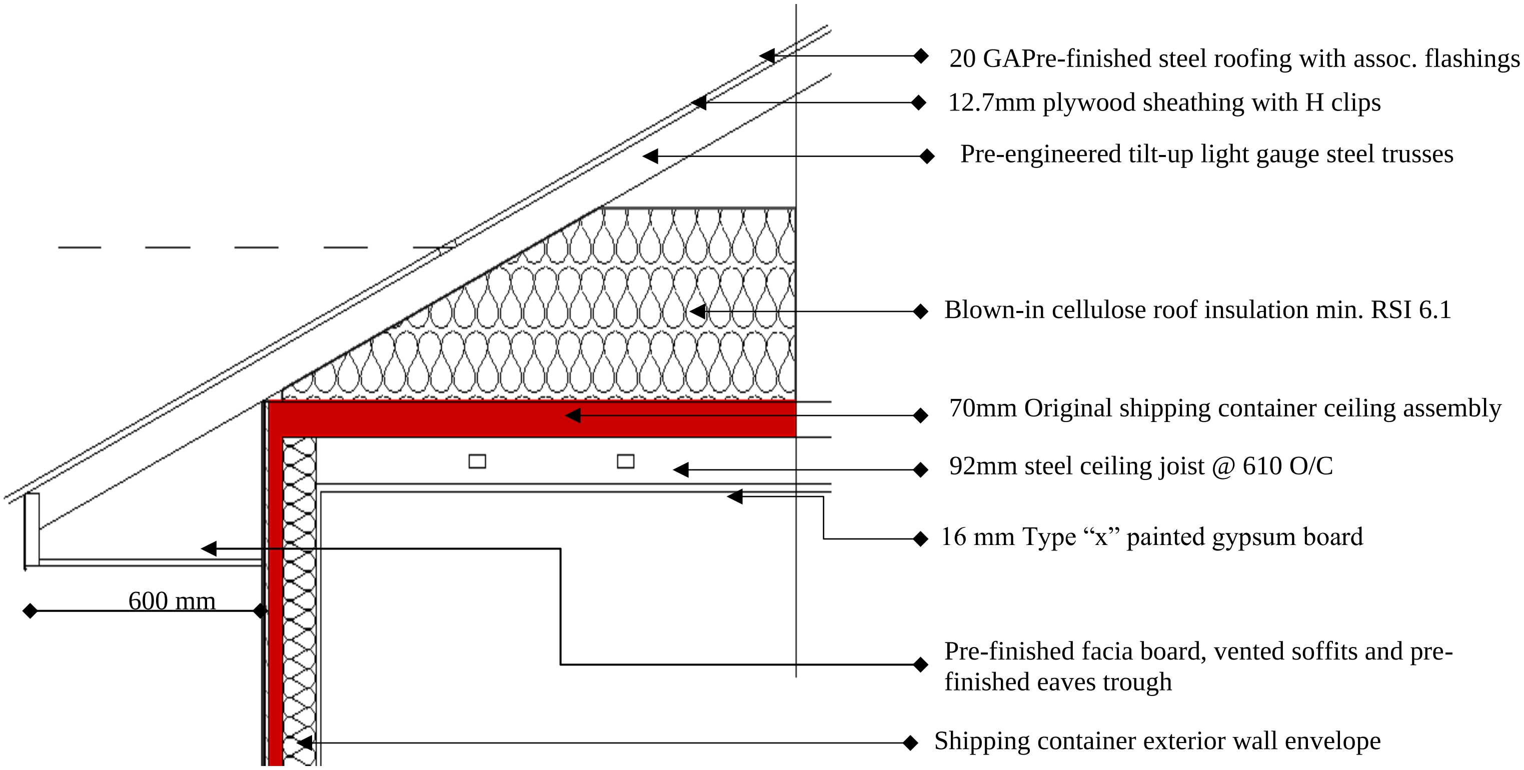


Figure 3.8 D-05 Container Envelope to Building Roof Connection Detailing

Note: Original shipping container envelope represented in red painting

3.1.2 Parametric Investigation and Design Assumptions

Figure 3.9 presents the study flowchart for the energy modeling process. The first stage of research consists of designing the reference model (Code case). The code case assumes building characteristics, specifications, and construction drawing details provided by the company, Ladacor in the case study project (Appendix A). The Ladacor case study is selected to demonstrate existing industry applications, as well as provide a more realistic exploration for container-based detached house energy performance. While assuming the physical design of the industry, the envelope characteristics of the building components, and other building science standard requirements of the code case complies with Alberta Building Code standards (National Research Council Canada, 2014), the National Building Code of Canada as recommended for low-rise housing and small buildings (National Research Council Canada, 2015a), and the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) standard for dwellings (ASHRAE 90.2) (American Society of Heating Refrigerating and Air-conditioning Engineers Inc (ASHRAE), 2007). For example, the window assembly assumes a triple pane, Low-E, argon-filled assembly.

The second phase is the main, involving extensive simulations of various building envelope components to assess their impact on the energy performance of the case study, employing EnergyPlus in conjunction with Google SketchUp Plugin. These include the insulation of opaque area, infiltration rate, window assemblies, thermal mass, window size, solar shading controls, phase change material and building orientation on the overall thermal loads. Parametrically changing and then analyzing the effects of different building designs and constructions eventually determine an improved model. The simulation results are compared to the code reference model. The reference model simulation calculates the heating, cooling, and thermal loads. Potential electricity generation from PV integrated on the roofs is then estimated to determine the potential of achieving net-zero energy status.

The third stage evaluates the effects of the improved envelope parameters on the energy performance of the row housing configurations. The improved model is used to conduct the energy simulation, combining two and four units and analyzing their energy performance.

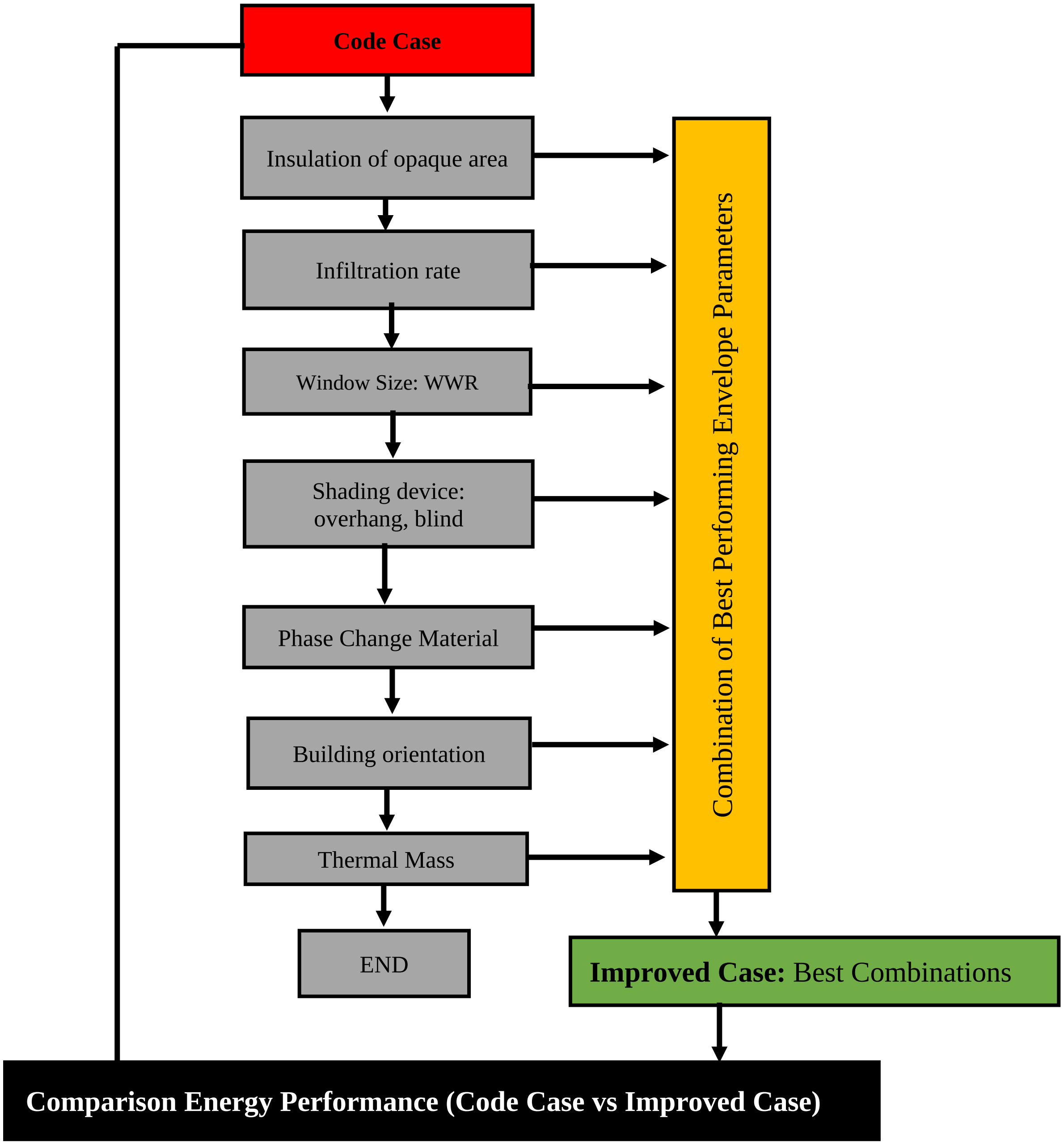


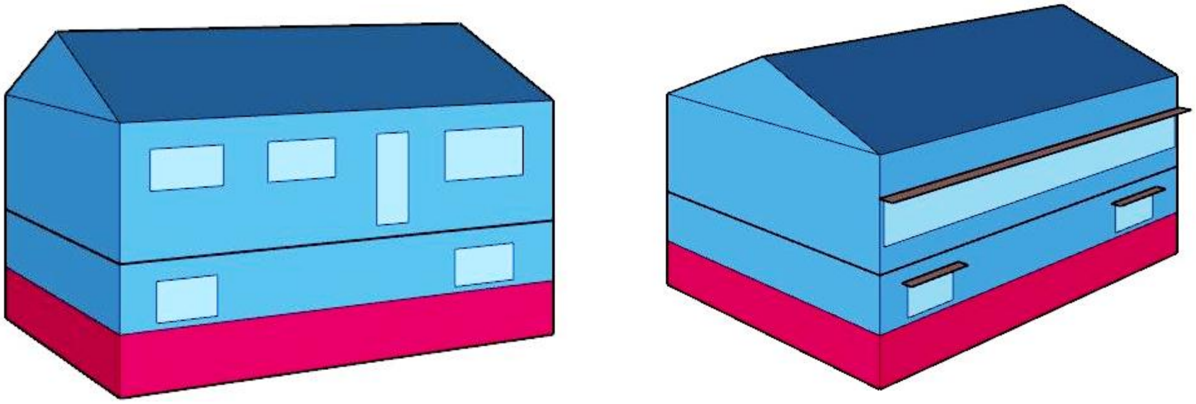
Figure 3.9 Study Flowchart of the Detached House Analysis

Summary of envelope upgrades include:

- **Thermal Insulation.** This study considers an increase of the thermal insulation values for the container walls, roof and floor envelope at subsequent m^2K/W increment. The impact on thermal loads is then analyzed to determine the improved insulation value for the container-based unit. The wall insulation value is increased from a code value of R20 (RSI 3.6) to R31 (RSI 5.46). To meet with passive design specifications, the roof insulation considers increment from RSI 6.1 (R35) to RSI 12.3 (R70). On the other hand, boundary floor insulation is modified from RSI 3.4 to RSI 0 decrement.

- **Air Infiltration Rate.** The air changes per hour (ACH) are modified from 5.0 to 0.4 at induced pressure of ACH50 to monitor the effect on the thermal loads with changes in building airtightness. The study assumes whole building air leakage testing, ACH at 50 Pascals (ACH50), to conform with historical data enclosure based on single-family home testing parameters (Speert & Legge, 2012). However, the author recommends an actual test verifiable through a blower-door test to confirm the actual airtightness of the container-based structures. Air changes per hour at 50 Pascals measurement value represents how many air changes per hour under unusual circumstances (e.g. depressurization at 50 Pascals). The code case assumes 3.0 ACH50 based on the recommendation by the NBC 2019 Alberta edition (National Research Council of Canada, 2019).
- **Window Size.** The study investigates the impact of varying window sizes on the south glazed area (0% - 60%) while maintaining the case study sized-windows on all other facades. The code is designed with 13% window-to-wall ratio (WWR) on the south facade.
- **Solar Shading Controls.** The impact of the overhang projection is considered only for the south window façade by varying the depth from 0.2 m to 1.2 m. Windows on all facades have interior blinds installed. Interior blinds for all glazing are shut at an indoor air temperature of 23.5°C. The base model has no overhang or interior blinds installed.
- **Phase Change Material (PCM).** The use of PCMs in building benefits lightweight structures with low thermal mass by improving the envelope ability to store heat while regulating the indoor temperature (Tabares-Velasco et al., 2012). This study utilizes micro-encapsulated PCM with 30% paraffin wax in the gypsum board, incorporated in the exterior wall and ceiling based on the EnergyPlus database.
- **Building Orientation.** Designing a building with the most efficient orientation can significantly impact natural daylighting, ventilation and reduce the amount of unwanted solar heat gain during the summer months (Hachem et al., 2014a; Tokbolat et al., 2013). The impact of building orientation is analyzed from 0° South to 360° South.

- **Thermal Mass: Concrete Slab.** The study evaluates the impact of concrete thermal mass on container main floor assembly by varying the thickness of the concrete slab from 50mm to 250mm.
- **Improved Case.** After analyzing the above parameters, an improved case presents a model with a combination of best-performing envelope parameters to achieve the most energy-efficient scenario. Comparative analysis of the code and improved case with reduced thermal loads is then established. Figure 3.11 shows the code model and improved case with updated envelope parameters such as 40% WWR on the south façade (main floor) and overhangs. Table 3.1 below contains the list of the different building envelope characteristics employed in the design and simulations.



(a) Code model (b) improved model

Figure 3.10 Illustration of SketchUp Model of the Case Study Detached House

Note: Blue shows conditioned spaces; red represents unconditioned below ground level.

Table 3.1 Reference Cases Building Characteristics

Building Characteristics	**Code Case (Reference)**	**Optimal Case (Improved)**
Total Building Area	238 m^2	238 m^2
Floor Area	119 m^2 per floor	119 m^2 per floor
Building Dimensions	Length x Width x Height (12.2 m x 9.75 m x 2.9 m)	Length x Width x Height (12.2 m x 9.75 m x 2.9 m)
Building Envelope: Container Floor (m^2K/W)	Container Wall: RSI 4.0 Roof: RSI 6.56 Boundary Floor: RSI 3.88	Container Wall: RSI 5.3 Roof: RSI 10.97 Boundary Floor: RSI 1.0 (without insulation)
Building Envelope: Basement Floor RSI (m^2K/W)	Basement Wall: RSI 4.75 Basement Floor: RSI 3.54	Basement Wall: RSI 4.75 Basement Floor: RSI 3.54
Door	RSI 2.62	RSI 2.62

Window Assembly	Low-e, triple-paned glazing, argon filled, high SHGC	Low-e, triple-paned glazing, argon filled, high SHGC
Air infiltration rate	3.0 ACH50	0.6 ACH50
Above Ground Window-Wall Ratio [%]	Total Façade Glazing: 6.4%	Total Façade Glazing: 10%
	South Façade: 13%	South Façade: 40%
	East Façade: 4.4%	East Façade: 4.4%
	West Façade: 0%	West Façade: 0%
	North Façade: 7.5%	North Façade: 7.5%
Envelope improvements	NA	See the summary of the building envelope improvements in results discussion below

Row Housing Configurations. In addition to the single-detached housing unit, the study includes evaluating two and four-unit houses. Figure 3.11 illustrates the 2-unit and 4 -unit row houses. The row housing study uses the improved model to determine how container units would perform when considered as multiple units.

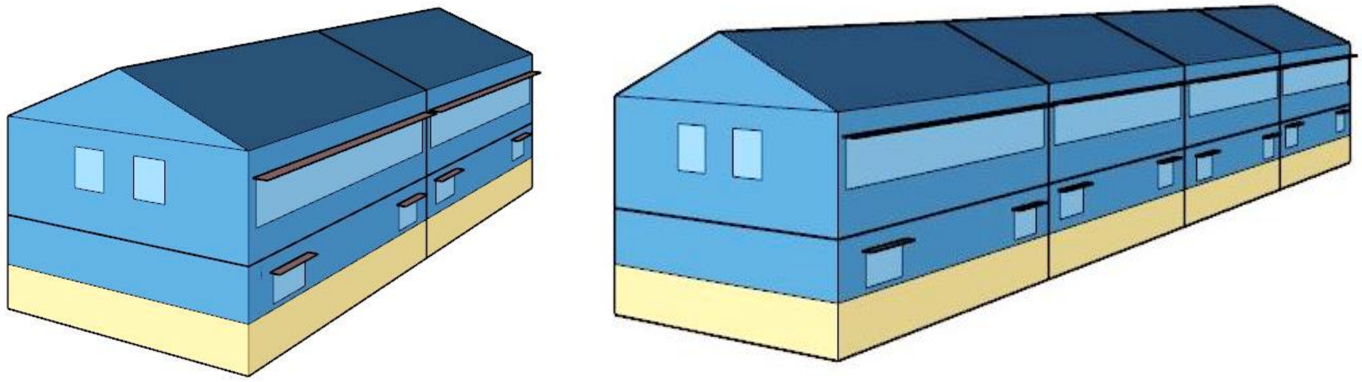

(a) 2-unit model (b) 4-unit model

Figure 3.11 Two and Four-unit Row Houses

Note: Blue shows conditioned spaces; yellow represents unconditioned below ground level.

Input Data and Assumptions. EnergyPlus (version 8.7), which allows combining whole building modeling with advanced dynamic energy simulation, is used in this study. Table 3.2 details the general input data applied during the energy simulation. As discussed in Chapter 2 methodology, two thermal zones are created for the basement and main floors. In modeling the zone infiltration design flow rate, the parameters are converted to air changes at the natural pressure of 4 pascals ACHNAT (under usual circumstances) from the assumed induced pressure of 50 pascals (ACH50). The study uses an established method of conversion of dividing ACH50 by 20 (Sherman, 1998). This is important as modeling air infiltration using the EnergyPlus software requires that the airflow parameters be presented as ACH natural values (Gowri et al., 2009; Speert & Legge, 2012). For example, 0.6 ACH50 will be modelled as 0.03 ACHNat in EnergyPlus. This conversion is made for all parameters studied under airtightness performance targets. Actual infiltration occurs at natural pressure difference that is closer to around 4 Pascals (ACH Nat. Equiv. ACH4), and EnergyPlus assumes the typical design conditions during the modeling process.

Improving airtightness in buildings and overall envelope design increases the need to provide fresh air into homes via mechanical or natural ventilation. Therefore, the study introduces a mechanical ventilation system to subsidize the required outdoor air and maintain healthy indoor air quality (National Research Council Canada, 2014). Whole-house forced ventilation is highly recommended when the air infiltration rate of the dwelling unit is less than 5 ACH when tested with a blower door at a pressure of 50 Pascals (Building Energy Codes, 2011). For this reason, a mechanical ventilation flow rate of 0.35 ACH is designed to comply with ASHRAE Standard 62.2 ventilation and acceptable indoor air quality in low rise residential buildings procedure (American Society of Heating Refrigerating and Air-conditioning Engineers Inc (ASHRAE), 2010; International Code Council Inc, 2009; Mudarri, 2010). However, the code case assumes whole building mechanical ventilation of 0.5 air change per hour as mechanically cooled space during the non-heating season based on Section 9.32. Ventilation, Part 9 – NBC 2019 Alberta Building Code (Housing and Small Buildings) (National Research Council of Canada, 2019). Mechanical ventilation is provided as an active process to remove exhaust indoor air or to supply fresh outdoor air at a given rate.

In addition to the building envelope characteristics discussed above, the modeling makes a few assumptions in EnergyPlus. Lighting, people and equipment schedules are set to suit weekly and daily activities. The interior lighting power density is calculated as 5.0 W/m2 high-efficiency LEDs for dwelling units provided by the National Energy Code of Canada for Buildings (National Research Council Canada, 2015b).

Table 3.2 EnergyPlus Input Data File (IDF) Assumptions

Energy Plus Input Data	
Design Parameters	**Selected Input**
Solar Radiation	Full interior and exterior
Weather Data	EnergyPlus Weather Data for Calgary Latitude: 51.12; Longitude -114.02
Simulation Run Period	1st January to 31st December
HVAC System	Ideal Loads
Thermostat Settings	Cooling Setpoint: 24.5 °C; Heating Setpoint: 20 °C
Thermal Zones: Two	Container and Basement Zones
Occupants	3.0 Persons. On weekday work schedule
Thermal zone lighting	LED lamps. 5.0 W/m2
Domestic Hot Water	1817 kWh/year (Sartori et al., 2010)
Electrical Loads	7961 kWh/year for necessary appliances and equipment.

Electricity Generation: Roof Integrated Photovoltaic (PV) Systems. This study determines the potential energy generation of the detached house and row housing units by assuming integrated photovoltaic (PV) systems on the south roof area of the building. A total of 3 scenarios are considered by changing the angle of inclination of the gable roof. First, the original base model roof angle of 22.5°, next inclination of 30° and 45°. The study generally adopts a gable roof design with a ridge in the roof's center, inclining south and north. In modeling the PV systems in EnergyPlus, the installed photovoltaic system is designed as decoupled from the building surface area (roof envelope). The assumption is made that PV installed on the building surface does not transfer heat to the exterior building surface and vice versa. Minimal heat transfer impact between envelopes is also expected as an improved model presents an upgraded envelope. Other assumptions during the PV simulation analysis in EnergyPlus include fixed PV cells module at 18% efficiency (Canadian Solar Inc, 2019) and 90% inverter efficiency (Kapsis & Athienitis, 2015).

3.2 Presentation and Analysis of Results

This section presents an analysis of the simulation results of the above-discussed building envelope configurations. The results focus on the effects of various design parameters on the heating and cooling loads and total thermal loads. Comparative analysis results present the annual energy consumption and electricity generation of selected scenarios for the single-detached and row houses configurations. The annual energy consumption comprises lighting, domestic hot water and equipment and thermal energy (i.e, heating and cooling) of studied scenarios.

3.2.1 Effects of Envelope Improvements on Detached House

The rest of the section compares the impact of various envelope parameters on the code case model. Results are presented for whole building heating, cooling and thermal loads. Overall, results demonstrate that heating loads mostly dominate the building thermal loads.

Impact of Thermal Insulation. The improved insulation model reports on the impact of a combination of changing insulation values of the container wall, roof, and floor. Using the code case as a benchmark, the improved insulation case yields an approximately 11% reduction in building thermal loads (see Figure 3.12). Key highlights of result comparison to Code case model include:

- Increasing the container wall insulation value from RSI 3.6 (R20) to RSI 4.8 (R27)
- Increasing the building roof insulation from RSI 6.1 (R35) to RSI 10.56 (R60)
- The building performs more efficiently with the removal of insulation between the boundary floor, thereby allowing for heat exchange and flow between the basement and main floor.

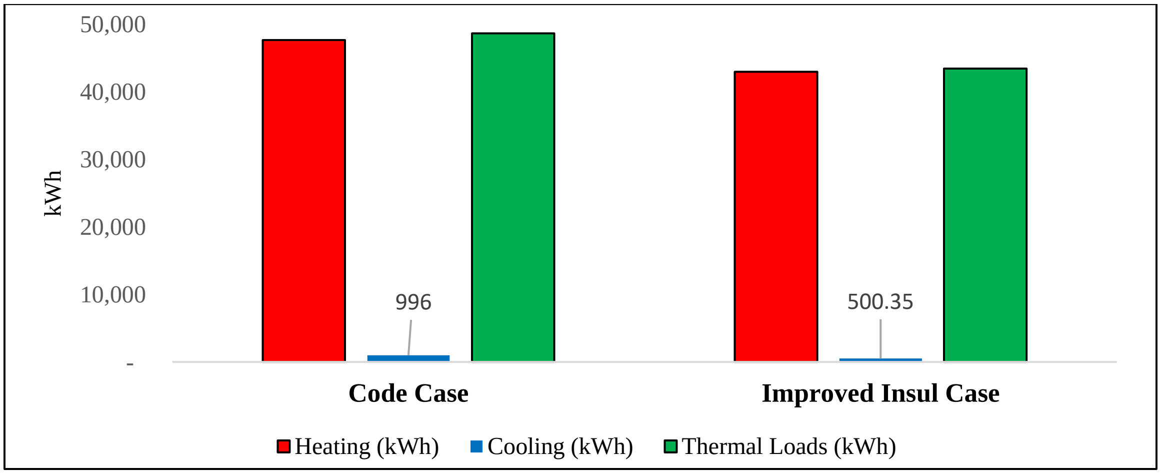


Figure 3.12 Comparison between Code Case and Improved Insulation Case

Impact of Air Infiltration Control. Figure 3.13 presents the impact of improving air changes per hour (ACH) on building thermal loads. Using a tighter building envelope target 0.6 ACH50 (0.03 ACH Nat.) reduced the total thermal loads by 38% compared to the code case. While the heating loads of the improved airtightness performance at 50 Pascals (0.6 air changes per hour) result in approximately 40% reduction than the code, the cooling loads increased by 33% from the original base value for the same reason. Overall, the heating loads have a more significant impact on the container building thermal performance than the cooling loads. A 0.6 ACH50 is assumed as the improved parameter for the comparative study.

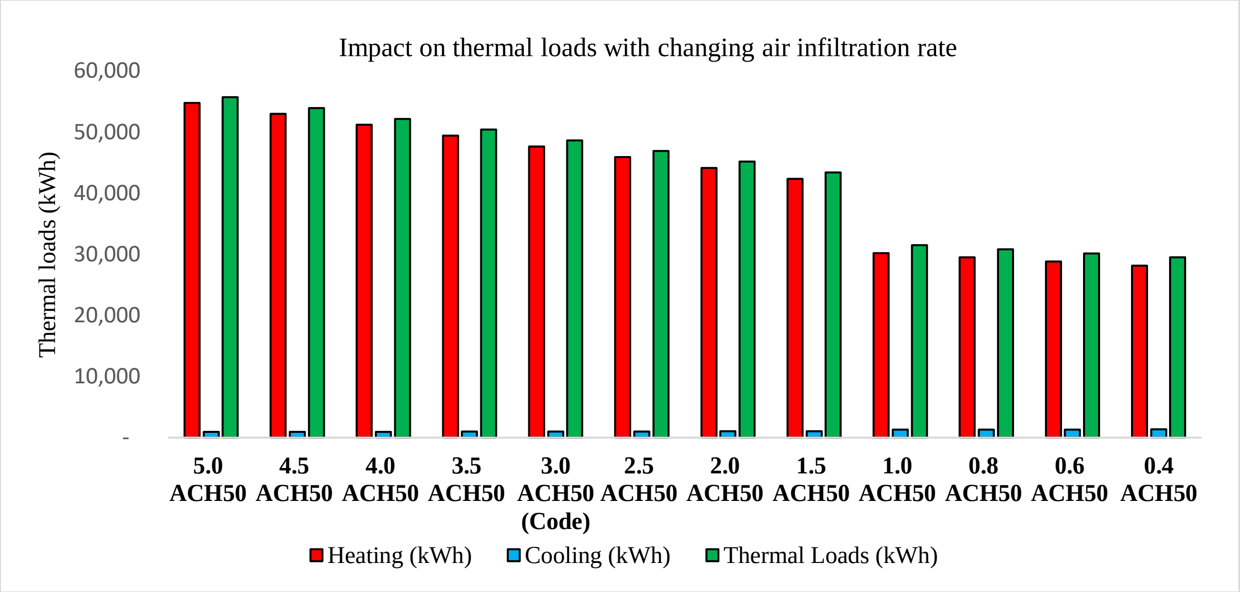


Figure 3.13 Impact of Changing Air Infiltration Rate on Thermal Load

Impact of Window Size. The models adopt Ladacor-sized windows on all facades except for the south. The window-to-wall ratio (WWR) ranges from 0% to 60% of the south façade. The simulation results show a slight improvement in heating load with 40% WWR on the south facade (see Figure 3.14). Increasing the window size results in twice an increase in cooling load from the code case. However, less than 1% increase in thermal load is observed by introducing 40% window-wall ratio on the south façade compared to the code model. It is expected that incorporating solar shading controls will further reduce the cooling load. The 40% WWR assumes the improved parameter for the window size simulations as it presents moderate combined heating and cooling loads.

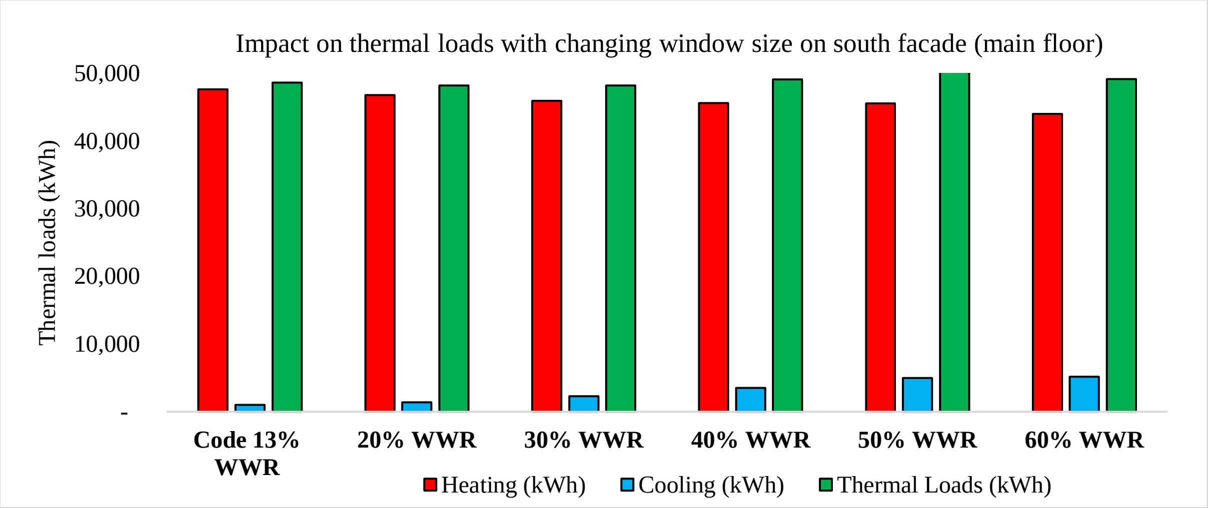


Figure 3.14 Impact of Changing Window Size on the South Façade

Impact of Solar Shading Controls. The study considers the use of high-reflectance interior blinds for all glazing. This is to understand the effect of adding blinds to all façade interiors as solar shading control. The simulations design for shading devices also introduced overhangs on the south façade windows. As expected, the results prove that the integration of shading devices reduces cooling loads by 30% and 41% for the 0.4 m and 1.2 m lengths overhang scenarios. As illustrated in Figure 3.15, between 0.2 – 0.4 m overhang shows the best performance in combined heating and cooling loads; thus, the study adopts the 0.4 m (i.e., 40% overhang) parameter for further parametric analysis improved envelope parameter.

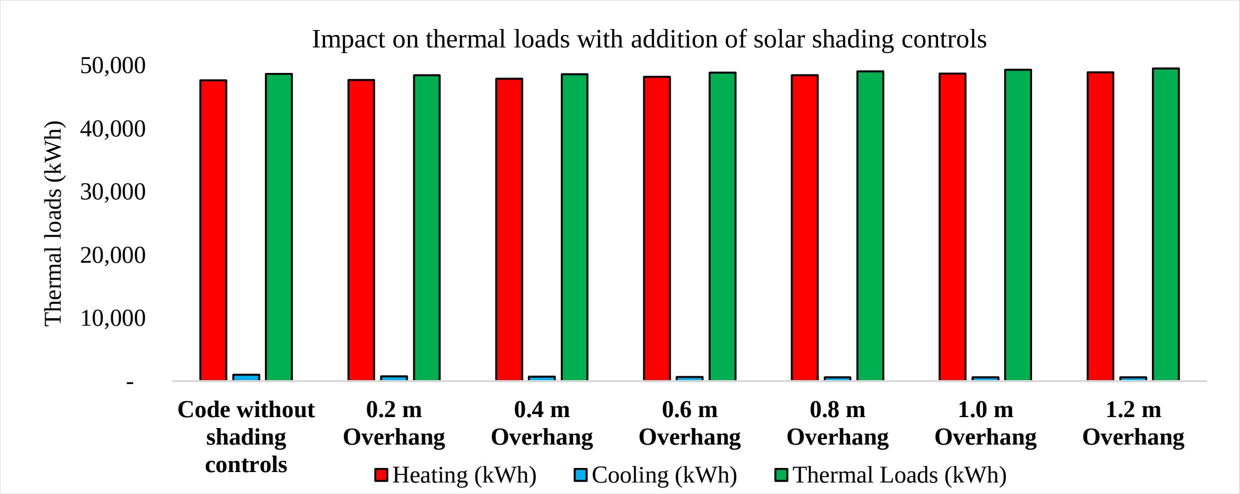


Figure 3.15 Combined Solar Shading Controls (Overhang on South Façade and Interior Blinds on all Façades)

Impact of Phase Change Material. The addition of Phase Change Material (PCM) in all exterior walls (basement and container) and container envelope ceiling reduces cooling load by 51% compared to the code model as shown in Figure 3.16. With the addition of PCM in only the container envelope construction, the simulation results show no significant reduction in total building thermal load.

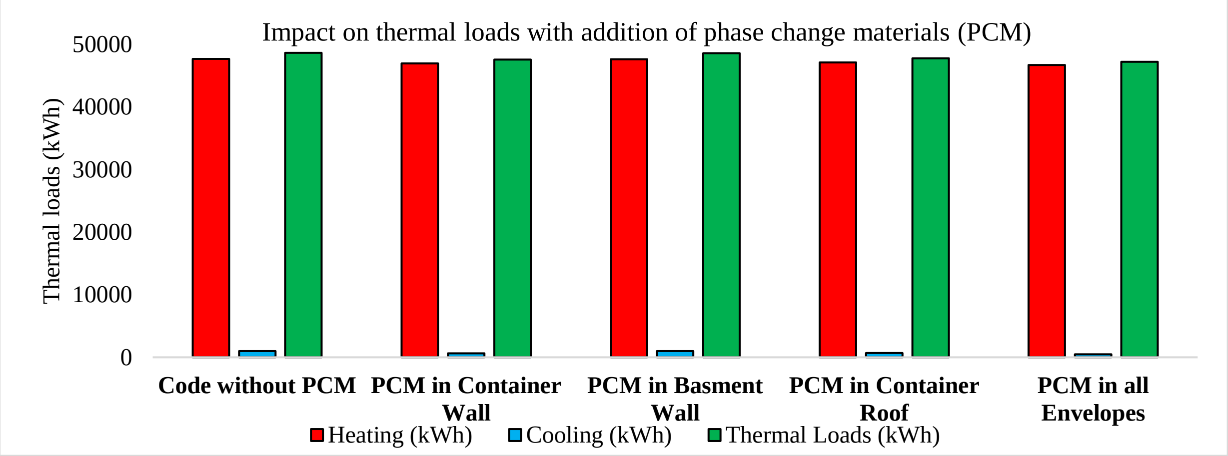


Figure 3.16 Impact of PCM on Container Envelope and all Envelopes

Effect of Building Orientation. The impact of building orientation on thermal loads is evaluated for eight different rotations (see Figure 3.17 below). The simulation results show that building orientation can affect the thermal performance of the building. The code model adopts the full south (0° South) orientation, which offers the most energy-efficient option with the lowest building thermal loads. Therefore, this study considers the south-facing (0° South) the best performing and improved parameter.

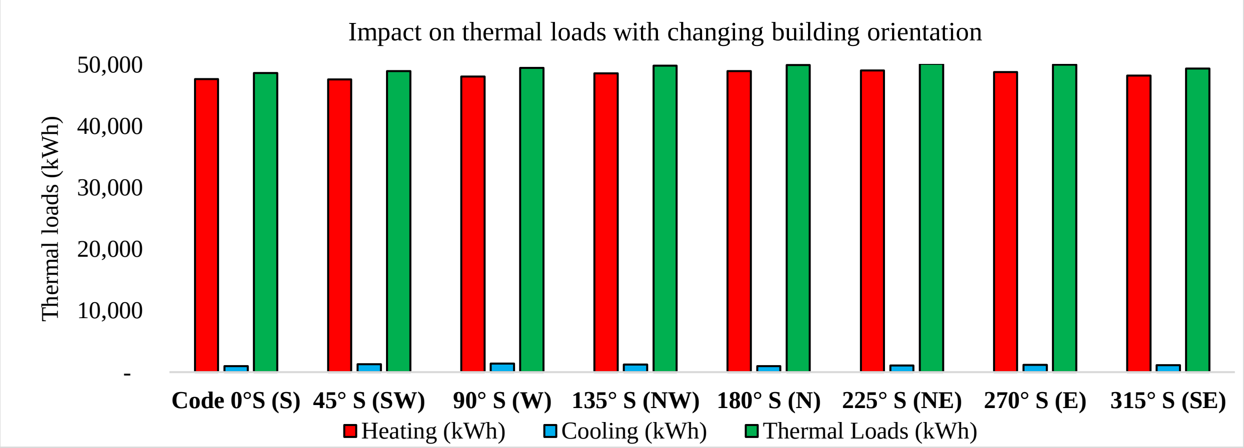


Figure 3.17 Impact of Building Orientation on Thermal Loads

Impact of Thermal Mass. The effect of adding thermal mass (concrete slab) to the container-boundary floor shows the possibility of reducing building cooling load (Figure 3.18). The impact is not significantly affected by the larger thickness of the concrete slab (e.g. < 2% difference with 150mm slab). This could be as a result of reduced glazing (13% WWR) for the code model. A combination of 100mm concrete floor mass with increased WWR (40%) suggests a reduction in cooling loads (see Figure 3.19).

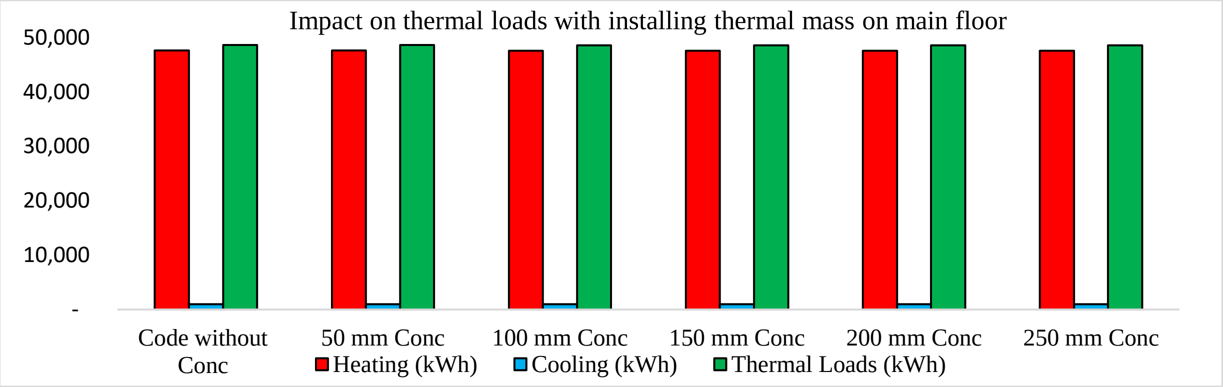


Figure 3.18 Impact on Thermal Loads with the Introduction of Thermal Mass

3.2.2 Comparison of Energy Performance of Detached House: Code Case and Improved Case

Comparison of Thermal Loads. Table 3.1 presents the results of the combined envelope upgrade for the improved model. Comparative results (Figure 3.19) show approximately 52% reduction in heating load, 33% decrease in cooling load and 52% decrease in combined thermal loads for the improved case than the base model. The Improved case parameters are selected from the results of the parametric investigations of various envelope improvements discussed above, combining configurations of best-performing parameters.

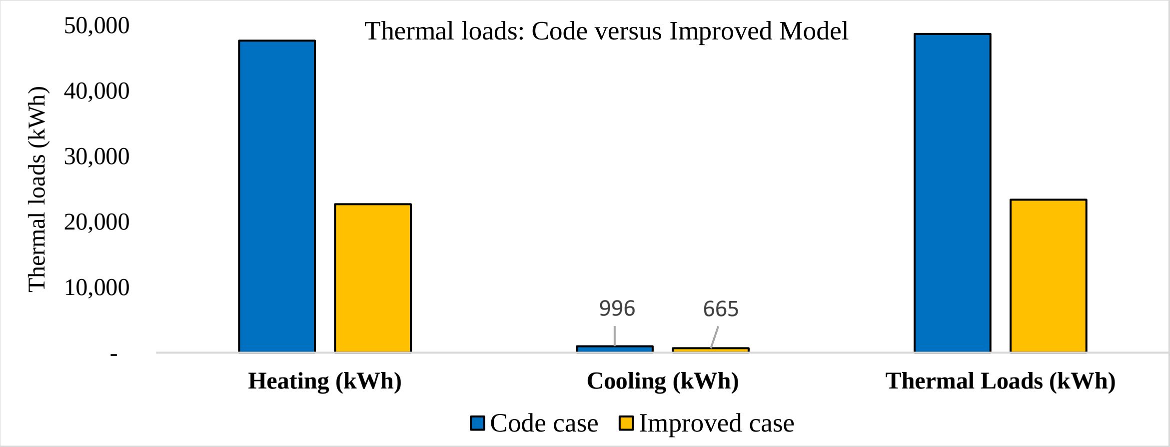


Figure 3.19 Comparison of Thermal Loads for Improved Envelope Design

Results of Annual Energy Consumption. Total energy consumption for heating, cooling, lighting, domestic hot water and equipment values utilized in the study is then computed. The study assumes an air-source heat pump average of 3.3 (COP) to determine the heating and cooling energy for increased energy efficiency (Safa et al., 2015). Computing the thermal energy, an air-source heat pump average of 3.3 (COP) is assumed for increased energy efficiency, then a total of 7,070 kWh for the improved case is attained. Overall, comparing results of annual energy consumption show that the improved case can reduce its building operational energy use by 31% than the code case (Figure 3.20).

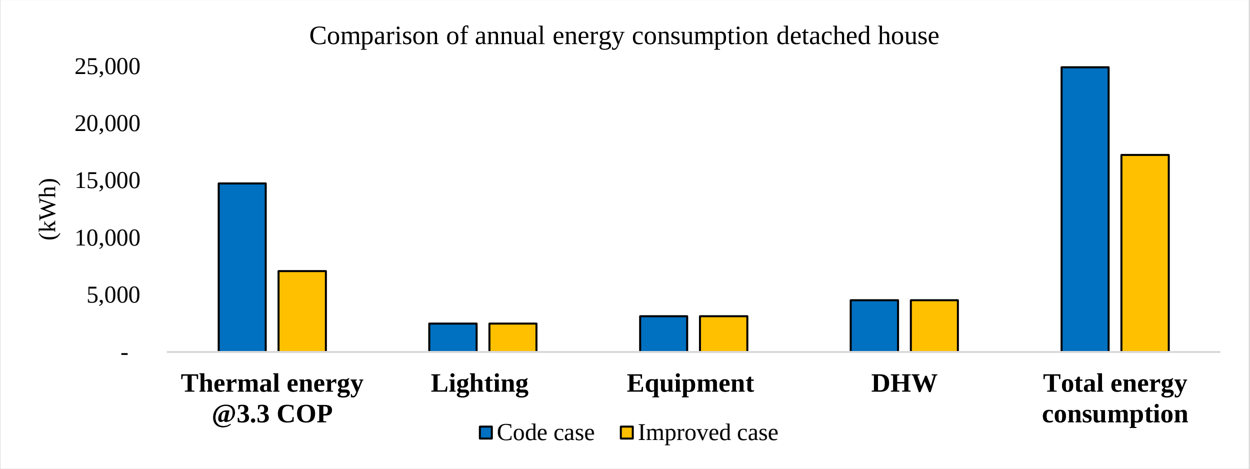


Figure 3.20 Comparison of Annual Energy Consumption

Results of Energy Performance and Net-Zero Energy Status. Figure 3.21 shows the impact of all envelope parameters on the overall energy performance. The energy performance presents a balance between annual energy consumption and electricity generation from PV integrated on the gable roof (south-facing area). The design considers no PV system for the code case. It assumes that PV integration on the total south-facing surface of the gable roof for the code and improved model adopting the roof's original inclination (i.e., 22.5°). Results show that the improved case can reduce its building operational energy use by over 95% through on-site electricity generation using the original gable roof design of the case study.

The net-energy consumption, after the electricity subsidy, shows a net-positive status for the improved model with modified roof angles 30° and 45° of the detached house. In other words, the integrated photovoltaic system can generate enough electricity to satisfy the building's energy demands for heating, cooling, lighting, electrical appliances, and domestic hot water system per year. This model produces from on-site renewables as much energy as it consumes in a year. A surplus or net-energy consumption of (- 3,582 kWh) of electricity per annum is obtainable with the container-based design with improved envelope parameters and higher energy efficiency considerations as shown in the discussion above. This surplus can offset up to 14% of the operational energy for the code case.

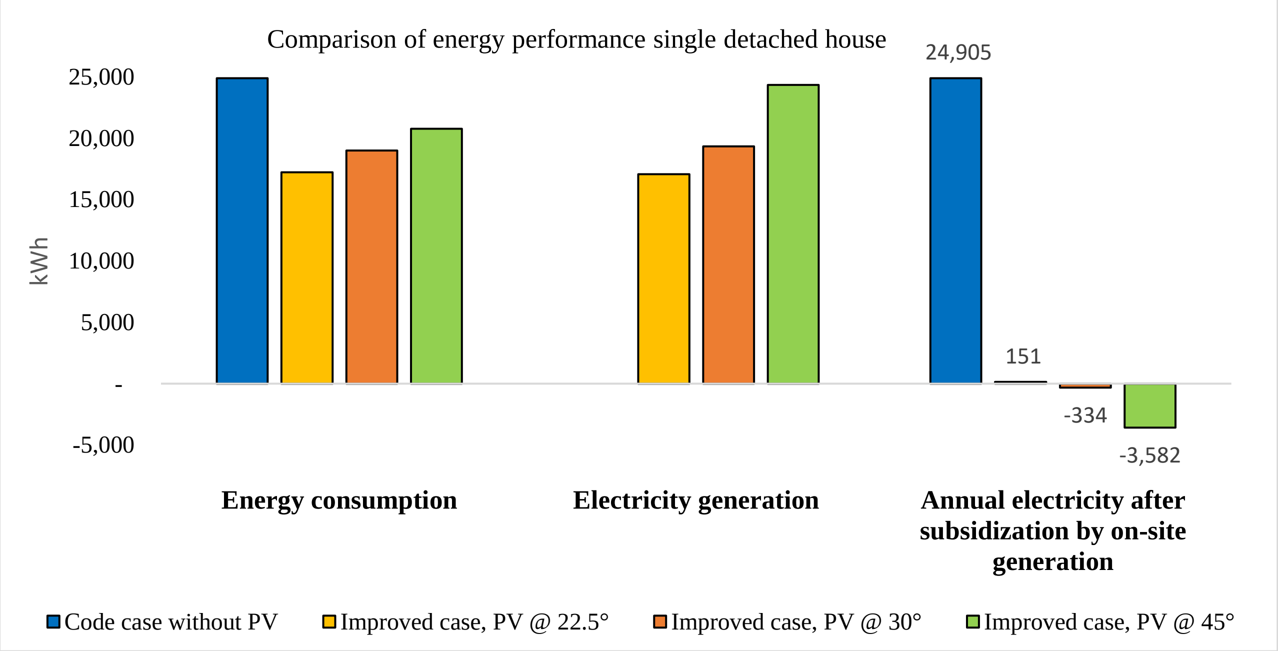


Figure 3.21 Comparison of Energy Performance for Detached House

3.2.3 Energy Performance of Row Housing Design

Thermal Loads. For heating loads, the row configuration of the 2-unit and 4-unit model reduces heating loads by 10% and 17% per unit average respectively compared to a single improved model. Average thermal loads per unit model decrease with increasing configurations, up to 15% for the 4-unit model. For example, individual units reduce thermal demands from 23,330 kWh per unit for the single-detached house to approximately 21,152 kWh and 19,947 kWh per unit for the two and 4-unit row housing, respectively (Figure 3.22). These average values are determined as the ratio of the total loads to the total number of units.

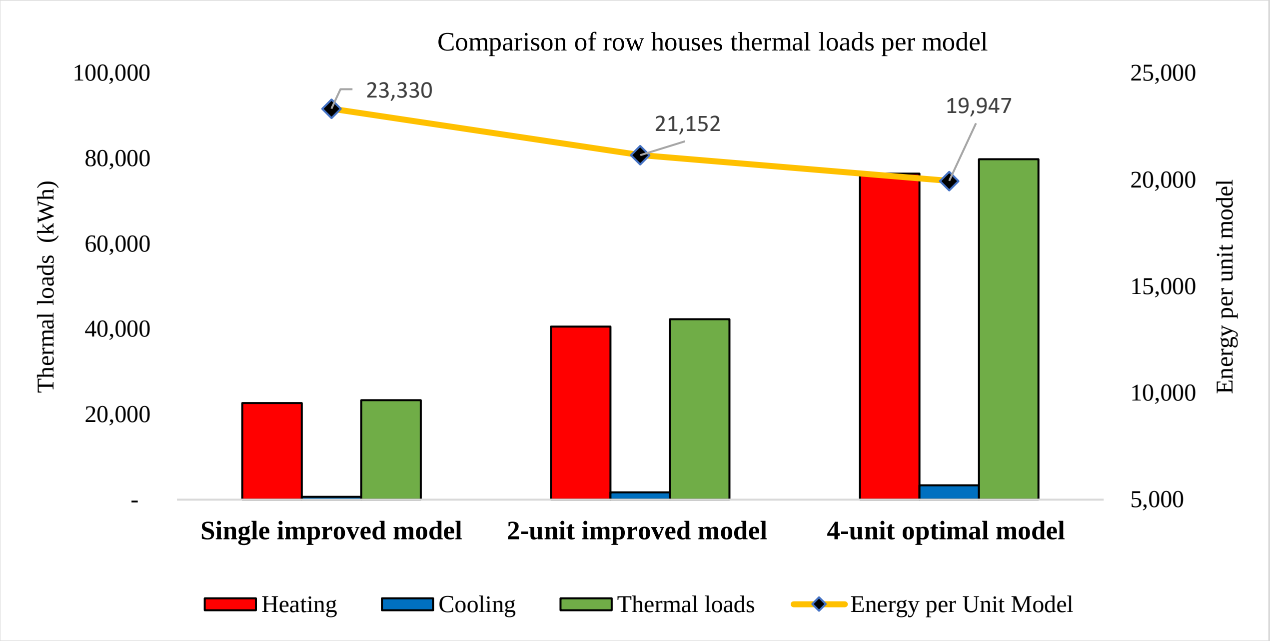


Figure 3.22 Comparison of Row Housing Design

Total Energy Consumption. Results on annual energy for lighting, electrical appliances, domestic hot water systems, heating and cooling demands. (Figure 3.23), show a slight increase in thermal energy with changing the angle of inclination of the gable roof from 22.5° original design to 45° maximum roof. Similar results are observed for all studied configurations. This is expected as increasing roof pitch creates an extra attic area for the inner envelope thermal boundary. In addition, the blown-in cellulose roof insulation R-value is not altered for all scenarios. Therefore, increasing surface area that leads to heat gain without increasing insulation level (R-value) for the higher roof pitch results in a slight increase in thermal loads. A recent study also suggests that increasing the roof pitch for both sealed and vented attic results in increased heating loads (Wang & Shen, 2012). The row housing suggests about 15% variation in total energy consumption per model. Therefore, the importance of adjacent units to reduce overall operational energy consumption and conserve more energy between units.

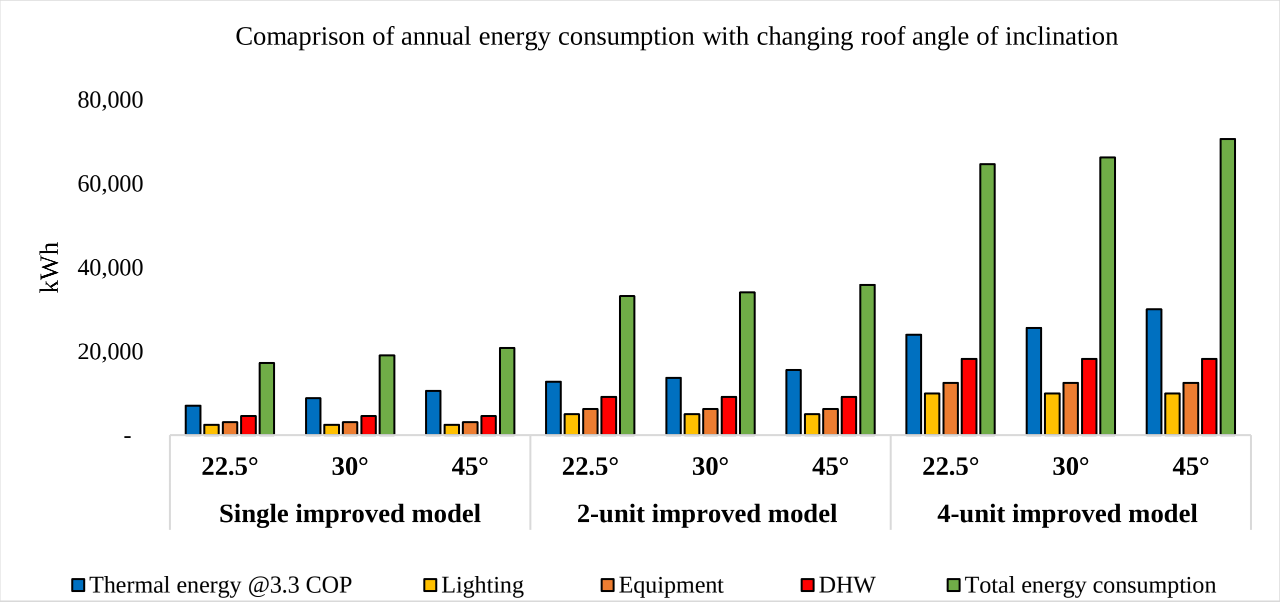


Figure 3.23 Impact of Roof Design on Energy Consumption of Row Housing Units

Results of Energy Performance and Net-Zero Energy Status. Figure 3.24 reports the effects of integrating photovoltaics on the row housing models. Similar to the improved detached model, the roof design assumes a gable with a ridge in the center of the roof, inclination towards south and north. The original model is designed with a south-facing gable roof inclined at 22.5°. The simulations for improved gable roofs with 30° and 45° angle of inclination show a significant increase in electricity generation for two and four units (Figure 3.24). However, the 45° angle of inclination generates approximately 26% more electricity than the 30° for the row housing. The simulation results show that roof design with a higher pitch (45°) can generate the most electricity for single-detached house and row housing units. The best-performing case is determined to be the four units with 45° tilt angle designed with an improved envelope.

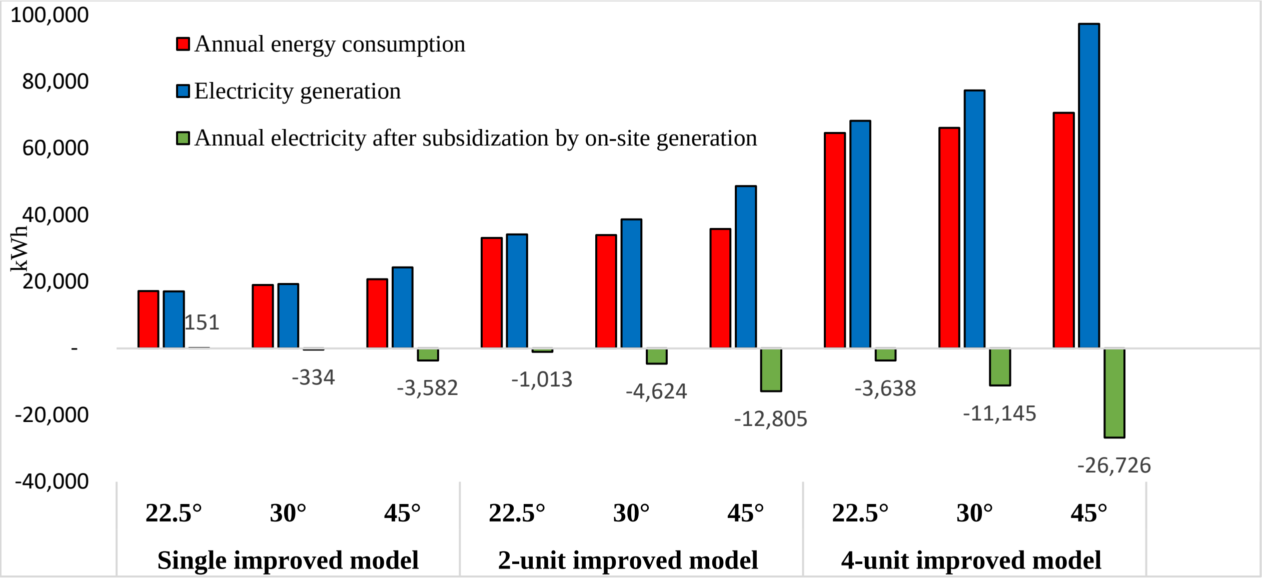


Figure 3.24 Effect on Energy Consumption by Integrated Photovoltaics on Row Configuration

Energy Consumption versus Energy Generation Potential. Results on balancing energy performance (Figure 3.25) show that while increasing the roof angle of inclination slightly increased the annual energy consumption for the scenario studied, it led to surplus energy generation for the row houses with 30° and 45°. For instance, an additional generation of approximately 13% and 43% is observed compared to the original scenario of 22.5°, with 45° having the highest efficiency. This is understandable considering the roof areas available on the south roof.

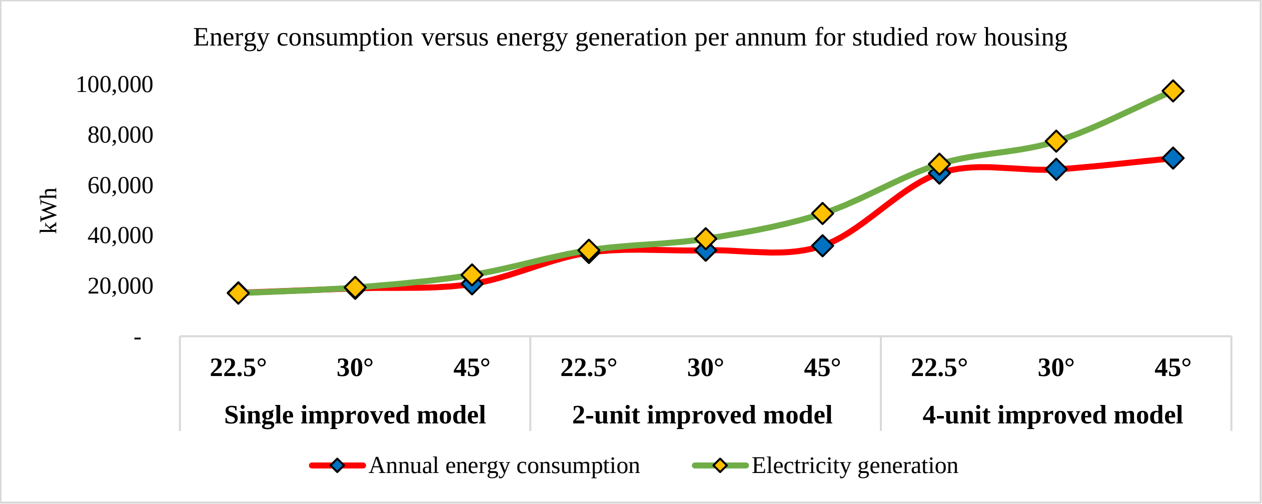


Figure 3.25 Energy Consumption versus Electricity Generation

3.2.4 Concluding Remarks

Container-based modular housing building market is gradually growing both in North America and globally. It is important, therefore, to understand the thermal performance of container-based housing, particularly for cold climate regions. Various design parameters are investigated in this chapter to determine design strategies that increase the energy performance for detached and row housing units. These parameters are systematically improved, and their effect on the energy performance compared to the code base model. The study methodology can be adopted as guidelines for the design of low-energy modular homes.

This study establishes that incorporating passive solar principles, for example, increasing thermal insulation can improve the energy performance of container-based housing. Most parameters studied reduced the heating loads while a few parameters such as incorporating concrete floor mass and solar shading devices reduced the cooling loads. Achieving a net-zero energy status is attainable for both detached and row housing by integrating photovoltaics on the south-facing roof. While designing with a high pitch roof (45°) suggests a significant increase in electricity generation up to 45%, designers should consider the challenges of height constraints during module transportation for on-site assembling. That said, 30° roof angle appears to offer a balance in the energy performance (energy consumption versus energy generation).

With every steel framing including container-based structures, there is a need to create a strong thermal boundary to ensure the constructed building attains the modeled energy performance. Advanced framing, insulating joints against air leakage, and choice of insulating material (spray foam) are deployed in this study to reduce thermal bridging effects predominate in steel structures. Ching & Shapiro (2014) suggest the introduction of rigid surfaces on both sides of insulation to further protect against heat loss (e.g. rigid insulation board to exterior cladding).

This study opens future research investigation on thermal bridging analysis for container-based envelopes. Developing construction details and methods to eliminate thermal bridges is of prime importance to achieve a high-performance level such as assumed in this thesis. For instance, investigating possible solutions of designing container panels as the only structural element (without steel studs), and continuous insulation (i.e., insulating exterior panels between cladding and container structure) can assist in reducing heat loss through thermal bridging in steel container design. Chapter 4 discusses the multi-storey application of container-based units.

Chapter 4 Impact of Geometric Design on Energy Performance of Container-Based Layouts and Multistoreys

Chapter 4 presents a detailed investigation of modular geometric patterns for multistorey and layout designs. Assuming a uniform trend, the study investigates the effect of vertical and horizontal modular expansion on energy performance (i.e. the balance between electricity generation from integrated photovoltaics and total energy consumption). Given the limited study on energy-efficient multi-unit complexes designed with shipping container structures, this chapter presents potentials for the design of low-energy MURBs using such structures.

1. Dara, C., & Hachem-Vermette, C., (2020). **Impact of geometric design on the energy performance of multi-unit modular buildings**. *Manuscript under preparation.*

4.1 Design of Container-based Multi-unit Envelope and Assumptions

This chapter highlights geometric design patterns for modular container-based MURBs. Figure 1 presents the study flowchart. It investigates the impact of varying geometric parameters on the building energy performance of studied layouts and multistorey buildings by exploring vertical and horizontal modular expansions adopting a 2-bedroom apartment as the prototype model. The first step focuses on horizontal modular expansion by modifying the building geometry into shapes to create different layouts. The floor plan design of the proposed layouts considers 8-unit apartments. The second step investigates the effects of combined vertical and horizontal modular reconfigurations into multistorey scenarios. The multistorey designs employ 24 self-sufficient modular units to create a maximum of 6-storey apartments by varying floor levels, building heights and aspect ratio per model. Overall, an equal number of apartments per building is maintained. The 5-storey design is excluded from this analysis as it doesn’t provide even distribution of apartments across multiple floor levels.

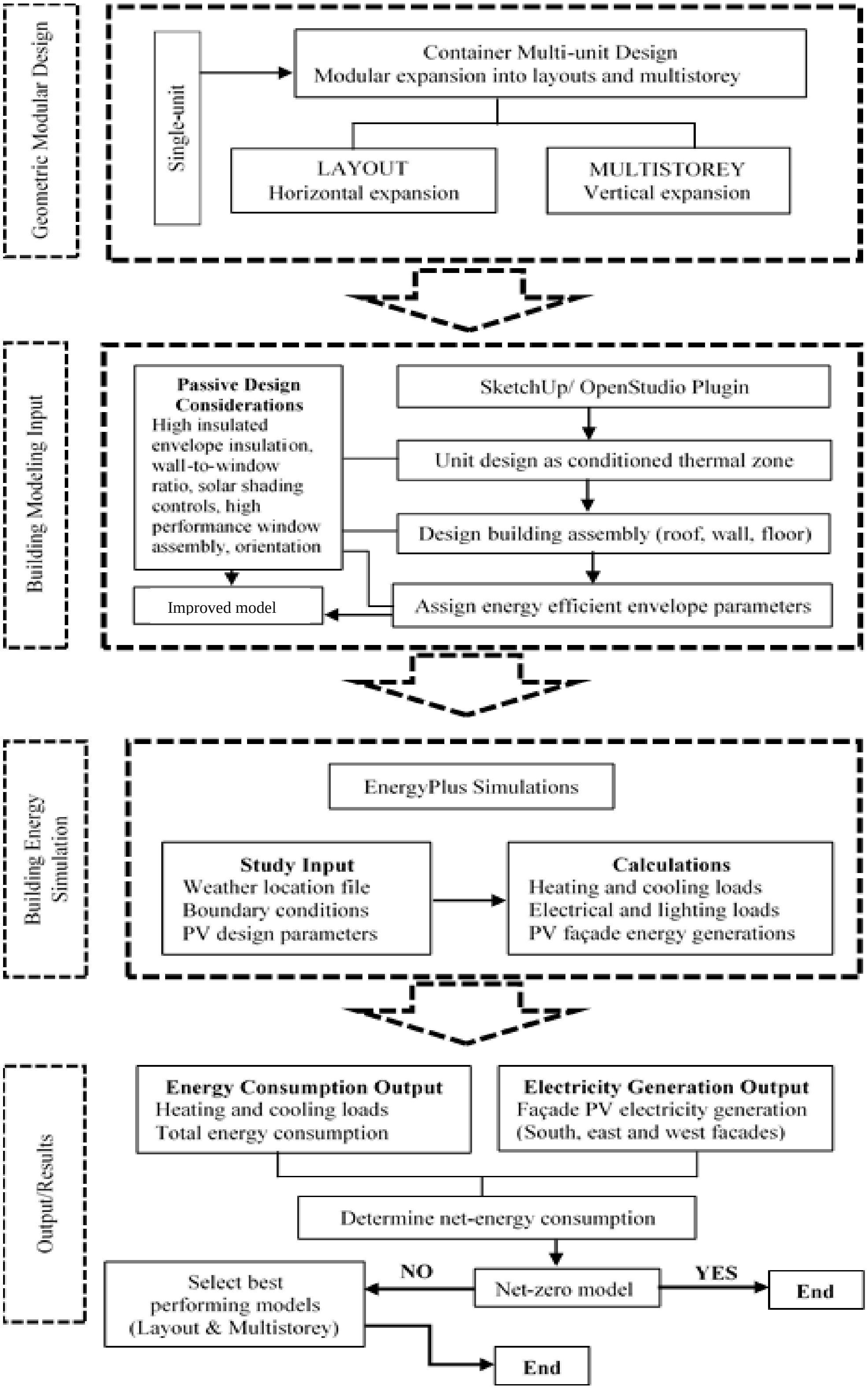


Figure 4.1 Study Methodology Flowchart

4.1.1. Preliminary Design of Prototype Unit

At the preliminary stage, the study develops a basic two-bedroom apartment as the reference design, and then modifies it accordingly to create the desired layouts and multistorey scenarios. As illustrated in Figure 4.2, the unit model has a floor area of approximately 89 m² and combines three 40-foot containers. This rectangular-shaped model has a plane length of 12.2 m and 7.32 m in width and comprises two bedrooms with a shared bathroom, kitchen and living area. The modular unit accommodates approximately 3-person households estimated based on the average number of persons per household in Alberta, Canada (Statista, 2018).

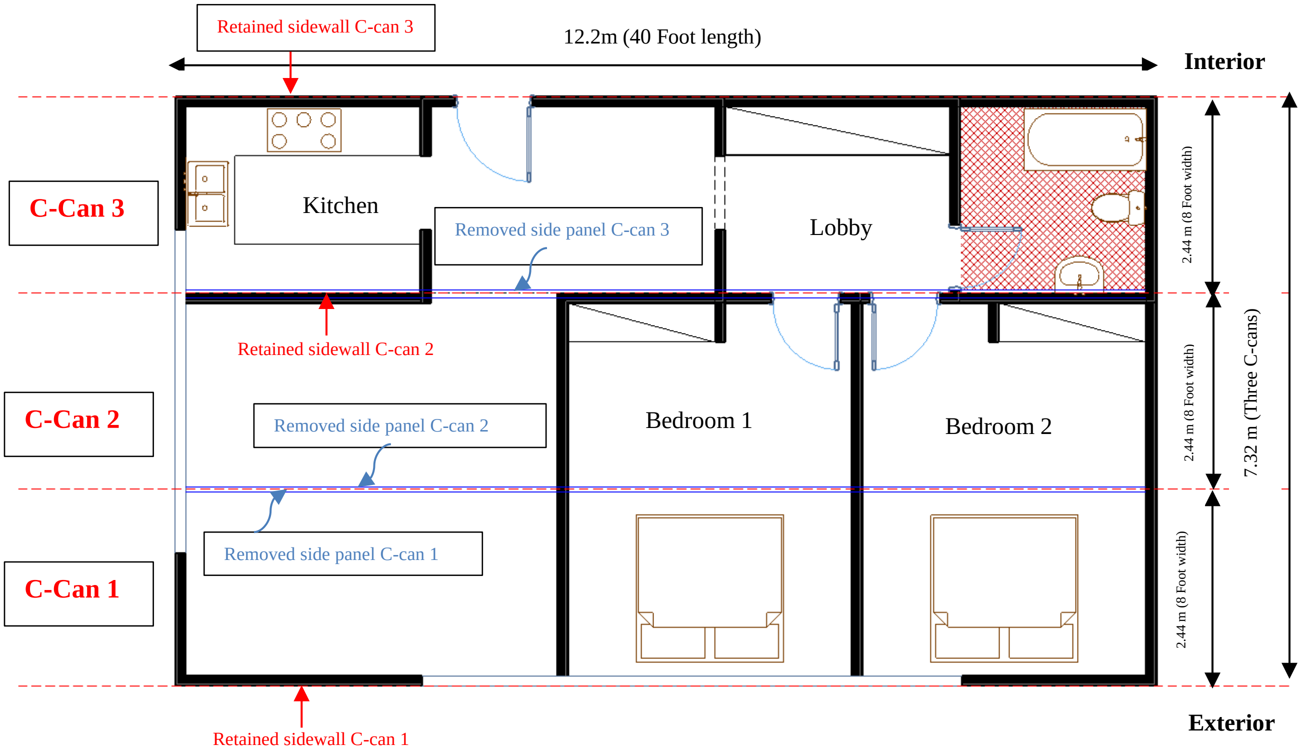


Figure 4.2 Conceptual Floor Plan of Unit Model

Note: Red hidden lines represent container module mate line connections. Blue lines show removed sidewalls of C-cans.

In principle, container building envelope relates to volume, mass and configurations of a typical building along with expected human anthropometrics. Different from conventional building forms, modifying shipping containers into buildings present few design constraints. For example, the difficulty of achieving spacious interior rooms with the standard 2.44 m widths of most container modules. In other words, maintaining the actual width of the general-purpose standard container cans as interior wall partitions results in narrow spaces when the design goal is to achieve a roomier interior layout. That said, the proposed generic unit modified the side panel of connecting modules to create a more comfortable indoor space arrangement for the occupants.

To that effect, the modular unit layout follows the parallel arrangement of modules close to each other. Openings such as entrances, doors and windows are assumed to be cut-off during modular fabrication. The conceptual design retains at least one side panel for each container can, and the other side cut-off to complete the floor layout. The side panels represent the longer side of the shipping containers. This present study chooses the side panels (walls) over the end walls as it results in less impact on structural integrity than cutting off the entire end walls. This is supported by research findings on shipping container building structural integrity tests. Giriunas et al., (2012) found the end walls as the most critical load resisting components of the ISO shipping container, and therefore, most effective at carrying a compressive point and transverse loads when subjected to a maximum applied force of 942KN. Nevertheless, the study uses steel stud framing to provide additional structural stability for the side panels with cut-offs. Overall, the total cut-off is less than 30% of the total exterior surface area of a shipping container.

4.1.2. Multi-unit Apartment Design Conditions and Envelope Connections

The multi-unit layout follows a basic configuration with clear function organization. Units align side-by-side to complete the floor layout and are stacked above each other to create additional floor levels. Figure 4.3 presents the typical modular layout connecting apartments, and Figure 4.4 shows the typical building section. Re-designing the envelope configuration is considered one of the most effective strategies to improve the thermal performance of container interior conditions. The rest of this sub-section summarizes the container building drawings detailing envelope connections and design decisions taken to improve energy efficiency.

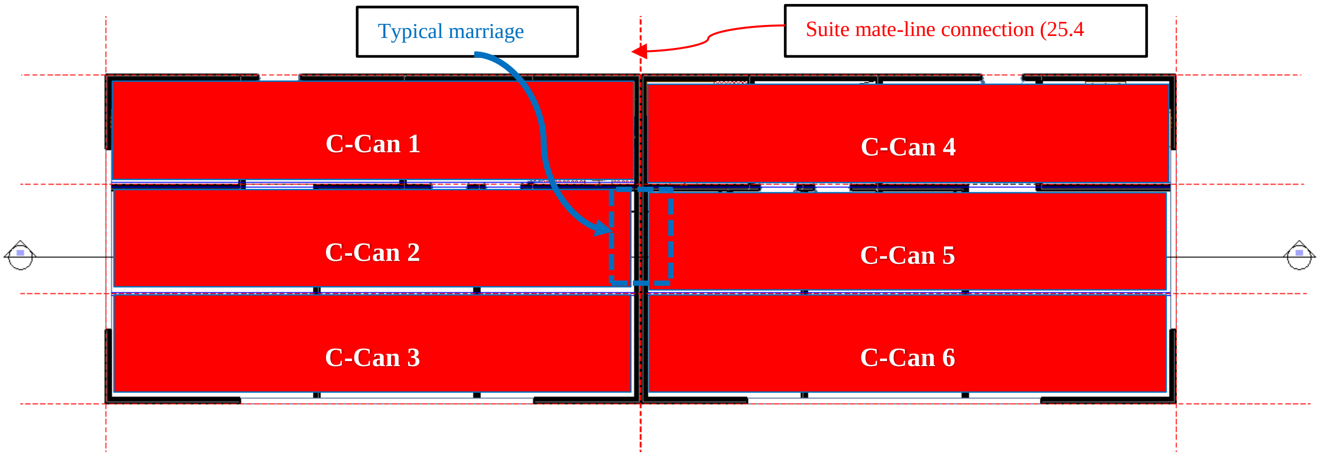


Figure 4.3 Typical Multi-unit Floor Plan showing C-can Layout and Modular Connection

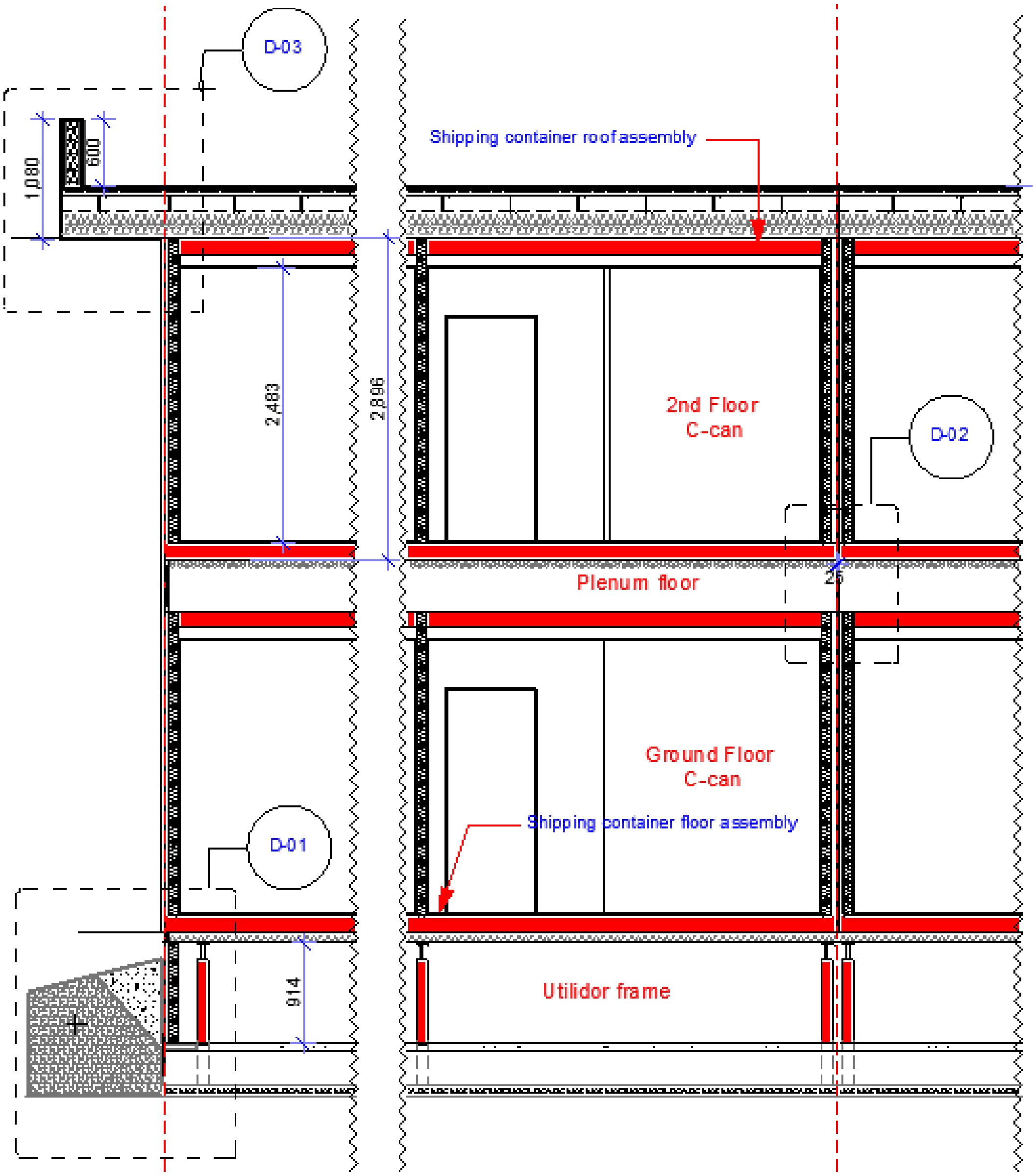


Figure 4.4 Cut-off Building Section of Multi-unit Design

Container Building Foundation Design. The multi-units utilize a crawlspace foundation for setting container building on stable soil. Similar to conventional design, the crawl space is designed as the utility and storage space to install plumbing, HVAC units and general storage purposes. The raised floor of 914 mm (36”) consists of footings, walls and concrete mud slab as the floor finish (Fig. 4.5). Walls are reinforced on the exterior with concrete and consist of an exterior container panel with insulated steel studs at 610mm spacing. Closed-cell spray foam insulation (RSI 3.6) is installed in the stud selected based on high R-value per inch which also acts as a vapour barrier. Energy-efficient design decisions include: eliminating vents; insulating enclosing walls to provide strong thermal boundary; placing vapour barrier on the floor to retard moisture migration into space and insulating the crawlspace ceiling as an added thermal layer to buffer the inner envelope from the outer envelope. While the floor of the crawl foundation is finished with 50 mm concrete mud slab, polyethylene continuous vapour barrier is installed to encapsulate the crawl space and offer protection against groundwater entry. Creating a well-sealed vapour barrier and then insulating the crawl space helps prevent pipes from freezing and bursting.

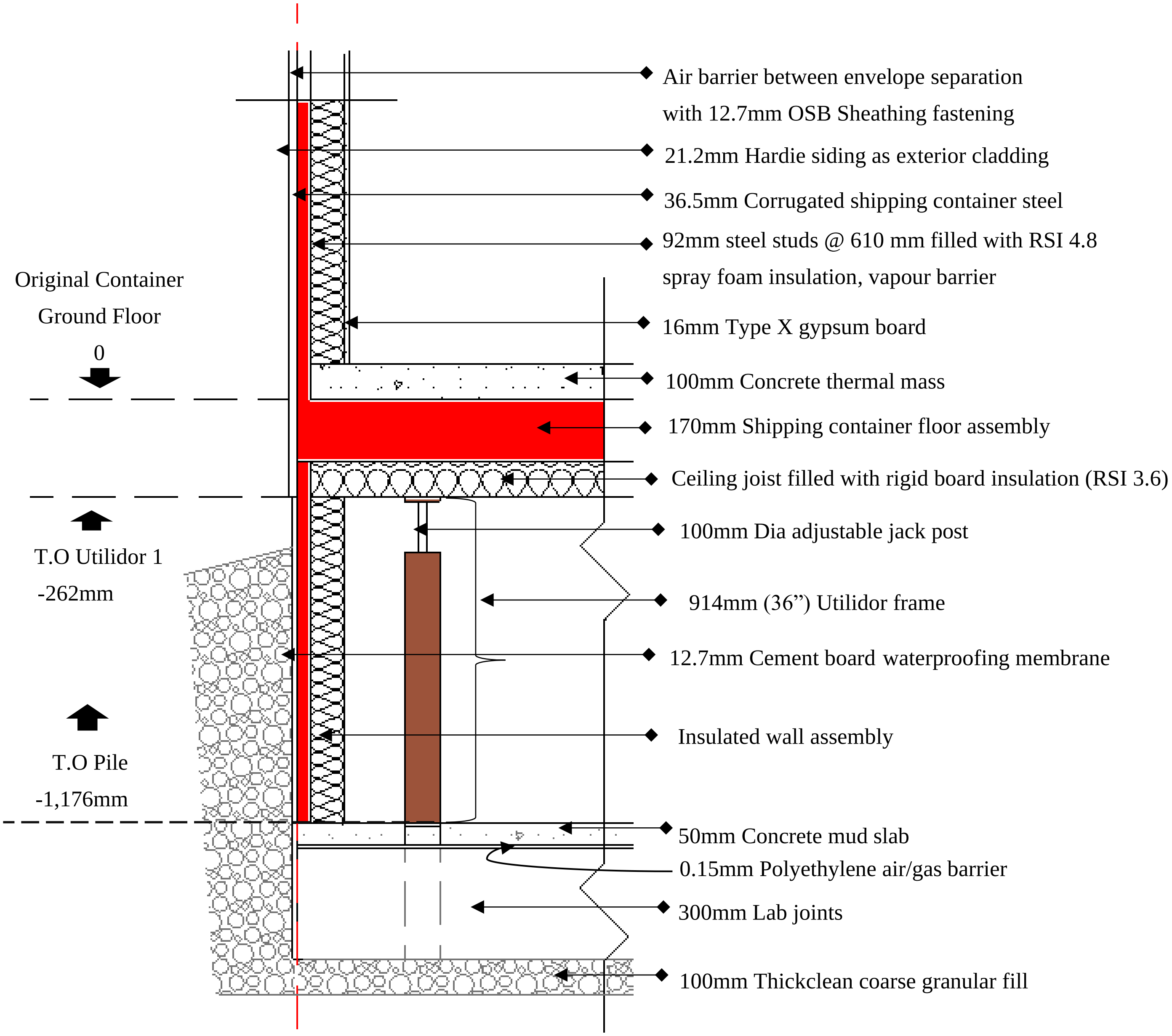


Figure 4.5 D-01 Container Building Foundation Design

Note: Original shipping container envelope represented in red colouring and lines

Container Multi-unit Floors and Walls Connection. Figure 4.6 presents section detail showing container apartment connections (i.e., vertical and horizontal). When stacking containers in the multistorey buildings, all units are connected to the main floor and welded to the foundation using an additional steel plate (see Figure 4.5). While the study considers a permanent welding method for connecting container buildings to the foundation, the anchor bolt connection method is assumed for module joint connections with other containers (floors, walls). Module pin connections are prefabricated with holes in the lower and upper corners of the units, ready to be locked together on-site during the building stacking process. The module pin sizes are predetermined by the structural engineers based on site conditions early before fabrications (Shen et al., 2020).

For the mate-line horizontal connections (unit-to-unit), ventilated air space is provided between the airtight adjoining container units to help regulate heat flow between heated spaces. Figure 4.6 suite connection detail shows that approximately 25.4mm (1 inch) envelope mateline connection between units. This is different from the exterior wall envelope using steel container as the middle panel, finished with exterior cladding and gypsum board interior finish (Ladacor Advanced Modular System, 2018). For example, a typical “connection wall” envelope is designed with the container exterior panel and batt insulation without wall substrates.

Floor to floor vertical stacking considers units welded to a plenum floor, connecting the shipping container existing assemblies (e.g., level 1 container roof to level 2 floor) while providing additional space for airflow, heat supply and circulation. The plenum floor referred here as utilidor frame assumes 457mm (18”) height is insulated with spray foam insulation at the cavity wall penetrations. The design assumes 3,357mm (11’3/16”) as total floor-to-floor height which includes the 2,900mm (9’6”) original high cube container and 457mm (18”) plenum height. The effective interior floor-to-ceiling height is 2,452mm (8’9/16”). The building floor thickness is approximately 270mm: the sum of 170 mm original container floor (bottom level to interior floor finish), and 100mm installed concrete thermal mass as the floor finish for passive heating and cooling. To maintain structural stability between units, module connections joints are welded top and bottom of the utilidor frame, permanently if needed. The joints are designed to be sufficient in the distribution of loads and the multi-units consider uniform stacking constructions (Shen et al., 2020).

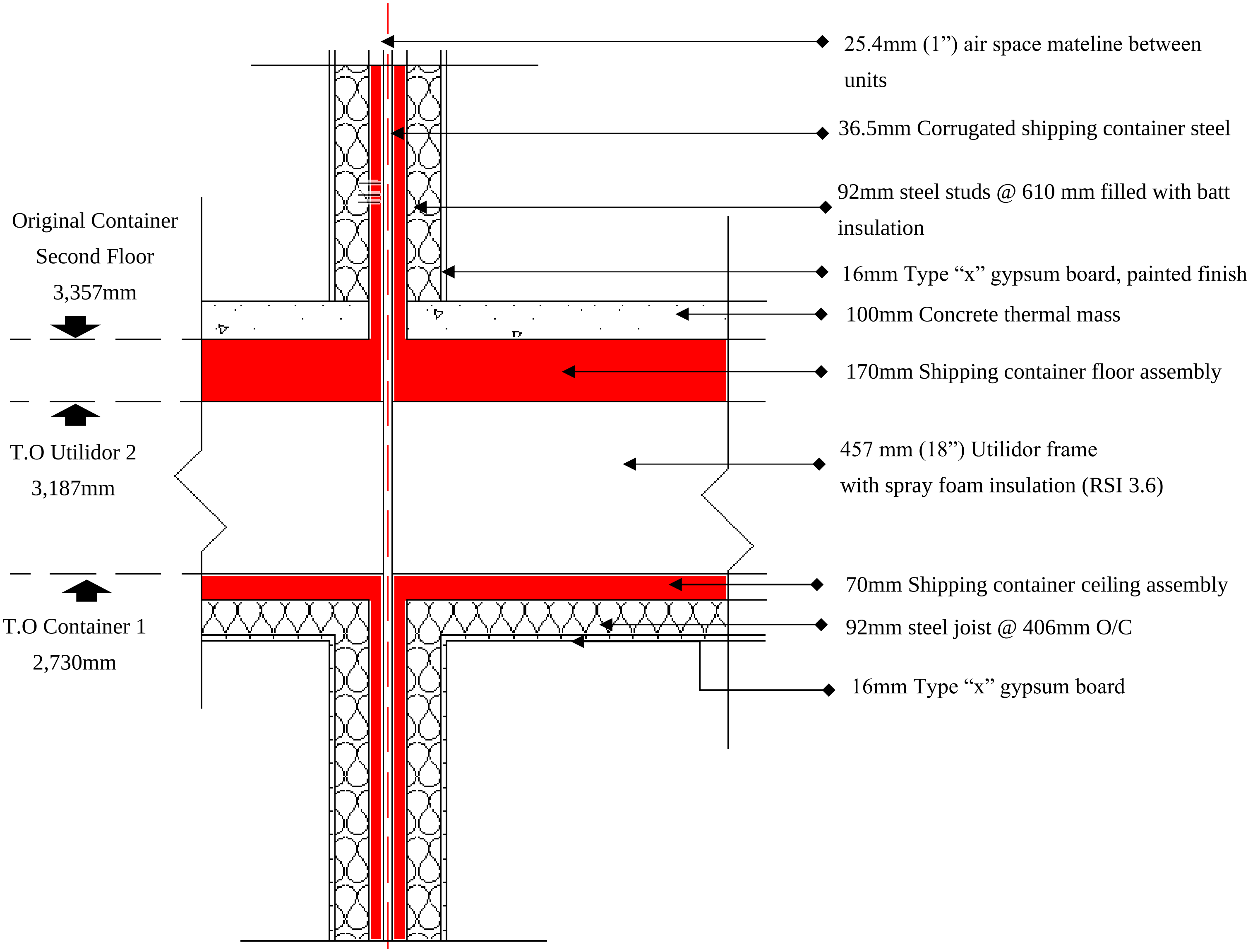


Figure 4.6 Container Building Floor to Floor Connections and Mateline

Note: Original shipping container envelope represented in red colouring and lines

For mateline connection wall designed with batt insulation, vapour barriers (polyethylene film) are installed at the interior (warmer side) of the insulation to protect it from moisture, vapour condensation, and material degradation (CMHC, 2014; Chiras, 2002; FPInnovations, 2014; Sadineni et al., 2011). Condensation occurs when water vapour escaping through a wall contacts a cold surface, such as insulation; it condenses and dampens the material. Pena & Schuzer (2012) suggest using closed-cell polyurethane spray foam with high R-value and waterproof as an insulating material that provides extra sealing to openings against moisture (Peña & Schuzer, 2012). Another control layer crucial in the design of the wall envelope is the use of air barrier separation to wrap the building sealing enclosed living spaces and further preventing air leakage between indoor climate and exterior environment

Container Building Roof Design. The container roof-to-wall connection detail of the typical multi-unit building is illustrated in Figure 4.7. A flat roof design is selected for the multi-units to avoid air leakage associated with pitched roof design and vented attic floor space. The flat container building roof design consists of a roof steel deck with an insulated steel roof frame. The roof connects with the existing shipping container corrugated roof deck from the top. The roof deck is finished on top with roof membrane integrating high-density asphalt-impregnated fibreboard and extended membrane up towards the parapet roof wall to protect the roof assembly from direct moisture. Cellulose blown-in insulation seals the existing container envelope at the top and provides an airtight interior space required for improved energy efficiency. Below the existing shipping, the container roof is finished with a fire-rated gypsum board and interior insulated ceiling to create strong thermal boundary for the inner envelope. Overall the inside floor height of the container building finished floor-to-ceiling of the interior dimension is approximately 2,452mm (2.5 m approximate).

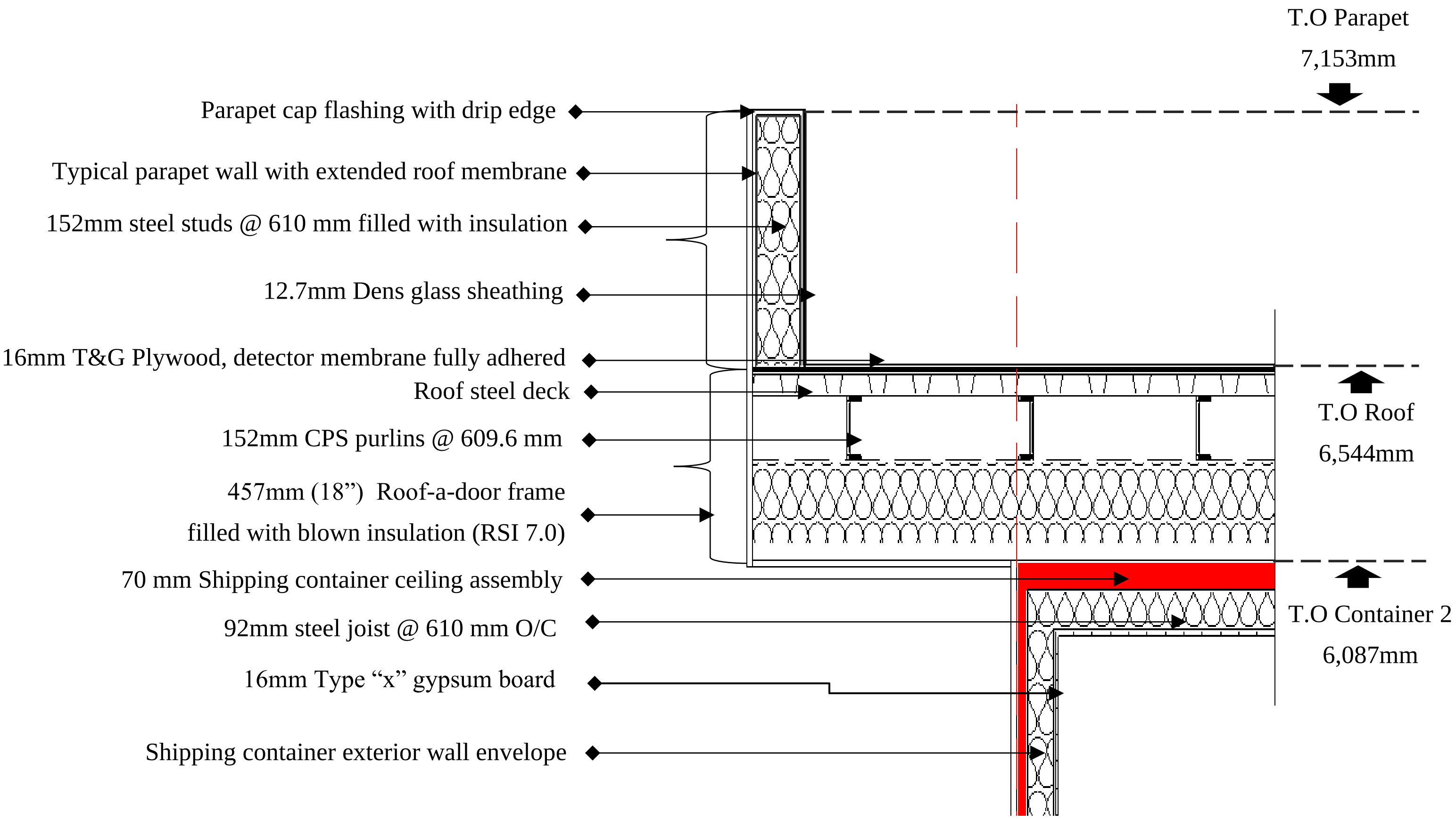


Figure 4.7 Container Wall Connection to Roof Detail

Note: Original shipping container envelope represented in red colouring and lines

4.1.3 Building Layouts Design

The study focuses on understanding their effects on the energy performance of studied scenarios. This first design strategy focuses on building layout by modifying apartment configurations into different layouts and shapes. The layouts include rectangular, I – shape (narrow rectangle), square, and U shape. The modular design breakdown shows that studied layouts utilize a total of twenty-eight shipping containers of 40-foot (12.2m) high cube size per layout. The container demarcations are represented with hidden red lines throughout the drawings. Each layout assumes (8) eight units per floor and a total floor area of 892 m2. The study maintains exact electrical loads and DHW for all layouts.

Building orientation is considered the first and critical parameter in passive solar design (Li Liu et al., 2017). A well-designed orientation harnesses direct solar radiation and daylight received by the building (Tokbolat et al., 2013). The general rule of passive design is to have the longer facade follow full south orientation, aligning its long axis to the east and west facades (Rodriguez-Ubinas et al., 2014; Tokbolat et al., 2013). This, of course, applies to the northern hemisphere, having the largest facade equatorial facing south. In contrast, a west orientation with short-facing south facades will lead to building overheating during the cooling season and reduce heat gain during the heating season. Building shape, on the other hand, is essential in improving the performance of MURBs. A properly designed layout not only influences the amount of solar radiation received by the building but can further reduce cooling energy by up to 25 percent (Pacheco et al., 2012), as well as increase solar energy generation potential when incorporated on the facade (Hachem-Vermette, 2018; Hachem & Elsayed, 2016).

Rectangular layout: Rectangular symmetrical layout serves as the reference model for this study (Figure 4.8). The red lines show the construction details of 40-foot C-cans, connections and modular arrangements to create the rectangular shape. The plan assumes full south orientation with an elongated east-west axis. It presents four (4) units on both the south and north façade divided by circulation space (two middle and two corners suites).

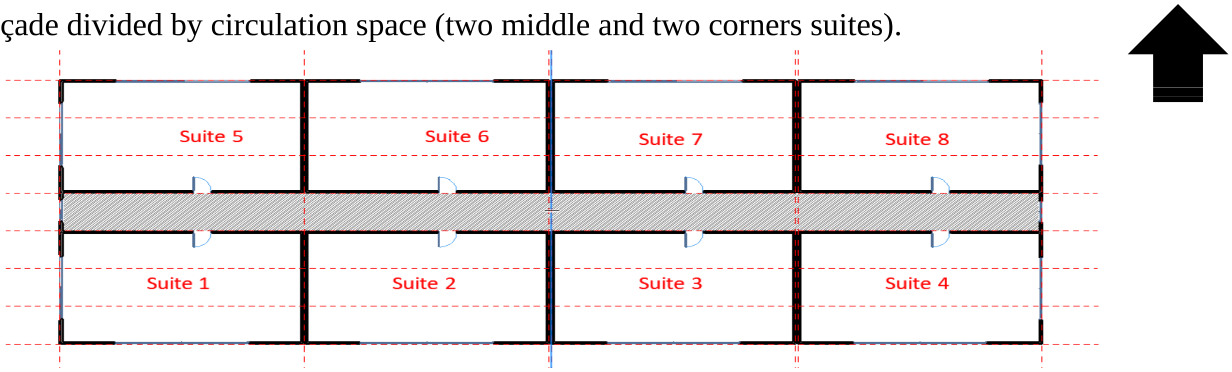


Figure 4.8 Rectangular Layout

I – Shape layout. Figure 4.9 presents an illustration of this layout. I-shape assumes an elongated plan on the north-south axis (narrow rectangle) to contrast the reference layout. However, it has a similar configuration as the rectangular base case layout, while maintaining a different building orientation angle (90°). This layout considers the impact of building orientation on the energy performance of the container-based MURB. I – shape layout contains two (2) corner units facing south and north façade each. The other four (4) apartments are divided equally between the west and east facades.

Square Layout. This layout characterizes units arranged all around the four facades with a centre core area resulting in a (3) three-unit per cardinal direction (see Figure 4.10). The design concept results in more complex resolution and material wastes compared to other layouts. While the other layouts utilize 40-foot cans, the square layout incorporates 20-foot cans in the lobby area and results in the highest cut-off during the design modifications.

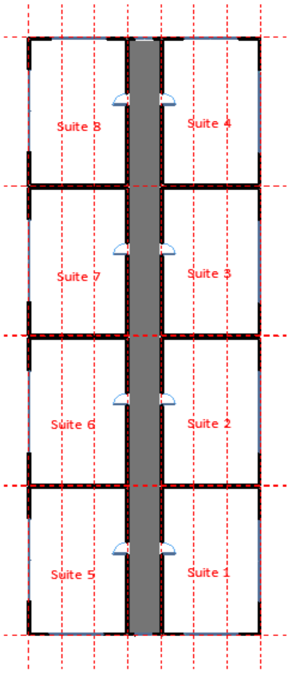


Figure 4.10 I-Shape Layout

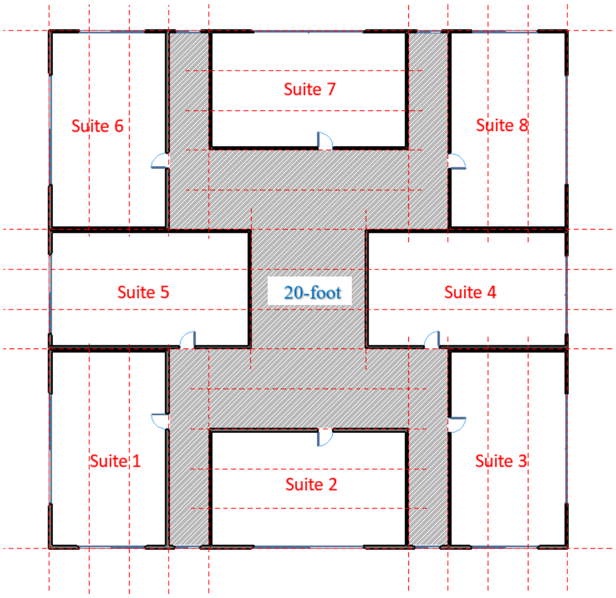


Figure 4.9 Square Layout

U – Shape Layout. This consists of four (4) elongated south-facing units, two (2) north-west and two (2) northeast with a central circulation space, an open hallway along the north façade (Figure 4.11). The units are south, west and east facing. The shipping container apartments and aligned to achieve the desired shape. The lobby utilizes four 40-foot containers with cut-off end walls to complete the modular design. The red lines show container demarcations throughout the layout.

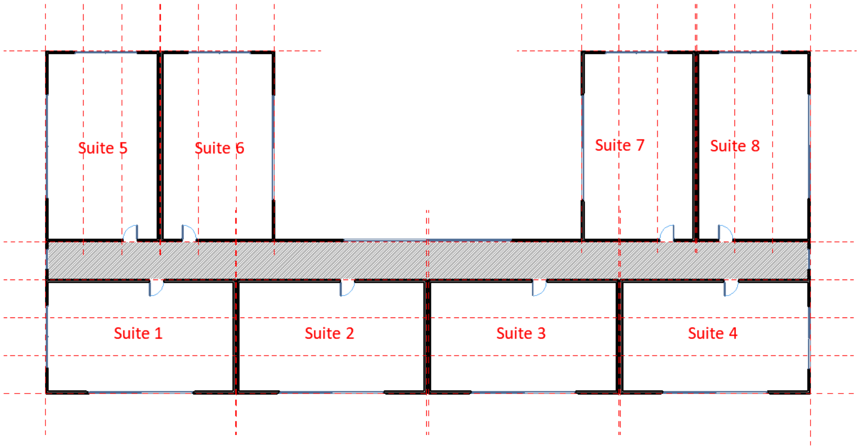
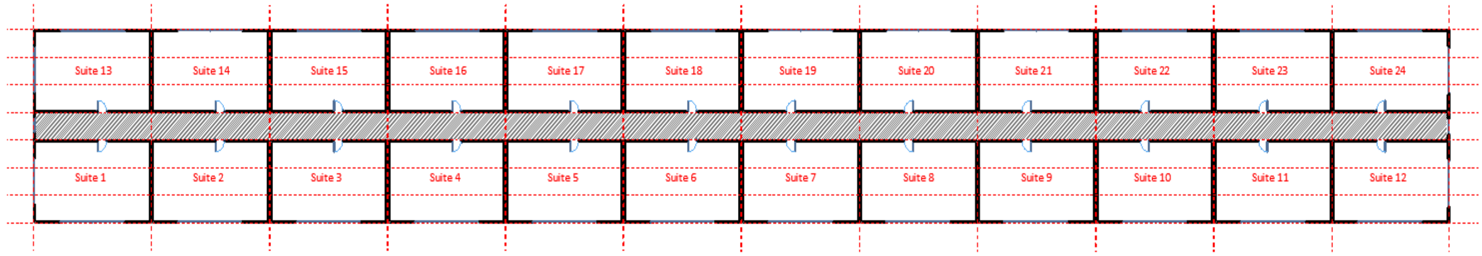


Figure 4.11 U-Shape Layout

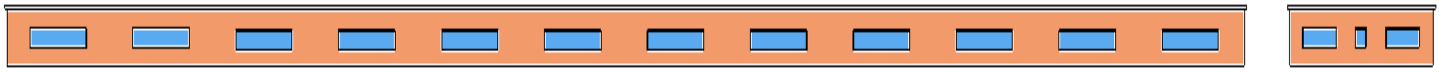
4.1.4 Multistorey Modular Design

The multistorey design utilizes eighty-four (84) 40-foot shipping container modules and considers a fixed total building area of 2,140 m² for all scenarios to a maximum of (6) six-storeys. The apartment units utilize a total of 72 high cube modules. Hallways are designed by aligning an additional 12 C-cans, which also divides the south and north units. The modular design concept starts with a single storey of 24-units and transposes into different higher floor levels (up to six storeys) by varying vertical configurations. Figures 4.12 – 4.17 present the floor plan diagrams of the multistorey scenarios. Each storey design assumes a south orientation with evenly distributed units on both south and north façades divided by a hallway. A total of four (4) corner apartments – southwest, southeast, northeast, and north-wests maintained. The Hallway design, which separates the south from the north units, assumes a constant width for all scenarios. This is decided to ensure comparable energy performance analysis, including BIPV electricity generation. The below section summarizes the design of the multistoreys.

Single-Storey. The single storey serves as the reference model for this segment. The design contains 24 units on a single floor of the apartment (Figure 4.12). It assumes (12) twelve-unit on the south and north sides, separated by a hallway. Each of the units is connected to other container wall panels as a marriage wall separated by 25.4 mm (1 inch) mateline. The red throughout the multistorey floor plans show the shipping container construction details and connection points to create the desired modular design.



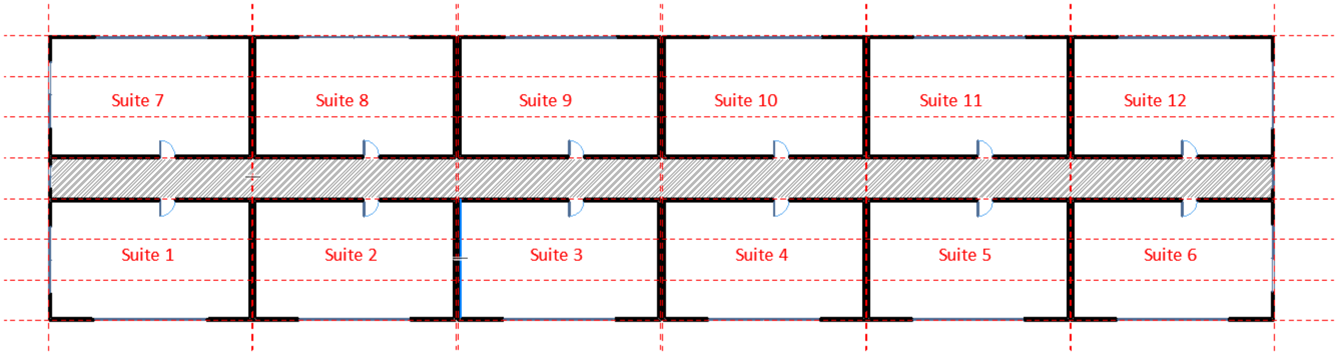
(a) Floor plan



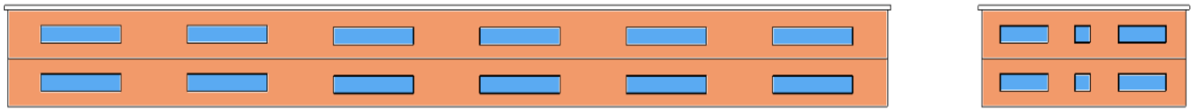
(b) South elevation (c) West elevation

Figure 4.12 Single Storey

Two – Storey. This design considers (12) twelve-unit per floor level. Figure 4.13 illustrates the floor plan showing six (6) south-facing units. Likewise, the hallway divides parallel units to be north facing.



(a) Typical floor plan

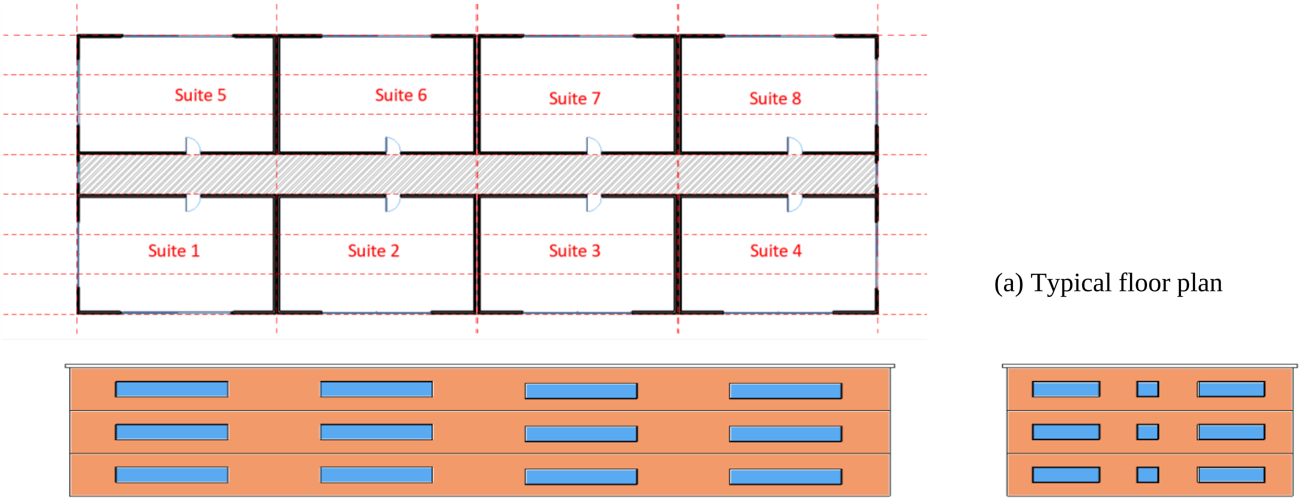


(b) South elevation (c) West elevation

Figure 4.13 Two Storey

Three – Storey Design. This scenario employs an exact configuration of (8) eight-unit per floor to a maximum of 3-floor levels (see Figure 4.14 above). Each floor level employs (4) four-unit on both the south and north façades. The east and west facades have a total of two units each per floor.

Four – Storey Design. This design ensures an exact configuration of the 24-units into 4-floor levels, assuming six-unit per storey height. A typical floor design assumes (3) three south-facing units, (3) three north-facing units, (2) two west-facing and (2) two east-facing units (Figure 4.15 below).

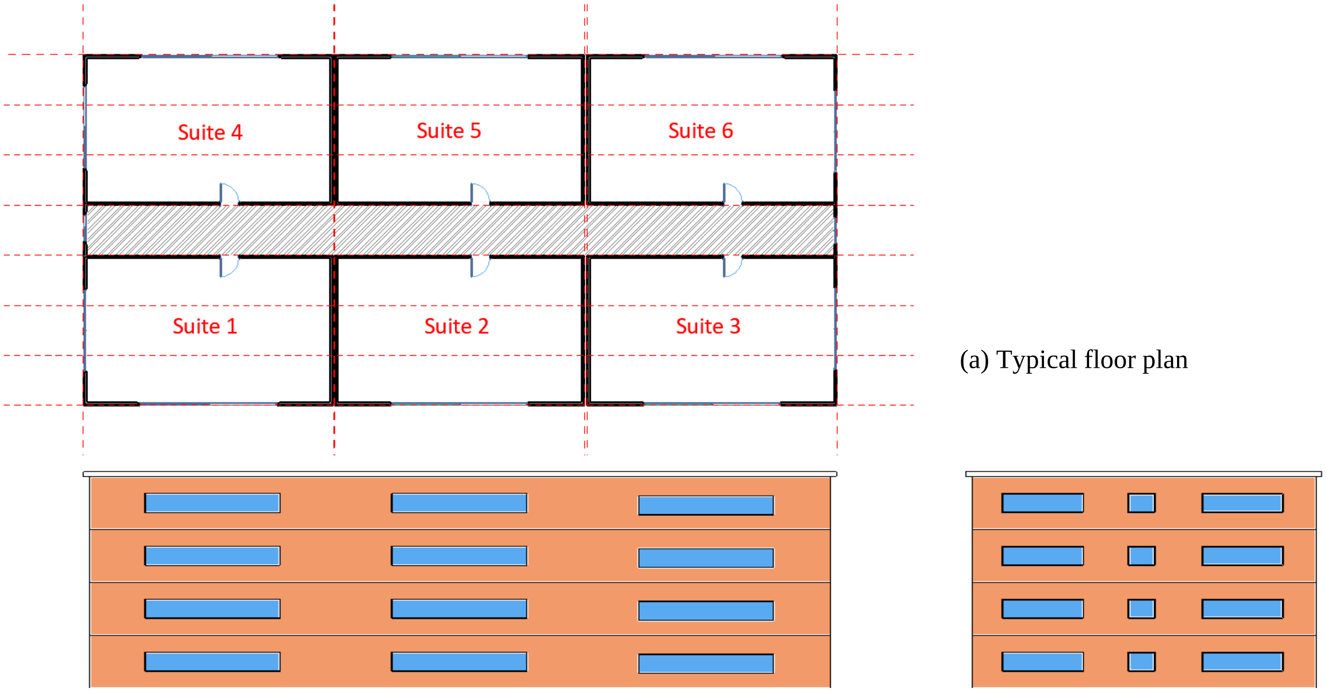


(a) Typical floor plan

(b) South elevation

(c) West elevation

Figure 4.14 Three Storey



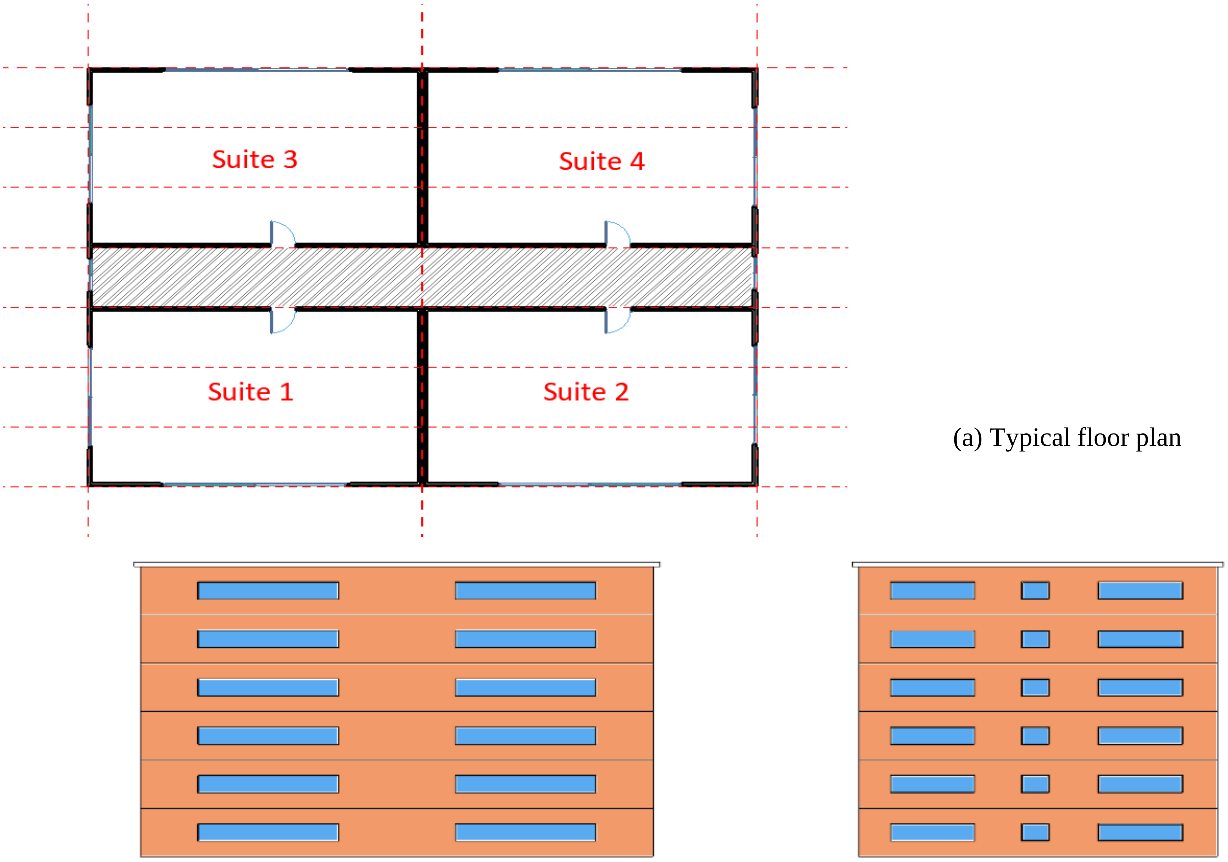
(a) Typical floor plan

(b) South elevation

(c) West elevation

Figure 4.15 Four Storey

Six – Storey Design. This assumes (4) four -units per floor level. Figure 4.16 represents a typical floor plan with (2) two-unit, both facing south and north facades. Given the design, the 6-storey has the maximum exterior surface area on all facades compared to other scenarios.



(a) Typical floor plan

(b) South elevation

(c) West elevation

Figure 4.16 Six Storey

4.1.5. Energy Modeling Assumptions

Figure 4.1 outlines the energy simulation environment's flowchart to determine the optimal design scenario for this study. Calgary (AB, 51°N, Canada) serves as the study location. Chapter 2 discusses the detailed methodology for energy performance modeling and analysis using EnergyPlus software (EnergyPlus, 2018). Table 4.1 presents assumptions for EnergyPlus modeling including envelope parameters, equipment, electrical loads, HVAC and photovoltaic systems. Energy requirements for lighting and equipment assume Canadian energy standards (National Research Council Canada, 2015b). Each apartment (unit) represents a single conditioned thermal zone. The energy performance of various study scenarios (multistoreys and layouts) is analyzed based on the total apartments' energy consumption and potential electricity generation employing PV systems integrated on the building facades' opaque area. Total energy consumption consists of heating, cooling, domestic hot water, electric appliances, and lighting. However, the energy analysis excludes energy consumption for the service areas such as the apartment hallways.

The study heating and cooling temperatures are determined using a regulated thermostat set at 20°C and 24.5 °C, respectively (Webster, 1999). The study assumes an air-source heat pump with a coefficient of performance (COP) range of 2.3 for heating supply and cooling following similar assumptions for Calgary (Natural Resources Canada, 2004). The COP of 2.3 at a given temperature (lower than 0°C) means that 2.3-kilowatt hours (kWh) of heat are transferred for every kWh of electricity supplied to the heat pump. This assumption follows the principle that COP decreases with temperature as it is more difficult to extract heat from cooler air. Following the EnergyPlus guidelines for modeling air infiltration rate, 0.03 ACH natural pressure difference is considered under typical conditions (Goweri et al. 2009). This is an equivalate of 0.6 ACH at 50 Pascals induced pressure.

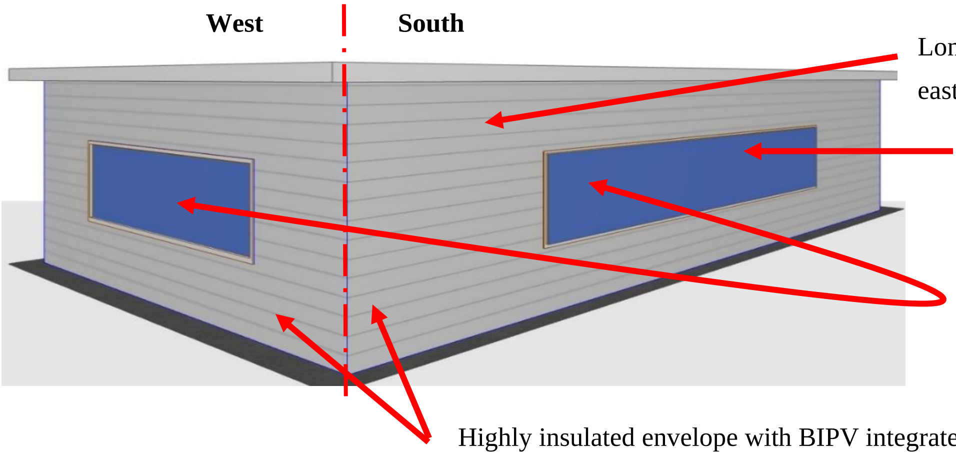
To increase the potential electricity generation for the proposed multistoreys and layouts, this study explores the integration of PV (photovoltaic) systems on opaque areas of the south, east, and west façades. The basic PV system is assumed to cover 80% of the façade areas, leaving 20% WWR for glazing. The reduced window area enables a total BIPV area of more than (2/3) two-third of the façade. The PV panels are assumed to be decoupled from the building surface. The study employs facade electricity given the flat roof of scenarios, resulting in reduced electricity generation surface area. However, this approach benefits the multistorey designed with taller building height. Net-energy consumption represents the balance between total energy consumption and potential electricity produced from PV integrated on facades. This study includes the ratio of energy generation to total energy consumption (ratio of performance – ROP) in the analysis.

Table 4.1 Assumptions for Electrical Loads HVAC System and Equipment

Parameters	Value	Units	Source/Notes
Weather Data	Calagary	.epw file	EnergyPlus, 2018
Suite Area	89	m^2	RDH, 2012
Storey Height including plenum floor	3.3	m	Author’s design
Suite lighting load	8.6	W/m 2	RDH, 2012
Plug load	5.6	W/ m2	RDH, 2017
Domestic Hot Water	2.62	kWh/occupant/day	Sartori et al., 2010
Suite lighting schedule	-	Fractional	
Occupants per suite	3	Persons	Statista, 2018
Occupancy schedule	-	Fractional	
Overall Wall RSI	5.3	m^2K/W	
Overall Roof RSI	7.4	m^2K/W	
Thermal Mass	100	mm	Author’s design
Ventilation	0.35	ACH	ASHRAE 62.1, IMC 2009
Airtightness target performance	0.03	ACHNat	EnergyPlus Software
Window to Wall ratio	20	Percent	Hachem-Vermette, 2018
Photovoltaic Cell Efficiency	0.18	Fraction	Canadian Solar Inc, 2019
PV Cell Area to Total Surface Area	80	Percent	Installed on all opaque areas (Decoupled)
PV Inverter Efficiency	90	Percent	Kapsis & Athienitis, 2015

The multi-unit design assumes parameters for improved energy performance in container-based units based on Chapter 3 research findings. The unit design employs passive solar design principles as per energy-efficient buildings (e.g., high insulation values, roofs, triple glazing

Low-E argon gas-filled windows, etc). Window assemblies designed with triple glazed, low e-argon filled with U-Value of 1.1 W/ m^{2}K and SHGC of 0.41 (see Figure 4.17).



Long south façade, elongated along east-west axis

Triple paned, low-e, argon filled glazing, SHGC 0.41

20% WWR glazing on all facades

Highly insulated envelope with BIPV integrated on opaque areas

Figure 4.17 Example of High-Performance Envelope Characteristics

4.2 Presentation and Analysis of Results

The energy performance results for all scenarios- layouts and multistoreys are discussed below and presented in Table 4.2 (layout) and Table 4.3 (multistorey). Results present energy consumption and electricity generation from PV systems integrated on the facades. The ratio of performance (ROP) included as part of the analysis represents the ratio of PV energy generation to energy consumption.

Table 4.2 Summary of Results Layout

	Rectangular	**I - shape**	**Square**	**U - shape**
	Energy consumption			
Heating energy	39,889	45,289	53,050	41,847
Cooling energy	3,891	5,448	2,946	4,566
Lighting	7,400	7,400	7,400	7,400
Equipment	23,026	23,026	23,026	23,026
DHW	22,951	22,951	22,951	22,951

Annual energy consumption	97,157	104,115	109,373	99,790
	Façade integrated PV electricity generation			
PV south facade	28,647	8,594	15,791	28,647
PV east facade	6,160	20,536	11,320	12,556
PV west facade	6,098	20,328	11,821	12,358
Total façade PV electricity	40,905	49,457	38,931	53,560
PV generation per square meter (PV/m2)	198	167	162	181
	Energy performance			
Net energy consumption	**56,252**	**54,658**	**70,981**	**46,230**
Net-energy use intensity (kWh/m2)	79	77	100	65
Ratio of performance (ROP)	0.42	0.48	0.35	0.54

Note: All values are presented in kWh/per annum, except for units included.

Table 4.3 Summary of Results Multistorey

	1-storey	**2-storey**	**3-storey**	**4-storey**	**6-storey**
	Energy consumption				
Heating energy	120,754	117,661	106,476	110,399	114,534
Cooling energy	6,717	9,739	12,175	15,200	17,856
Lighting	22,199	22,199	22,199	22,199	22,199
Equipment	69,078	69,078	69,078	69,078	69,078
DHW	68,854	68,854	68,854	68,854	68,854
Annual energy consumption	**287,601**	**287,531**	**278,782**	**285,730**	**292,520**
	Façade integrated PV electricity generation				
PV south facade	85,924	85,928	85,928	85,928	85,928
PV east facade	7,188	14,392	21,548	28,788	43,136
PV west facade	7,116	14,254	21,380	28,511	42,672
Total façade PV electricity	**100,227**	**114,573**	**128,856**	**143,227**	**171,735**
PV generation per square meter (PV/m^2)	216	212	208	206	202
	Energy performance				
Net energy consumption	**187,374**	**172,958**	**149,926**	**142,503**	**120,785**
Net-energy use intensity *(kWh/m^2)*	88	81	70	67	56
Ratio of performance (ROP)	0.35	0.40	0.46	0.50	0.60

Note: All values are presented in kWh/per annum, except for units included.

4.2.1 Energy Performance: Building Layout

Annual Heating and Cooling. Figure 4.18 presents heating and cooling energy demands associated with the layouts studied. Results of the layouts are presented as compared to the rectangular base case. There is no significant difference between the rectangular, base case and U-shape layout in terms of heating (less than 5% increase). The heating demand increases up to 14% and 33% for the I-shape and square layout respectively when compared to the rectangular layout. The square layout has the highest heating demands and poses design constraints of achieving a perfect square utilizing the shipping container modules.

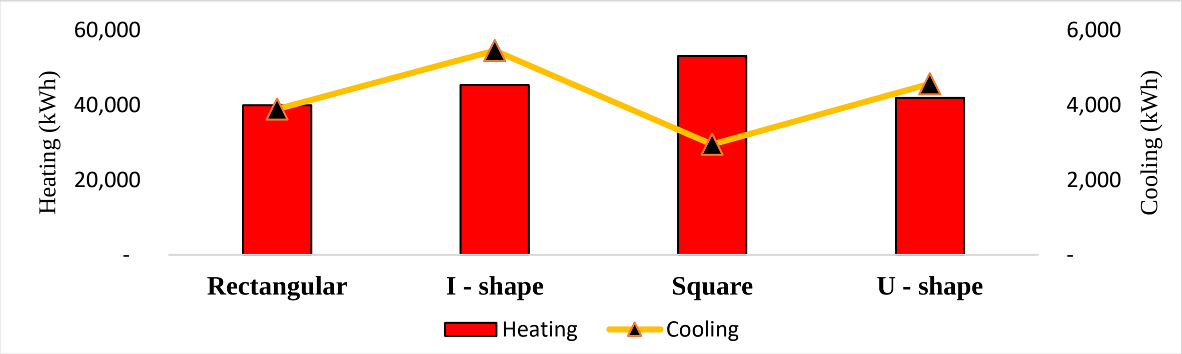


Figure 4.18 Annual Heating and Cooling per Layout

The square layout demonstrates the benefit of designing a compact shape to minimize cooling loads. The square layout has the least need for cooling as compared to other layouts. For example, results show 24% less need in cooling for the square layout than the reference, rectangular layout. The results also show the impact of building orientation on studied layouts. As an illustration, the I-shape designed with an elongated north-south axis has the highest need for cooling, up to 40% increase in cooling compared to the rectangular layout. While there is no significant difference in heating results for the U-shape compared to the rectangular layout, a different observation is reported for the cooling demands, showing up to 32% increase in cooling demands for the U-shape compared to the rectangular layout. Comparing the results of combined thermal energy, the square layout has the highest 26% increase (55,996 kWh) compared to the rectangular shape with the least value (43,780 kWh). I- shape shows 16% increase in overall thermal energy while the U-shape has less than 6% increase compared to the rectangular shape. Thermal energy estimates the sum of heating and cooling energy for each layout.

Electricity Generation of Layouts. Electricity generation potential is explored for the layout designs by integrating PV (photovoltaics) systems on the south, east, and west façades. Figure 4.19 presents the comparison of combined PV electricity production from the above three facades. The BIPV energy generation results show a significant difference for the layouts. The overall energy generation indicates that while the U-shape can supply additional electricity, up to 31% compared to the rectangular base layout. The square layout shows reduced potential in production, 6% less than the reference layout. The U-shape performs much better than others as its design allows for increased exterior façade surface areas. The impact of building orientation to increase façade energy generation is seen with the I-shape with a different orientation (90°) to generate more 21% electricity than the rectangular layout (reference case) designed with similar configurations. This is made possible through the combined generation from the extended east and west facades *(refer to Table 4.2 on layout results).*

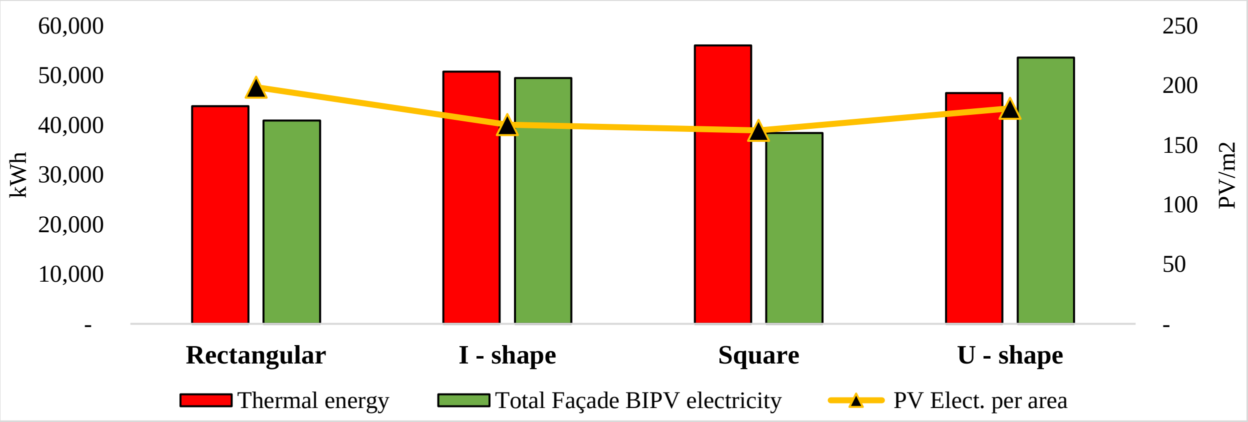


Figure 4.19 BIPV Façade Generation of Layouts

In contrast, comparing the ratio of electricity generation to façade opaque surface area (i.e., PV generation per square meters of opaque areas) shows that the rectangular layout has the highest generation of 198 PV/m^2 of electricity. The total façade area sums up the south, east, and opaque west areas with integrated BIPV. Research findings record a difference of about 9% less generation for the U-shape and 16% less for the I-shape layout compared to the rectangular layout. Although these two layouts could generate more due to higher exterior wall surface areas on the west and east facades, the rectangular layout performs better in terms of PV/M^2 based on the available south façade opaque area. The square layout has the least, 18% decrease compared to the rectangular layout.

Net-Energy Consumption of Layouts. Overall energy performance indicates that under the conditions employed in this study, the net-energy consumption differs for all layouts. While calculating the results for total energy consumption, constant parameters are designed for the lighting, equipment, and domestic hot water system (see Table 4.2 above). However, the impact of thermal energy is witnessed for each layout's overall energy consumption. For instance, the rectangular shape has the least annual energy of 97157 kWh (Figure 4.20).

The net-energy consumption after subsidizing onsite electricity generation presents U-shape as the best performing layout, 46,230 kWh of electricity per annum for the eight units. In contrast, the square layout with the least performance will result in 70,981 kWh per annum. The U-shape and I-shape layouts having a larger combined wall opaque area on west and east facades realize 18% and 3% reduction in net-energy consumption than the rectangular layout.

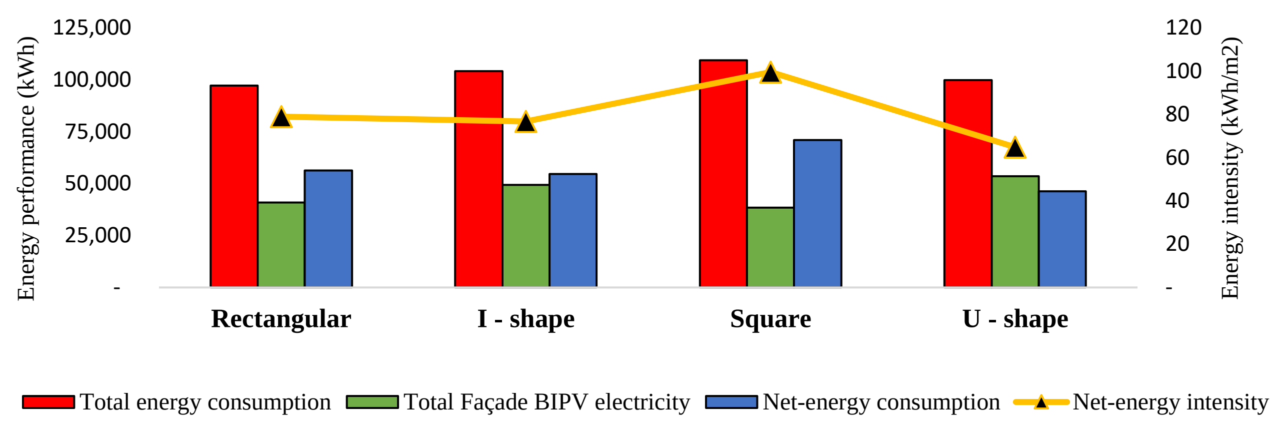


Figure 4.20 Comparison of the Energy Performance of Studied Layouts

Comparing the ROP (ratio of performance) shows the potential of layouts studied to meet at least half of their energy demands through the BIPV system. For example, rectangular and I-shapes can supply over 40% of their total energy use from potential façade integrated PV systems *(refer to Table of results, Table 4.2).* Overall, the U-shape generates up to 54% of its total energy consumption from façade integrated PV systems. On the other hand, the square generates could generate one-third of its energy consumption as well. This study demonstrates that incorporating façades BIPV systems within container-based layouts and implementing passive design strategies and energy-efficient mechanical systems (e.g., heat pumps) ensures the actualization of low-energy container-based layouts. For example, the rectangular layout attains a net-energy intensity of 79 kWh/m^2 after substituting electricity generations, much lower than the energy use intensity (EUI) of 136 kWh/m^2 before electricity production substitution.

4.2.2 Energy Performance: Multistorey

Annual Heating and Cooling. Figure 4.21 presents the result of annual heating and cooling energy. The results of heating demands indicate a slight decrease of less than 5% for the middle floor such as between single-storey to 2-storey, and between 4-storey and 6-storey.

Comparing the low-rise apartments (i.e., buildings less than 3-storey height) to the single-storey, approximately 11% reduction in thermal heating energy can be realized by choosing the 3-storey apartment with the lowest heating demands over the single-storey with the highest heating demands amongst the multistorey scenarios studied. The compactness of the low-rise, 3-storey apartment having more units per floor area results in a more regulated heat flow/exchange rate between units placed above /below each other and side-by-side within the building.

In contrast, the cooling energy results suggest an increasing need for cooling with every increase in building height and subsequently highest for 6-storey. For example, the 6-storey indicates over twice the value in cooling energy compared to the single-storey with the least value. This increase perhaps is due to increased exterior surface area for the multistoreys. An energy performance study for low and mid-rise multistorey residential buildings in Montreal, Canada, reports similar research trends (Hachem et al., 2014b).

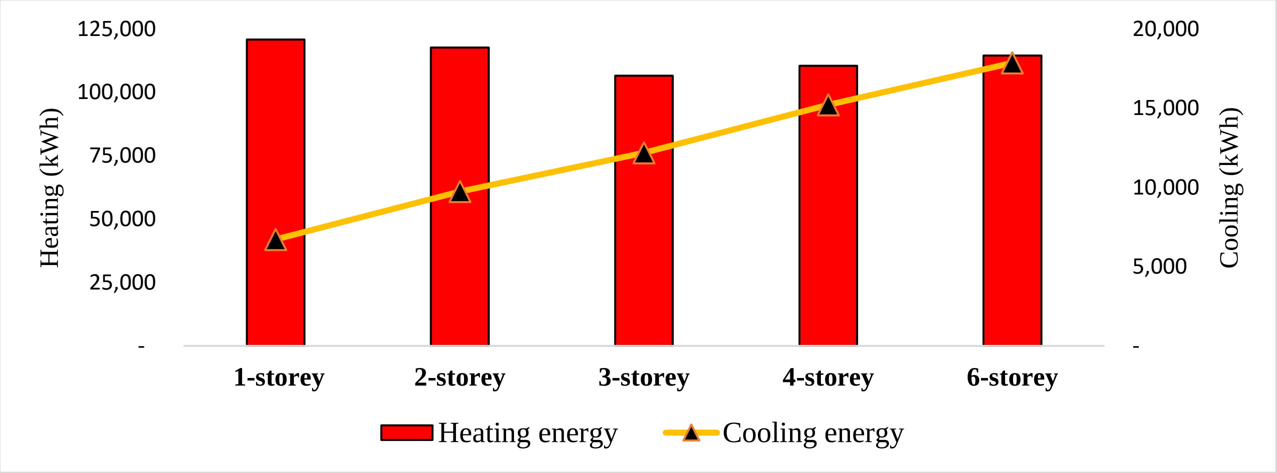


Figure 4.21 Annual Heating and Cooling of Multistorey Apartments

Electricity Generation for Multistorey Buildings. In terms of combined thermal energy from heating and cooling, results do not significantly differ among multistoreys (less than 5%). However, the mid-rise 3 storey has the potential to attain upto 7% decrease than the single storey. Figure 4.22 suggests that electricity generation increases with increasing number of storeys height, starting from single-storey to 6-storey. See also Table 4.3 for a summary of electricity generation per facades (south, east and west). Comparing the PV electricity generation for the multistorey, a progressive increment in production is realized, from 14% to 71% between 2-storey to 6-storey, much higher potential production than the single-storey apartment. This increase in supply results from the increased exterior surface area of facades with increasing building heights. The 6-storey has the highest potential for electricity generation, 171,735 kWh per annum.

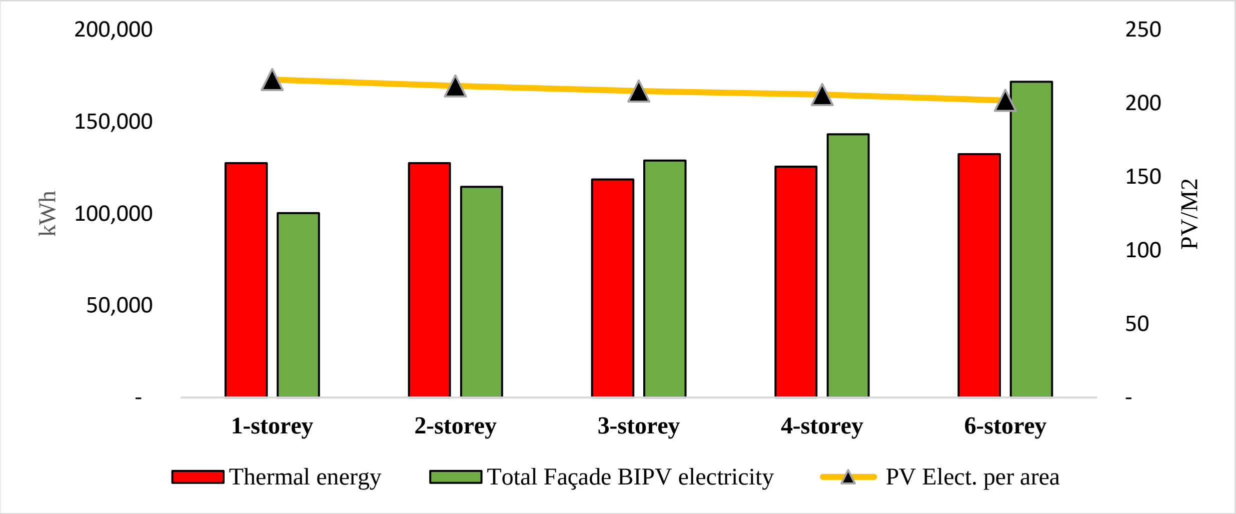


Figure 4.22 Comparison of Electricity Generation for Multistorey Result

Overall, the results of the ratio of electricity generation to façade opaque surface area (PV/m^2) demonstrate a reverse trend. While the single-storey generates the least combined electricity, comparing the PV electricity generation per square meter indicates that the single storey generates the most, about 216 PV/m^{2,} compared to other scenarios (i.e., 14PV/M^2 more). While the multistorey designs benefit from additional surface areas to other west and east facades on multiple floors, the single-storey having the highest ratio of the south to combined west and east facades shows the highest electricity generation potential. The 6-storey reports least, (202 PV/m^2) for the same reason.

Net-Energy Consumption of Multistorey Buildings. Figure 4.23 compares the energy generation to total energy consumption. Although results of energy consumption present the 3-storey as having the least energy demands as the most compact with more regulated heat flow within units to moderate indoor temperature. However, based on the study results on net-energy consumption after onsite electricity subsidization, the 6-storey assumes the best energy performance, 171,735 kWh per annum. Thus, the net-energy consumption reduces with increasing storey height simultaneously. To summarise, the multistorey results record a significant reduction in net-energy consumption of about 20% and 36% for the 3-storey low-rise, and 6 storey mid-rise respectively, compared to the reference single-storey apartment.

Integrating the ratio of performance (ROP) in the analysis indicates that a 6-storey scenario can substitute approximately 60% of its total energy consumption from the BIPV system. The single-storey apartment records the least ROP, about 35% per annum. Other low-rise apartments (2-storey and 3-storey) achieve between 40% to 46% savings in energy consumption. The 4-storey on the other hand has the potential to substitute half its annual energy consumption through integrated BIPV on the building facades. Overall, the container-based mid-rise apartments (e.g., 6-storey) demonstrate a much higher possibility of attaining a low-energy design than low-rise apartments (1-3 storeys). The 6-storey container-based multistorey records 54 kWh/m^2 as net-EUI after the integration of renewable energy sources.

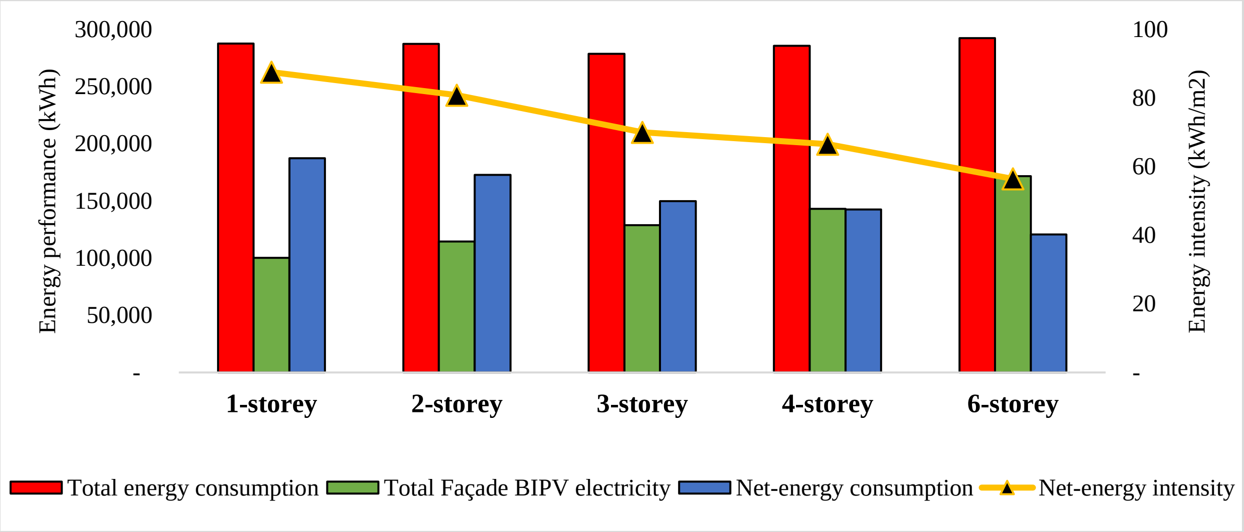


Figure 4.23 Comparison of the Energy Performance of Multistorey Design

4.2.3 Design Deductions: *Situating Container-based Applications in Modular Architecture*

This study analyzes apartment buildings' energy performance following two modular designs: layouts and multistoreys. It investigates various methods to increase energy performance and generation in container-based modular residential buildings through geometric design. The overall study deductions are as follows.

First Strategy: Building Layout. Findings explain the potentiality of achieving low-energy design with container-based buildings. Nevertheless, achieving greater flexibility in concepts with the layout design remains a challenge in advancing modular architectural solutions. Thus, posing the need for careful design decisions as it relates to the choice of building layouts and forms. There are other benefits of designing with regular shapes such as the rectangular form. First, the rectangular shape conforms to the standard modular shape of shipping container boxes and thus, ensures a close to reality building design. It fits better into modular standards and results in minimal material waste during modular fabrication. However, exploring other shapes can increase the possibility of electricity generation through façade BIPV, as seen in this study. A key observation from the layout study is the limitation of effectively designing non-rectangular shapes for container-based structures. For instance, the square layout results in more complex design resolution and material wastes compared to other layouts. While the other layouts utilize 40-foot cans, the square layout incorporates 20-foot cans in the lobby area and results in the highest cut-off during the design modifications. Adopting repurposed shipping containers to design building layouts that combine energy efficiency and electricity generation presents an opportunity for mass customization of low-energy container-based buildings.

Second Strategy: Multistorey Design. Under this study assumptions, while a total building area of 2140 m^2, the total floor area per scenario changes with increasing floor levels. Increasing the exterior surface area through this process leads to an increase in cooling demands. This, however, benefit higher electricity generation for scenarios with an increased exterior surface area. The study shows that the low-rise, 3-storey apartments with elongated south-facing façade has the least energy. consumption and could be considered the best-performing case in absence of on-site electricity generation options. This is because it presents more compact and regulated heat flow within units to moderate indoor temperature. Nonetheless, the 6 storey is the most suitable in energy performance based on the study results comparison of the net-energy consumption.

Integrating Electricity Generation. Consideration of integrating electricity generation from PV systems to improve container-based layouts and multistoreys' energy performance is evident through this study. One of the important aspects of high-energy performance buildings is the ability to accumulate and use solar energy to supply electricity needs, reducing building energy consumption. The study results indicate the potential benefits of exploitation combined façades PV generations to produce more sustainable on-site electricity. Another contribution towards the study of container-based multi-units is the findings on the effects of building heights on potential on-site energy production. For instance, electricity generation increased with an increasing number of storeys with the 6-storey apartment generating more electricity than other scenarios. As shown, a façade BIPV system on 80% of opaque areas can generate about 60% of its energy use for a 6-storey container-based apartment. The south facade can receive more than twice the east and west facades' heat gain in the winter. Nevertheless, the east and west facades significantly impact overall heat gain in the summer months, as seen with the mid-rise apartment (4 – 6 storeys).

4.2.4 Concluding Remarks

This research has proved the benefits of adaptive re-use of the shipping containers in multi-unit residential buildings. Research suggests that container steel can be stacked up to 10 storeys but will need a supporting frame with higher shear resistance to complement skyscraper design (Berbesz & Szefer, 2018; British Columbia Housing, 2014). The low-rise, 3-storey apartment performs better in terms of combined thermal energy and building energy consumption. However, the 6-storey design shows a significant improvement in building energy performance than the 3-storey, up to (20%). That said, this study considers the 6-storey mid-rise apartment best performing in terms of overall energy performance, having also achieved a low-energy status. On the other hand, adopting the single-storey design can lead to other design constraints such as the increased need for traffic control for the desired ingress and egress rate, increased walkability and suite travel distance to access outdoor/exit, and greater consumption of land area.

In this study, designing complex geometric layouts can be identified as a limitation in utilizing shipping containers in multi-unit complexes. For example, more complex layouts (i.e., circular or curved shape) will result in significant modifications and cut-offs from the container envelope. There is a possibility that such designs might compromise the energy performance of the desired layouts. In container-based design, improved energy performance and structural stability are attainable with mostly regular shapes which can easily conform to its modular geometric pattern. That said, the rectangular layout assumes a better option as it works best for passive solar design (Chiras, 2002; Pacheco et al., 2012). Utilizing a rectangular layout offers benefits of plug-in housing in the future as a quick expandable and adaptive replacement of individual modular units (Coffman et al., 2017). The interior spatial arrangement can also be re-adapted to accommodate changing household dynamics needs (British Columbia Housing, 2014). Furthermore, consideration should be given to designing layouts with increased layouts near south, and east and west orientation, such as U shape as analyzed in this study, for improved energy performance than a rectangular layout. Thus, stressing the importance of exploring geometric shapes in low-energy design.

Chapter 5 Life Cycle Impact Assessment and Life Cycle Costing of Single-Detached House: A Case Study

Chapter 5 builds on the previous chapter (Chapter 3) with an integrated building performance assessment of the case study (single-detached house) to further determine the overall life cycle benefits or limitations of container-based housing. It presents a comparative life cycle assessment of container-based house to conventional lightwood frame house, developing a holistic LCA approach to evaluate cumulative energy demands, environmental impacts, and building costs. The chapter attempts to identify and assess differences in overall performance at all life cycle stages pre-use, use and operation, and end-of-life. The typical lightwood frame house is selected for the comparative analysis as it represents the most common and acceptable housing system in Canada. The study does not attempt to project container housing as superior in standard; instead, it uses the lightwood house as a benchmark to consolidate its research findings on building performance, which currently appears to be a gap towards the advancement of container-based buildings in the industry market.

This chapter combines two published journal articles, reused with copyright permissions as part of the author's thesis (see Appendix B). The chapter uses full content from paper 1, "Dara, C., Hachem-Vermette, C., & Assefa, G. (2019)[2], and partly paper 2, "Dara, C., & Hachem-Vermette, C. (2019)[3] to support the reporting of research findings."

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[2] Dara, C., Hachem-Vermette, C., & Assefa, G. (2019). Life cycle assessment and life cycle costing of container-based single-family housing in Canada: A case study. Building and Environment, 163, 106332.

[3] Dara, C., & Hachem-Vermette, C. (2019). Evaluation of low-impact modular housing using energy optimization and life cycle analysis. *Energy, Ecology and Environment*, *4*(6), 286-299.

5.1 Design and Methodology

This study uses a container-based case study, a two-storey detached family house manufactured by Ladacor Advanced Modular System, Inc (see Chapter 3). Due to the difficulty of finding a comparable typical building construction with a similar gross floor area and envelope design as the container house, this study designed the lightwood frame house to align with the container case study floor area, envelope design, and building height. The main difference is the selection of building materials, components and assemblies. The lightwood case study is designed using industry reference data for a typical house built in Canada and based on information supplied in the Canadian Wood Councils Wood report (Canada, 2003).

The different building systems are as follows:

1. Container code (CC): the container code is primarily designed with a corrugated shipping container and structured with 39 x 92 mm steel studs at 600 mm spacing and serves as the reference model. While assuming the physical design of the industry, the envelope characteristics and building components, the code case complies with Alberta Building Code standards (National Research Council Canada, 2014), and the National Building Code of Canada as recommended for low-rise housing and small buildings (National Research Council Canada, 2015a). Specifically, the thermal resistance value of the insulating materials, sheathing material, gypsum board, and envelope airtightness to the code minimum requirements and specifications. However, the study maintains polyurethane spray foam insulation with a high thermal resistance (R-value) as the container case insulating material based on chapter 3 research findings.

2. Lightwood code (LC): In this case, the main floor follows a typical lightwood system. It assumes similar envelope design parameters and minimum code requirements as the container code (CC). However, the LC is structured with 38 x 140 mm wood studs as its main exterior wall structural element. The partition and foundation walls are structured with 38 x 89 mm wood studs. Other differences in building composition include a brick-veneer wall finish and wood joist assembly used in the boundary floor to replace the container floor design.

3. Improved container (IC): This model is created by improving the thermal performance of the container code (CC) model. Through a parametric study incorporating energy efficiency measures and upgraded building envelope (see chapter 3). Few design assumptions include:

- Improving container wall and roof thermal resistance to RSI 5.3 and RSI 10.97 respectively
- Increasing the glazing on the south façade to 40%
- Incorporating 100mm concrete on container main floor as thermal mass
- Introducing window overhangs and interior blinds as shading devices to mitigate indoor space against excessive solar heat gains
- Assuming an airtight enclosure of 0.6 air change per hour at 50 Pa pressure (ACH50) for residential buildings based on passive house standards (PassiveHouse, 2017).
- PCM is removed from the analysis

4. Improved lightwood (IL): This model uses a structural system and components of the lightwood code. Besides, it assumes envelope improvements as utilized in the improved container (IC) case. As a result, the envelope design ensures both improved energy efficiency and structural stability.

5.1.1 Life Cycle Assessment Methodology

Life cycle assessment (LCA) is defined as a broad methodology for the quantitative evaluation of material, energy inputs, and outputs, and environmental impacts of a product throughout its life cycle (Sharma et al., 2011). It considers from cradle-to-grave and life cycle contributions of all building stages from manufacturing, construction, operation, maintenance, disposal, and end-of-life (Islam et al., 2015; Kumar et al., 2015; Marszal & Heiselberg, 2011; Paleari et al., 2016; Ramesh et al., 2010; Stazi et al., 2012). A generic LCA methodology performed according to the International Organization for Standardization (ISO) standards comprises four (4) distinct analytical stages (International Organization for Standardization, 2006a; Kotaji et al., 2003):

- Goal and scope definition
- Life cycle inventory analysis
- Life cycle impact assessment
- Interpretation of results.

Goal and Scope Definition. This study evaluates the integrated life cycle impact (i.e., energy, environmental and cost) of a modular container-based single-family house compared to lightwood frame houses. A more specific research objective is to assess case studies' validity as low energy and low carbon housing models. The study considers four case studies; container and lightwood house designed to code specifications, serving as the base models and two improved container and lightwood models designed by incorporating energy efficiency measures and passive solar design standards. The typical lightwood frame house is selected for the comparative analysis as it represents the most common and acceptable housing system in Canada. The research outcome will provide an in-depth understanding of the broader benefits (i.e., energy, environmental, and economics) of upcycling container products into permanent livable structures.

Functional unit. The starting point of comparative life cycle analysis is to identify products as interchangeable and equivalent alternatives for a specific function or use (Kotaji et al., 2003; Vadenbo et al., 2017). Lavagna (2012:81) defines a functional unit or functional equivalence as *"the challenge of ensuring that two or more products (or buildings) provide the same level of service."* To meet the "functional equivalence" required for the comparative analysis of container cases versus lightwood cases, the models assume a gross floor area of 238 m^2 (see Chapter 3). The case study house accommodates a 3-person household estimated based on the average number of persons per household in Alberta, Canada (Statista, 2018)**.** Selected building life expectancy allows for significant life cycle activities (i.e., manufacturing, construction, operation, maintenance, and end-of-life). 50-year service life is considered – from cradle-to-grave – following similar LCA studies conducted for Canadian residential and commercial buildings (Kumar et al., 2015; Trusty, W. B., & Meil, 2009; van Ooteghem & Xu, 2012).

Athena Impact Estimator for Buildings. This study employs Athena Impact Estimator (IE) for building version 5.2, for the life cycle impact assessment. While several LCA tools exist for various world regions, Athena IE is the only North American tool for whole-building life-cycle assessment, and an internationally recognized LCA method (Athena Sustainable Materials Institute, 2016; Reza et al., 2014). In Canada, this tool has been employed in LCA studies to assess environmental impacts of different building types and systems (Kumar et al., 2015; Reza et al., 2014; Trusty, W. B., & Meil, 2009; van Ooteghem & Xu, 2012). The ISO 14044 standard on LCA offers a basis for the research's underlying LCA approach (International Organization for Standardization, 2006b). Athena reports environmental footprint data based on the TRACI methodology developed by the United States Environmental Protection Agency (Athena Sustainable Materials Institute, 2016).

System Boundary. Establishing a system boundary ensures the completeness of inputs and outputs variables of unit processes (Kotaji et al., 2003). Figure 5.1 demonstrates system boundaries and flows. Primary inputs include raw materials and energy. The Athena software provides a cradle-to-grave LCA of buildings, including resource extraction, manufacturing, construction, related transportation, maintenance, replacement effects, building operation demolition, and disposal (Athena Sustainable Materials Institute, 2014). The study considers nine (9) impact categories: global warming potential (GWP), smog potential (SP), total primary energy (TPE), fossil fuel consumption (FFC), acidification potential (AP), human health particulate (HHP), ozone depletion potential (ODP), eutrophication potential (EP), and solid wastes generation (SWG). These indicators are selected to ensure an in-depth life cycle assessment of the case study buildings.

Figure 5.1 System Boundary

Note: *Benefits and loads beyond system boundary modelled in Athena include carbon sequestration of wood and steel recycling.*

LCA Approach and Modeling. The first step in modeling the case studies in Athena is to input and define building location, gross floor area, building type, height, and building life expectancy. Table 5.1 below outlines the input parameters below. Calgary, listed as a reference city in Athena, is selected as the study location to obtain background data for appropriate life cycle activities. In Athena, the main building envelope, such as walls and roofs, modeling is represented as an assembly group, while openings (e.g., doors and windows) are subsets of the wall assembly. The software applies structural algorithms to generate desired output variables for all life cycle phases, pre-determines the building assemblies' structural systems and loads. Table 5.2 summarizes the bill of materials' quantities and provides a breakdown of the building characteristics of the four case studies.

Table 5.1 Study Parameters as Input in Athena IE Tool

Parameters	Details
Project location	Calgary
Building type	Single-family residential
Building life expectancy	50 years
Units	International System (SI Units)
Building height	7.6 m
Gross floor area	238 m^2
Operational energy consumption	Input based on selected case study annual operational energy results

Table 5.2 Bill of Materials Quantities of Case Studies

	Total Quantity – Mass Unit (Tonnes)			
Material	**Container Code (CC)**	**Lightwood Code (LC)**	**Improved Container (IC)**	**Improved Lightwood (IL)**
#15 Organic Felt	0.33		0.33	
1/2" Regular Gypsum Board	10.99	10.99	10.99	10.99
5/8" Fire-Rated Type X Gypsum Board	6.22	6.22	8.22	8.22

6 mil Polyethylene	0.72	0.10	0.72	0.10
Air Barrier	0.02	0.02	0.02	0.02
Blown Cellulose	0.50		0.77	
Cold Rolled Sheet	6.30	0.03	6.30	0.03
Cedar Wood Bevel Siding	1.21		1.21	
Concrete Benchmark CAN 15 - 20 MPa	85.85	85.85	97.91	97.91
FG Batt R20 -R30	0.14	0.34	0.14	0.38
FG LF Open Blow R30 -R60		0.30		0.52
Galvanized Sheet		0.13		0.13
Galvanized Studs	3.00		3.46	
GluLam Sections		10.00		10.00
HL4 Asphalt Stone	0.08	0.08	0.08	0.08
Hollow Structural Steel	0.62	0.62	0.62	0.62
Joint Compound	1.85	2.00	1.93	2.00
MBS Metal Roof Cladding - Commercial (24 -26 Ga.)	0.51		0.51	
Laminated Veneer Lumber		0.74		0.74
Mortar		7.12		7.12
MW Batt R15 – R20	0.79	0.81	0.63	0.84
Nails	0.14	0.24	0.14	0.24
Ontario (Standard) Brick		16.46		16.46
Oriented Strand Board	4.12	4.37	7.10	7.95
Paper Tape	0.02	0.02	0.02	0.02
Polyiso Foam Board (unfaced)	0.40		0.55	
Rebar, Rod, Light Sections	0.88	1.12	0.88	1.12
Roofing Asphalt		2.87		2.87
Screws Nuts & Bolts	0.12		0.16	
Small Dimension Softwood Lumber, kiln-dried	2.66	8.90	2.66	8.90
Softwood Plywood	1.18	3.23	1.18	3.23
Steel Tubing	0.99		0.99	
Triple Glazed Hard Coated Argon	0.87	0.87	0.87	0.87
Vinyl Clad Wood Window Frame	0.64	0.64	0.64	0.64
Water Based Latex Paint	0.14	0.05	0.14	0.05
Welded Wire Mesh / Ladder Wire	0.11	0.11	0.22	0.22
Total Materials Mass (Tonnes)	**132.40**	**164.23**	**149.39**	**182.27**

Modeling Shipping Container in Athena. To complete the environmental impact assessment, the study assumes a steel-floor container as more efficient design. This offers a few advantages: lighter weight and cheaper cost, almost odourless with no use of chemical treatments, higher resistance capability, stability and other sustainability benefits (i.e., longer life cycle without wear and tear, 100% recyclable) than the traditional floor made from plywood boards (Hapag-Lloyd, 2016). The general-purpose shipping containers are often wooden floors, consisting of three main materials: steel (Corten, mild, stainless), plywood, and rubber. According to (Buchanan, 2018), typical shipping container is made from 83.7% steel, 16.1% plywood and 0.2% rubber by mass, with Corten steel being the major component (94%) of the steel component. Corten is considered a sustainable choice with a rust protective coating that slows the rate of future corrosion. On the other hand, the most recent general-purpose containers are designed with corrugated walls and steel floor, resulting in over 95% steel of envelope content.

The steel containers floor utilized in the code and improved cases are modeled as a special assembly using the 50/50 method LCA approach for estimating the environmental burdens of recycled/reused products. Two materials are used to replace container steel components in Athena: cold-rolled sheet and steel tubing. Assumption is made that corrugated steel sheets are made from cold-form process, pressed flat, and run through a roll-forming machine to create the desired corrugations without the need for heat. Screws Nuts & Bolts are used to replace anchor bolts and twist locks. The container weight is calculated for 4 modules excluding cut-off of approximately 25% of the overall exterior surface area of a shipping container (as the removed sidewall). Assumption is made for 4.2 Tonnes tare weight of 40-foot-high cube empty container (Alconet Containers, 2021; Hapag-Lloyd, 2016). Therefore, the modeling considers replacing the weight of environmental loads of containers with the 50/50 method LCA approach (which is half the total load of 12.60 Tonnes). A 75% weighted load of 50/50 method is approximately 6.30 Tonnes.

Life cycle phases. The study considers three distinct phases: pre-use, use and operation, and end of life. These phases are as follows:

- ***Pre-use Phase.*** This phase accounts for environmental loads of all primary material extraction, production, and fabrication, transportation of building materials, and construction. The modeling of the materials inputs data follows standard reference units of products, i.e., mass (kg), area (m^2), and volume (m^3) to calculate the environmental loads of materials effectively. Material energy intensity and transportation distances (tKm) are pre-calculated in Athena based on project details and material specifications provided as study input.
- ***Use and Operation Phase***. This phase includes environmental loads of building operational and energy use, building maintenance, and replacement of damaged building envelopes and materials. The annual energy consumption for building operations is externally sourced and estimated as secondary energy. Then, Athena re-calculates total primary energy for the life cycle assessment by converting the estimated secondary energy into primary energy (Kumar et al., 2015; Reza et al., 2014). EnergyPlus, 8.4 whole building simulation software, is used in this study to estimate the secondary energy consumption of the case studies (EnergyPlus, 2018). The annual energy consumption accounts for heating, cooling, lighting, domestic hot water, and equipment values. The annual energy consumptions: 24,905 kWh, 25,592 kWh, 17,280 kWh, and 17,690 kWh for the container code (CC), lightwood code (LC), improved container (IC), and improved lightwood (IL) respectively. The energy analysis assumes electricity as the primary energy source for heating and cooling and the domestic hot water system.

- ***End-of-life Phase.*** This phase accounts for the post-occupancy and includes de-construction, demolition, recycling of reusable materials, transportation, and disposal. Also included are environmental impacts associated with transportation activities during dismantling to landfill sites or recycling plants. This study assumes that all the building materials are disposed to landfill at the end of life based on defined system boundary, except for steel scraps, which is recycled.

Study Assumptions and Limitations: This study identifies transportation distance estimation for modular construction as a modeling limitation in Athena. This tool assesses transportation impacts for delivering building materials and equipment to the manufacturing plant gate, from the manufacturing plant to the site and landfill at the end of life. Athena tool does not account for factory modular fabrication and construction processes; instead, it considers the on-site construction method for all building systems. Nevertheless, research proves that module transportation contributes only 2% of embodied carbon emissions. This amount is considered insignificant compared to the total life cycle impact (Monahan & Powell, 2011). In addition, the embodied energy utilized in container steel fabrication is predetermined in Athena.

Given that the study focuses on the case studies’ material dimensions and difficulty obtaining modular transportation calculations for the container cases, the study assumes module transportation distance similar to conventional building construction. Besides, phase change materials (PCM) used in the design of the improved cases are not inventoried in the analysis and not identified as a product in the Athena database. A substitution by creating individual materials into a component will result in an inaccurate estimation of the product’s impact.

5.1.2 Sensitivity Analysis of Container Case Studies

The study assesses the weighted impact of the shipping container from the first life cycle transferred to the second life cycle as a container house through sensitivity analysis using several LCA approaches designed to allocate and distribute environmental burdens between products with multiple life cycle situations. Two-product life cycle situations are considered for the container case studies: (i) first, primary product life cycle, shipping container used for transportation or storage, and (ii) subsequent product life cycle recycled into a container house. Three critical parameters include: environmental burdens associated with virgin raw material extraction and production, impacts through product recycling (if any), and disposal impact at end-of-life. In this study, the container steel is upcycled and directly reused in housing; therefore, the impact of product recycling between life changes is excluded in the analysis.

The sensitivity analysis considers the embodied impact at different life cycle stages (e.g., pre-use, use, and end-of-life); and total life cycle embodied impacts for both container code (CC) and improved container (IC). While the use-phase is included in part of the analysis, these present identical results for the container code/improved regardless of the scenario under analysis. Therefore, results of embodied impacts at the use phase excludes operational energy (B6) from the life cycle embodied impact. The scenarios analyzed are based on three dominant approaches; Scenario CC (100:0) – cut-off method, Scenario CC (50/50) based method, and Scenario CC (0:100) – end of life recycling for the container code (CC) (Karen Allacker et al., 2017; Bontempi, 2017; Frischknecht, 2010; Koffler & Florin, 2013; Nicholson et al., 2009; Vadenbo et al., 2017). Similarly, the improved container (IC) evaluates three scenarios – Scenario IC (100:0), Scenario IC (50:50), and Scenario IC (0:100).

Each approach presents a different perspective as follows:

1. Scenario (100: 0): Cut-off Method or Recycled Content. In this scenario, all primary production's environmental burden goes to the first product life cycle. There is no environmental burden of virgin production associated with the secondary product (i.e., container house) (Frischknecht, 2010; Koffler & Florin, 2013; Nicholson et al., 2009). Accounting for product recycling impacts in this analysis of the second life cycle situation is not considered as the shipping container is upcycled and re-purposed into housing without any need for re-manufacturing and recycling processing (Frischknecht, 2010).

2. Scenario (50/50) Based Method: This scenario allocates fifty percent (50%) of all burdens of virgin material production and product disposal to both product life situations (Karen Allacker et al., 2017; Ekvall, 2000; Nicholson et al., 2009). The strong emphasis on the equal distribution of environmental impacts amongst products has made the 50:50 approach a significant force for recycled product modeling in LCA.

3. Scenario (0:100): End of life Recycling or Avoided Burden Approach. This scenario is the opposite of Scenario (100:0). In this case, all burden associated with production and disposal is assigned to the second life cycle, representing the container house (Karen Allacker et al., 2017; Frischknecht, 2010; Koffler & Florin, 2013; Nicholson et al., 2009). However, product recycling's full impact (if any) goes to the life cycle chain's first product. The assumption is made that future material recycling results in the avoided impact of virgin production.

In modeling the sensitivity analysis for the container code and improved scenarios, all product properties and material assemblies, except for the container steel under investigation, are kept constant, equivalent to the building envelope parameters described in the bill of materials (*refer to Table 5.2).* The only changing parameter is the weight of environmental loads of containers associated with a specifically selected scenario. The service life expectancy is adjusted to align with the assumption of each scenario analyzed. For example, in analyzing the 50/50 method scenario, the container service life assumes 25 years lifespan for the second life cycle. In contrast, other building materials under analysis assume at 50 years lifespan based on the overall study life cycle expectancy. Nevertheless, within the product's two life cycles, 50 years of study, lifespan is maintained for all scenarios.

5.1.3 Building Life-cycle Cost Analysis

Life cycle costing (LCC) evaluates the overall economic performance of the four-case studies: container code (CC), lightwood code (LC), improved container (IC), and improved lightwood (IL) in order to determine the economic life cycle benefit of container-based housing and if it can result in better cost investment decisions in housing. The LCC calculation considers establishing the main assumptions and parameters, estimating all building costs and time of occurrences, discounting future costs to present value, computation, and comparative analysis of results (Fuller & Petersen, 1996). The study sums up the initial investment costs, energy costs, non-energy operation, maintenance, and repair costs for 50 years lifespan. Capital replacement costs, water costs, and residual costs are excluded from this study. Using Equation 1 (Eq. 1), the total life-cycle cost calculates:

Eq. (1).

$$LCC = I + E + OM\&R$$

where:

LCC = Total LCC in present-value dollars

I = Present-value investment costs

E = Present-value energy costs (electricity)

OM&R = Present-value non-fuel operating, maintenance, and repair costs.

The present value method prepares a comparable cost and transfers all project timeline costs to a base year (Linn Liu et al., 2016). Discounting all future costs to a present-value equivalent as of the study base date (2018) offers a near-accurate estimation for the LCC analysis (Fuller & Petersen, 1996). A 6% discount rate sums up all gains and losses occurring at different periods to present value (Kotaji et al., 2003; Snodgrass, 2008). The study estimates electricity costs at a base rate of $0.068/kWh based on residential electricity supply regulation assuming price index rates of 0.3% for all future costs (Alberta Government, 2017). The single present value (SPV) factor discounts a one-time occurring cost (X), calculated using Eq. 2 (Fuller & Petersen, 1996). For annually recurring costs, Y (i.e., annual operational cost), the uniform present value is calculated in Eq. 3 (Fuller & Petersen, 1996). For other non-recurring costs, Z (i.e., energy cost), the present value (PV) is calculated using Eq. 4 (Fuller, & Petersen, 1996).

Eq. (2). *single present value (SPV)*

$$X = \frac{F_t \times 1}{(1+d)^{t}}$$

Where: F_t = Future cash amount occurring at the end of the year t, d = 6% discount rate. The single present value (SPV) factor is used to calculate the present value of a future cash amount occurring at the end of the year, t F_t given a discount rate, d.

Eq. (3). *uniform present value (UPV)*

$$Y = A_o \times \frac{(1+d)^n - 1}{d(1+d)^n}$$

The UPV factor is used to calculate the PV of a series of equal cash amounts that recur annually over a period of n years.

Where: n = 50 years, d = 6%

Eq. (4). *non-uniform recurring cost*

$$Z = A_o \frac{(1+e)}{1+d}\left[1 - \frac{(1+e)}{(d-e)}^{n}\right]$$

The UPV factor is used to calculate the PV recurring annual amounts that change from year to year at a constant escalation rate, e over n years given d.
Where: n = 50 years, d = 6%, e = 3%

Initial investment costs include all costs incurred up to the land acquisition, design, and construction costs, including personnel, materials, and transportation. Based on market data gathering for single-family housing, construction costs are estimated at nine \$9/m^2 and \$12/m^2 for modular (shipping container house) and conventional (lightwood house) construction respectively (Altus, 2017; Ladacor Advanced Modular System, 2018). Estimating design costs at 1.5% of construction costs follow similar project development and design standards (Ford, 2017). For the improved cases, an additional lump sum of (CAD 12,000) is added to the investment costs to cover the cost of building envelope upgrades (Modular Home Owners, 2015). The annual building non-energy operation, maintenance, and repair costs (OM & R) costs per annum are estimated at \$3,190, \$4,189, \$3,346, and 4,345 for CC, LC, IC, and IL, respectively. These values are brought to the present value using the equation. The energy costs are estimated based on operational energy consumption. The life cycle costing is then calculated for the case studies.

5.2 Presentation and Analysis of Results

This section presents the results of a comprehensive LCA and LCC study of the four (4) case studies in Calgary, Canada. These include container code (CC), lightwood code (LC), improved container (IC) and improved lightwood (IC). The discussion of the sensitivity analysis of the container-based structures (i.e., container code – CC and improved container – IC) focuses on environmental burdens of product extraction, manufacturing and disposal, and avoided impacts associated with embodied impacts throughout the life cycle stages. Results of comparative building life cycle costs for initial investment, energy cost and non-energy related costs is also presented.

5.2.1 Life Cycle Assessment Results

This section presents results on environmental life cycle assessment results of nine impact categories: global warming potential (GWP)**,** smog potential (SP)**,** total primary energy (TPE), fossil fuel consumption (FFC)**,** acidification potential (AP), human health particulate (HHP), ozone depletion potential (ODP), eutrophication potential (EP), and solid wastes generation (SWG). Tables 5.3. summarizes the results of the total life cycle impact assessment for 50 years lifespan presented in absolute values. Other LCA results are presented in three life cycle phases: pre-use, use and operation, and end of life.

Total Life Cycle Impacts. The LCA results of the code models (CC and LC) show that majority of the life cycle environmental impacts (over 95%) occur at the use and operation phase, followed by the pre-use phase (about 4%), except for SP and EP. The end-of-life phase has a negligible impact (less than 1%). For the improved models (IC and IL), the results show that the use phase and operation phase also dominates the life cycle impacts (average 92% of total impact); however, a higher pre-use impact (7% of the total impact) is reported. The end-of-life phase remains negligible at only 1%. The SWG shows the least reduction of 13% less than CC. The SWG results suggest significant end-of-life impact (36% - 54%) contributions to the total life cycle impact with the improved cases showing much higher impact than the code scenarios.

These results are comparable to LCA findings published in the literature (Faludi et al., 2012; Kim, 2008; Kumar, V., Hewage, K., & Sadiq, 2015; Ramesh et al., 2010). For example, Kumar et al. (2015) and Kim (2008) report that operational energy and operational environmental impacts account for 93-95% of the total life cycle impacts. Previous studies also show approximately 1% as a percentage impact associated with the end of life phase (Faludi et al., 2012; Ramesh et al., 2010). While the results suggest use and operation phase dominates the four case studies' life cycle impacts, the pre-use phase increases from 4% for the code cases to 7% for the improved cases. However, higher pre-use impact is recorded for SP and EP categories, between 20-34% and (63-77%) at the use and operation phase. Higher impact at the use and operational phase for SP and EP is observed for the code cases.

This demonstrates the potential benefits of improved energy performance to reduce the use and operation impacts of conventional and modular building systems, including container-based units. Nevertheless, it is essential to point out that envelope upgrade could lead to a possible increase in embodied impact emissions (especially at pre-use and end-of-life phases) as suggested by this study. Comparative life cycle assessment between the container cases to lightwood cases shows only a 3% difference in environmental impact across most LCA measures. Overall, a total life cycle reduction of 28% average is expected comparing the container code (CC) to the improved container (IC) across most impact categories.

Table 5.3 Results of Life Cycle Impact Assessment by Life Cycle Phases

Global Warming Potential (t CO2 eq)				
	Container Code (CC)	Lightwood Code (LC)	Improved Container (IC)	Improved Lightwood (IL)
Pre-use	51	46	60	52
Use and operation	1,257	1,292	878	908
End of life	2	2	3	3
Total LCA	1,310	1,340	941	963
Smog Potential (kg O3 eq)				
	Container Code (CC)	Lightwood Code (LC)	Improved Container (IC)	Improved Lightwood (IL)
Pre-use	4,343	4,762	5,282	5,369
Use and operation	16,595	16,910	11,711	11,972
End of life	612	927	843	1,097

Total LCA	21,550	22,599	17,836	18,438
Total Primary Energy (GJ)				
	Container Code (CC)	Lightwood Code (LC)	Improved Container (IC)	Improved Lightwood (IL)
Pre-use	692	729	833	816
Use and operation	16,118	16,637	11,259	11,724
End of life	29	34	38	40
Total LCA	16,840	17,400	12,130	12,580
Fossil Fuel Consumption (GJ)				
	Container Code (CC)	Lightwood Code (LC)	Improved Container (IC)	Improved Lightwood (IL)
Pre-use	592	627	698	692
Use and operation	15,515	16,006	10,823	11,276
End of life	29	34	38	40
Total LCA	16,136	16,666	11,559	12,008
Acidification Potential (kg SO2 eq)				
	Container Code (CC)	Lightwood Code (LC)	Improved Container (IC)	Improved Lightwood (IL)
Pre-use	270	334	325	369
Use and operation	7,005	7,193	4,890	5,059
End of life	21	29	28	34
Total LCA	7,297	7,555	5,243	5,462
Human Health Particulate (kg PM2.5 eq)				
	Container Code (CC)	Lightwood Code (LC)	Improved Container (IC)	Improved Lightwood (IL)
Pre-use	51	51	64	60
Use and operation	900	921	629	648
End of life	2	1	2	1
Total LCA	953	974	695	709
Ozone Depletion Potential (mg CFC-11 eq)				
	Container Code (CC)	Lightwood Code (LC)	Improved Container (IC)	Improved Lightwood (IL)
Pre-use	334	235	288	295
Use and operation	74	76	70	72
End of life	0	0	0	0
Total LCA	408	312	358	367
Eutrophication Potential (kg N eq)				
	Container Code (CC)	Lightwood Code (LC)	Improved Container (IC)	Improved Lightwood (IL)
Pre-use	17	18	20	21
Use and operation	54	55	38	39

End of life	1	2	2	2
Total LCA	71	75	60	62
Solid Wastes Generation (Tonnes)				
	Container Code (CC)	Lightwood Code (LC)	Improved Container (IC)	Improved Lightwood (IL)
Pre-use	13	17	17	22
Use and operation	91	95	64	68
End of life	57	90	73	104
Total LCA	160	202	154	194

Pre-use Impacts. Figure 5.2 presents a breakdown of the total pre-use environmental impact of the four case studies. The improved models (IC and IL) show a higher impact at this phase due to the increased embodied emissions of additional materials used for the envelope upgrade. Similar findings correspond with LCA studies on energy-efficient buildings (Faludi et al., 2012; Kamali & Hewage, 2016; Paleari et al., 2016). To that effect, improved container (IC) claims the higher average embodied impact values, an increase between 18% - 25% across six impact categories (e.gs., GWP, TPE, FFC, SP, AP and HHP). The improved lightwood case (IL) has the highest impact of 37% increase for AP, and a significant increase of 70% for SWG when compared to container code (CC). The weighted amount of material solid wastes generation at the production and construction sub-phases accounts for a significant portion of this sum. The improved lightwood (IL) shows a higher impact on AP, EP, and SWG because of the greater amount of construction timber waste and dust. Overall, the container code (CC) has the least embodied emissions across most LCA measures compared to other cases, except for the GWP and ODP categories. The lightwood code (LC) has a much lower impact on the ODP, 29% less pre-use impact than the CC.

Considering a more specific analysis focused on embodied carbon emissions (GWP), the lightwood cases outperform the container models. For example, 10% of initial embodied carbon emissions can be mitigated by selecting the lightwood code (LC) over CC. The Global Warming Potential (GWP) metric measures impacts of greenhouse gases relative to carbon dioxide (CO_2) emissions in Tonnes. These results are expected due to the higher embodied energy intensity required to manufacture steel studs and insulation utilized in the container design. Whereas the lightwood models are designed with natural materials, such as wood stud and batt insulation which requires a low level of industrial processing, higher embodied energy is required during the manufacturing of steel products. The production and industrial processing of steel and spray polyurethane foam insulation requires greater petroleum consumption, resulting in increased embodied energy, carbon emissions, and other related embodied impact.

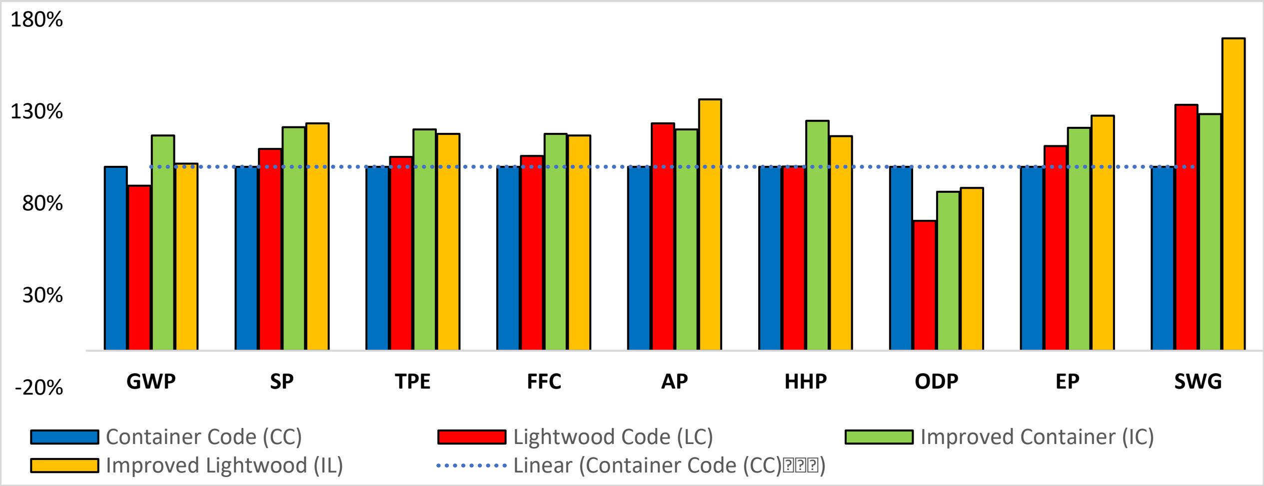


Figure 5.2 Results of Pre-use Impacts Relative to Container Code (CC)

Use and Operational Impacts. Figure 5.3 illustrates the result of the environmental impacts at the use phase and operation phase. Comparing the case studies featuring similar building envelope characteristics (e.g. CC to LC), an average difference of 3-4% is observed across impact categories (i.e., GWP, TPE, FFC, AP, HHP, EP, and SWG). The findings are comparable to the results reported by Van Ooteghem and Xu (van Ooteghem & Xu, 2012).

Lowering the modular container design’s infiltration rates to assume an airtight envelope can significantly improve thermal performance (Kim, 2008). However, this is not the case for this study as the same envelope airtightness is adopted for comparable cases (0.6 ACH @ 50 Pa).

For the improved cases, the effects of building envelope upgrade in reducing operating energy is witnessed in the results of most impact categories. For instance, the improved container (IC) shows approximately 30% lower operational impact than the container code (CC) across all impact categories, except for ODP. Clearly, the reduction in environmental impacts witnessed with the IC model results from the envelope upgrades and not credited to the container performance. Similar results are reported for the lightwood scenarios. A combination of envelope design techniques in the improved cases creates the opportunity to reduce the operating energy use that often dominates most buildings’ life cycle environmental impacts.

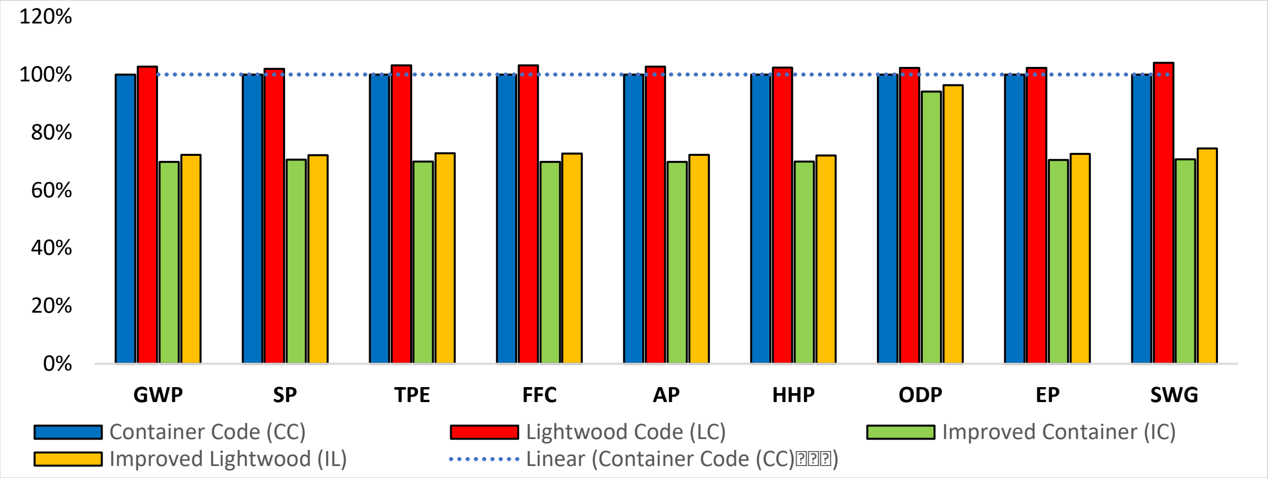


Figure 5.3 Results of Use Impacts Relative to Container Code (CC)

End of life Impacts. Limited LCA studies conducted on the end of life show that it contributes the least to the total life cycle environmental impacts (Faludi et al., 2012; Ramesh et al., 2010), and similar to this study as well. The results of the four case studies (Figure 5.4) show identical impacts for three out of nine impact categories studied (e.gs., GWP, PEU, and FFC).

The lightwood cases show higher impacts between 15 – 35% for GWP, TPE, FFU, AP, and ODP, than the container cases. It is paramount to underline that demolition and disposal of the traditional timber house result in a significant amount of solid wastes generation (60%) of SWG and release of air pollutants, leading to increased environmental impacts. The improved lightwood reports the highest end-of-life impact between 77% - 84% for SP, EP and SWG impact categories. Clearly, the associated environmental impacts for the wood-based products are higher than that of container steel products with greater recycling potentials. However, for the HHP impact category, about 44 - 47% lower impact is attained with lightwood cases as a result of wood-based natural materials with less human health impact. Overall, the container cases out-performs the lightwood cases, with the container code (CC) having the least impact across most indicators.

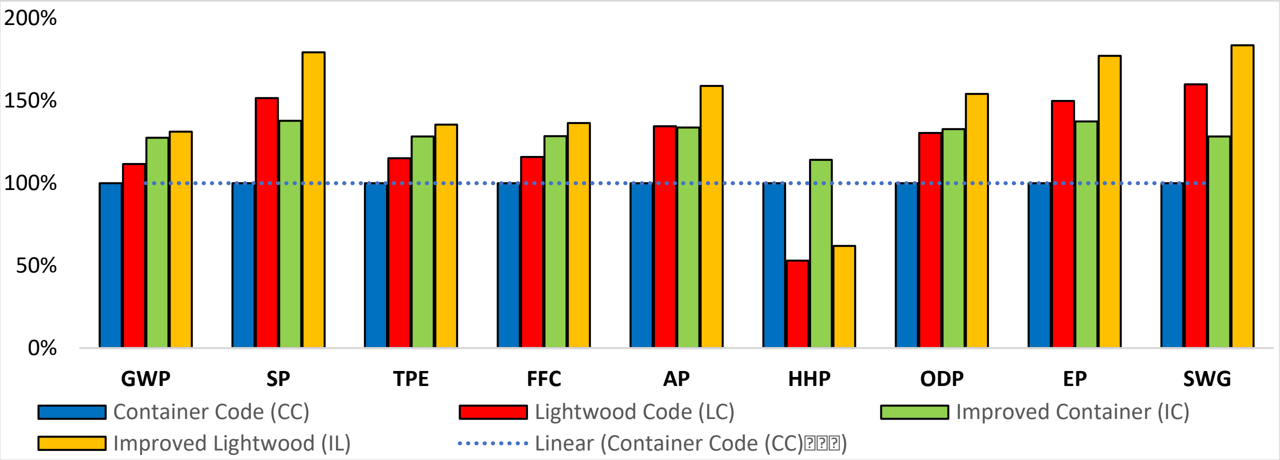


Figure 5.4 Results of End of Life Impacts Relative to Container Code (CC)

5.2.2 Results of Sensitivity Analysis of Container Models

Table 5.4 presents a summary of the results for the sensitivity analysis. Results are presented for embodied impact at different life cycle stages and total life cycle embodied impacts for the six Scenarios: CC (0:100), CC (50/50), CC (100:0), IC (0:100), IC (50:50) and IC (100:00).

Table 5.4 Results of Sensitivity Analysis of Container Code (CC) and Improved Container (IC)

Global Warming Potential (t CO2 eq)						
	Container Code (CC)			Improved Container (IC)		
	Scenario CC (100:0)	Scenario CC (50:50)	Scenario CC (0:100)	Scenario IC (100:0)	Scenario IC (50:50)	Scenario IC (0:100)
Pre-use	38	51	63	47	60	72
Use and operation	4	4	4	4	4	4
End of life	2	2	3	2	3	3
Total embodied impact	44	57	70	53	66	79
Smog Potential (kg O3 eq)						
	Container Code (CC)			Improved Container (IC)		
	Scenario CC (100:0)	Scenario CC (50:50)	Scenario CC (0:100)	Scenario IC (100:0)	Scenario IC (50:50)	Scenario IC (0:100)
Pre-use	3,504	4,343	5,180	4,113	4,934	5,753
Use and operation	419	419	419	419	419	419
End of life	542	612	681	645	714	783
Total embodied impact	4,466	5,374	6,280	5,177	6,067	6,956
Total Primary Energy (GJ)						
	Container Code (CC)			Improved Container (IC)		
	Scenario CC (100:0)	Scenario CC (50:50)	Scenario CC (0:100)	Scenario IC (100:0)	Scenario IC (50:50)	Scenario IC (0:100)
Pre-use	537	692	847	679	833	987
Use and operation	63	63	63	63	63	63
End of life	23	29	36	31	38	44
Total embodied impact	624	785	946	773	934	1,095
Fossil Fuel Consumption (GJ)						
	Container Code (CC)			Improved Container (IC)		
	Scenario CC (100:0)	Scenario CC (50:50)	Scenario CC (0:100)	Scenario IC (100:0)	Scenario IC (50:50)	Scenario IC (0:100)
Pre-use	454	592	729	560	698	834
Use and operation	47	47	47	47	47	47

End of life	23	29	35	31	37	44
Total embodied impact	524	668	811	638	782	925
Acidification Potential (kg SO2 eq)						
	Container Code (CC)			Improved Container (IC)		
	Scenario CC (100:0)	Scenario CC (50:50)	Scenario CC (0:100)	Scenario IC (100:0)	Scenario IC (50:50)	Scenario IC (0:100)
Pre-use	227	270	312	265	307	349
Use and operation	29	29	29	29	29	29
End of life	18	21	25	21	25	28
Total embodied impact	275	321	367	315	361	406
Human Health Particulate (kg PM2.5 eq)						
	Container Code (CC)			Improved Container (IC)		
	Scenario CC (100:0)	Scenario CC (50:50)	Scenario CC (0:100)	Scenario IC (100:0)	Scenario IC (50:50)	Scenario IC (0:100)
Pre-use	41	51	61	51	61	71
Use and operation	5	5	5	5	5	5
End of life	1	2	3	1	2	3
Total embodied impact	48	59	70	58	69	80
Ozone Depletion Potential (mg CFC-11 eq)						
	Container Code (CC)			Improved Container (IC)		
	Scenario CC (100:0)	Scenario CC (50:50)	Scenario CC (0:100)	Scenario IC (100:0)	Scenario IC (50:50)	Scenario IC (0:100)
Pre-use	334	334	334	288	288	288
Use and operation	60	60	60	60	60	60
End of life	0.0	0.0	0.0	0.1	0.1	0.1
Total embodied impact	394	394	394	348	348	348
Eutrophication Potential (kg N eq)						
	Container Code (CC)			Improved Container (IC)		
	Scenario CC (100:0)	Scenario CC (50:50)	Scenario CC (0:100)	Scenario IC (100:0)	Scenario IC (50:50)	Scenario IC (0:100)
Pre-use	14	17	19	16	18	21
Use and operation	1	1	1	1	1	1
End of life	1	1	1	1	1	2

Total embodied impact	17	19	21	19	21	23
Solid Wastes Generation (Ton)						
	Container Code (CC)			Improved Container (IC)		
	Scenario CC (100:0)	Scenario CC (50:50)	Scenario CC (0:100)	Scenario IC (100:0)	Scenario IC (50:50)	Scenario IC (0:100)
Pre-use	13	13	13	17	17	17
Use and operation	3	3	3	3	3	3
End of life	56	57	57	72	73	73
Total embodied impact	72	72	73	92	92	92

The total life cycle embodied emissions is highly influenced by the amount of embodied impact across all studied LCA categories. Except for solid waste generation (SWG), results of sensitivity analysis suggest that the pre-use phase accounts for a significant amount of the embodied impact across all scenarios. Comparing the pre-use impact for the container code scenarios to improved container scenarios, higher embodied impact is recorded for the improved container scenarios. Embodied impacts at the pre-use phase account for a significant amount, between 82 – 90% of life cycle impact, followed by the use impact contributing between 5 –10% across most LCA measures. However, SP shows a higher impact at end-of-life (10%) contribution to life cycle impact than the use impact. The SWG results show a reverse trend, over 75% higher impacts in all scenarios at the end of life. The pre-use impact is approximately 18% for CC and IC scenarios.

Re-purposing four 40-foot container modules (8 "twenty-foot equivalent units," or TEU) into housing can avoid about 26 (t of CO_2 eq) of carbon emissions to the atmosphere and 89,444 kWh (322 GJ) primary energy use as seen in this study. To put this into context, the avoided emissions can offset total greenhouse gas (GHG) emissions generated by an average household in Calgary for at least 1.5 years (Fercovic & Gulati, 2016). A typical household emits 18.2

tonnes of CO_2 equivalent in a year. On a larger scale, this implies that if only 50% of the shipping containers (about 2.7 million TEUs) that arrive at Port Metro Vancouver per annum are re-purposed into housing, approximately 11 megatonnes of CO_2 equivalent (11 Mt CO_2 eq) of GHG emissions can be avoided. Other indirect benefits will include reducing environmental burdens associated with the re-manufacturing and recycling of container steel after the first life cycle and avoiding environmental impacts relating to re-transportation to the country of origin.

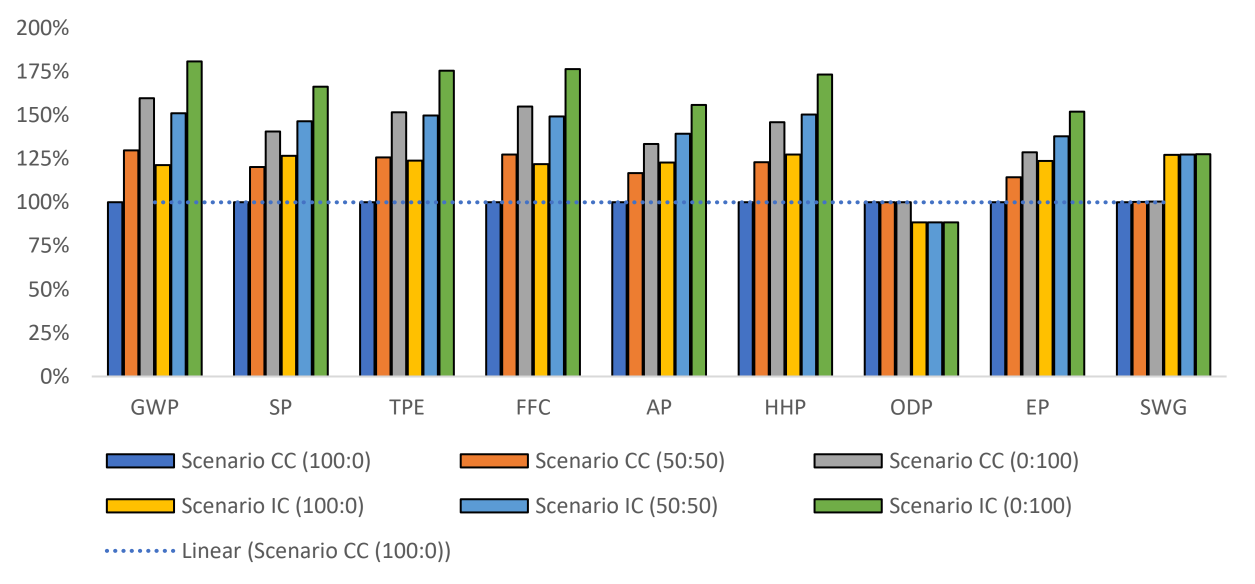


Figure 5.5 Sensitivity Analysis of Container Models Relative to Scenario CC (50:50)

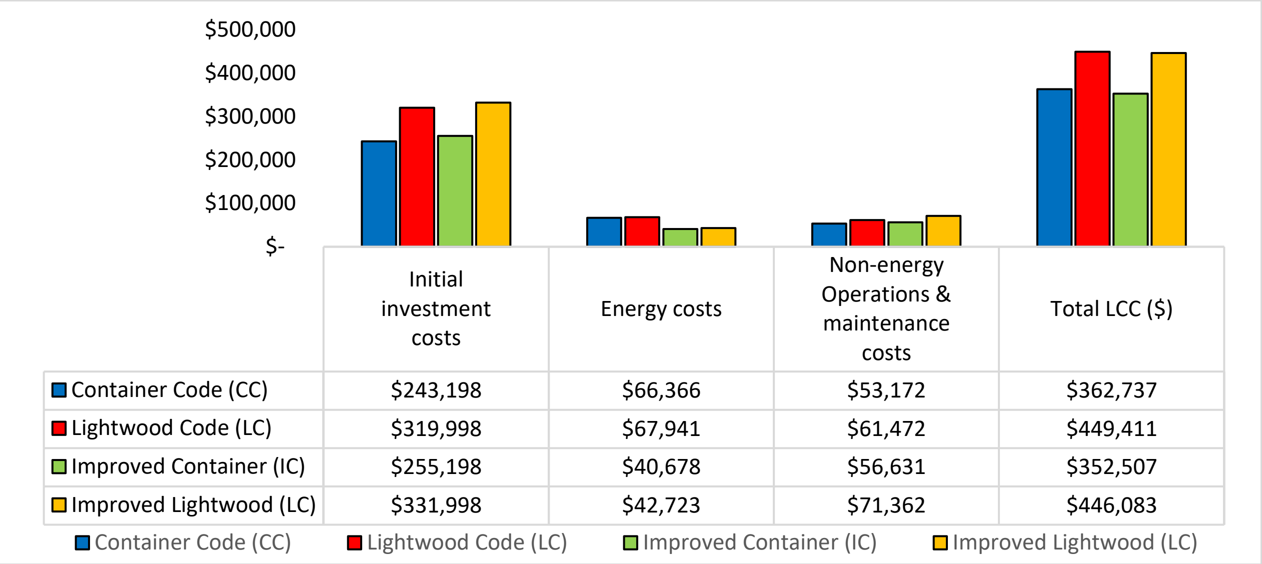
Considering the avoided impact, the container code Scenario 100:0 (cut-off method) performs better than other scenarios (code and improved container models) for all LCA measures except ODP and SWG (Figure 5 5). Scenario 100:0 avoids all environmental impacts associated with of manufacturing and processing of shipping container steel. To that effect, the Scenario CC (100:0) – cut-off method has the least embodied avoided impact up to 20% less than the Scenario CC (50:50). Comparing the Scenario CC (100:0) to the highest impact scenarios, Scenario CC (0:100) shows additional 46% impacts for the code cases. For the improved case, Scenario IC

(0:100) increases over 50% for most impact categories. The most avoided impact for the IC scenarios is witnessed for ODP (11%), lower than CC scenarios. The highest impact occurs for GWP, SP, TPE, FFU and HHP, while the least avoided impact occurs for SWG.

Although Scenario CC (100:0) – cut-off method results in the least environmental impacts in terms of life cycle embodied phases for the sensitivity analysis, a notable concern with adopting this method lies in the unequal distribution of environmental burdens of virgin material production. Scenario CC 100:0 benefits from the environmental credit of avoidance of embodied energy required to re-produce and recycle parent material steel processing. However, adopting the Scenario (50/50) based method, as with this study, provides the opportunity for even distribution of burdens of virgin material production, recycling impacts, and disposal impacts between two-product life cycles.

5.2.3 Building Life-cycle Cost Results

A comparative analysis of building life-cycle cost (Figure 5.6) shows higher initial investment costs for the lightwood cases than container cases (i.e., code and improved). A potential 32% of initial investment cost is obtainable utilizing container design based on the cost analysis. Whereas envelope upgrades increased the initial investment costs by 5% for the improved cases (IC and IL), 37-39% of lower energy costs are achieved through improved energy performance. The lightwood cases also increase by 26% for the non-energy operations & maintenance costs as it requires more maintenance over its life cycle. These include the cost of material replacement of wood-based products. As shown in the study, adopting the improved container (IC) will result in a 27% total life cycle cost savings over the improved lightwood (IL). Overall, the improved cases result in less than 5% reductions in total building life cycle costing.



	Initial investment costs	Energy costs	Non-energy Operations & maintenance costs	Total LCC ($)
🟦 Container Code (CC)	$243,198	$66,366	$53,172	$362,737
🟥 Lightwood Code (LC)	$319,998	$67,941	$61,472	$449,411
🟩 Improved Container (IC)	$255,198	$40,678	$56,631	$352,507
🟨 Improved Lightwood (LC)	$331,998	$42,723	$71,362	$446,083

Figure 5.6 Results of Life Cycle Costing of Case Studies

5.2.4 Discussion and Concluding Remarks

The chapter provides some innovations in developing envelope design concepts and an in-depth understanding of container-based housing life cycle performance. An integrated life cycle approach is employed to assess the benefits and challenges of re-purposing used shipping containers into a single-family house. This case study analysis helps assess the life cycle impact of a container-based modular house and compares its performance to the conventional lightwood house built in Canada. Over 50 years' lifespan, most life cycle environmental impacts of the four case study buildings occur at the use and operation phase, 92% for the improved cases, and 95% for the code cases. Whereas the improved cases benefit from envelope upgrade to reduce building operating energy, this also contributes to a much higher pre-use impact than the code cases (LC and CC). Overall, the comparative results of the life cycle assessment, from the cradle to the grave, show that lightwood cases compared to the container cases to lightwood cases, from the cradle to the grave, differ at most by only 3%. This indicates that regardless of the desired structural system, the difference in life cycle environmental impacts after 50 years is minimal.

Thus, re-purposing containers into permanent structures can match conventional buildings in terms of life cycle benefits.

Research findings also show with the improved container (IC) model that container-based buildings, like other structural systems, can benefit from low-energy design compared to building code specifications. While there are chances of increasing material volume and resources, embodied effects, and investment costs through an envelope upgrade as witnessed by this study, integrating energy-efficient measures such as high insulation levels and envelope airtightness in the IC case creates the opportunity to reduce operating energy that often dominates the total life cycle environmental impacts and life cycle costs of most buildings. This shows that although structural systems may influence the environmental performance of buildings (e.g. steel), the long-term impacts of incorporating energy-efficient measures, in terms of reducing building-associated life cycle environmental impacts, cannot be neglected.

If mass-produced, container-based modular housing can offer affordable/community housing in the future. As shown in this study, adopting the improved container (IC) will result in 27% total life cycle cost savings over the improved lightwood (IL). While social acceptance has inhibited its viability in the housing market, re-purposing containers in the design of affordable modular housing can promote low-cost housing delivery, especially in the rural communities in Canada. An action plan towards tackling the housing crisis by promoting affordable housing schemes through modular container-based units has begun in Canada (Alberta Rural Development Network, 2019). However, its adoption as a primary structural system targets market transition towards modular housing by promoting its sustainability benefits, the potential for mass customization and cost savings and financial returns on investment over its lifespan.

While the literature shows that wood-based construction compared to reinforced concrete and steel generally result in lower impacts as a result of less industrial processing (Zabalza

Bribián et al., 2011), research findings demonstrate that upcycling steel-based shipping containers and re-purposing them into housing structures may also result in lower environmental impact compared to wood-based housing. Whether this will offset the tremendous amount of embodied energy and carbon emissions required for steel re-manufacturing and recycling will also depend upon the material composition of the building envelope and energy-efficient technologies utilized in the design other than the container structural system. The study demonstrates that design decisions and careful selection of building materials can be prioritized and directed through a life cycle assessment. For instance, selecting materials with less embodied impact and a yet more significant amount of reusable content will reduce material impact intensity and benefit from a life cycle perspective.

The study further demonstrates that container-based units can contribute to the drive towards designing out wastes from the building. When comparing improved container case to improved lightwood case, it is paramount to underline that demolition and disposal of the traditional timber house result in a significant amount of solid wastes generation (26%) and the release of air pollutants leading to increased environmental impacts. Therefore, substituting lightwood code (LC) with container code (CC) can eliminate approximately 40 Tons of SWG over the 50 years of building lifespan based on this present study's considerations.

The container models' sensitivity analysis has highlighted some crucial issues for the life cycle assessment of recycled products. Comparing the container models to lightwood cases prove that the container code Scenario 100:0 (cut-off method) performs better than other scenarios (code and improved container models) for all LCA measures except ODP. However, a notable concern with adopting this method lies in the unequal distribution of virgin material production's environmental burdens. The emerging concept of the 50/50-based approach utilized in this study for the total life cycle assessment recognizes the equal allocation of environmental burdens, and credits for avoided impacts between two-product life cycle situations appear as a more realistic LCA approach allocation. Besides, the steel scrap gets recycled after its useful life as a container house.

Exploring the opportunity to utilize used shipping containers in housing construction can maximize its life cycle performance and address the global affordable housing problem. More research on life cycle assessment (LCA) and life cycle costing of upcycled container structures will benefit the transitioning to affordable, net-zero energy/carbon buildings. Further research may be required for large-scale residential and commercial applications to justify its benefits as a building system. If applied at the early design stage using an integrated life cycle approach, such research will provide more sustainable, long-term project decisions and support practical applications in Canada and elsewhere.

The next chapter focuses on the life cycle embodied impact of panelized container wall systems to build on the research findings from this chapter. Chapter 6 focuses on reducing the life cycle embodied impact associated with the wall assembly design. It presents an in-depth study of the different exterior and adjacent wall envelope scenarios and assesses the life cycle embodied impacts energy (MJ) and global warming potential (kg CO_2 eq.).

Chapter 6 Life Cycle Assessment of Building Materials and Components

Container-based Wall Systems

Chapter 6 provides a detailed analysis of the wall assemblies for potential low-impact design over its life cycle. The chapter focuses on evaluating the design of various materials choices that reduce the life cycle impact associated with the wall assembly. It presents an in-depth study of the different exterior and adjacent wall designs and assesses the life cycle embodied impacts energy (MJ) and global warming potential (kg CO_2 eq.). This research is presented as a conference paper and currently accepted for journal publication with "The Constructed Environment"[4]

6.1 Design and Methodology

This chapter evaluates how different modular wall envelope compositions influence the life cycle energy and life cycle GWP of container-based units. It intends to identify a wall assembly material composition that results in low energy and low-carbon impact over its life cycle.

The study objectives are:

1. Explore three (3) alternatives (i.e., exterior, middle, and interior) to integrate shipping container panels as part of the exterior wall envelope
2. Investigate building material selections for "adjacent wall" connecting two modular apartments using four (4) modular wall designs.

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[4] **Dara, C.,** & Hachem-Vermette, C. (2021). Life cycle embodied energy and carbon emissions of panelized wall systems. *International Journal of Architectonic, Spatial, and Environmental Design*. *The Constructed Environment.* Artcile 76440: Final Mansucript Accepter for December 2021 Publication (Vol. 4).

6.1.1 Athena Impact Estimator Methodology

The Athena IE includes cradle-to-cradle life cycle stages of resource extraction; manufacturing; construction; transportation; maintenance; replacement of building materials; building operation; demolition; disposal; and beyond life. Although various environmental impact categories exist, the study focuses on assessing the environmental impacts of two main categories: life cycle primary energy (MJ) and life cycle global warming potential (kg CO_2 eq) from the cradle to the grave.

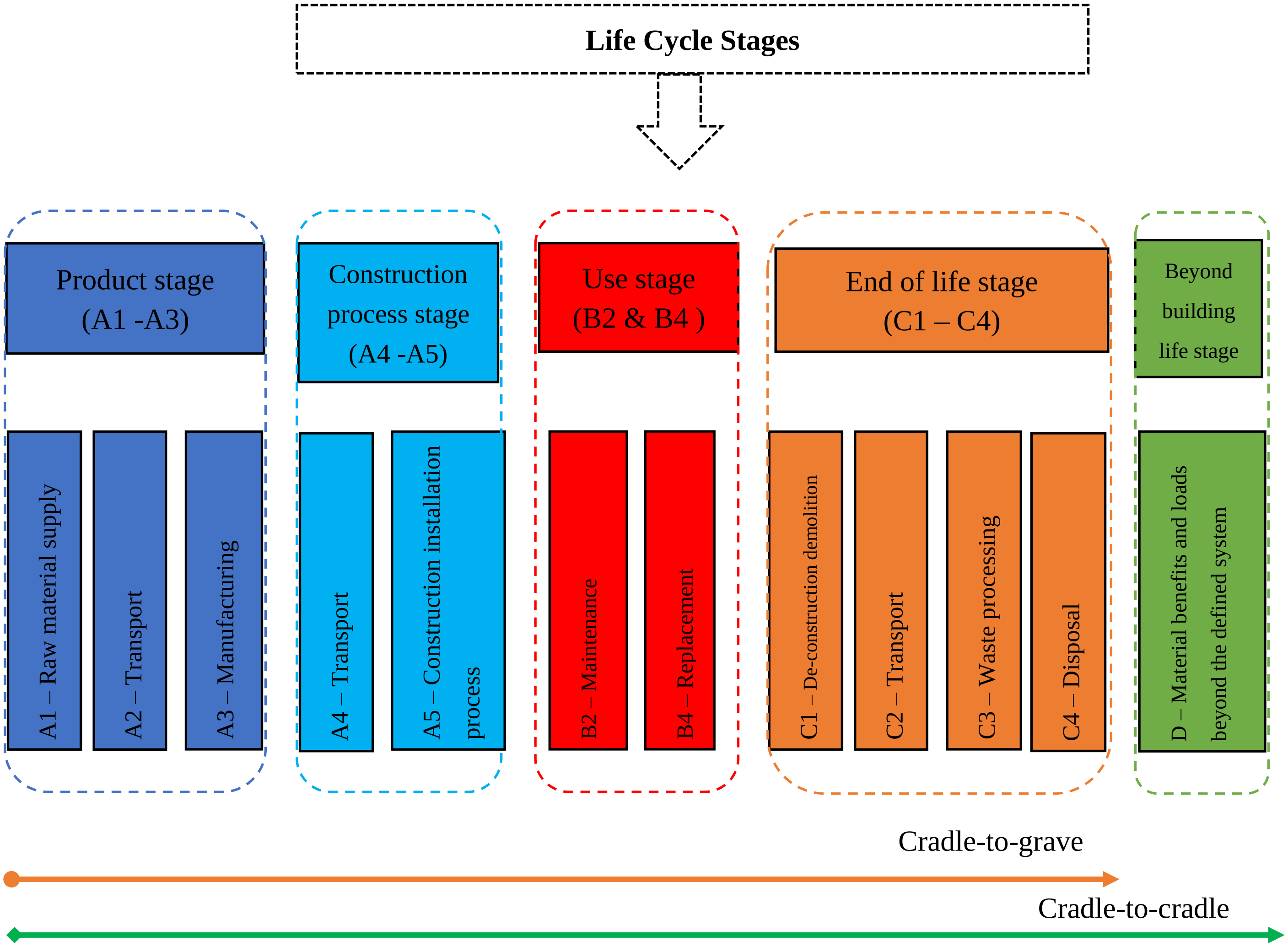


Figure 6.1 System Boundary

Figure 6.1 represents an illustration of the system boundary. The study also assesses cradle to cradle of studied scenarios to highlight additional material benefits and loads beyond the defined system boundary. It excludes operational energy use (B6) from this analysis because all scenarios are optimized, and preliminary results of energy analysis report no significant change in performance. Nevertheless, chapter 5 covered the above topic extensively as part of the thesis key research findings. The selected life cycle parameters are considerable with the exclusion of operational energy contributions at the use phase, given that it intends to focus on providing results on low material impacts.

6.1.2 Container-based Wall Systems under Analysis

This study examines the life cycle impact of building materials used in designing two container-based wall systems: exterior and adjacent unit wall assemblies. The case study comprises two adjoining apartments with a total floor area of approximately 178 m^2. The first research milestone is to re-configure the exterior walls by varying the container panel position in the wall assembly for three alternatives. Scenario 1a maintains the case study typical application as a middle panel. Scenario 1b represents the integration of the container panel as part of the exterior building façade. Scenario 1c assumes the design as an interior side of the wall.

The exterior wall assemblies assume the same thickness for typical material compositions irrespective of the change in products. For example:

- insulation thickness of 128 mm (RSI 4.41)
- drywall thickness of 16 mm
- 12.7 mm-oriented strand board as wall sheathing
- 50/50-based environmental impact allocation method for the shipping containers.

This research follows a 50/50 method of allocating burdens for the upcycled container model based on the sensitivity analysis study results (Dara et al., 2019). This approach provides the opportunity for an even distribution of burdens of virgin material production, recycling impacts, and disposal impacts between the two-product life cycles.

The adjacent unit wall design selects four scenarios based on the need to reduce embodied impacts associated with building materials by reducing the quantity (amounts) of materials utilized in the design of multiple modular units (Figure 6.2). The scenarios assume a variety of complete envelope design and partition wall separation (Scenario 2a -2d). They question contemporary modular construction practices of installing complete envelope materials on both sides of an apartment's adjoining units. It also tries to explain if high-performance insulating materials alone or/and gypsum board will significantly reduce the life cycle embodied impact of the wall systems.

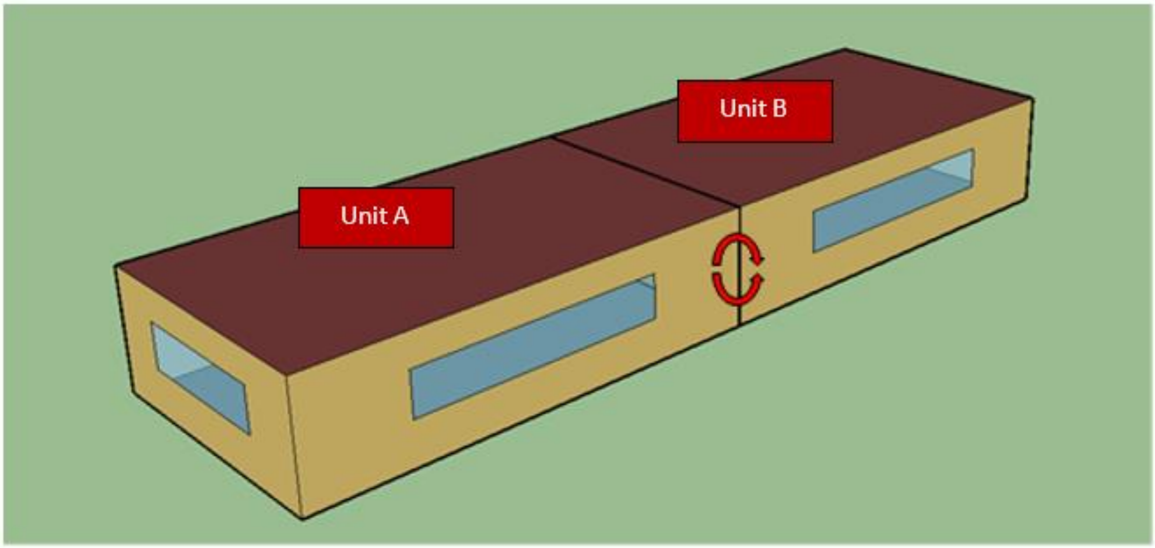


Figure 6.2 Three-dimensional Perspective Showing Adjacent Wall under Analysis

Scenario 1: Exterior Wall Design

Scenario 1a **–** is designed as a middle panel (Figure 6.3) to retain the steel stud framing as the most typical application in Canada (Hachem-Vermette et al., 2018; Ladacor Advanced Modular System, 2018). It assumes wood (Hardie plank) siding exterior finish as façade covering and gypsum board interior finish. Light gauge 92 mm steel stud is installed at 610 mm spacing to help keep the thermal insulation in place (Canada Mortgage and Housing Corporation, 2014). This advanced framing approach involves increasing stud spacing from 405 mm standard to 610 mm, reducing the amount of steel materials while allowing for more insulation and less heat loss through the building envelope (Way & Kendrick, 2008). This is possible as the stud is not necessarily a load-bearing frame. Although reduced stud web area could be considered a design option to reduce thermal bridging effects, Athena data input allows for full stud web design during the modeling process.

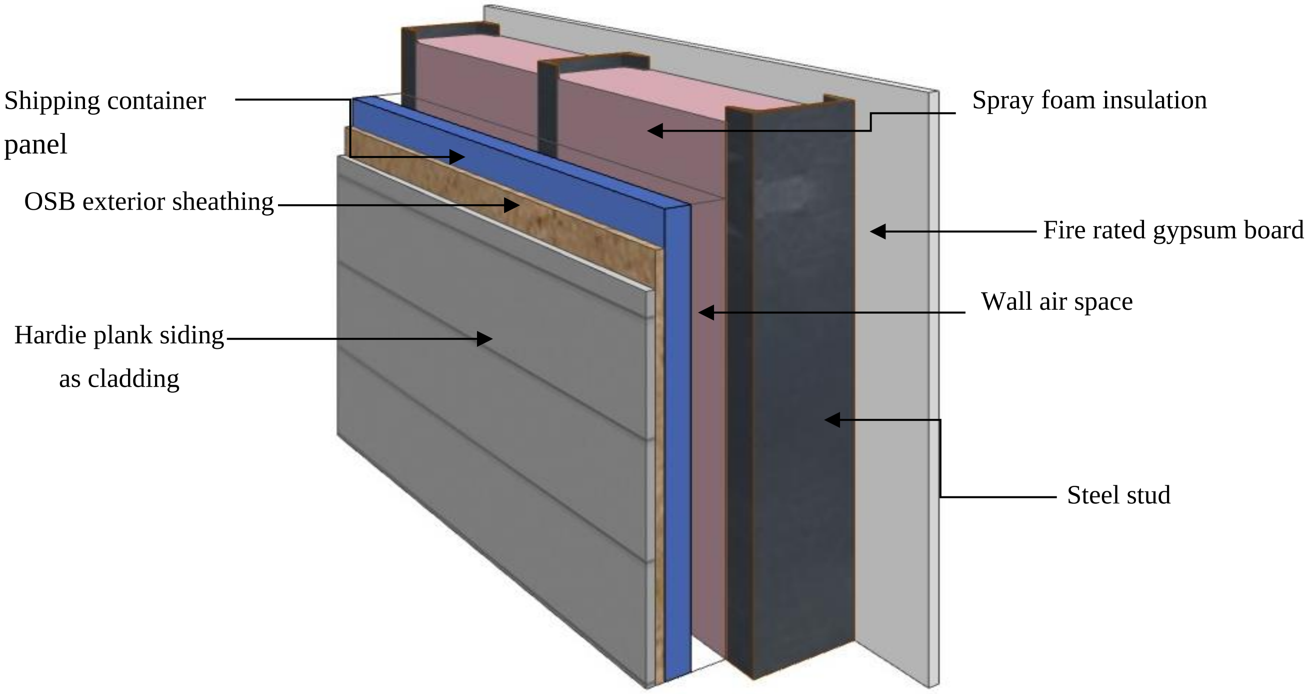


Figure 6.3 Typical Middle Panel Design

***Scenario 1b* –** Exterior panel utilizes the shipping container as the exterior envelope material (Figure 6.4). This envelope pattern most portrays the container design as an element of the building facade. Scenario 1b uses wood furring strip boards to replace the steel stud. The board size of 19 mm x 89 mm is placed horizontally between insulated spaces to accommodate higher insulation thickness (Canada Mortgage and Housing Corporation, 2014). Wood furring strips are commonly applied in wood framing design to provide continuous channels for insulation material and reduce heat loss present in stud framing as well as mitigate the effect of thermal bridging.

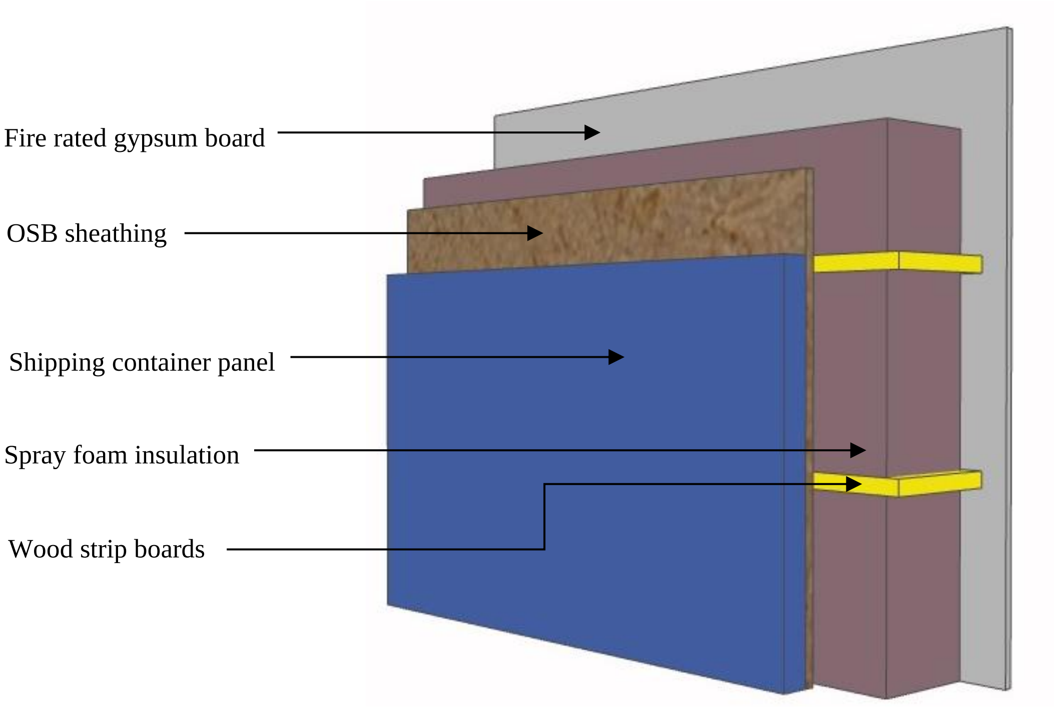


Figure 6.4 Exterior Panel Design

***Scenario 1c* –** Interior panel (Figure 6.5) considers eliminating the steel stud and introduces the insertion of the insulation panels into the corrugated container steel to provide higher thermal resistivity. These specially designed panels designed for container-based structures provide continuous insulation, thereby reducing thermal bridging effects between container metal and other materials (InSoFast, 2020). For this option, wood cladding is used as the exterior wall finish, while acoustic wall tiles are used as the drywall finish, closely attached to the interior container panel. The design assumes acoustic tiles as the interior wall finishes to reduce noise propagation into interior spaces common in steel structures.

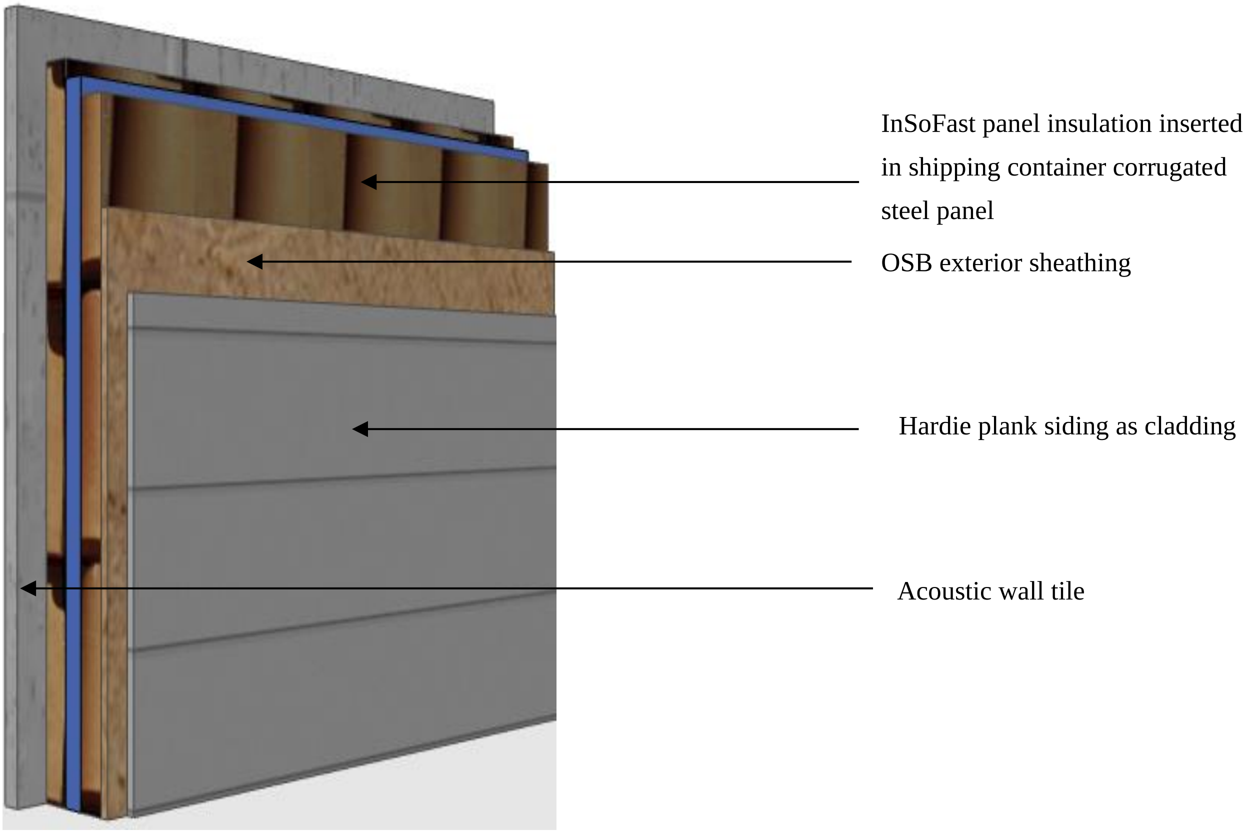


Figure 6.5 Interior Panel Design

Scenario 2: Apartment Adjacent Wall Design

A breakdown of the design parameters for the adjacent wall is as follows:

Scenario 2a – Double Full Envelope. The double-wall consists of full container envelope design on both walls (unit A and unit B) using the typical middle panel design. This is the most common modular application in practice. However, the design excludes the exterior wall cladding material between walls connections (Figure 6.6).

Scenario 2b – Single Full Envelope. Consists of full envelope design for unit A and 16 mm fire-rated gypsum board attached to container panel as unit B wall design (Figure 6.7). The concepts seek to reduce the number of materials used in the design of the adjacent wall.

Scenario 2c – Container Panel Only. 16 mm fire-rated gypsum board attached to the container panel for both unit A and unit B from the inside (Figure 6.8). Here the container panel acts as the main envelope structure, whereas the gypsum boards assume interior finishes on both sides of the wall. The analysis excludes other wall components.

Scenario 2d – *Insulation Only.* 16mm fire-rated gypsum board for both walls (unit A and unit B) with the insertion of 128 mm spray foam insulation, RSI 4.41 in-between (Figure 6.9). This scenario assumes complete removal of the container panels from both walls (cut-off).

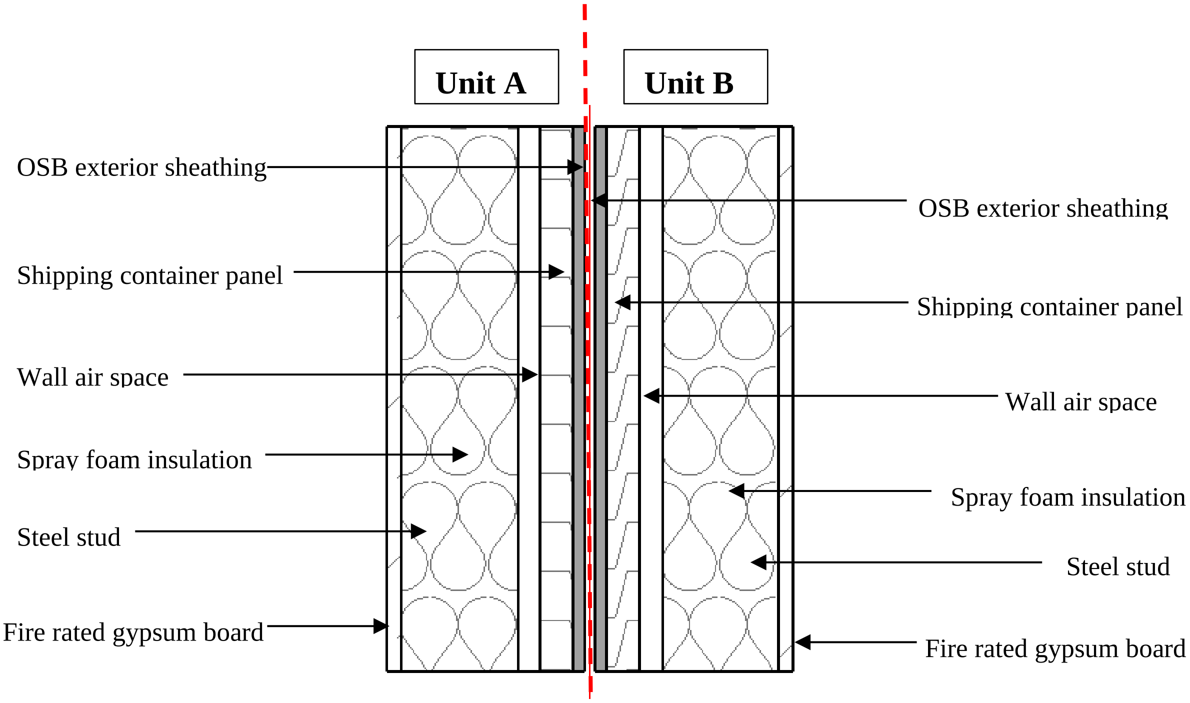


Figure 6.6 Scenario 2a, Double Full Envelope Design

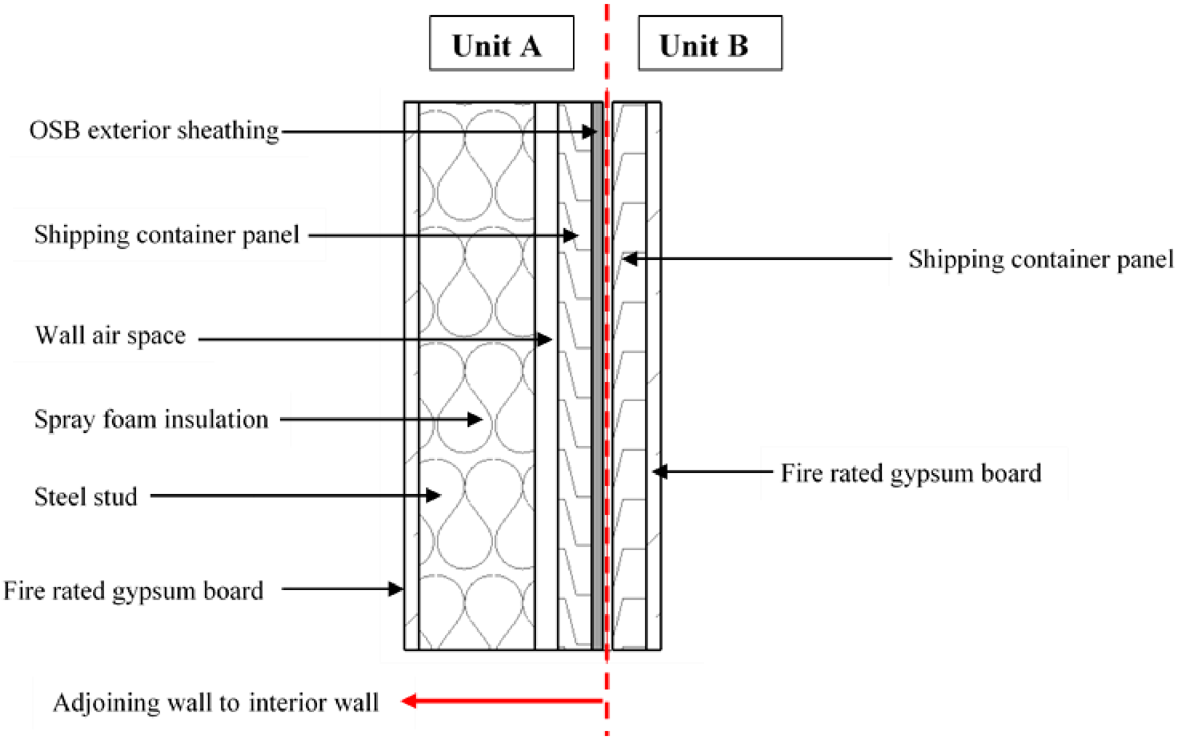


Figure 6.7 Scenario 2b, Single Full Envelope Design

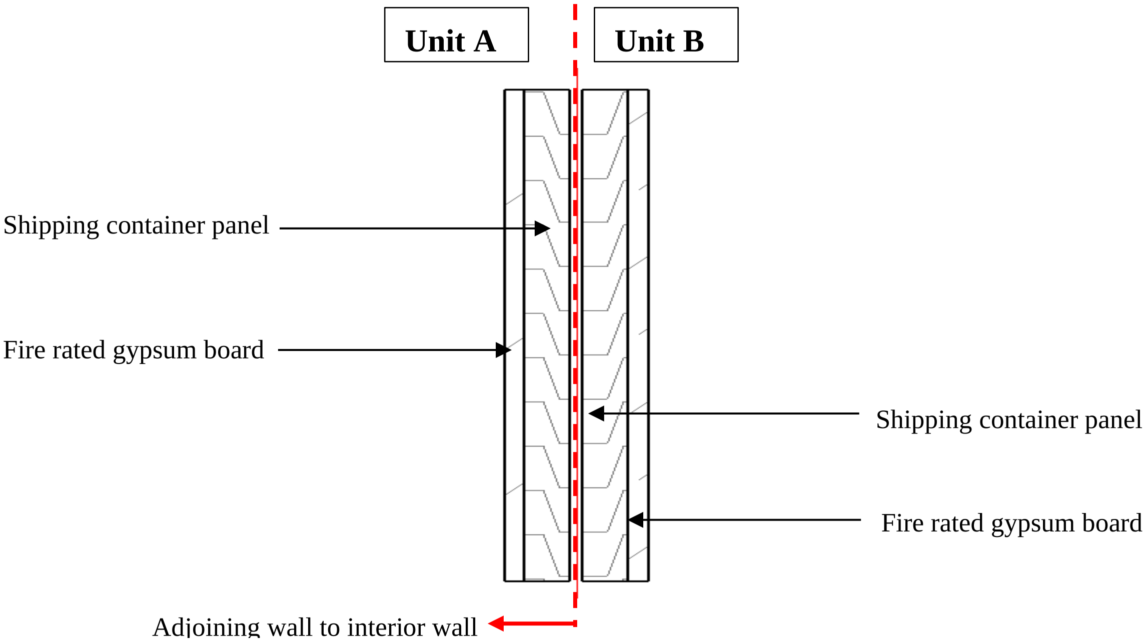


Figure 6.8 Scenario 2c, Container Panel Only

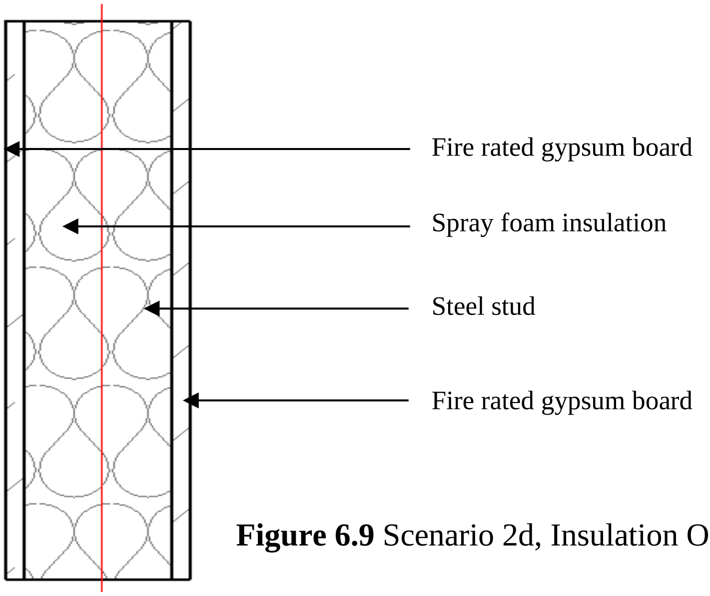


Figure 6.9 Scenario 2d, Insulation Only

6.1.3. Minimizing the Effects of Thermal Bridging in Container Wall Envelope

Crucial design consideration for container-based structures is to find ways of reducing thermal bridging effects within the wall envelope. Steel products having higher thermal conductivity than their surrounding insulating materials often lead to thermal bridging. The thermal conductivity of a material is determined as the rate at which heat passes through it. The lower the conductivity, the more thermally efficient the material will be.

A strategy used in this study to mitigate the effects of thermal bridging is to provide continuous thermal insulation with spray foam insulation using wood furring (e.g., Scenario 1b– Exterior Panel) and advanced framing using stud spacing (i.e., Scenario 1a– Typical Middle Panel). Spray foam insulation is characterized by high R-value (thermal resistance) with a slower rate of heat transfer compared to contemporary insulation materials (Pena and Schuzer, 2012). This further reduces the contact area between the high conductive steel material and other low conductive materials within the wall assembly. This approach has been successfully applied in similar studies to eliminate thermal or cold bridges in steel construction (Kosny, Childs, and Gorgolewski, 2002). Thermal resistivity, R-value or RSI is a measure of a material's resistance to heat flow.

A second strategy to eliminate thermal bridging effects applies to Scenario 1c - Interior Panel, involving the integrating insulating panels with the corrugated container panels. These insulating panels are inserted into the corrugated shipping container panel as thermal breakers to reduce heat flow rate within the high conductive steel material, thus eliminating the need for metal stud framing (InSoFast, 2020). The use of thermal breakers is crucial in the design of steel structures, and good thermal insulation material having a low thermal conductivity complements the steel design (Sadineni, Madala, and Boehm, 2011). In addition, Scenario 1c insulating panel takes on the physical characteristics of expanded polystyrene (EPS) foam, a non-toxic material, closed-cell insulation, which maintains high RSI value throughout its life cycle (InSoFast, 2020). The EPS polystyrene has low moisture permeability, ensuring moisture is not trapped in the wall envelope and serves as a Class III vapour barrier (CMHC 2014). It also acts as fire-retardant material when used as part of the wall component.

6.2 Presentation and Analysis of Results

This section presents the life cycle assessment results of embodied impacts associated with building materials and components of the wall systems. First, the life cycle GWP and life cycle primary energy of the exterior wall designs is presented, followed by results of the apartment unit connection (adjoining) wall. Scenario 1a- middle panel and Scenario 2a – double full envelope assumes the reference cases for the comparative analysis of the exterior and adjoining walls respectively. The reference scenarios are selected as they represent the typical industry application. However, this study presents its LCA research findings in absolute values.

6.2.1. Results: LCA Exterior Wall Systems

Life Cycle Global Warming Potential (kg CO_2 eq.). Figure 6.10 displays the total global warming potential of life cycle stages for three exterior wall envelopes. Results show a similar pattern of embodied impacts for the life cycle stages, from cradle to grave (i.e., product stage to the end of life). The product stage (A1-A3), comprising of raw material supply (A1), transport (A2), and manufacturing (A3), represents the most contributor for embodied carbon emissions throughout the building life cycle. Results show 76% for Scenario 1a middle panel, and 78% for Scenario 1b exterior panel designs. Scenario 1c, interior panel reports 73% as contributions of the product stage to the total life cycle. The product stage accounts for the highest embodied carbon emissions from upfront carbon associated with building material production and other material inherent initial embodied impact. The use phase, which for this study covers only the maintenance (B2) and replacement (B4), contributes between 14 – 21% of the recurring embodied carbon emissions for the exterior wall scenarios. The construction stage and end-of-life contribute less than 5% each to the overall life cycle GWP.

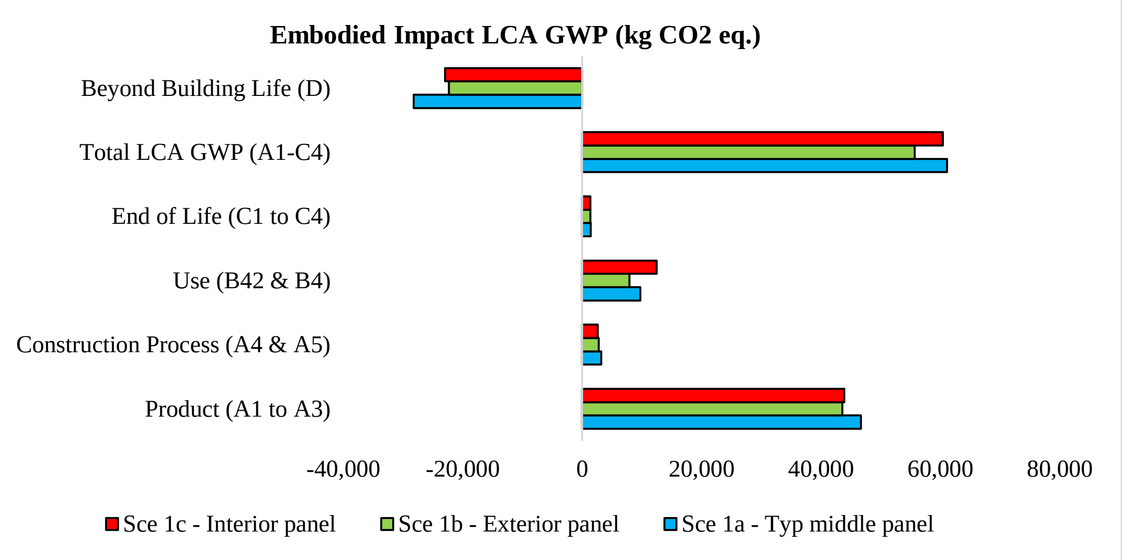


Figure 6.10 Comparison of Life Cycle GWP of Exterior Wall Systems

Total life cycle comparative results show Scenario 1b exterior panel as having the least embodied carbon emissions from cradle to grave (A1-C4). In other words, a total of 10% reduction in material carbon emissions (MCE) can be achieved by selecting Scenario 1b material choices (envelope design) over Scenario 1a typical industry application. At the use phase, up to 28% increase in recurring carbon emissions is anticipated for the interior panel (Scenario 1c) compared to Scenario 1a (middle panel). However, in Scenario 1b exterior panel design, further reduces its recurring embodied carbon emissions by 18% compared with the reference case (Scenario 1a) middle panel. Assessing the overall impact after the end-of-life (cradle to cradle) shows that including beyond building life stage (D) as part of the analysis can offset between 38% - 46% of embodied carbon emissions from recycled and reclaimed building materials for the exterior wall envelope. Further analysis of cradle to cradle proved that Scenario 1a designed with steel studs has a higher potential to recover material residues after the end of life, for possible recycling.

Life Cycle Primary Energy (MJ). The life cycle primary energy records a similar pattern of embodied impact contributions from the various building life cycle. Similarly, the product stage reports the highest embodied energy, between 73% - 80%, for the three scenarios in the life cycle impact from the cradle to the grave (Figure 6.11). Next, the use phase is between 13% - 21%.

The comparative LCA result shows the use phase as having the highest energy use variation for material maintenance and replacement. Replacing the steel studs with metal wood strips for insulation framing and replacing the wood cladding with container panels show a significant potential to reduce recurring embodied energy associated with maintenance and replacement of worn-out building materials. For example, adopting Scenario 1b, the exterior panel can reduce its embodied energy by 28% at the use phase. As the interior panel (Scenario 1c) wall requires additional material replacements for acoustic tile and insulating panels, a much higher embodied impact is expected (26% increase) compared to Scenario 1a, the reference case. Perhaps, the use of spray foam insulation reduces the need for maintenance and replacement for the above two scenarios. This points to the benefit of replacing high carbon materials with low carbon materials with less need for recurring embodied energy throughout the building life cycle.

Further assessment, cradle to cradle, shows 10% reclaimed embodied energy after end-of-life for the three scenarios. Overall, the cradle-to-cradle LCA of primary energy embodied in materials proof that careful selection of materials and components for the design of a container-based wall system can reduce life cycle primary energy by 94,000 MJ, approximately 12% reduction in embodied energy for the Scenario 1b, exterior panel compared to reference typical case design (Scenario 1a).

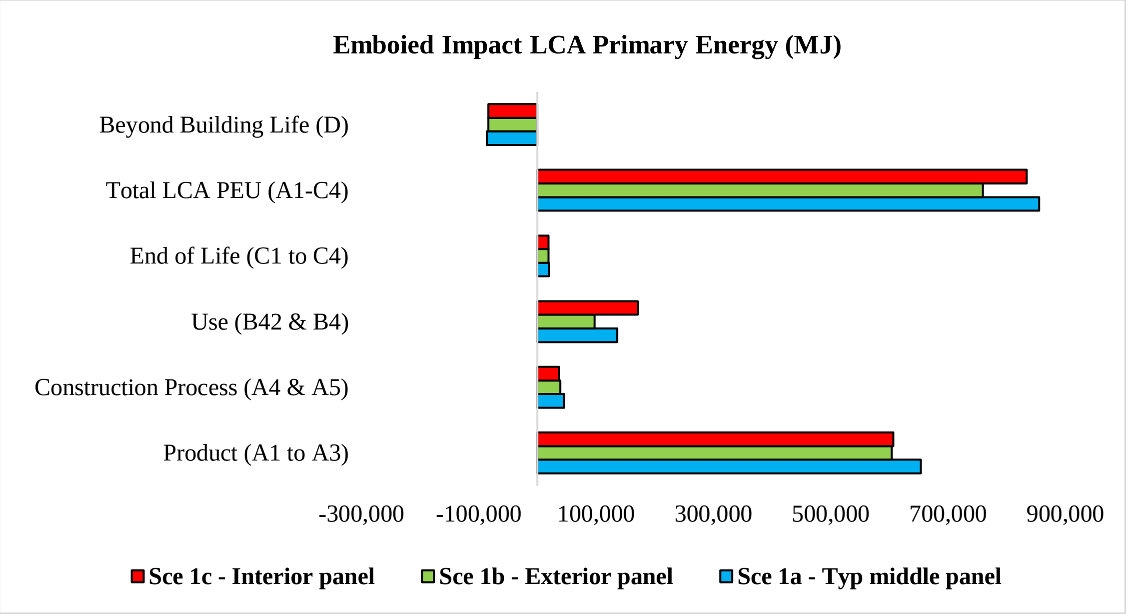


Figure 6.11 Comparison of Life Cycle Primary Energy of Exterior Wall Systems

6.2.2 Results: Apartment Adjacent Wall Design

When comparing adjoining wall design options, combinations of scenarios designed with double and single wall envelopes are analyzed. Results are analyzed as compared to Scenario 2a – Full envelope design on both walls.

Life Cycle Global Warming Potential (kg CO_2 eq.). Figure 6.12 shows results for life cycle GWP with the highest impact occurring at the product stage across all scenarios, then followed by the use stage. Although the end-of-life contributes the lowest to the life cycle carbon emission for all scenarios, the comparative analysis results suggest that most avoided carbon emissions from envelope materials occur at this stage. For example, Scenario 2d – insulation only shows the highest reduction in embodied carbon emissions of 35% than scenario 2a, double full envelope (reference case). An additional reduction in initial embodied carbon emissions, about 30% and 21%, can be recovered at the product and construction process, respectively for Scenario 2d compared to the reference case. In other words, this Scenario offers much more benefit in terms of material carbon emissions and a combination of the envelope can be classified as the best available carbon material selection going by the other scenarios presented in this study. In addition, a combination of steel products in the container design results in higher embodied carbon emissions during production, industrial processing, and construction phases (Dara, Hachem-Vermette, and Assefa, 2019). This relates to Scenario 2a and 2b designed with steel studs full envelope.

Given that most embodied carbon stems from material manufacturing, Scenario 2d – insulation only consumes fewer natural resources for reduced embodied carbon emissions. Overall, the study suggests that through the iteration of wall envelope materials and balancing design tradeoffs about 21% reduction in life cycle GWP can be achieved without compromising the building envelope's energy performance. However, there is no significant difference observed in the total life cycle GWP of Scenario 2a – 2c designed with dominant steel products.

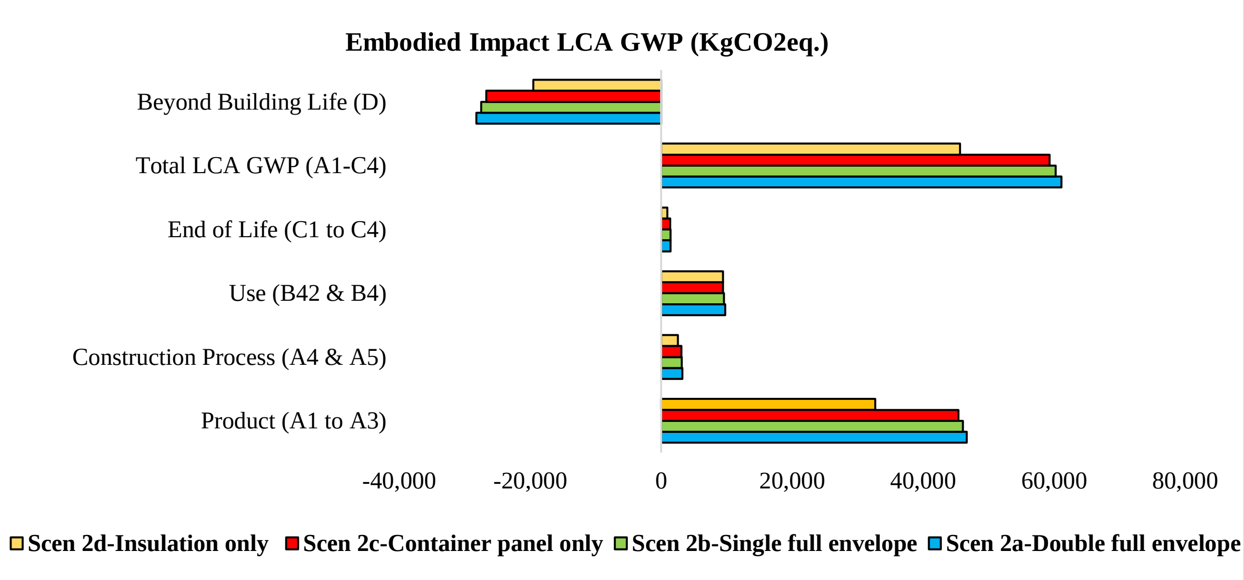
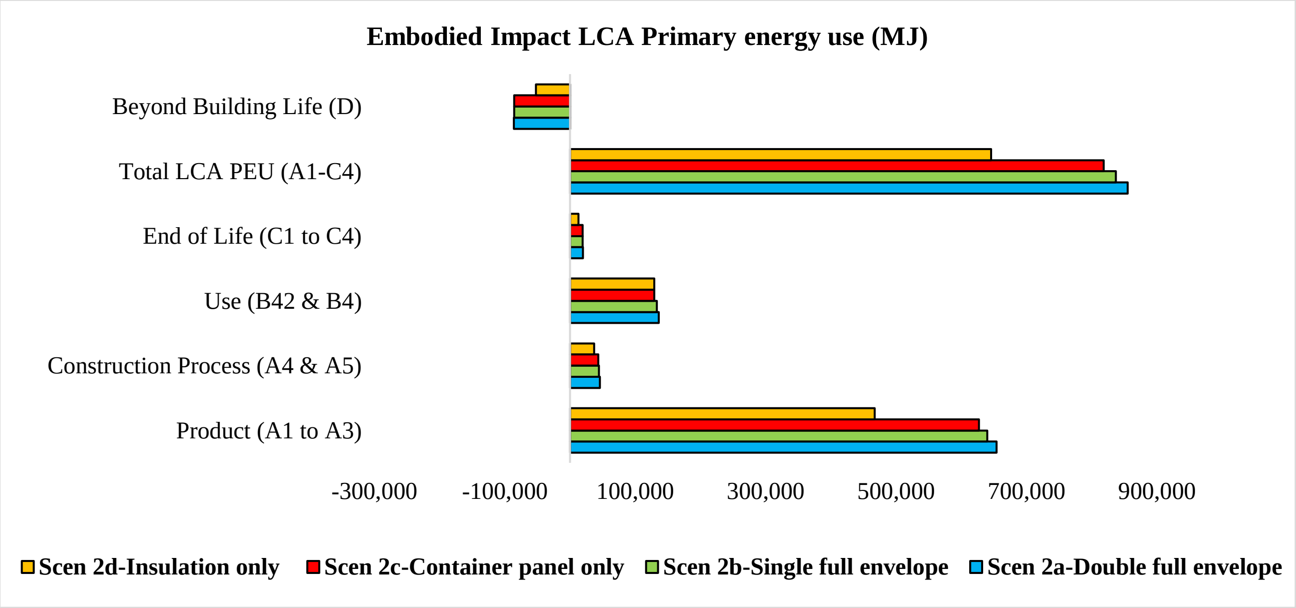


Figure 6.12 Comparison of LCA GWP of Adjacent Wall Systems

Life Cycle Primary Energy (MJ). Figure 6.13 illustrates a summary of the results of the life cycle of primary energy for the apartment connecting wall. Scenarios 2 analysis of adjacent wall configurations demonstrates less than 5% embodied impact in primary energy for Scenario 2b, single full envelope and Scenario 2c, the container only design compared to the reference case, Scenario 2a (double full envelope). In contrast, Scenario 2d – insulation only results in a significant reduction in embodied energy. The cradle-to-cradle LCA proves the highest reduction (about 23%) in material carbon emissions for Scenario 2d – insulation only from recycling and reusing products. In other words, in Scenario 2d, insulation only offsets a total of 177,000 Mega joules of life cycle energy (49,167 kWh) compared to the reference case, Scenario 2a.

Life cycle comparative analysis shows that most embodied carbon emissions occur at the product, construction process, and end-of-life stages. Breakdown of results of life cycle embodied energy suggests that highest reduction occurs at the product stage, reducing material associated embodied energy by 52% for Scenario 2d, insulation only compared to reference case (Scenario 2a, double full envelope). The end-of-life stage accounts for deconstruction and demolition (C1), transport (C2), waste processing (C3), and disposal (C4). Similarly, a significant difference in results is observed. Approximately 40% and 25% reduction in embodied energy use is obtainable at the end-of-life and construction process stages respectively, for Scenario 2d – insulation only, compared to the reference case. Notably, the use of steel products (i.e., steel stud and container panel) in Scenarios 2a – 2c results in much higher energy intensity for these scenarios than Scenario 2d. However, the relative benefit of utilizing steel products in the adjacent wall design is only seen at the beyond-building-life stage (D). For example, Scenario 2a – 2c designed with steel products will possibly reclaim about 39% of embodied energy from products recycling and reuse if consideration is given to cradle-to-cradle assessment (i.e. beyond the defined system boundary).



F**Figure 6.13** Comparison of total primary energy Adjacent Wall Systems

6.2.3 Discussion and Analysis on Life Cycle Embodied Impact

This study investigates cumulative embodied carbon emissions and embodied energy of material technologies used in the envelope design of container-based wall systems. The exterior and adjacent wall scenarios show the highest impact at the product stage (A1-A3). Due to the close correlation between global warming potential (GWP) and primary energy consumption, about 72% to 79% embodied impact is recorded for both impact categories of life cycle impact from the cradle to the grave (A1-C4). These are attributed to upfront carbon emissions and embodied energy associated with selected material products. The use phase contributes 14% to 21% recurring carbon emissions to the exterior wall scenarios' life cycle impact. Although embodied impact occurs at all life cycle stages, a significant amount is inherent at the product stage (A1-A3).

To inform design decisions on low carbon material selections, assessment of carbon emissions (GWP) associated with envelope materials of all study scenarios is conducted, from cradle-to-grave. Comparing the outcome for exterior wall scenarios, up to 10% avoided embodied impact is observed for other scenarios compared to Scenario 1a (typical middle panel). While Scenario 1c achieves the highest reduction in embodied impact, the role of material arrangement within the wall envelope is insignificant in reducing the magnitude of the associated materials' carbon emissions. That said, while material choices may directly impact environmental performance, these may not have much impact on energy performance if a similar thermal resistance value is selected, for example, insulation material.

For the adjoining wall systems, the double full envelope (Scenario 2a) compared to the single full envelope (Scenario 2b) and container panel only (Scenario 2c) show insignificant impact, less than 3% in all. In contrast, results of the insulation only (Scenario 2d) suggest that a significant amount of material embodied emissions can be avoided, 20% reduction if selected over the double full envelope (Scenario 2a). However, assumptions made in the design of the comparative scenarios may have influenced results. For example, In Scenario 2d, it is assumed that 128 mm spray foam insulation, together with the 16mm fire-rated gypsum wallboards, would function as the complete modular envelope design.

While Athena Impact Estimator tool accounts for the environmental burden of demolishing/deconstruction of the building, disposal and transporting materials to landfill, to mark the end of a building's life cycle; this is, however, not so for individual component materials or products that face subsequent recycling/reuse/recovery beyond defined study system boundary. While the study system boundary considers 50 years of life expectancy from cradle-to-grave (A1-C4) for all products or materials and building components. The software calculates and presents end-of-life effects in two ways: (i) end-of-life: results on the producer pay principle and does not give credit to a building for future reuse of recovered demolition waste or recycled materials. In this case, environmental impact will be appropriately assigned to the next use of the material, not the current use;(ii) beyond building a life: this method includes material recovery, recycling and carbon sequestration scenario effects beyond the building's life (avoided burden) methodology (Athena Sustainable Materials Institute 2016). In other words, the environmental credits for recycling or building material reuse are fully assigned under the beyond life cycle, cradle to cradle analysis. Therefore, this study conducts the cradle-to-cradle assessment to highlight additional material benefits and loads beyond the defined system boundary.

The adjusted building life cycle accounting for cradle to cradle of materials further proves the benefits of utilizing low-carbon material selections. This is witnessed in the adjacent wall design, where Scenario 2a with the highest life cycle embodied carbon emissions, still results in a greater amount of steel products recovery and recycling potential after the end-of-life;

more than the amount of insulating material recovered for Scenario 2d. Therefore, the study reinforces the assumption that steel products have a recovery content close to 100%.

6.2.4. Concluding Remarks

This study, to the author's knowledge, is the first of its kind to present an LCA-based methodology to capture the impacts of material products and their interrelationships in contributing to the overall life cycle impact of building assemblies in container-based wall envelope in Canada, including the evaluation of avoided impacts of material trade-offs. The purpose of this study is to provide lifecycle-based design decisions that will offer practical solutions in the design of upcycled container-based structures. The results fulfill this purpose by identifying the best alternative design based on focused analysis of the embodied impact of various building components, materials, and design options. However, this study's data is limited to materials available in the composition of the various wall assemblies under analysis read from typical wall detailed drawings and others modified by the authors.

While the building industry still takes a conservative approach to life cycle assessment assuming materials manufacturing, demolition and disposal practices will always remain as they are today. Therefore, it is paramount to note that there is a shift in the production content of sustainable materials that makes room for a more flexible building materials characteristic with multiple life cycle chains. These material technologies encourage the use of alternative upcycled material or refurbished products with reduced embodied carbon emissions; therefore, the necessity to investigate actual embodied effects associated with individual materials that make up the building component or envelope.

It is also important to understand different life cycle situations for products with multiple life chains. This will be beneficial in explaining the uncertainties involved in predicting future waste management practices. Besides, applying this life cycle approach in real case studies, as in the case of this research, can further inform design decisions for low-carbon design. Proposing design solutions and monitoring the life cycle performance of materials towards reducing the building footprint is also a vital contribution of this chapter.

Taking a life-cycle approach can reduce the environmental impact of materials and building components if applied early during the design stage. Life cycle assessment is considered a performance approach to sustainable materials and building design. In other words, before building materials are ascertained as low impact, it is crucial to support the argument with logical data such as conducting LCA focused on analyzing materials' embodied impact. This is key to increasing the sustainability of building materials and products, particularly promoting upcycled and recycled products. As concerns relating to embodied carbon emissions, environmental degradation and climate change actions have amplified - is it possible that post-2020 will witness more significant progress in implementing zero carbon buildings agenda? With successful research advancement, operational energy and carbon emissions are becoming solvable and have already been given significant attention. On the other hand, embodied energy and carbon emissions appear to have significant potential for mitigating the remaining life cycle environmental impacts and merit all attention and action from the industry and researchers. This chapter contributes to understanding ways of reducing embodied impacts not only in the building sector, but it can also benefit the broader construction sector to lessen or zero out embodied emissions from infrastructure and other energy-intensive facilities. It contributes to the advancement of net-zero emissions from buildings.

Chapter 7 Design Guidelines, Recommendations and Conclusions

This chapter focuses on developing design guidelines for low-energy and low environmental impact container-based modular residential buildings. It presents design recommendations based on thesis design deductions intended to serve as a design decision-aiding tool, enabling the careful selection of envelope design for improved performance. The rest of the chapter presents a conclusion of the thesis summarizing chapter contributions, the overall significance of the study and proposed future works.

7.1 Summary of Thesis Research Findings

The research investigation centers on energy performance analysis of various container-based modular residential classifications, consisting of three main types: 1) building envelope and components design, 2) detached and row housing configurations, and 3) apartment residential buildings (i.e., multistoreys and layouts). The research develops a systematic life cycle performance-based approach to support the selection of envelope design parameters and building materials for the case study of a detached house (Chapter 2). The approach uses energy, environmental and economic criteria and relevant assumptions. This thesis identified the integrated benefits and limitations of repurposing shipping containers in second life as a building system based on this approach. It uses the lightwood house as a benchmark to consolidate its overall life cycle performance, which currently appears to be a gap towards the advancement of container-based buildings in the industry. Thereby providing some potential innovations in developing envelope design concepts and an in-depth understanding of container-based modular life cycle performance as self-sufficient and affordable housing. The paragraphs below summarize chapter-specific research findings.

Chapter 3 highlights the importance of understanding the thermal performance of container-based housing for cold climate regions. Various design parameters are investigated in the study to determine design strategies for improving the energy performance for detached and row housing units. This improved model introduces a combination of passive and active solar design strategies and energy efficiency measures to balance energy consumption and generation. With parametric investigations of various envelope improvements discussed in Chapter 3, the improved model designed with an upgraded envelope reduces its operational energy consumption by approximately 31% compared to the code case. Results also show that the improved design can reduce its annual energy consumption up to 99% through on-site electricity generation from roof-mounted PV systems (22.5° gable roof). In the same vein, the other improved models with 30° and 45° roof inclination achieve a net-zero energy status.

For row housing configurations, average thermal loads per unit model decrease with increasing configurations, up to 16% for the 4-unit model. Balancing energy performance, 45° roof design has the highest efficiency. It is important to note that these research findings are presented as rough approximation values based on design parameters under consideration. That said, building energy performance monitoring at the post-construction phase is required to fully determine the actual energy performance. However, this may be influenced by a few factors including end-users/ occupants’ habits and daily operational activities.

Part of this thesis reports on the design of the geometric pattern to improve energy performance in multi-unit residential buildings designed out of upcycled shipping containers (chapter 4). It investigates various methods to increase energy efficiency and generation in container-based modular residential buildings through careful geometric design. For example, the façade BIPV system integrated on 80% of opaque areas of the 6-storey container-based apartment generates about 60% of its energy use per annum. Chapter 4 identified designing complex geometric layouts (i.e., non-linear or circular) as a limitation of utilizing shipping containers in multi-unit complexes. However, flexibility and structural stability are attainable with regular shapes based on the modular container envelope geometric pattern.

An integrated life cycle approach is employed to assess the potentials of re-purposing used shipping containers into a single-family detached house (Chapter 5). The life cycle impact assessment compared the environmental performance of a container-based modular house to a traditional lightwood house. Over 50 years’ lifespan, most life cycle environmental impacts of the four case study buildings occur at the use and operation phase, up to 95% across LCA measures. Whereas the improved cases benefit from envelope upgrade to reduce building operating energy, this also contributes to a much higher pre-use impact, 7% higher than the base code cases.

Summary of sensitivity analysis of container-based models shows that Scenario CC (100:0) – cut-off method has the least embodied avoided impact up to 23% less than the Scenario CC (50:50), as it is designed to avoid all environmental impacts associated with manufacturing and processing of shipping container steel. Comparing the Scenario CC (100:0) to the highest embodied impact Scenario IC (0:100) approximately 50% increase is witnessed across most impact categories. Steel has a high economic value, and its versatility enables it to be easily recycled and remanufactured according to demand. Corten steel which constitutes over 90’% of shipping containers is a sustainable choice, with minimal surface maintenance as it is manufactured with rust protective coating that slows the rate of future corrosion.

By completing this study, the thesis demonstrates that the systematic design of building materials and envelopes can be rationally prioritized in a design decision process and directed through a life cycle assessment. For instance, selecting materials with less embodied impact and a yet more significant amount of reusable content will reduce material impact intensity and benefit from a life cycle perspective. Besides, applying this life cycle approach in real case studies, as in the case of this research, can further inform design decisions for low-energy and low-carbon container-based design. Proposing design solutions and monitoring the life cycle performance of materials towards reducing building carbon footprint is the vital contribution of this study.

Chapter 6 highlights building assemblies and materials in contributing to low energy and low-carbon design from a life cycle perspective. It focuses on the role the wall envelope design can play in reducing the life cycle embodied impact by careful selection of material choices that constitutes the wall envelope. Investigating cumulative embodied impacts of material technologies toward proposing low-impact assemblies for existing container-based buildings requires a detailed study that iteratively assesses the LCA of different wall assemblies (both exterior and interior modular walls). Proposing design solutions and monitoring the life cycle performance of materials towards reducing the building footprint is the vital contribution of this study. For example, the study deductions prove that a significant amount of embodied impact can be recovered through systematic material reductions for adjacent walls of modular units without limiting the building’s energy performance. Careful iteration of wall envelope materials and balancing tradeoffs can result in 21% reduction in life cycle GWP without compromising the energy and environmental performance of the building envelope.

While the building industry still takes a conservative approach to life cycle assessment with the assumption that materials manufacturing, demolition, and disposal practices will always remain as they are today, it is paramount to note that there is a shift in the production content of sustainable materials that makes room for materials characteristic with multiple life cycle chains. These material technologies encourage the use of alternative upcycled material or refurbished products with less environmental impacts; therefore, the necessity to investigate actual embodied effects associated with individual materials that make up the building component or envelope, which is the case of this thesis focused on reusing upcycled shipping containers in housing. It is very important to understand both life cycle situations because of the high level of uncertainty required in predicting future waste management practices.

7.2 Design Guidelines and Recommendations

The design principles are fundamental considerations to guide decision-making for building designers and developers. The proposed design considerations mainly focus on container-based structures and are categorized by residential building types; for example, single-detached houses, row housing and apartment multistorey buildings. Other aspects considered part of the proposed guidelines are building shape and form and building envelope materials. However, this thesis identifies general design guidelines as recommendations that apply not only to container-based structures but also to all building structures, e.g., wood and steel frames. While adopting the following design guidelines, the designers should keep in mind their desired design goals and then prioritize their design choices and decisions early at the design stage.

7.2.1 General Design Guidelines for Single-Detached House: Integrated Building Performance

This section provides general design guidelines on integrated building performance for the single-detached house. The design principles are fundamental objectives to provide a more robust understanding of the life cycle impact of the studied design choices and guide decision-making for low energy and low-impact design at a reasonable operational cost. Table 7.1 summarizes general design considerations broadly on integrated building performance conducted in chapters 3 and 5. While this study is focused on Calgary weather conditions, the prioritized design considerations are more generic to container design for cold climates and can be used by designers to evaluate their design decisions for other locations. These design considerations based on overall long-term life cycle performance of the studied models focused on four (4) sustainable design goals: (i) building envelope and energy performance targets, (ii) life cycle environmental performance and sustainability targets, (iii) long-term cost efficiency, and (iv) potential for zero energy/zero-carbon buildings.

Table 7.1 General Design Guidelines for Single-Detached House

Design Principles and Objectives	Design Considerations	Design Prioritization	Thesis Chapter
	Building Envelope and Energy Performance Targets		
Thermal Performance	• Thermal insulation: Carefully insulate container envelope with for example spray foam insulation to reduce heating load without significantly increasing cooling load. • Recommendation includes: i) Container Wall: RSI 5.3 ii) Roof: RSI 10.97 iii) Boundary Floor: RSI 1.0 (without insulation)	**Prioritize**	Chapter 3
Airtightness	• Airtightness performance has a huge impact on the energy performance of buildings. However, determining the infiltration rate can be more beneficial when a blower test is conducted. • Recommendation includes: i) Average Code standard – 3.0 air changes per hour @ 50 Pa induced pressure, ACH50 ii) Improved container (IC): Airtight envelope – 0.6 ACH50	**Prioritize**	Chapter 3
Building Orientation	• Consider building orientation up to 15° west or east; otherwise, complete south orientation is desirable at all times based on passive design principles.	**Prioritize**	Chapter 3
Window and Glazing Area	• The Window-to-wall ratio (WWR) should be at least 40%, and shading controls (40% overhang and interior blinds) can be introduced to minimize cooling loads caused by increased glazing.		Chapter 3
Life Cycle Environmental Performance and Sustainability Targets			
Operational Energy and GWP Emissions	• A combination of envelope design techniques in the improved cases creates the opportunity to reduce the operating energy use that often dominates most buildings' life cycle environmental impacts up to one-third compared to code model.	**Prioritize**	Chapter 5

	- Reducing operating energy through the envelope upgrade is vital to reducing operational GWP emissions throughout the building life cycle for the improved case.		
Other environmental impacts	- Designing high energy-efficient buildings will also benefit improved indoor air quality and health impacts. - Given that smog potential could be caused by high temperatures from non-renewable primary energy sources in the building, an upgraded envelope reduces these impacts		Chapter 5
Long-Term Cost Efficiency			
Building Operational Costs	- Cost-benefit of envelope design decisions can reduce building operational cost over 50 years life span.		Chapter 5
Potential for Zero-Energy/Zero-Carbon Building			
On-site Electricity Generation	- Typical container-based house designed with 22.5°original inclination of the roof can achieve a near net-zero status through energy generation.		Chapter 3
Zero Energy Target	- Maximize electricity generation potential; consideration of 30° and 45° gable roof angles are recommended. - South-facing roof-integrated PV systems should be considered at all times.	**Prioritize**	Chapter 3

7.2.2 Guidelines for Container-based Building Envelope Design

This sub-section provides lifecycle-based design guidelines and offers practical solutions to container-based designers. Recommendations are based on the best design alternative focusing on results from the life cycle embodied impact of various building components, materials, and design options (see Table 7.2). It evaluates avoided impacts of material and trade-offs by highlighting the need for products and materials selections/choices in contributing to the overall life cycle impact of container-based building assemblies. Although these design considerations are focused on container-based structures, few also apply to general building construction.

Table 7.2 Container-based Specific Guidelines: Building Envelope and Materials

Design Principles and Objectives	Design Considerations	Design Prioritization	Thesis Chapter
	Appearance and Environmental Performance		
Exterior Wall	- Exterior container panels are durable for cladding and offer an aesthetically beautiful appearance. This creates an ultra-	High	Chapter 6

	modern and vintage look suitable for residential and commercial wall finishes. • Exterior panel should be coated with water-dilutable spray painting as a protective finish for improved durability. • Replacing Hardie plank siding with container panel can be more advantageous to reduce recurring embodied emissions from maintenance and replacement at use phase. • Steel container panel should be maintained as the structural member. If envelope modification leads to excessive cut-offs of more than 50%, stud framing (e.g., steel, wood) should be installed to ensure structural integrity. • Advanced framing or replacing stud with wood furring should be considered to reduce thermal bridging effects.		
Mate Connection Wall	• Mate connection walls designed as double-wall systems with full envelope can be replaced with single-wall designed with spray foam insulation as insertion and drywall on both wall interiors. • Double-wall design results in twice embodied impacts.		Chapter 6
Interior Wall	• Interior walls can be designed with single-envelope or gypsum board separation. • Acoustic tile and insulating panels should be avoided, and low emittance materials selected instead.	High	Chapter 6
	Embodied Impact		
Embodied Carbon Emissions	• Recommendation for exterior wall envelope on avoiding materials with high initial upfront embodied carbon emissions, where possible, applies to the interior wall. • Upcycled container steel as a structural system is desired as it lowers the amount of carbon emissions up to 100%. • Careful iteration of wall envelope materials and balancing tradeoffs can result to a reduction in life cycle GWP without compromising the energy performance.	High	Chapter 6
Embodied Energy	• Designing with an upgraded envelope, the focus should be on design decisions that reduce embodied energy/impacts. • The amount of materials used for the envelope design determines the value of embodied energy intensity at the production phase. Material compositions within an envelope should focus on lowering embodied energy intensity by using a lesser quantity.	High	Chapter 6
Construction Impact	• Beyond the production stage, most of the avoided impact through building material selection is recorded at the construction process stage. • Modular construction method is recommended to reduce the impact of on-site building construction.		Chapter 6
	Wastes and Circularity		

Landfill waste Diversion and Recycling	• Designing with reusable and recyclable materials should consider the avoided impacts of recycled and reclaimed building materials beyond the building life stage (D). For instance, after the end-of-life (cradle to cradle), assessing the avoided impact shows that external wall envelope scenarios can offset a significant amount of embodied carbon emissions. • Container panels are proven as a good option for waste to landfill diversion. Reusing shipping containers can be advantageous; two-third of embodied energy can be reclaimed at end of life.	High	Chapter 6
Circularity	• A careful selection of steel products with high recovery content is suggested. This should only be considered if the product is designed as a close loop system to reduce embodied impact at the next life cycle.	High	Chapter 5

7.2.3 Design Considerations based on Evaluation of Energy Performance of Multi-units

Table 7.3 summarizes design considerations based on energy performance on multi-unit residential building types', considering two objectives: (i) minimize heating, cooling, and energy consumptions, and (ii) maximize electricity generation.

Table 7.3 Design Guidelines for other Residential Building Classifications

Design Principles and Objectives	**Design Considerations**	**Design Prioritization**		**Thesis Chapter**
	Row Housing	**General Application**	**Container Specific**	
Insulation	• If the cooling load is large, insulation insertions between adjacent unit walls should be readjusted or removed.	**X**		Chapter 3
Thermal Performance	• The attached row configurations are good alternatives to reduce thermal loads per unit model.	**X**		Chapter 3
Roof Design	• Roof design: gable roof with 30° tilt angle is a good compromise to increase energy generation from south-facing roof area while not significantly increasing the heating loads/consumption. • Roof tilt angle: Row housing with adjacent units is more beneficial than a detached house.	**X**		Chapter 3
Building Orientation	• Design the adjacent units to be south-facing orientation should be considered to maximize passive design benefits further.	**X**		Chapter 3

Zero Energy Target	• If zero-energy status is desired, roof tilt angle as much as 30° - 45° south inclined gable roof should be highly considered to produce surplus energy at peak hours. This also benefits easy runoff of snow and rain.	**X**		Chapter 3
Overall Recommendation	• 2-unit and 4-unit row configurations with south inclined gable roof design at 45° are recommended to realize peak energy performance. • Design recommendations for detached can be applied to row configurations. However, tradeoffs should be made between balancing additional energy consumptions with generations.	**X**		
	Multistorey			
Land-use, Egress and Travel Distance	• The single storey should not be considered because of other design constraints such as extended travel distance to suites, means of egress and exits. This is a safety concern for be occupant's emergency such as fire.	**X**		Chapter 4
Floor Heights	• Design recommendations for layouts should be followed, in addition to respecting the impacts of increasing floor levels.	**X**		Chapter 4
Heating and Cooling Demands	• 3-storey apartment is a good compromise for reduced heating and cooling demands		**X**	Chapter 4
On-Site Electricity Generation	• For buildings with increased heights, facade electricity generation increases progressively with the increasing number of storey and exterior surface area of facades. • For the single-storey, it is recommended to use roof-mounted PV for increased production based on the roof area. • The south façade area ratio to other sides should be used since this enables a balance for peak generation for PV/m^2.	**X**		Chapter 4
Overall Recommendation	• Recommendations for stacking containers in multistorey are valid, as 6-storey can generate two-third of its energy use.		**X**	Chapter 4
	Building Form and Layout Design			
Building Orientation	• Full south orientation with rectangular shape up to 0° south facades should be considered. • In the case of a 40-foot C-Can design, the whole unit can be oriented with the longer side along the east-west axis, assuming south orientation.	**X**	**X**	Chapter 4
Material Reduction and	• Designing along the rectangular modular standards of container boxes is recommended to minimize C-cans' cutting, which can		**X**	Chapter 4

Spatial Arrangement	comprise energy performance through air leakage in the envelope. • Careful design of multiple C-cans arranged parallel to each other is suggested, especially in multi-unit. This will result in minimal material wastes during modular fabrication.			
Space Heating	• Rectangular shape with south-facing orientation should be considered for reduced heating loads.	**X**		
Cooling Demand	• Square layout with a compact shape is advantageous when there is a need to reduce cooling load/consumption.	**X**		Chapter 4
Geometric Shape and Thermal Loads	• Avoid I shape, 90° orientation with elongated plan on the north-south axis unless intended to benefit from façade electricity generation combining east and west.	**X**		Chapter 4
Maximum Façade Electricity Generation	• The amount of electricity generation from integrated PV systems on façades largely depends on the ratio of opaque wall area to the total surface area of the wall. Greater consideration should be given to south, east, and west façade electricity generation. • U-shape are good alternatives, enabling high exterior surface area for increased generation potential in container-based layout design. • Rectangular layout with a larger south surface area is recommended to obtain peak PV per square meter of electricity generation and aligns best with container module shape. • I-shape is advantageous when combined generation is required from east and west facades. Otherwise, I-shape with full west orientation should be avoided.	**X**	**X** **X** **X**	Chapter 4

7.3 Significance of the Research

This research contributes to the development of design guidelines for low energy and low environmental impact container-based design. It also promotes an integrated life cycle methodology for a holistic building performance analysis. The significance of this research relates to multiple parts: the scientific community, building industry, and policy-makers

Scientific Community. The application of shipping containers as a form of modular construction is still a new and evolving research area. Original research findings disseminated through peer-reviewed publications and conference presentations will contribute to advancing the field of research. This thesis presents the first design methodology that combines envelope upgrade and environmental life cycle assessment to reduce whole building impacts for container-based structures to the best of the author's knowledge. This research characterizes the utilization of this integrated research methods in guiding academic scholars in developing low-energy and low-impact design strategies.

Building Industry: In transitioning to zero-carbon building standard**s,** designers and developers need to respond to regulatory requirements. The developed design guidelines will serve as templates for modular developers, architects, and building engineers interested in advancing effectiveness and efficiency in designing, planning, and managing container-based projects, mainly single-family housing and multi-unit residential buildings. Corrugated steel sheets, the primary component of shipping containers have the highest strength-to-weight ratio compared to other construction materials. The proposed design prototypes can easily be mass-produced and replicated in other locations to provide immediate, quality housing for the ever-growing city and urban populations. As the adaptive re-use of container-based buildings continues to gain popularity, the undetectable errors and uncertainty in construction efficiency created due to DIY (Do-it-yourself) make this research more relevant to anyone interested in container-based buildings. By providing recommendations on how to exceed the code requirements and attain high performance, this thesis promotes innovation for end-users and investment decisions through the highlighted strategies for achieving high performance and net-zero energy status using such structures.

Policy-makers: The dimension of reducing building-associated energy and environmental impacts is becoming of great interest to policy-makers and world leaders. This thesis relies on the systematic investigation of envelope design parameters of residential buildings that govern their overall energy and environmental performance, separately and in combinations. It sets a foundation for developing comprehensive design guidelines and procedures for low energy and low-impact modular buildings based on integrated life cycle perspectives, which will perhaps support existing policies on expanding modular design and construction in Canada. For instance, research findings can guide policy-makers when formulating environmental regulations on sustainable building materials, such as trade-offs through material substitution or environmental credits towards carbon neutrality and other benefits of reducing building embodied impacts.

7.4 Thesis Limitations

In order to complete the energy analysis and life cycle assessments, assumptions were made (refer to sections 2.3.2 and 2.3.2 above). The thesis makes a primary assumption that the case study project, which is considered the starting point of the parametric investigation is designed to the building code characteristics (see 2.2.1 Description of Case Study: Single-Detached House). The energy performance analysis also considers whole building modeling using the EnergyPlus simulation engine to analyze energy consumption, thermal loads, and present comparative analysis of selected scenario cases. In the simulations, it is assumed that issues such as thermal bridges are eliminated and that high airtightness can be achieved and as such analyzing these aspects is excluded from the thesis. However, methods of construction to eliminate issues of thermal bridges and ensure continuous insulation and airtightness in container buildings should be covered in future research, to ensure that high performance such as analyzed in the thesis can be reached.

7.5 Final Conclusion and Future Research Work

The findings of this research have contributed to the domains of integrated life cycle methodology for performance-based analysis, using container-based buildings as a case study. While this research addressed some of the gaps in the literature, it also presented opportunities for future research.

The obvious starting point is the continuation of this research into the current trend of whole building performance studies. This thesis has evaluated the effectiveness of integrated life cycle methodology as a successful approach to building performance-based analysis using these two case studies. This holistic approach can further be applied in the investigation of zero-carbon buildings and neighbourhoods. The thesis lays the groundwork for future research as its findings indicate positive outcomes for expanding research in this area. This, coupled with the recent trend in zero-carbon buildings, offers an opportunity to extend this study to other types of building structures and classifications for a more holistic application of the methodology. More specifically, evaluating different ways to reduce embodied impacts of building materials that currently presents a blind spot in the life cycle assessment of buildings.

As concerns relating to embodied carbon emissions, environmental degradation and climate change have amplified - is it possible that post-2020, will see significant progress in implementing zero carbon buildings agenda? With successful research advancement, mitigating operational energy and carbon emissions are becoming solvable and have already been given significant attention. On the other hand, embodied energy and carbon emissions reduction appear to have significant potential to further mitigate building life cycle impacts. Therefore, merits all attention and action from the building industry and researchers.

This research field presents a blind spot within the blind spot. Because it requires more actions in understanding the materiality of the building components and services from a more holistic life cycle approach. The future research question should focus on how the design community can choose between two envelope assemblies or products, assuming both present equivalent energy performance and cost implication? Consideration, then will be given to materials and building envelope design with much higher recycled content, half carbon footprint: How are these materials sourced, processed, transported and constructed? What is the life span of individual products that makes up the entire building's carbon footprint? That said, future research work in this area can focus on understanding the beyond life cycle assessment and investing in low carbon material options or evaluation of reducing the carbon intensity of existing building materials.

An important conclusion stemming from this study is that many designers appear to still, doubt the appropriateness of using shipping container structures in the design of high-performance buildings. As reported in the design guidelines (Chapter 7), there are still benefits for its adoption in the construction of high-performance buildings. Additionally, this research opted for a narrow classification of buildings on the container-based structure by selecting case studies for residential buildings. The next step is to extend these study recommendations to commercial and institutional applications to meet a much broader scope. Other important areas for future research investigations include undertaking thermal bridging analysis of steel envelopes, and methods of achieving airtightness of container-based envelopes. Thus, this research is exploratory in that it sets the stage for future research to extend the same design, methods and recommended guidelines across these remaining areas. This will provide a more holistic understanding of the benefits of container-based structures in the building industry.

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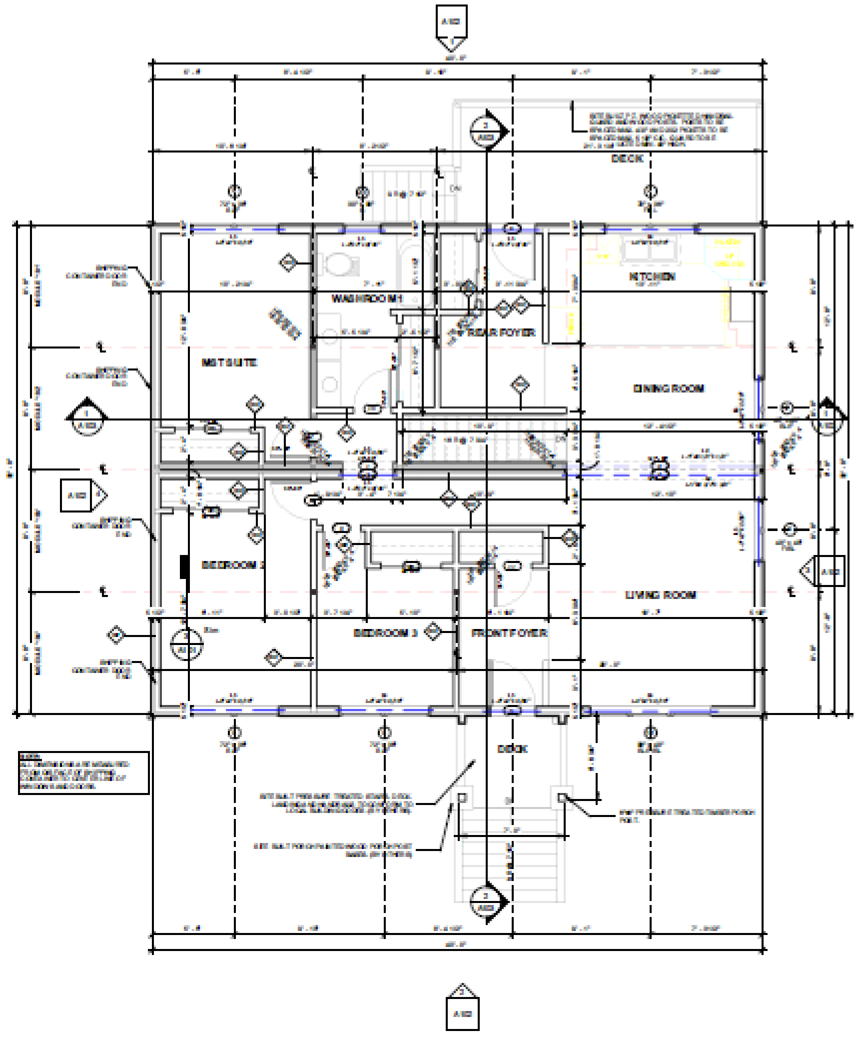
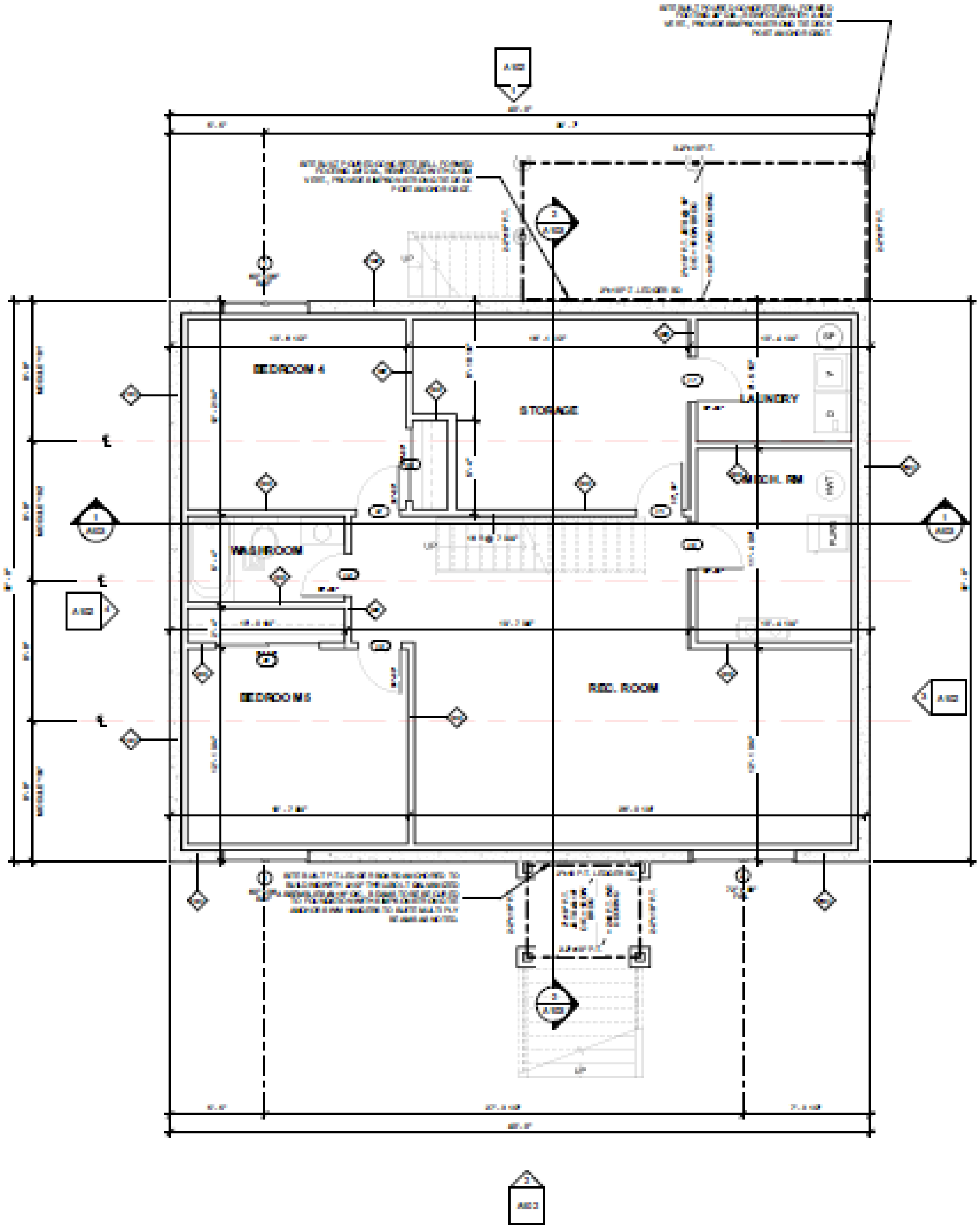
Appendix A. Case Study Drawings: Single Detached House

Appendix A1: Floor Plan Drawings

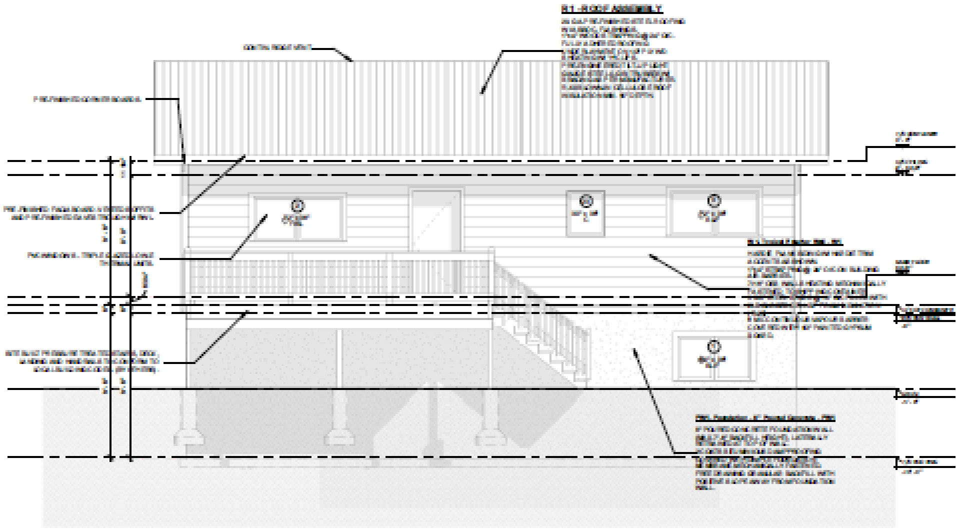


① MAIN FLOOR PLAN

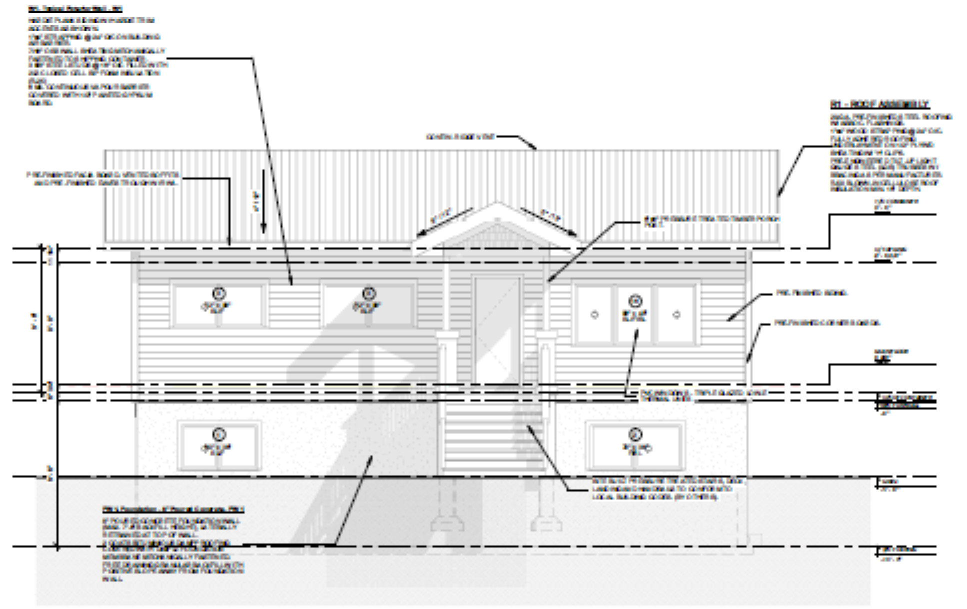


② BASEMENT PLAN
1/8" = 1'-0"

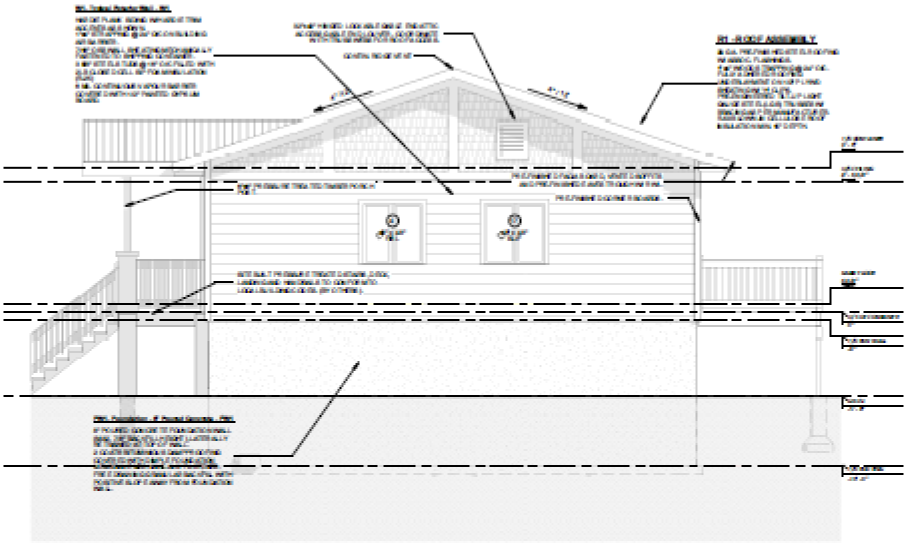
Appendix A2: Elevation Drawings



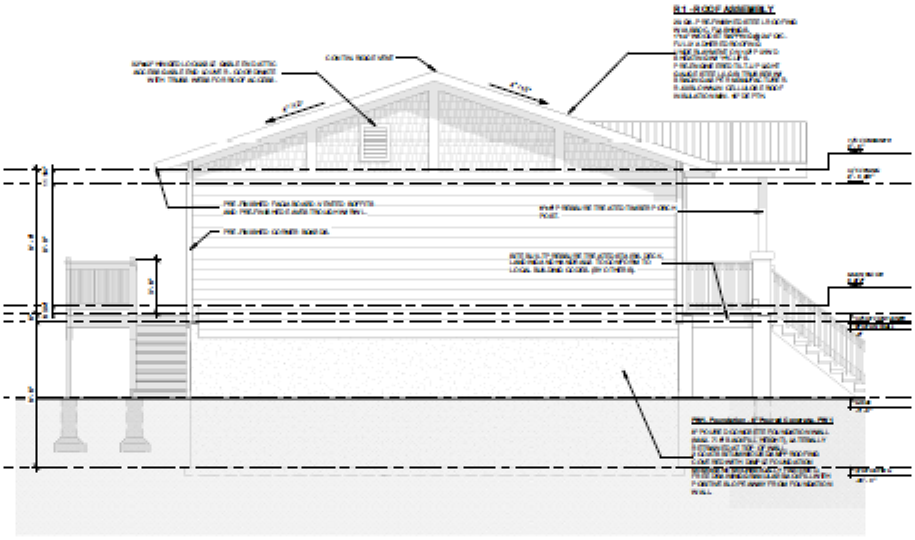
① REAR BUILDING ELEVATION



② FRONT BUILDING ELEVATION

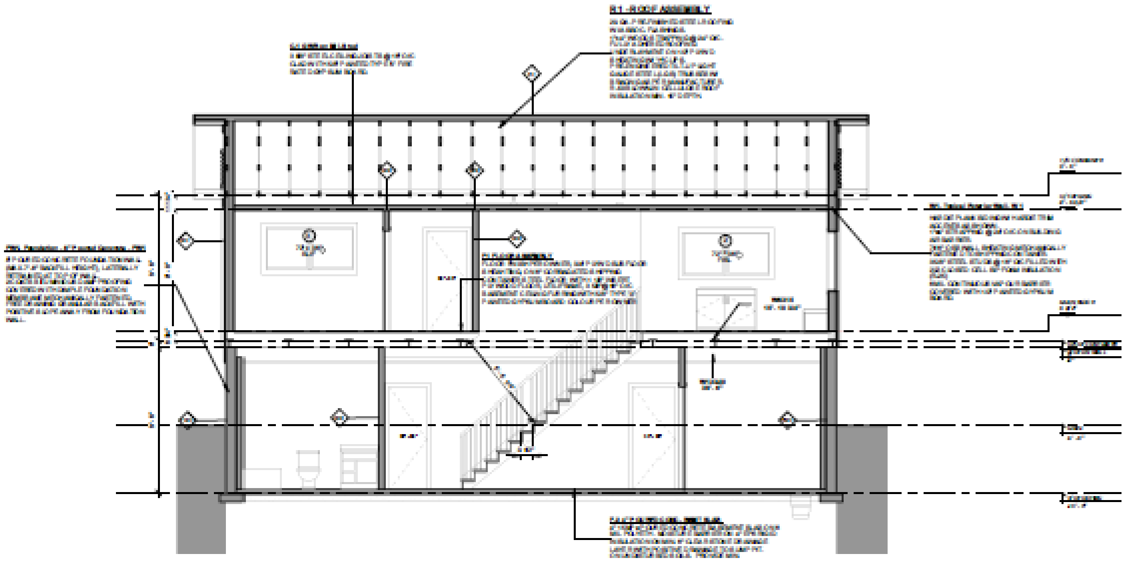


③ RIGHT BUILDING ELEVATION

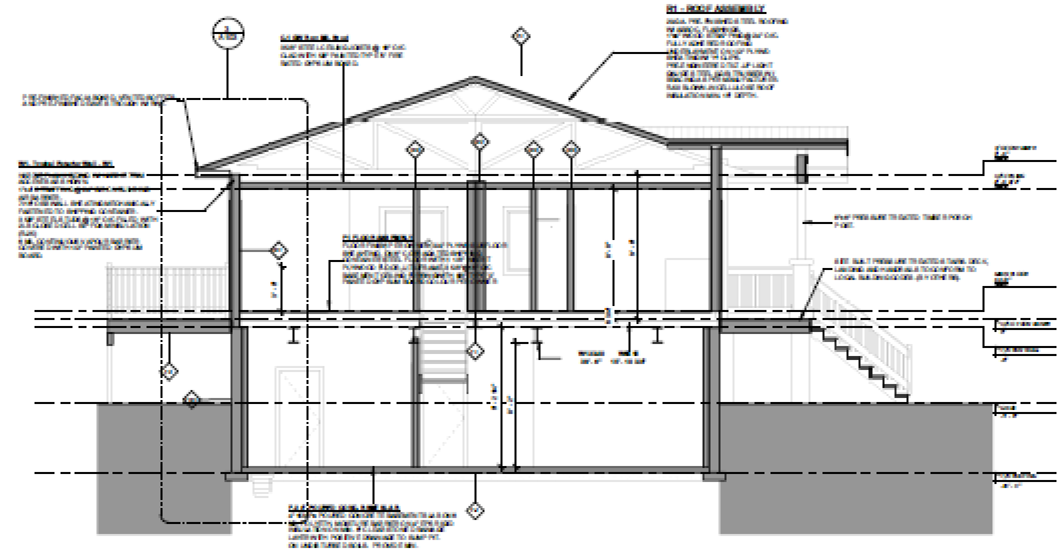


④ LEFT BUILDING ELEVATION

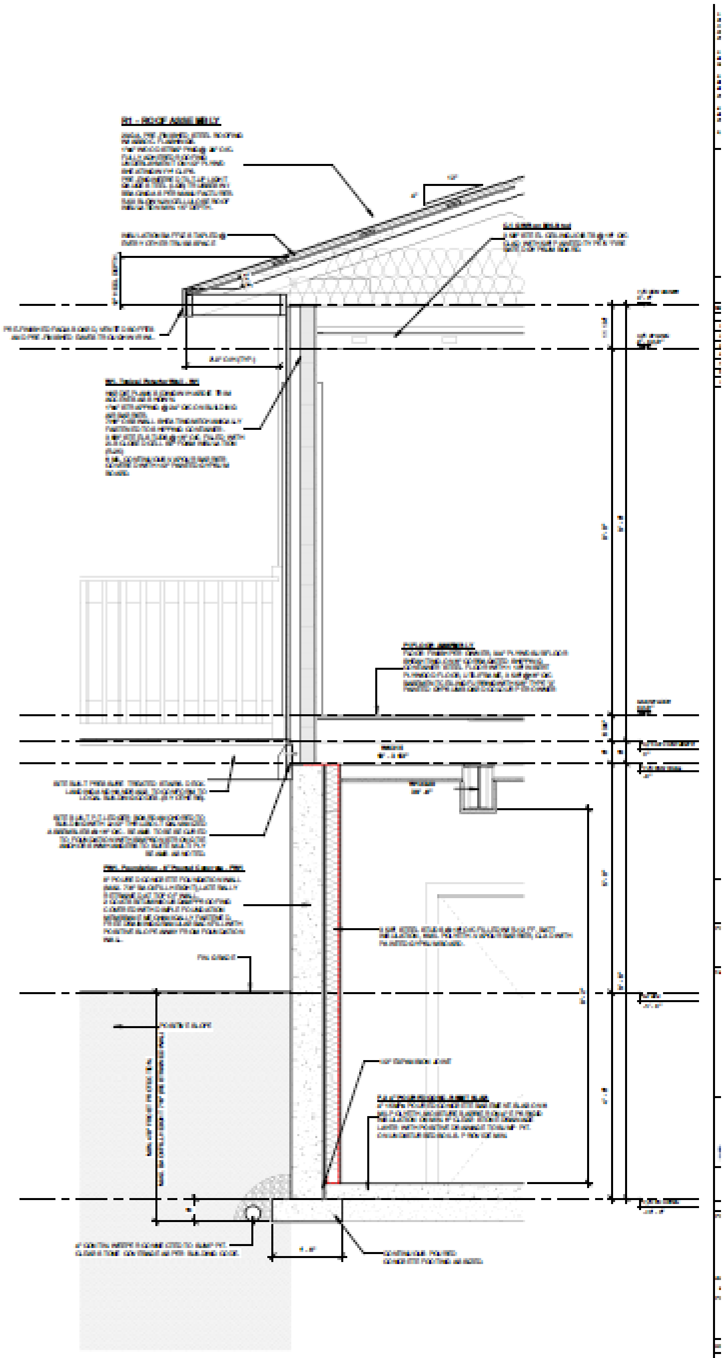
Appendix A3: Sections and Details



① BUILDING SECTION A-A

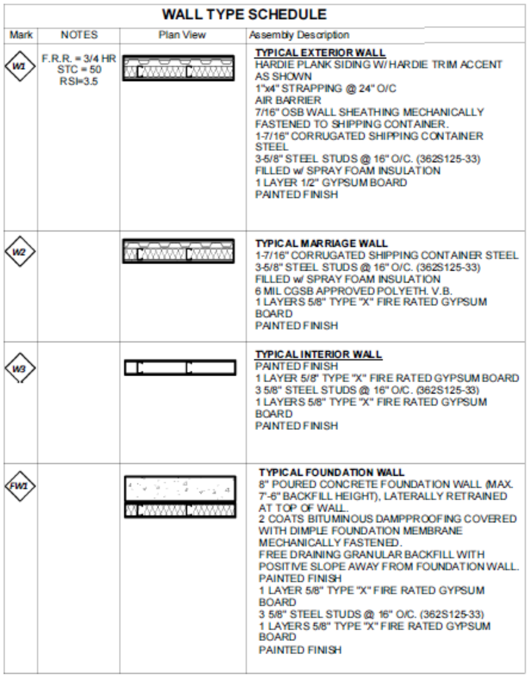


② BUILDING SECTION B-B



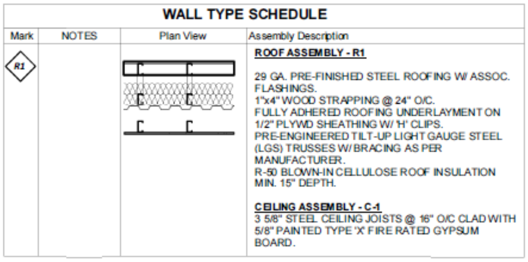
TYPICAL WALL SECTION
3/4" = 1'-0"

Appendix A4: Envelope, Building Assemblies, Doors and Windows Schedule



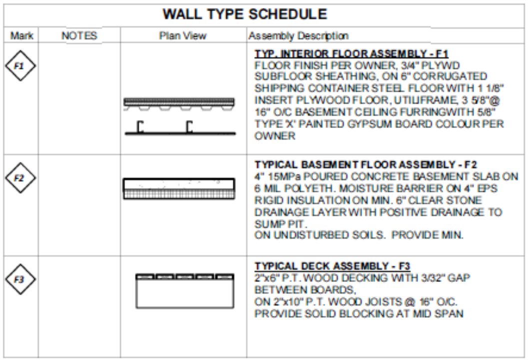
WALL TYPE SCHEDULE

Mark	NOTES	Plan View	Assembly Description
W1	F.R.R. = 3/4 HR STC = 50 RSI=3.5		**TYPICAL EXTERIOR WALL** HARDIE PLANK SIDING W/ HARDIE TRIM ACCENT AS SHOWN 1"x4" STRAPPING @ 24" O/C AIR BARRIER 7/16" OSB WALL SHEATHING MECHANICALLY FASTENED TO SHIPPING CONTAINER. 1-7/16" CORRUGATED SHIPPING CONTAINER STEEL 3-5/8" STEEL STUDS @ 16" O/C. (362S125-33) FILLED w/ SPRAY FOAM INSULATION 1 LAYER 1/2" GYPSUM BOARD PAINTED FINISH
W2			**TYPICAL MARRIAGE WALL** 1-7/16" CORRUGATED SHIPPING CONTAINER STEEL 3-5/8" STEEL STUDS @ 16" O/C. (362S125-33) FILLED w/ SPRAY FOAM INSULATION 6 MIL CGSB APPROVED POLYETH. V.B. 1 LAYERS 5/8" TYPE "X" FIRE RATED GYPSUM BOARD PAINTED FINISH
W3			**TYPICAL INTERIOR WALL** PAINTED FINISH 1 LAYER 5/8" TYPE "X" FIRE RATED GYPSUM BOARD 3 5/8" STEEL STUDS @ 16" O/C. (362S125-33) 1 LAYERS 5/8" TYPE "X" FIRE RATED GYPSUM BOARD PAINTED FINISH
FW1			**TYPICAL FOUNDATION WALL** 8" POURED CONCRETE FOUNDATION WALL (MAX. 7'-6" BACKFILL HEIGHT), LATERALLY RETRAINED AT TOP OF WALL. 2 COATS BITUMINOUS DAMPPROOFING COVERED WITH DIMPLE FOUNDATION MEMBRANE MECHANICALLY FASTENED. FREE DRAINING GRANULAR BACKFILL WITH POSITIVE SLOPE AWAY FROM FOUNDATION WALL. PAINTED FINISH 1 LAYER 5/8" TYPE "X" FIRE RATED GYPSUM BOARD 3 5/8" STEEL STUDS @ 16" O/C. (362S125-33) 1 LAYERS 5/8" TYPE "X" FIRE RATED GYPSUM BOARD PAINTED FINISH



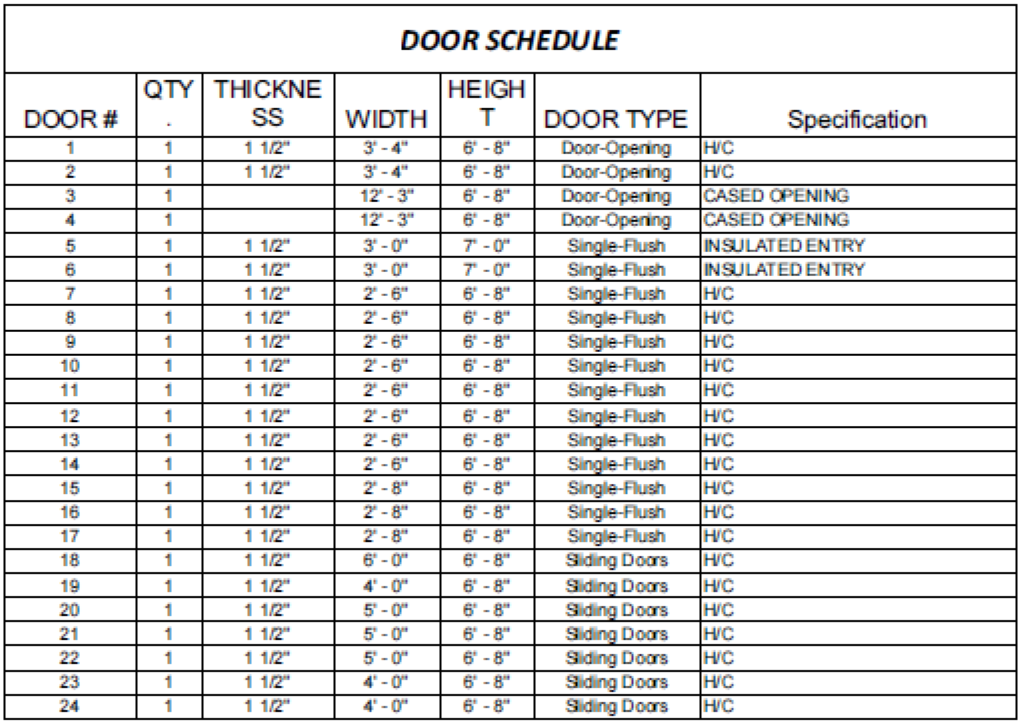
WALL TYPE SCHEDULE

Mark	NOTES	Plan View	Assembly Description
R1			**ROOF ASSEMBLY - R1** 29 GA. PRE-FINISHED STEEL ROOFING W/ ASSOC. FLASHINGS. 1"x4" WOOD STRAPPING @ 24" O/C. FULLY ADHERED ROOFING UNDERLAYMENT ON 1/2" PLYWD SHEATHING W/ 'H' CLIPS. PRE-ENGINEERED TILT-UP LIGHT GAUGE STEEL (LGS) TRUSSES W/ BRACING AS PER MANUFACTURER. R-50 BLOWN-IN CELLULOSE ROOF INSULATION MIN. 15" DEPTH. **CEILING ASSEMBLY - C-1** 3 5/8" STEEL CEILING JOISTS @ 16" O/C CLAD WITH 5/8" PAINTED TYPE 'X' FIRE RATED GYPSUM BOARD.



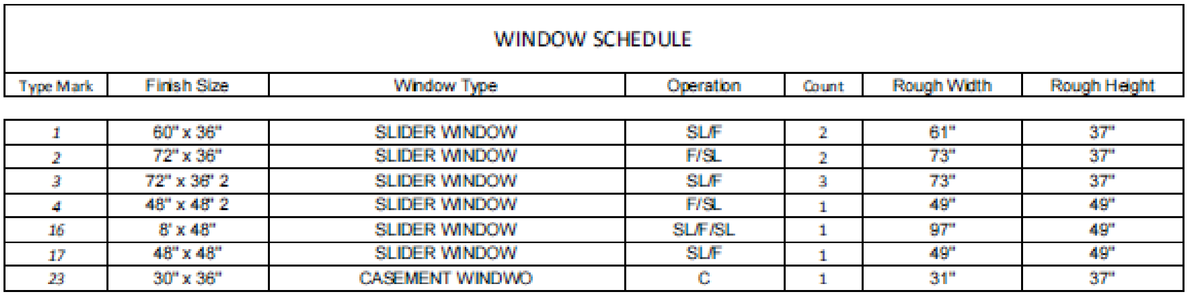
WALL TYPE SCHEDULE

Mark	NOTES	Plan View	Assembly Description
F1			**TYP. INTERIOR FLOOR ASSEMBLY - F1** FLOOR FINISH PER OWNER, 3/4" PLYWD SUBFLOOR SHEATHING, ON 6" CORRUGATED SHIPPING CONTAINER STEEL FLOOR WITH 1 1/8" INSERT PLYWOOD FLOOR, UTILIFRAME, 3 5/8"@ 16" O/C BASEMENT CEILING FURRINGWITH 5/8" TYPE 'X' PAINTED GYPSUM BOARD COLOUR PER OWNER
F2			**TYPICAL BASEMENT FLOOR ASSEMBLY - F2** 4" 15MPa POURED CONCRETE BASEMENT SLAB ON 6 MIL POLYETH. MOISTURE BARRIER ON 4" EPS RIGID INSULATION ON MIN. 6" CLEAR STONE DRAINAGE LAYER WITH POSITIVE DRAINAGE TO SUMP PIT. ON UNDISTURBED SOILS. PROVIDE MIN.
F3			**TYPICAL DECK ASSEMBLY - F3** 2"x6" P.T. WOOD DECKING WITH 3/32" GAP BETWEEN BOARDS, ON 2"x10" P.T. WOOD JOISTS @ 16" O/C. PROVIDE SOLID BLOCKING AT MID SPAN



DOOR SCHEDULE

DOOR #	QTY.	THICKNESS	WIDTH	HEIGHT	DOOR TYPE	Specification
1	1	1 1/2"	3' - 4"	6' - 8"	Door-Opening	H/C
2	1	1 1/2"	3' - 4"	6' - 8"	Door-Opening	H/C
3	1		12' - 3"	6' - 8"	Door-Opening	CASED OPENING
4	1		12' - 3"	6' - 8"	Door-Opening	CASED OPENING
5	1	1 1/2"	3' - 0"	7' - 0"	Single-Flush	INSULATED ENTRY
6	1	1 1/2"	3' - 0"	7' - 0"	Single-Flush	INSULATED ENTRY
7	1	1 1/2"	2' - 6"	6' - 8"	Single-Flush	H/C
8	1	1 1/2"	2' - 6"	6' - 8"	Single-Flush	H/C
9	1	1 1/2"	2' - 6"	6' - 8"	Single-Flush	H/C
10	1	1 1/2"	2' - 6"	6' - 8"	Single-Flush	H/C
11	1	1 1/2"	2' - 6"	6' - 8"	Single-Flush	H/C
12	1	1 1/2"	2' - 6"	6' - 8"	Single-Flush	H/C
13	1	1 1/2"	2' - 6"	6' - 8"	Single-Flush	H/C
14	1	1 1/2"	2' - 6"	6' - 8"	Single-Flush	H/C
15	1	1 1/2"	2' - 8"	6' - 8"	Single-Flush	H/C
16	1	1 1/2"	2' - 8"	6' - 8"	Single-Flush	H/C
17	1	1 1/2"	2' - 8"	6' - 8"	Single-Flush	H/C
18	1	1 1/2"	6' - 0"	6' - 8"	Sliding Doors	H/C
19	1	1 1/2"	4' - 0"	6' - 8"	Sliding Doors	H/C
20	1	1 1/2"	5' - 0"	6' - 8"	Sliding Doors	H/C
21	1	1 1/2"	5' - 0"	6' - 8"	Sliding Doors	H/C
22	1	1 1/2"	5' - 0"	6' - 8"	Sliding Doors	H/C
23	1	1 1/2"	4' - 0"	6' - 8"	Sliding Doors	H/C
24	1	1 1/2"	4' - 0"	6' - 8"	Sliding Doors	H/C



WINDOW SCHEDULE

Type Mark	Finish Size	Window Type	Operation	Count	Rough Width	Rough Height
1	60" x 36"	SLIDER WINDOW	SL/F	2	61"	37"
2	72" x 36"	SLIDER WINDOW	F/SL	2	73"	37"
3	72" x 36' 2	SLIDER WINDOW	SL/F	3	73"	37"
4	48" x 48' 2	SLIDER WINDOW	F/SL	1	49"	49"
16	8' x 48"	SLIDER WINDOW	SL/F/SL	1	97"	49"
17	48" x 48"	SLIDER WINDOW	SL/F	1	49"	49"
23	30" x 36"	CASEMENT WINDWO	C	1	31"	37"

Appendix B Copyright Clearance Letters and Permission from Co-authors

Appendix B1: Building and Environment Journal, Elsevier

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Author: Chinyere Dara, Caroline Hachem-Vermette, and Getachew Assefa

Publication: Building and Environment

Publisher: Elsevier

Date: October 2019

DOI: https://doi.org/10.1016/j.buildenv.2019.106332.

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Appendix B2: Energy, Ecology and Environment Journal, Springer Nature

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Title: Evaluation of Low-Impact Modular Housing using Energy Optimization and Life Cycle Analysis

Author: Chinyere Dara, and Caroline Hachem-Vermette

Publication: Energy, Ecology and Environment

Publisher: Springer Nature

Date: September 2019

DOI: https://doi.org/10.1007/s40974-019-00135-4

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Appendix B3: Co-author Copyright Permission Letter – Dr. Caroline Hachem-Vermette

Chi Dara
Fri 2020-10-02 1:35 PM
To:Caroline Hachem-Vermette

Good afternoon Dr. Caroline,

In accordance with the Copyright Act of all University publications, the University of Calgary requires the student to obtain written permissions (email confirmation) from co-authors of published manuscripts that form part of the final thesis document. My Ph.D. thesis is entitled: "Design Investigation of Container-based Residential Building Types for Improved Performance Using Integrated Life Cycle Perspective: A Performance-based Research."

Can you please confirm that you accept to include a version of the published papers of which you are co-author as chapters in my Ph.D. thesis to be submitted to the University of Calgary, Faculty of Graduate Studies?

1. Towards net-zero energy modular housing: a case study. *Modular and Offsite Construction (MOC) Summit Proceedings*.

2. Life cycle assessment and life cycle costing of container-based single-family housing in Canada: A case study. *Building and Environment*, *163*, 106332.

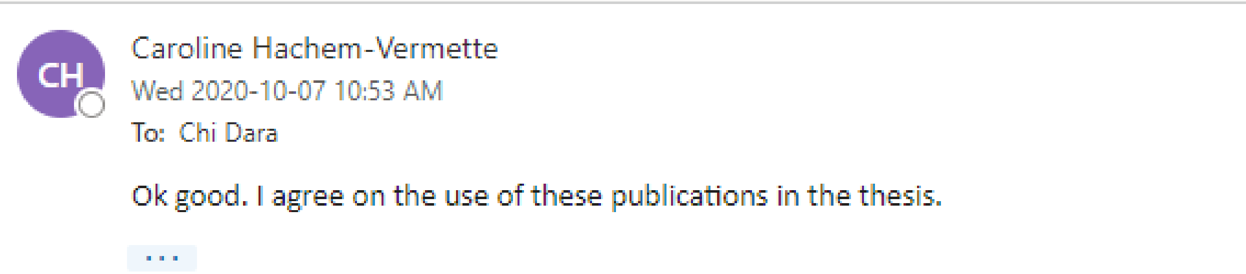
3. Evaluation of low-impact modular housing using energy optimization and life cycle analysis. *Energy*, *Ecology and Environment*, *4*(6), 286-299.

An email confirmation will be great.

Thanks,

Chi Dara, MSc (Arch), LEED Green Associate

Reply from Dr. Caroline Hachem-Vermette



Caroline Hachem-Vermette

Wed 2020-10-07 10:53 AM

To: Chi Dara

Ok good. I agree on the use of these publications in the thesis.

Appendix B5: Co-author Copyright Permission Letter – Rhys Kane

Copyright Permission Letter

Good afternoon Rhys,

I hope all is well with you.

In accordance with the Copyright Act of all University publications, the University of Calgary requires the student to obtain written permissions (email confirmation) from co-authors of published manuscripts that form part of the final thesis document. My Ph.D. thesis is entitled: "Design Investigation of Container-based Residential Building Types for Improved Performance Using Integrated Life Cycle Perspective: A Performance-based Research."

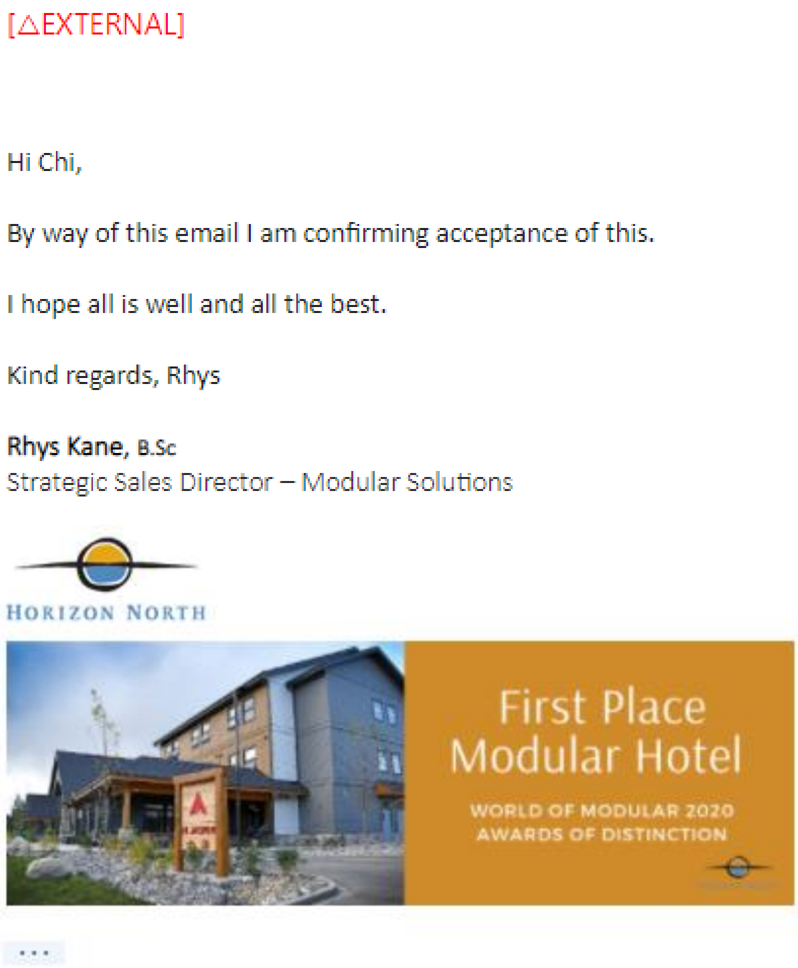
Can you please confirm that you accept to include a version of the published paper of which you are co-author as chapters in my Ph.D. thesis to be submitted to the University of Calgary, Faculty of Graduate Studies?

1. Towards net-zero energy modular housing: a case study. *Modular and Offsite Construction (MOC) Summit Proceedings*.

An email confirmation will be great.

Thanks,
Chi Dara, MSc (Arch), LEED Green Associate

Reply from Rhys Kane



[△EXTERNAL]

Hi Chi,

By way of this email I am confirming acceptance of this.

I hope all is well and all the best.

Kind regards, Rhys

Rhys Kane, B.Sc
Strategic Sales Director – Modular Solutions