

Life Cycle Carbon Assessment (LCCA) of modular buildings for northern Canada applications

Golnaz Vakili Sohrofirouzani

A Thesis

In The Department of Building,
Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of

Master of Science (Building Engineering) at

Concordia University

Montreal, Quebec, Canada

October 2025

© Golnaz Vakili Sohrofirouzani, 2025

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

By: Golnaz Vakili Sohrofirouzani

Entitled: **Life Cycle Carbon Assessment (LCCA) of modular buildings for northern Canada applications**

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Building Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

Dr. C. Mulligan Chair

Dr. C. Mulligan Examiner

Dr. P-H. Chen Examiner

Dr. F. Nasiri Co-Supervisor

Approved by _____ Dr. Mourad Debbabi _____

November 5, 2025 _____

Abstract

Life Cycle Carbon Assessment (LCCA) of modular buildings for northern Canada Applications

Golnaz Vakili Sohrofirouzani

More than a third of all CO₂ emissions from energy sources come from the building industry, making it a significant contributor to the global greenhouse gas problem. This challenge is especially pronounced in Canada's northern territories, such as Nunavut, where communities rely heavily on diesel for heating and electricity due to extreme climates and geographic isolation. These factors result in disproportionately high per capita emissions, despite the region's lack of industrial activity. In response to both environmental and housing challenges, modular construction represents a viable and sustainable solution, enabling off-site prefabrication and rapid on-site assembly, with the potential to significantly reduce carbon emissions, construction costs, and housing shortages.

The modular home envelope at Cambridge Bay, Nunavut, was the subject of a Life Cycle Carbon Assessment (LCCA) in this research. Following the guidelines laid out by ISO 14040, this study focuses on the A1-A5 system boundary, which encompasses the processes of extracting raw materials, transporting them, producing them, and finally assembling them on-site. Experimental data for each phase was collected in collaboration with the Arctic Modular Home Factory located in Manitoba, including design documentation, manufacturing and assembly information, and logistics. Autodesk Revit and SimaPro software (TRACI method) were used for modeling and environmental impact analysis to identify the most carbon-intensive life cycle stages.

Furthermore, scenario analyses were conducted to explore carbon reduction strategies, including alternative material selection, optimized transportation logistics, and modular factory relocation. The results provide a baseline for understanding the environmental performance of modular construction in Arctic regions and offer practical pathways for emission reductions. Though conducted on a single unit, this study represents a scalable model for broader modular housing developments in northern communities. Its findings aim to inform policymakers, construction practitioners, and local governments seeking to implement low-carbon, resilient, and cost-effective housing solutions in remote regions of Canada.

Acknowledgments

I would like to express my deepest gratitude to my supervisor for his invaluable guidance, encouragement, and support throughout this work. I also wish to extend my sincere appreciation to Arctic Modular Home, especially Stuart Rostant, for providing real-time data, which served as a pivotal foundation for this project.

Finally, I am truly thankful to my family, my husband and my friends for their endless love, patience, and encouragement, which have given me strength throughout this journey.

To My oldest friend, my dearest brother,

Jalal

Table of Contents

List of Figures	ix
List of Tables	xii
 Chapter 1: Introduction	 1
1.1 Background	1
1.2 Research Gaps and Significance	2
1.3 Problem Statement.....	4
1.4 Research Objectives	6
1.5 Thesis Organization	8
Chapter 2: Literature Review	10
2.1. Carbon Emissions in the Construction Sector.....	10
2.1.1. Construction Sector Contribution to Global Carbon Emissions	10
2.1.2. Construction Sector Contribution in Canada’s Carbon Emissions	11
2.1.3. Nunavut Carbon Emissions	12
2.2. Modular Construction and Carbon Emissions.....	14
2.2.1. Definition of Modular Construction.....	14
2.2.2. Background of Modular Construction	17
2.2.3. Benefits of modular construction.....	18
2.2.3.1. Construction-related Benefits.....	18
2.2.3.2. Environmental and Carbon Emission Benefits.....	20
2.3. Life Cycle Assessment (LCA) for Carbon Inventory Analysis	22
2.3.1. LCA Definition	22
2.3.2. LCA Phases	22
2.3.2.1. Goal and Scope	22
2.3.2.2. Life Cycle Inventory Analysis.....	23
2.3.2.3. Life Cycle Impact Assessment	23

2.3.2.4.	Life Cycle Interpretation	23
2.3.3.	LCA Approaches	24
2.3.3.1.	Processed-based Approach	24
2.3.3.2.	Input-Output Approach	25
2.3.3.3.	Hybrid Approach	26
2.3.4.	LCA of Buildings	27
2.3.4.1.	Convencional versus Modular method	30
2.3.4.2.	Integration of BIM and LCA	36
Chapter 3:	Case study - Cambridge Bay.....	38
3.1.	Cambridge Bay Climate.....	39
3.2.	Energy Challenges and Carbon Emissions in Cambridge Bay	40
3.3.	Construction challenges in Cambridge Bay.....	41
3.4.	Arctic Modular Home Unit: Building overview	43
Chapter 4:	Methodology	47
4.1.	Goal and Scope of the Study	47
4.1.1.	Functional Unit	47
4.1.2.	System Boundary.....	47
4.2.	Life Cycle Inventory Analysis Levels	48
4.2.1.	LCI Parameter for A1: Raw Material and BIM application	49
4.2.2.	LCI Parameter for A2 and A4: Transportation	55
4.2.3.	LCI Parameter for A3: Manufacturing.....	58
4.2.4.	LCI Parameter for A5: On-site Construction	61
4.3.	LCA Software	62
4.3.1.	SimaPro Characteristics	62
4.3.2.	Simapro Inputs	64
Chapter 5:	Result Analysis	65
5.1.	Life Cycle Interpretations	65
5.1.1.	Raw Materials	65
5.1.2.	Transportation	66

5.1.3.	Manufacturing.....	67
5.1.4.	On-site Construction	68
5.1.5.	Comparative Analysis.....	69
5.2.	Scenario Analysis (Consequential Analysis).....	71
5.2.1.	Alternative Raw Material Selection	71
5.2.2.	Port relocation.....	74
5.2.3.	Local worker.....	76
5.2.4.	Modular Factory relocation	77
Chapter 6: Conclusions.....		79
6.1.	Summary of contributions	79
6.2.	Limitations	80
6.3.	Future work	82
Appendices		92
Appendix A : Quantity Take-offs		92
Appendix B: Life Cycle Inventories		94
Appendix C: Life Cycle Carbon Inventories		99

List of Figures

Fig. 1. Share of buildings in total final energy demand and GHG emissions (kg CO ₂ eq in 2022)	11
Fig. 2. Research Focus Areas in Life Cycle Assessment	13
Fig. 3. Focus of LCA Research by Material Type	13
Fig. 4. Regional Focus of the LCA Research	13
Fig. 5. Comparing GHG emissions per capita in tonnes in electricity sector in 2022	15
Fig. 6. Comparing GHG emissions per capita in tonnes in 2022	15
Fig. 7. Research framework based on ISO1404	18
Fig. 8. Mauna Loa tracks the global CO ₂ trend	20
Fig. 9. Canada 's total greenhouse gas emissions from 1990 to 2022	21
Fig. 10. Change in greenhouse gas emissions by economic sector in Canada from 2005 to 2022	22
Fig. 11. Provincial CO ₂ emissions change per capita in Canada from 2009 to 2020	23
Fig. 12. GHG emissions by sector in Nunavut in 2022	24
Fig. 13. System boundary of Prefabrication building	25
Fig. 14. Panelized Modular building type and Volumetric Modular building type	25
Fig. 15. LCA framework	34
Fig. 16. Number of Articles on Process-Based LCA, I_O LCA, and Hybrid LCA Methods (2009-2024)	36
Fig. 17. Building Life Cycle based on EN 15978	37
Fig. 18. Life Cycle of on-site and prefabricated building	40
Fig. 19. Overview of BIM and LCA data exchange methods [M2]	48
Fig. 20. Location of the case study site: Cambridge Bay, Nunavut	49
Fig. 21. Temperature and Precipitation Graph for 1991 to 2020 Canadian Climate Normal Cambridge Bay	50
Fig. 22. Electricity Capacity and projections from 2010-2023	51

Fig. 23. Construction feasibility analysis for Clear Space Force Station, Alaska	53
Fig. 24. Mean Temperature in Cambridge Bay	54
Fig. 25. 3D models of the Modular Unit	56
Fig. 26. Layout of the Modular Unit with the highlighted modular parts analyzed in this study ...	56
Fig. 27. The system boundary of this study based on EN15978	58
Fig. 28. Life Cycle Inventory Analysis flowchart	59
Fig. 29. Cross-section of the modular unit, showing structural components and material specifications	60
Fig. 30. A sample of provided shop drawings of the ICE Panel, showing the location and number of galvanized steel studs within the panel structure and openings	61
Fig. 31. 3D model of two modular units in Revit	62
Fig. 32. 3D sections showing the detailed modeling of the envelope	62
Fig. 33. Sections of Roof (left) and Floor and Walls (right) showing the detailed modeling of the envelope	63
Fig. 34. Supplementary Transportation of Raw Materials (A2 Phase)	66
Fig. 35. Transportation of completed units from Reinfeld to Montreal port to Cambridge Bay ...	66
Fig. 36. Main transportation means used to ship the Units to Cambridge Bay (50" trailers and Large Cargo ship NSSI)	67
Fig. 37. Modular company layout and six working stages.....	70
Fig. 38. Arctic Modular Home Company view and layout	72
Fig. 39. Moving the pods from the shore to the assembly site	74
Fig. 40. LCA process in SimaPro.....	75
Fig. 41. Global warming Potential of greenhouse gases relative to CO ₂ (IPCC, 2021)	76
Fig. 42. Carbon emissions breakdown (kgCO ₂ eq) of raw materials	79
Fig. 43. Carbon emissions breakdown (kgCO ₂ eq) of Transportation	80
Fig. 44. Carbon emissions breakdown (kgCO ₂ eq) of Manufacturing	81
Fig. 45. Carbon emissions breakdown (kgCO ₂ eq) of on-site construction activities	82
Fig. 46. Contribution of each life cycle phase to total CO ₂ emissions in modular building construction	84
Fig. 47. Impact of material substitution on carbon reduction in the structure	85

Fig. 48. Impact of material substitution on carbon reduction in the Cladding system	86
Fig. 49. Relocating the port from Montreal to Churchill port	87
Fig. 50. First and Second Highest Contributors to Transportation CO2 Emissions	88
Fig. 51. Impact of relocating the port on carbon reduction in the Transportation phase	88
Fig. 52. Third Major Source of Transportation CO2 Emissions	89
Fig. 53. Impact of using local workers on carbon reduction in Transportation phase.....	89
Fig. 54. Transportation CO ₂ Contribution of Complete Module Shipping.....	90
Fig. 55. Impact of relocating the modular factory on carbon reduction in Transportation phase.....	90
Fig. 56. Contribution of Electricity to CO ₂ Emissions in the Manufacturing Phase	91
Fig. 57. Impact of relocating the modular factory on carbon reduction in electricity consumption of manufacturing.....	91

List of Tables

Table 1. A Carbon Reduction Comparison between Modular and Conventional Building Practices	15
Table 2. Literature review on carbon emission reductions in modular versus conventional construction	25
Table 5. Material Takeoff and LCI Mapping for SimaPro	40
Table 6. Transportation Inventory LCI Mapping for SimaPro	43
Table 7. Electricity Consumption and Gas Consumption for Modular Factory and LCI Mapping for SimaPro	45
Table 8. Fuel Consumption and Energy Use for Machinery and Generator for on-site assembly and LCI Mapping for SimaPro	46
Table 9. Carbon emissions in the product stage and the Construction stage of the LCA	52

Chapter 1: Introduction

1.1 Background

Scientific studies have shown that greenhouse gas emissions (i.e., carbon dioxide, methane, and nitrogen oxides) are the primary driver of global warming (Mastrucci et al., 2017). Among greenhouse gases (GHG), carbon dioxide (CO₂) is now the most potent in terms of its effect on climate change. As stated by Khoshnava et al. (2018), with a combined use of 37% of the world's energy and 23% of all emissions (Khoshnava et al., 2018), buildings are the largest single source of carbon dioxide emissions (UNEP, 2022).

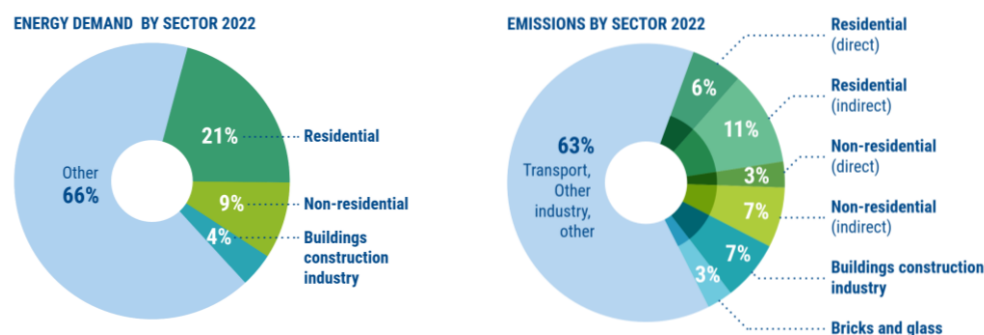


Fig. 1. Share of buildings in total final energy demand and GHG emission (kg CO₂ eq in 2022)(IEA, 2023)

This global trend is also evident in Canada. Although Canada's overall carbon emissions have declined (mainly due to certain provinces transitioning to hydroelectric power), CO₂ eq emissions from the building sector have been increasing (Canada, 2023a). Across Canada, remote communities in the northern regions have experienced high carbon emissions levels despite being non-industrial areas. In terms of household carbon emissions, only three provinces (Manitoba, Newfoundland, and Nunavut) have shown an increase. In Nunavut, diesel-based electricity generation is among the main contributors to this rise. While some provinces, such as Quebec, have transitioned to hydroelectric power, remote areas still rely entirely on fossil fuels for electricity production, most of which is consumed by the building sector.

Alongside high carbon emissions, northern communities in Nunavut face extreme construction and energy challenges due to geographic isolation, harsh climate, and high transportation costs.

With no road connections, materials, goods, and labor must be transported by sealift, which is limited to summer or airfare, making building supplies among the most expensive in Canada. The reliance on skilled workers from southern Canada further increases costs, as flying tradespeople in and out is expensive. Additionally, high energy costs and dependence on fossil fuels for electricity, heating, and transportation place a significant financial burden on both households and community budgets, exacerbating the region's economic and infrastructural difficulties (Corporation, 2023).

In recent years, modular construction has emerged as a potential solution for mitigating the environmental impacts of the construction industry (Du et al., 2019) and addressing other challenges in the Arctic region. Modular construction in this context means that building components are made in a central factory rather than being built directly on individual construction sites (Pan & Goodier, 2012). By preparing the Modular units elsewhere in Canada and shipping them to remote areas for installation, we can reduce Carbon emissions in that region by decreasing construction time and increasing building quality. Additionally, this approach helps reduce construction costs and alleviate house shortages.

1.2 Research Gaps and Significance

As it is concluded from the literature review chapter, there is a dearth of research on the environmental effects and carbon emissions of modular construction in the Arctic region, despite the numerous benefits of this method in remote parts of Canada.

As shown in Fig. 2, most existing studies focus on the environmental impact of prefabrication, with only a few covering Modular Construction. The number of studies is even less in North America, with only one study conducted on a modular home in Alaska (Hossain & Marsik, 2019), which addresses the remote harsh climate.

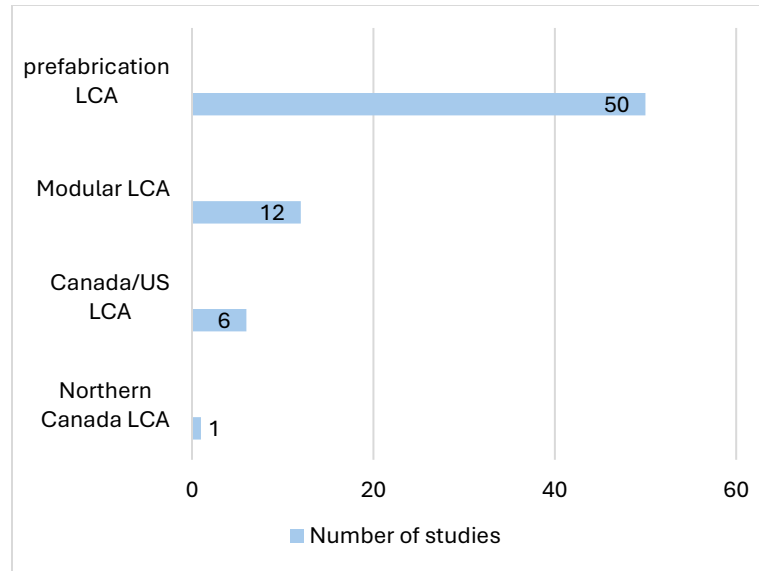


Fig. 2. Research Focus Areas in Life Cycle Assessment

While many studies have examined the environmental impact of concrete buildings, few have explored the potential of wood, steel, or new technology-based alternatives. Fig. 3 illustrates that comparatively few investigations have focused on materials other than concrete. Besides, Fig. 4 highlights that most of the studies have been conducted in China and Europe, with limited research focusing on North America, particularly North of Canada.

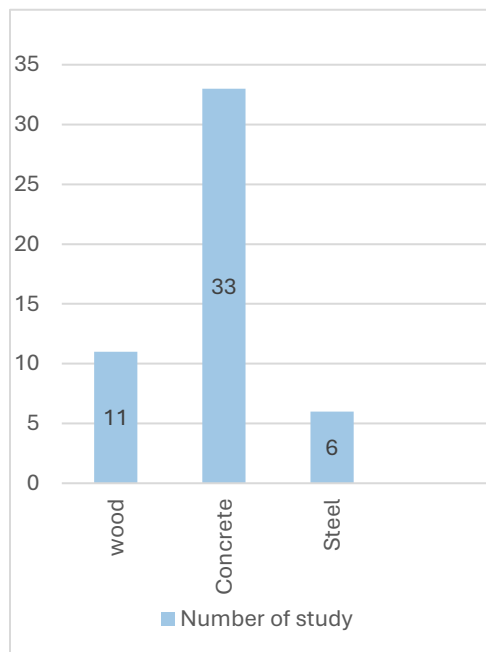


Fig. 3. Focus of LCA Research by Material Type

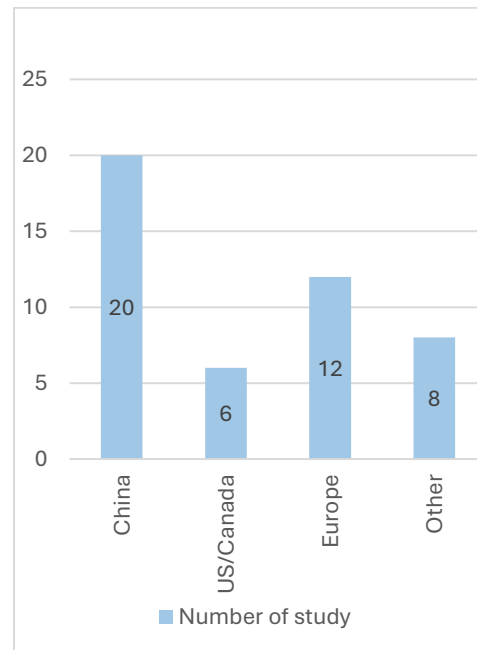


Fig. 4. Regional Focus of the LCA Research

While modular construction is recognized as a strategy for sustainable building practices, its application in Canada's remote regions requires more comprehensive analysis. To address these gaps, the present study aims to provide valuable insights into the feasibility and benefits of modular construction in extreme climates. By assessing the carbon emissions of modular construction in this region, we developed different scenarios to reduce Carbon emissions and enhance the sustainability of this building practice.

Ultimately, this research will support decision-making on sustainable construction practices, ensuring that modular solutions are optimized for remote arctic areas and contribute to long-term environmental sustainability.

1.3 Problem Statement

There are two main problems regarding the construction in northern territories of Canada, such as Nunavut that necessitates further research and analysis: a high rate of Carbon emissions and Housing issues.

- Carbon emissions:

Although Nunavut has no major industrial or agricultural activities, its greenhouse gas emissions are still high at 16.67 tonnes per capita. This value is only slightly below the Canadian average of 18.2 tonnes per capita (Fig. 5). However, the problem becomes apparent when examining the electricity sector's carbon emissions, which are four times higher in Nunavut than in Canada (Fig. 6). In this region, most of the electricity is consumed by households in buildings.

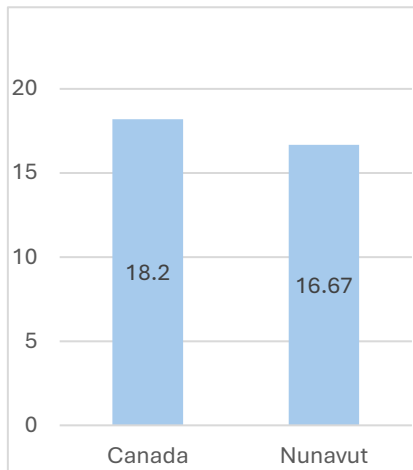


Fig. 5. Comparing Carbon emissions per capita in tonnes in 2022

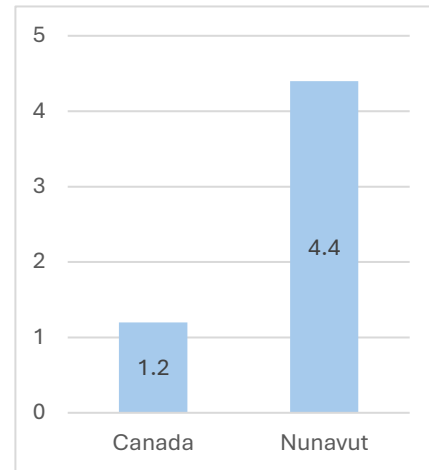


Fig. 6. Comparing Carbon emissions per capita in tonnes in electricity sector in

- Housing issues

In terms of the building sector, in addition to the high carbon emissions rate, northern territories face several critical challenges. These factors include a very limited construction season due to harsh weather conditions and extremely high costs of building materials, resulting in housing that is not only expensive but often of low quality and poor energy efficiency. Furthermore, these regions experience severe housing shortages, forcing multiple families to share a single household or live in inadequate and temporary accommodations.

Adding to the urgency is the threat of coastal erosion, which places existing housing stock at further risk and increases the pressure to develop resilient and sustainable construction solutions.

The expansion of modular construction in remote regions can address both issues by utilizing industrialized construction methods at centralized, well-equipped facilities and then transporting the completed modules to the remote site. Optimal material utilization, reduced on-site activities, and improved energy efficiency of the buildings through the use of the latest technology are the main components of this method that limit carbon emissions during construction and the building's operational phases. Beyond its environmental benefits, modular construction also supports social

and economic development by lowering building costs, improving housing affordability, and lowering maintenance requirements. By decreasing energy consumption and operational expenses, this method enhances sustainability and resilience in remote communities.

In this study, the carbon emissions of a modular construction envelope are assessed to establish a baseline, providing a better understanding of the modular construction processes in this region and its carbon footprint, and enabling the development of alternative scenarios to reduce carbon emissions throughout the modular construction lifecycle. This research, although conducted on a single unit, serves as a representative case for a larger modular construction project comprising 50 units. Scaling the results allows for estimating the total carbon emissions associated with the transformation of conventional construction into modular construction in northern communities. The results of this study could significantly influence sustainable building strategies in northern regions. It highlights how carbon emissions can be reduced through modular construction, which may support the development of environmental policies and potentially lead to financial incentives, such as reduced carbon taxes or eligibility for green building credits in the region.

This study would benefit northern residents by providing a comprehensive overview of the modularization process, thereby facilitating the adoption of modular construction in remote regions with less environmental impact. The insights gained can encourage government bodies, community leaders, and modular construction practitioners to consider modular approaches as a viable solution.

1.4 Research Objectives

In terms of reaching the objectives of this study, as shown in the figure 7, the process began with a comprehensive literature review of modular and prefabricated construction Life Cycle Carbon Assessment (LCCA) studies using the related keywords. This review revealed a notable gap: the lack of LCCA research on modular construction in Canada, particularly in the northern territories, where modular construction could be essential to addressing both carbon emissions and housing challenges.

The main objective of this study is to carry out an extensive LCCA of a modular construction situated in a remote region in Northern Canada by establishing the inventory for the modular

construction industry. The study scope focuses on the building envelope, and the system boundary is defined as the Cradle-to-Site phase (A1-A5), encompassing raw material extraction, transportation, manufacturing, and on-site construction. By analyzing these phases, the Carbon impact of the modular construction envelope was evaluated, and the key contributors to Carbon emissions were identified in the interpretation phase.

This objective is addressed by following the ISO 14040 LCA framework, which is broken into four key phases as illustrated in Fig. 8:

- Phase 1:
Establishing the study goal to evaluate the carbon emissions of a modular single-family envelope and defining the system boundary as Cradle-to-Site (A1-A5).
- Phase 2:
Data collection in collaboration with Arctic Modular Home Factory through surveys and interviews by providing shop drawings, sections, layouts, and utility bills. This phase supports accurate material quantity estimation using tools like Autodesk Revit and Autodesk Take-off to generate a Bill of Quantities (BOQ).
- Phase 3:
Using inventory data in SimaPro software and the TRACI method to evaluate environmental impacts, focusing particularly on global warming potential (carbon emissions).
- Phase 4:
Interpreting the results to identify major carbon contributors in the building envelope's life cycle.

The second objective of this research is to find solutions to lower carbon emissions by performing independent scenario analyses for the mentioned stages. This objective involves evaluating various strategies, including alternative raw material selection, optimizing transportation logistics, and relocating the manufacturing facility. This comparative analysis provides valuable insights into

low-carbon design and construction strategies to enhance the sustainability of modular construction practices in remote regions.

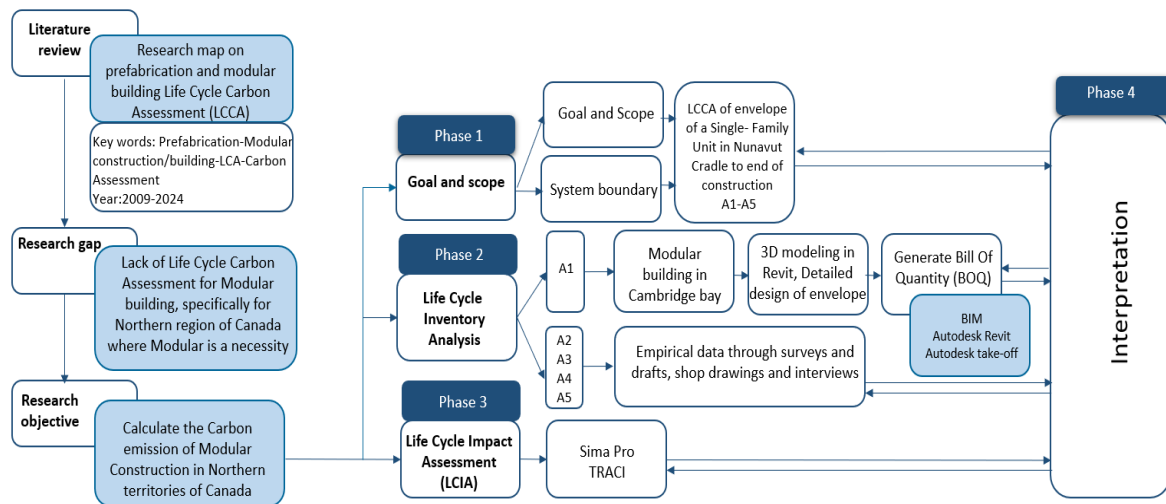


Fig.7. Research framework based on ISO14040

1.5 Thesis Organization

This thesis consists of the following chapters:

Chapter 1 consists of a comprehensive introduction and an overview of this study.

A thorough literature review of works pertinent to this research is included in Chapter 2. To gain a deeper understanding of this study, it explored four key ideas. It begins with an overview of climate change and carbon emissions challenges, followed by an examination of the off-site construction method and its advantages over conventional methods. Then, it explores the Life Cycle Assessment application in analysing the environmental impact of Modular Construction.

Chapter 3 describes the selected Case study in Cambridge Bay, Nunavut, in collaboration with Modular Arctic Home Factory.

Objectives and scope, system boundary definition, and data collection for the life cycle inventory phase are all covered in depth in Chapter 4, which also presents the study approach. Afterward, it discusses how to integrate BIM and LCA for data collection and the parameters involved.

Chapter 5 presents a comparative analysis for each stage separately and then finds the most Carbon-intensive phase. Additionally, a scenario analysis was conducted to analyze different alternatives for reducing carbon emissions within the defined system boundary.

Chapter 6 presents the conclusion and key findings of the study, which aims to reduce Carbon emissions by applying different scenarios at various phases of modular construction.

Chapter 2: Literature Review

2.1. Carbon Emissions in the Construction Sector

2.1.1. Construction Sector Contribution to Global Carbon Emissions

The greenhouse effect is the primary driver of global warming, which is produced by the incomplete combustion of fossil fuels, resulting in massive emissions of gases such as carbon dioxide, methane, and nitrogen oxides (Mastrucci et al., 2017). According to Khoshnava et al. (2018), among greenhouse gases (GHG), Carbon is currently the most significant contributor to climate change (Khoshnava et al., 2018) due to its lengthy cycle (approximately 120 years on average). Fig. 7 illustrates that by 2022, atmospheric carbon emissions will have climbed from 340 ppm to approximately 420 ppm (Laboratory, 2025)

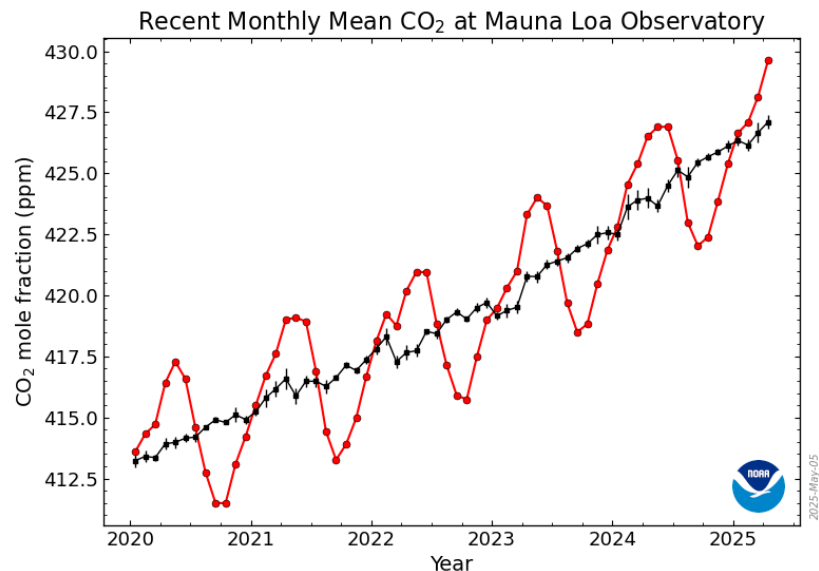


Fig. 8. Mauna Loa tracks the global CO₂ eq trend (Laboratory, 2025)

Buildings contribute to environmental degradation throughout their entire lifecycle, from the extraction of raw materials to their operation, and ultimately to the demolition and disposal of waste at the end of their lifespan. All these processes require energy and emit greenhouse gases as well as other pollutants that negatively impact our environment. The construction industry has been identified as one of the seven primary contributors to global greenhouse gas (GHG) emissions

in the IPCC's Fourth Assessment Report. Worldwide, the building industry accounts for 37% of all energy consumption (UNEP, 2022), and it is also responsible for an estimated 23% of annual greenhouse gas emissions (Huang et al., 2018). In this respect, 40-60% of all raw materials are extracted from construction sites (Kamali et al., 2019).

Global carbon emissions from construction activities reached approximately 10 gigatonnes in 2022, representing a 1% increase over the previous year. Nearly a quarter of all carbon emissions worldwide are attributed to buildings in terms of energy. Approximately 37% of the world's energy and process-related carbon emissions originate from the buildings and construction sector, with an additional 7-9% attributable to the manufacture of essential building materials, including concrete, steel, aluminum, glass, and bricks. With the inclusion of materials such as textiles, foams, and plastics, this number would reach an even greater height (IEA, 2023). Hence, almost a third of all emissions related to energy came from building operations and construction, totaling approximately 13.6 gigatons of carbon dioxide (Gt Carbon) (GlobalABC, 2024).

2.1.2. Construction Sector Contribution in Canada's Carbon Emissions

Greenhouse gas emissions in Canada fell from 761 megatonnes in 2005 to 708 megatonnes in 2022, according to the most recent National Inventory Report. However, according to Fig. 10, the country's population continued to grow, increasing from 32.4 million in 2005 to 39.3 million in 2022 (Canada, 2023a).

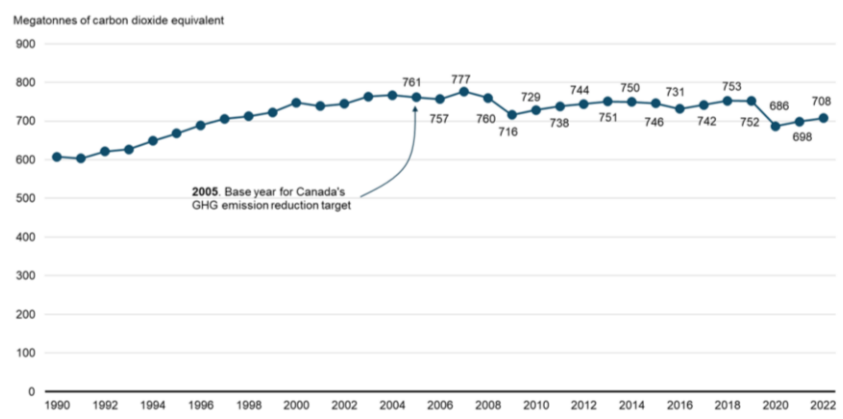


Fig. 9. Canada's total greenhouse gas emissions from 1990 to 2022 (Canada, 2023a)

As shown in Fig. 9, greenhouse gas emissions have increased in several sectors since 2005.

The oil and gas sector saw the largest rise, with an increase of 21 megatonnes (Mt). This rise

was followed by the agricultural sector, which grew by 4.6 million tonnes, and the building sector, which increased by 3.9 million tonnes.

Nevertheless, other sectors have significantly reduced their emissions, which has largely compensated for these increases. The electrical industry experienced the steepest drop, at 69 Mt, possibly due to the transition of certain provinces to cleaner energy sources, such as hydro, wind, and solar, in places like Quebec. Additionally, the heavy industry sector reduced its emissions by 10 million tonnes, and the waste and other sectors saw a combined decrease of 4.3 million tonnes (Canada, 2023a).

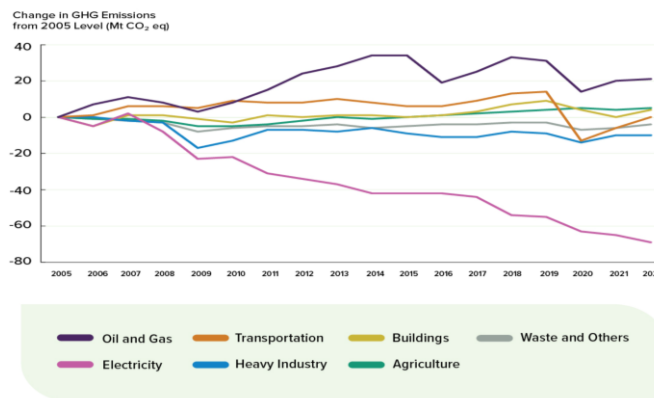


Fig. 10. Change in greenhouse gas emissions by economic sector in Canada from 2005 to 2022 (Canada, 2023a)

In 2018, the building sector contributed more than 8% of Canada's greenhouse gas emissions (90 Mt CO₂ eq), despite meeting only one-third of the country's housing demand (Yoffe et al., 2024).

2.1.3. Nunavut Carbon Emissions

According to Fig. 10, among all provinces in Canada, Nunavut, Newfoundland, and Manitoba are the only provinces that experienced an increase in carbon emissions in households from 2009 to 2020 (Canada, 2021).

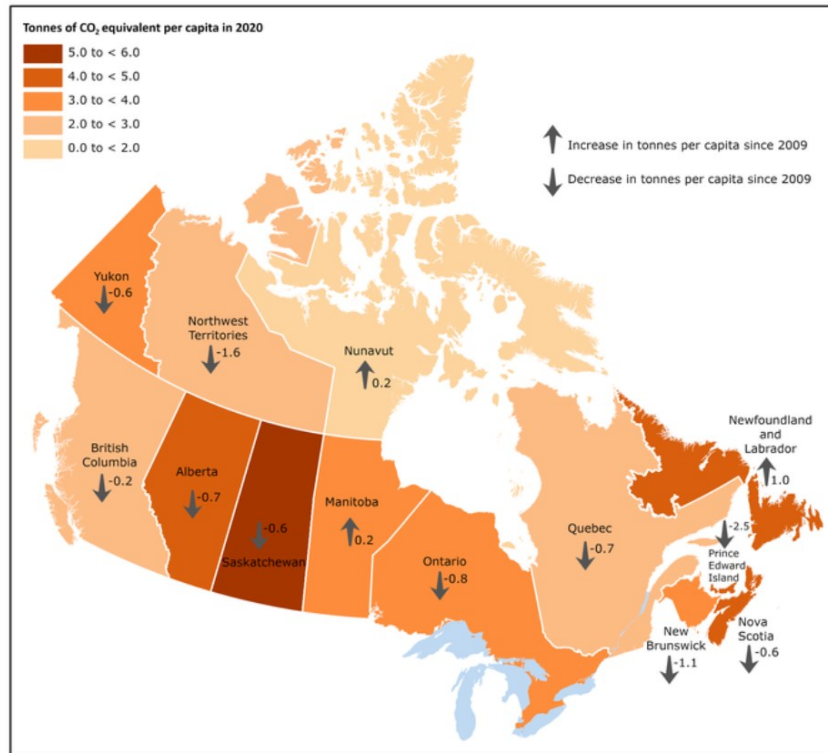


Fig. 11. Provincial CO₂ emissions change per capita in Canada from 2009 to 2020 (Canada, 2021)

Fig. 11 shows that in 2022, the energy sector was the primary contributor to Nunavut's greenhouse gas (GHG) emissions, which totaled approximately 414 kt of CO₂ equivalent. This sector alone represents the vast majority of total emissions in the territory. Other contributing sectors include waste, which emitted about 33 ktCO₂eq, and industrial processes and product use, responsible for 20 kt CO₂eq. Emissions from land use were minimal, recorded at only 0.09 kt CO₂eq, while the agriculture sector contributed no measurable emissions in that year (Canada, 2023b). This distribution highlights the significant impact of energy-related activities, particularly fuel combustion for heating and electricity generation, on Nunavut's emissions profile.

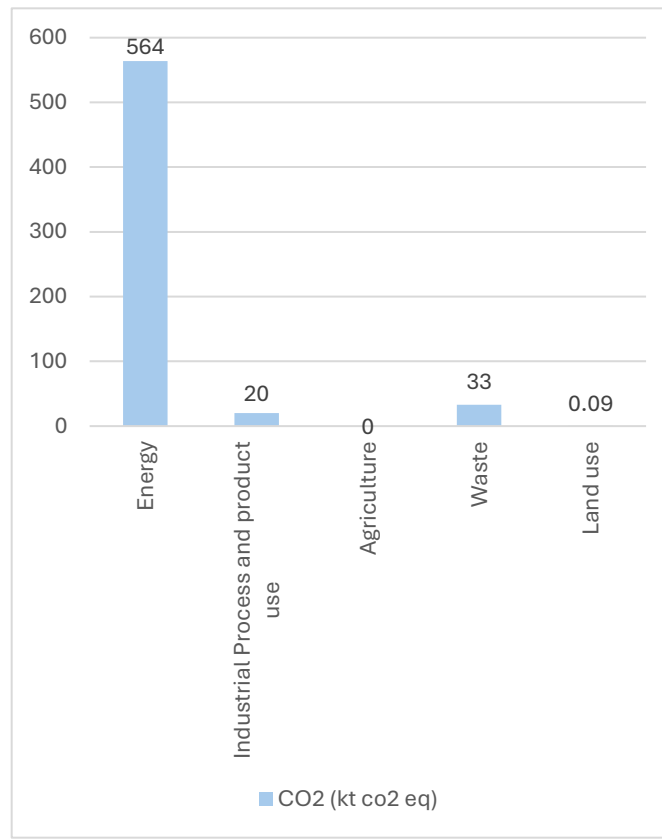


Fig. 12. GHG emissions by sector in Nunavut in 2022(Canada, 2023b)

In terms of the building sector’s contribution to GHG emissions, Nunavut’s remote geography and dispersed population result in a heavy reliance on diesel for electricity generation, making it difficult to adopt alternative energy sources. Every Nunavut town uses diesel generators to power their homes and businesses; in the summer, diesel fuel is brought in from outside the territory and stored for the rest of the year. Nunavut’s generation intensity was 840 grams of CO₂eq per kilowatt-hour, the highest in Canada. As mentioned above, it is primarily used for heating and lighting in buildings (Regulator, 2020).

2.2.Modular Construction and Carbon Emissions

2.2.1. Definition of Modular Construction

A definition of prefabrication is necessary before we can discuss modular construction. In prefabrication, various materials are combined to form a component of the finished installation.

This procedure (Fig. 12) typically occurs at a specialized facility (Gibb, 1999). Some regional and national variations in the meaning of “prefabricated buildings” include “off-site manufacturing”, “prefabrication”, and “pre-assembly” (Wang et al., 2020).

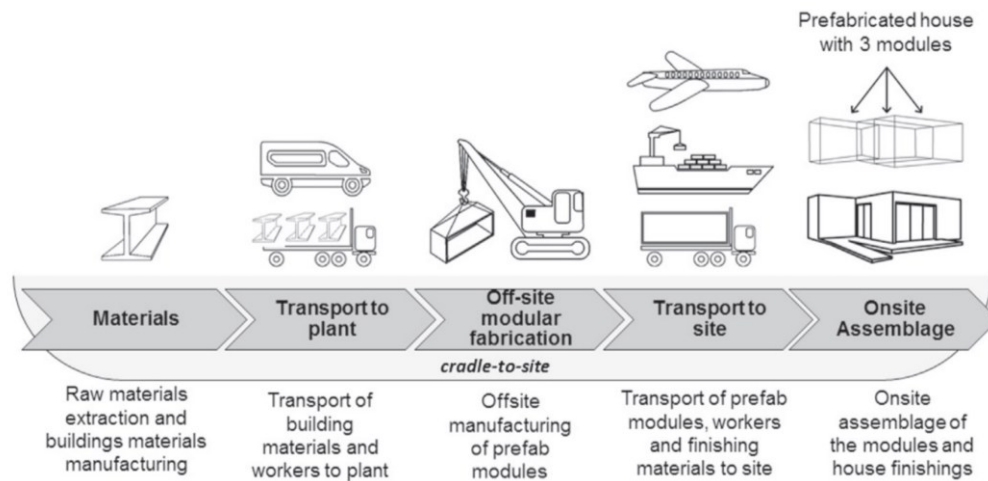


Fig. 13. System boundary of Prefabrication construction (Tavares et al., 2019)

Levels of off-site construction are determined by the amount of work that has been done off-site (Gibb & Pendlebury, 2006):

- **Component sub-assembly:** The assembly of small-scale parts, such as windows and doors, takes place in industrial settings.

- Non-volumetric preassembly 2D (Panelized System): Products, such as cladding panels (Fig. 15), are manufactured in factories into non-volumetric pieces before being installed on construction sites (Kamali & Hewage, 2016). Flat, two-dimensional panels, known as

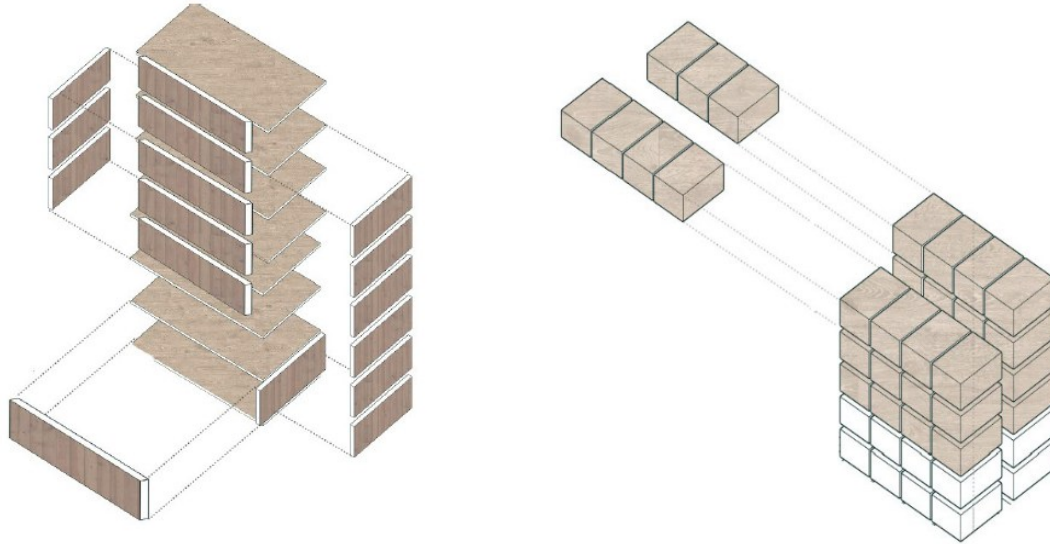


Fig. 14. Panelized Modular building type and Volumetric Modular Construction type (Rezzag Lebza, M., 2022)

“prefabricated panelized systems”, are manufactured in a factory and then transported to the

- building site to be assembled into a three-dimensional structure. These panels form part of the building’s structural system and may include walls, floors, or roof elements. In their basic form, panelized systems consist of simple structural elements; however, they can be enhanced during manufacturing to include additional components, such as windows, piping, insulation, or electrical fittings, thereby improving their functionality and reducing the need for further on-site work. A notable example of this system in practice is the Forte building in Australia, completed in 2012. This residential high-rise was constructed entirely using Cross-Laminated Timber (CLT) panels, which were prefabricated and delivered to the site ready for installation. The structural system of Forte relies exclusively on these CLT panels, which are strong and stable enough to support their own weight, eliminating the need for conventional framing systems (Rezzag Lebza, 2022).
- Volumetric preassembly 3D: When it comes to off-site construction, volumetric prefabrication is a step above panelized methods. Akin to the preceding stage, construction components are built in controlled circumstances within the factory. However, this time

around, they are transformed into three-dimensional volumetric units that encapsulate usable space before being brought to the site for setup (Kamali & Hewage, 2016). These volumetric modules are typically structurally self-supporting and can be stacked or arranged on-site to form entire buildings or parts of buildings.

These units are usually fully finished internally, meaning that most architectural, mechanical, and electrical systems are completed in the factory. A common example is the toilet or bathroom pod, which is delivered as a complete, ready-to-install unit, reducing on-site labor and construction time (Rezzag Lebza, 2022).

- **Modular Construction:** Approximately 85-90% of modular construction occurs off-site, while a small fraction, around 10-15%, takes place on-site. Foundation construction and utility hookups are included in this little section. Due to their focus on efficiency and production economy during construction, or because they aim to minimize building process disruptions for business or planning reasons, certain sectors may find modular construction particularly advantageous (Kamali & Hewage, 2016; Lawson et al., 2014). Modular construction is most commonly used in the general building sector, especially for projects involving repeated units. These applications include apartment complexes, educational institutions such as schools and student housing, as well as hotels, hospitals, and office buildings (Kamali & Hewage, 2016).

2.2.2. Background of Modular Construction

Rapid development and global application of modular construction have occurred since their first use in 1851 (Arif & Egbu, 2010; Wang et al., 2020). Modular housing was originally developed to provide temporary shelter that only met essential needs. Over time, however, advancements in technology and design have transformed modular construction into a versatile approach, capable of delivering customized layouts and high-quality finishes to meet modern standards (Hatmoko et al., 2023).

In the 1990s, factory-produced homes accounted for 25-28% of Japan's total housing completions (Pervez et al., 2021). Japan was an early pioneer in factory-based home construction, which allowed for the standardization of design techniques, the simplification of residential component

assembly, and the mass production of building elements (Wang et al., 2020). In 2016, the State Council of China issued official directives emphasizing the importance of adopting innovative construction methods, with a particular focus on promoting prefabricated buildings. The goal was to ensure that prefabricated buildings would account for 30% of all new constructions within the next 30 years. As a result, prefabrication technology is now being actively advanced, particularly in the residential sector, which constitutes a significant portion of the construction market (Du et al., 2019).

In 1999, the Peabody Trust introduced an innovative approach to social housing with the construction of Murray Grove in Hackney, North London. Using 80 factory-built modules, they constructed a five-story L-shaped building with open walkways and balconies surrounding a central courtyard. A pioneer in the field of modular architecture, this project transformed ordinary modules into a stylish and comfortable home for its inhabitants (Lawson et al., 2014).

2.2.3. Benefits of modular construction

2.2.3.1. Construction-related Benefits

Time: Modular construction offers a significant advantage in reducing the time between the start of construction and the building's occupancy. In this method, site preparation and factory production of building modules can occur simultaneously, unlike traditional construction, where each step must wait for the previous one to finish. Site work comes first, followed by the construction of the structure, and finally, interior work. This ability to work in parallel helps shorten the overall timeline. Since the modules are prefabricated and lifted into place by crane, on-site work is faster and requires fewer workers (Noordzy et al., 2021). The fact that most of the work occurs in a manufacturing setting also makes it less likely that factors such as bad weather, vandalism, or theft will cause delays (Kamali & Hewage, 2016). As more work is done off-site, modular construction will become increasingly efficient over time (Bertram et al., 2019; Thai et al., 2020).

The total amount of time needed to complete a project can be cut in half using modular construction as opposed to conventional methods (Kamali & Hewage, 2016). For instance, Zenga & Javor (2008) reported a 10-month time savings during the construction phase, and an 11-month difference in the design, engineering, and permitting stage when using modular methods. Faster

construction in modular projects reduces labor and site management costs, which in turn lowers overall expenses and leads to quicker returns on investment (Lawson et al., 2014).

Minimized Impact on Site: Modular construction reduces disruption at the building site because most of the work is done off-site in a factory, resulting in less noise, dust, and waste during installation. This issue makes the site cleaner, quieter, and safer compared to traditional construction, where all activities take place on location (Kamali & Hewage, 2016).

Workmanship and productivity: Modular construction and prefabrication reduce the need for highly skilled labor on-site, as the assembly process is generally less complex compared to traditional methods. Improved supervision, shorter transition times between trades, and a more consistent workforce are just a few ways in which the modular approach boosts efficiency in the construction industry. Additionally, the factory-based environment enables multiple tasks and operations to be carried out simultaneously without interruption, resulting in significantly higher productivity levels compared to on-site construction (Kamali & Hewage, 2016).

Quality (product quality): The implementation of modular construction contributes significantly to improving overall building quality, largely due to the controlled conditions of factory-based manufacturing environments. Within these settings, repetitive tasks, consistent workflows, and the use of automated machinery contribute to enhanced precision and consistency, resulting in fewer errors and a higher standard of output. Additionally, the modular approach often involves specialized assembly lines, where tasks are broken down into smaller, more manageable segments, allowing workers to acquire skills more quickly and perform their duties with greater efficiency. This form of task specialization shortens the learning curve and reduces the likelihood of material damage or product defects during the production phase. Furthermore, since prefabricated modules must be strong enough to withstand transportation by truck, manufacturers are required to use high-quality materials that are not only structurally durable but also lightweight and resistant to various weather conditions. The reduced exposure of materials and components to on-site environmental stresses such as rain, wind, or temperature fluctuations enhances the finishing quality of the buildings (Kamali & Hewage, 2016).

Safety: In traditional construction, worker safety is often compromised due to numerous on-site hazards, including working at heights, site congestion, unpredictable weather conditions, and interference from adjacent construction activities. These risks are difficult to manage due to the

constantly changing nature of on-site environments, where coordination and control are limited. Modular construction, however, significantly enhances safety by relocating approximately 85% of the construction process to factory settings, where tasks are performed under controlled conditions. This shift not only reduces exposure to high-risk activities but also allows for more structured and repetitive on-site operations, which are easier to manage and inherently safer (Navaratnam et al., 2019).

Cost: Off-site construction offers a new approach to reducing overall project costs by altering the design and assembly of buildings. According to the Construction Industry Institute (CII), modular methods can cut total project expenses by as much as 10%, with on-site labor costs dropping by up to 25%. These savings result from producing modules simultaneously in a controlled environment, which enables bulk purchasing and minimizes the need for constant movement of workers and machinery to the site. With fewer workers needed on-site, modular construction also reduces overcrowding, allowing skilled trades to work more efficiently and productively (Kamali & Hewage, 2016).

2.2.3.2.Environmental and Carbon Emission Benefits

Modular construction offers many advantages to the environment:

Waste reduction: One of the major advantages of modular construction is its ability to reduce construction waste, made possible through accurate material planning, controlled cutting processes, and increased opportunities for recycling and reuse. The ease of implementation and monitoring of waste management procedures in an industrial setting (e.g., correct disposal, recycling, and reuse) is a major aspect in improving waste management. Moreover, modular components are typically dismantled, relocated, or reconditioned for future use, which reduces the need for demolition and waste disposal when a building's life cycle comes to an end (Kamali & Hewage, 2016).

Carbon Emissions Reduction: It is commonly believed that modular construction has more positive environmental effects than traditional methods. These effects are especially true when considering the reduction in energy consumption and greenhouse gas emissions that occur during the life cycle of a modular construction (Ahn & Kim, 2014; Nahmens & Ikuma, 2012).

As mentioned earlier, modular construction, including prefabrication, has been the primary focus of studies examining the environmental effects of off-site construction. Table 1 summarizes findings from several studies, highlighting the potential of prefabrication to reduce carbon emissions by between 9.61% and 43.30% compared to traditional on-site construction methods.

Table 1. A Carbon Reduction Comparison between Modular and Conventional Building Practices

	Author	Year	Country	System Boundary	Carbon reduction Percentage
1	Li et al. (2022)	2022	China	Cradle-to-gate	19
2	Kamali et al. (2019)	2019	Canada	Cradle-to-gate	10.52
3	Hao et al. (2020)	2020	China	Cradle-to-gate	17
4	Jayawardana et al. (2023)	2023	Sri Lanka	Cradle to grave	8.06
5	Pons & Wadel (2011)	2011	Spain	Cradle to grave	15.80
6	Wen et al. (2015)	2015	Malaysia	Cradle-to-end-of-construction	13.38
7	Du et al. (2019)	2019	China	Cradle-to-end-of-construction	18
8	Al-Hussein et al. (2009)	2009	Canada	On-site activities	43.30
9	Cheng et al. (2023)	2023	China	Cradle-to-grave	13.94
10	Gao et al. (2024)	2024	China	Cradle-to-grave	9.61
11	Cheng et al. (2023)	2023	China	Cradle-to-grave	31.78
12	Gao et al. (2024)	2024	China	Cradle-to-end-of-construction	31.62
13	Quale et al. (2012)	2012	US	Cradle-to-end-of-construction	30.24

2.3.Life Cycle Assessment (LCA) for Carbon Inventory Analysis

Previous studies have focused on the operational phase of buildings, as it accounts for more than 70% of the energy consumed throughout a building's life cycle (Fay et al., 2000; Ortiz et al., 2009; Passer et al., 2012; Verbeeck & Hens, 2007). The relevance of other phases of the life cycle, such as material manufacture and construction, has grown, nevertheless, as energy efficiency solutions have evolved and operational consequences have diminished (Verbeeck & Hens, 2007). In the case of nearly Zero-Energy Buildings (nZEBs), for example, these earlier life cycle stages can contribute 50% or more to the total environmental impact (Hafner et al., 2012). Consequently, there has been growing interest in analyzing the environmental performance of all stages of the building life cycle (Dodoo et al., 2009; Venkatarama Reddy & Jagadish, 2003; Thormark, 2006).

2.3.1. LCA Definition

Life cycle assessment (LCA) is now part of the ISO 14000 series, the global standard for environmental management systems, according to the International Organization for Standardization (ISO). ISO defines LCA as the process of gathering and analyzing data on the inputs, outputs, and potential environmental consequences of a product system throughout its entire life cycle. Determining the evaluation's aim and scope, conducting an inventory analysis, assessing the impact, and interpreting the results are the main phases of LCA. The four processes are connected and recursive (ISO14044, 2006)

2.3.2. LCA Phases

2.3.2.1.Goal and Scope

According to ISO14044, a clearly defined goal is essential in any LCA to establish the foundation for the study by identifying its intended use, primary objectives, and the targeted audience.

An organized and thorough process is necessary to define the scope of a LCA in a manner consistent with the study's aims. To evaluate the system's performance, it is necessary to consider the product system under study, its functions, and, most significantly, the functional unit. By standardizing both the input and output data, this unit enables consistent comparison of alternatives. When assessing various systems, it is particularly important to have a well-defined and consistently used functional unit. There needs to be open communication regarding any

exceptions or differences. The system boundary is also essential, as it defines which processes are included in the evaluation. These limits, derived from well-defined standards, must be compatible with the study's objectives (ISO14044, 2006).

2.3.2.2.Life Cycle Inventory Analysis

The Life Cycle Inventory (LCI) phase of an LCA is based on the purpose and scope specification. It involves collecting and quantifying data to measure the energy and material flows linked to the product system. Essential for the subsequent Life Cycle Impact Assessment (LCIA) is information regarding resource use and environmental releases to air, water, and land. The inventory phase is not fixed; it often requires iterative refinement, as data gaps or limitations may emerge during the process. In such cases, adjustments to the initial goal, scope, or data collection approach may be necessary to maintain consistency with the study's intended objectives (ISO14040, 2006).

2.3.2.3.Life Cycle Impact Assessment

In the Life Cycle Inventory (LCI) step, known as the Life Cycle Impact Assessment (LCIA), the potential environmental implications associated with the inputs and outputs are sought after. In contrast to approaches such as risk assessment and environmental impact assessment, LCIA employs a functional unit-based relative approach; nonetheless, it still utilizes data from these other methods. To adhere to the study's objectives and scope, this part must be well-organized and account for any unknowns, such as data gaps, system limitations, or poor data quality. LCIA connects the inventory data to specific environmental effects, helping to understand their importance. The level of detail depends on what the study is trying to achieve. Because LCA is an iterative process, this phase may reveal issues that require adjustments to earlier stages. Last but not least, LCIA incorporates both mandatory and discretionary procedures, culminating in an impact profile that displays the potential environmental consequences of the system under investigation (ISO14040, 2006; ISO14044, 2006).

2.3.2.4.Life Cycle Interpretation

The interpretation phase of a LCA brings together the results from the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA) to provide clear conclusions and practical

recommendations, always in line with the study's original goal and scope. This stage involves identifying key issues that emerge from the analysis, followed by a careful evaluation to ensure the results are complete, consistent, and sensitive to key assumptions. Based on this evaluation, the study presents its conclusions, highlights any limitations, and provides relevant recommendations. When necessary, this phase may also lead to refining the scope or improving data quality to strengthen the overall reliability of the assessment(ISO14040, 2006; ISO14044, 2006).

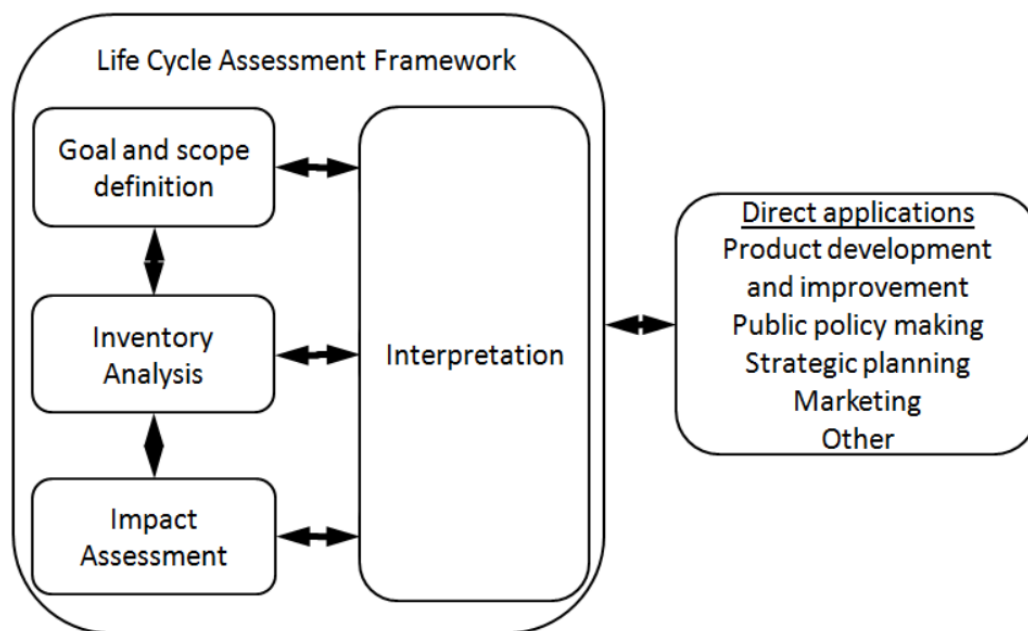


Fig. 15. LCA framework (ISO14044, 2006)

2.3.3. LCA Approaches

There are three separate approaches to LCA, each tailored to a different set of ideas and system scope.

2.3.3.1.Process-based Approach

Process LCA is a bottom-up method. The purpose of this tool is to track and identify the physical movement of services and things within specific processes, products, or production chains. (Bullard et al., 1978).This method is highly accurate for specific systems but has limitations due

to truncation errors, where certain upstream processes are excluded because of system boundary constraints.

The process involves three main steps: first, measuring all direct energy inputs of the main process over a specific period; second, identifying the additional product inputs required; and third, determining the energy embodied in these inputs. However, this method often focuses only on basic materials, overlooking the services and processes involved in their transformation. As a result, process-based LCA tends to cover only a few stages upstream, making it detailed but incomplete.

Although more precise than Input-Output LCA, process-based LCA struggles to capture the full environmental impact of complex systems, especially in construction, where upstream energy-intensive processes can be significant (Zhang & Wang, 2016).

2.3.3.2. Input-Output Approach

Wassily Leontief initially introduced input-output analysis in 1941, when he created the first US input-output tables. Since then, the technique has been widely adopted in economic research. Tables depicting the relationships between various producers within an economy are currently available for more than 90 nations, and they have since been used to evaluate labor and energy intensities (Bullard et al., 1978; Division, 1999). One top-down linear macroeconomic approach to environmental impact evaluation is the Input-Output (IO) approach in LCA. This method analyzes the inter-industry interactions in terms of economic transactions. Derivatives of an input-output matrix are utilized. Statistical information gathered from the census and translated into a tangible form. The IO method includes both direct and indirect impacts from all sectors, unlike process-based LCA, which only considers a small number of suppliers. This includes sectors that are not typically included, such as office supplies or administrative services (Hendrickson et al., 1997; Huovila et al., 2009). The method has become the mainstream method used to study the environmental impact from the macro perspective (country, region, sector, etc. (Wang et al., 2020). This method provides a more comprehensive view of environmental impacts without requiring extensive data collection for each individual process (Hendrickson et al., 1997).

Input-output LCA methods can be useful for assessing the national production of fundamental materials, particularly when specific data is inaccessible due to industry confidentiality. However,

these methods are generally not well-suited for evaluating individual buildings due to the inherent inaccuracies of input-output analysis and the complexity involved in construction projects (Crawford & Treloar, 2004).

2.3.3.3. Hybrid Approach

With the introduction of hybrid LCA, the advantages of both process-based LCA (which provides in-depth analysis) and Input-Output (I-O) LCA (which offers a more generalized system boundary) can be better leveraged. This approach combines I-O LCA, which considers the flow of materials and construction activities across an entire economy, with process LCA, which measures materials and processes in physical units (Omar, 2018).

Based on literature reviews of the prefabrication LCCA (Fig. 16), approximately 87% of studies apply the process-based LCA method, while only 13% adopt hybrid or input-output approaches. In most cases, the study's goals, the availability of data, and the required degree of precision and accuracy determine the LCA technique used. When thorough and trustworthy data are available, process-based LCA is generally considered the best option for case study research (Sandanayake et al., 2019). The process-based LCA method was chosen because this study is focused on a single case study.

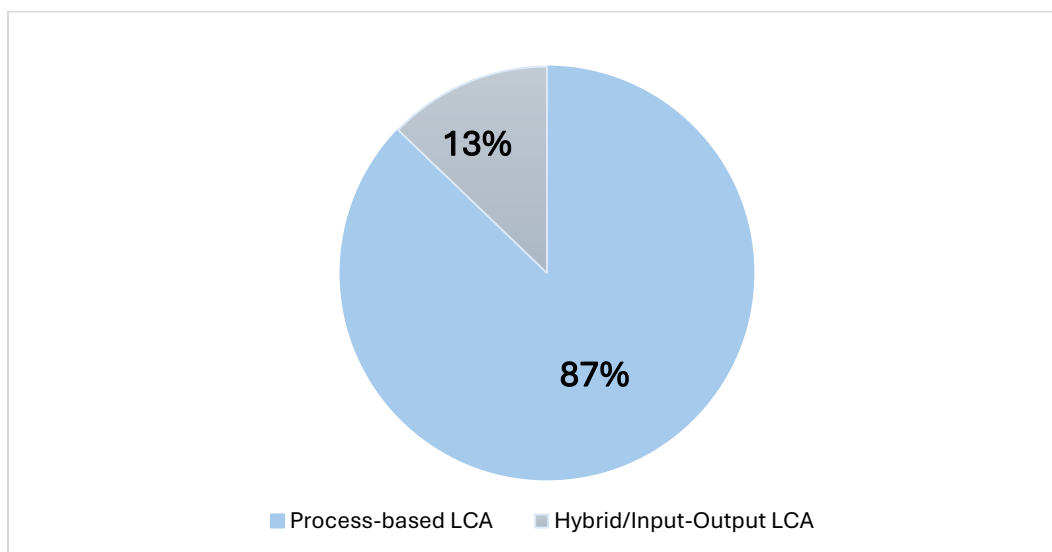


Fig. 16. Number of Articles on Process-Based LCA, I_O LCA, and Hybrid LCA Methods (2009-2024)

2.3.4. LCA of Buildings

In Europe, building-related environmental impacts are commonly evaluated using LCA following the EN 15978 standard. This standard offers a systematic method for assessing the sustainability of buildings and is part of a larger set of standards designed to evaluate environmental performance at both the product and whole-building levels (Global, 2018).

According to EN 15978, the system boundary for evaluating a building's environmental performance includes both the building itself and the boundary is determined based on distinct life cycle stages, which are visually represented in Fig. 17. These stages align with the modular approach used for structuring environmental data related to construction products, as outlined in EN 15804.

Transparent comparisons of environmental consequences are made possible by this framework, which also guarantees a uniform and consistent methodology for conducting LCAs in the construction sector.

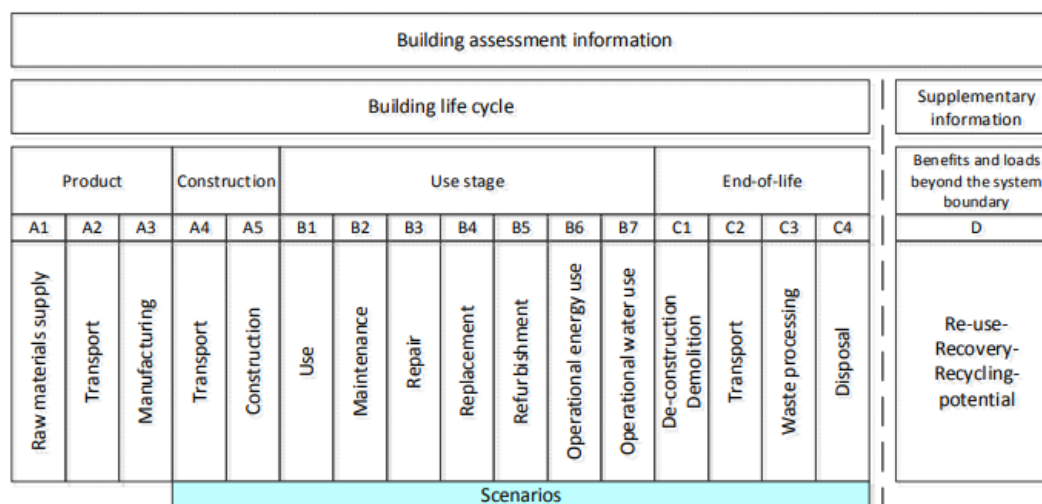


Fig. 17. Building Life Cycle based on EN 15978

Product Stage (Modules A1 to A3) EN 15978 - Clause 7.4.2

This procedure encompasses everything, from sourcing the necessary materials and services to delivering the finished product.

Construction Stage (Modules A4 and A5) - EN 15978 Clause 7.4.3

A4 (Transport): Covers the delivery of construction materials and equipment to the site, including storage and distribution, but excludes personnel transport.

A5 (Construction & Installation): Encompasses material installation, energy and water use, ancillary materials, waste disposal, and replacement of wasted materials. It also includes on-site transport, storage, landscaping, groundworks, and temporary works.

Use Stage (Modules B1-B7) - EN 15978 - Clause 7.4.4

It encompasses the operation and performance of the building from its construction to its deconstruction or demolition. This phase covers both building materials and technical systems.

B1 (Use): Environmental emissions generated during the building's normal operation throughout its reference study period (RSP).

B2 (Maintenance): It covers maintenance activities to ensure a building component remains functional, such as cleaning floors or replacing worn rubber seals. It includes both preventive and regular maintenance, addressing planned cleaning, servicing, and repairs during the reference study period (RSP). The assessment accounts for material replacement, disposal, and associated resource consumption like energy, water, and ancillary materials.

B3 (Repair): Module B3 involves repairing building components to restore their functionality, such as replacing a broken glass pane. It covers corrective, responsive, or reactive repairs throughout the RSP, estimating the frequency of such interventions. The assessment includes material replacement, waste disposal, and the use of energy, water, and ancillary materials like glue.

B4 (Replacement): It refers to the substitution of building components that have either deteriorated beyond repair or reached the end of their functional lifespan within the Reference Study Period (RSP). Windows, walls, and roofing systems are all part of this, as are other non-structural components. Additionally, B4 takes into account waste management and disposal associated with these replacements. It is distinct from B5 (Refurbishment), which involves planned upgrades or improvements rather than replacements driven by damage or wear.

B5 (Refurbishment): This involves major renovations or repurposing of a building, such as modifying layouts or renewing structural components. The stage includes planned upgrades,

maintenance, or the replacement of significant portions of the structure to restore or improve its functionality. This stage covers scheduled refurbishments rather than replacements due to damage, which are classified under B4.

B6 (Operational Energy Use): This stage accounts for energy consumption during a building's operation within the Reference Study Period (RSP) for essential functions, such as HVAC, lighting, water heating, and automated systems. It excludes energy use by non-building-related appliances unless reported separately and prioritizes building-related energy demands over exported energy. Any energy generated on-site is first allocated to the building's needs, with surplus energy reported under a different module.

B7(Operational Water use): A building 's operational water use includes the water used for drinking, sanitation, heating, and integrated systems like fountains and irrigation while the facility is operating normally. It does not include water used for maintenance, repairs, or replacements, which fall under other categories. Additionally, non-building-related water consumption should be separately reported to maintain clarity in the assessment.

End-of-Life Stage (Modules C1 to C4) - EN 15978 - Clause 7.4.5

It covers the decommissioning of a building when it is no longer in use. This phase includes:

C1 (Deconstruction/Demolition): Deconstruction of the structure, encompassing both on-and off-site operations.

C2 (Transport): Transferring debris from demolition projects to an appropriate facility for recycling or disposal.

C3 (Processing): Reducing, reusing, recycling, or disposing of trash via collection, sorting, and treatment.

C4 (Final Disposal): Taking care of garbage at dumps, including treating it accordingly.

The benefits and loads beyond the system boundary- Module D - EN 15978 - Clause 7.4.6

When a building's materials and components are reused, recycled, or put into energy recovery after leaving the system, their positive and negative consequences are considered. These materials have reached the end of their useful life and are derived from construction (A4-A5), usage (B1-B7), or

end-of-life (C1-C4) phases. It also includes exported energy that is recovered beyond the building's lifecycle (Global, 2018).

2.3.4.1. Conventional versus Modular method

Modular and conventional construction differ in several aspects, including design, installation, energy efficiency, cost, and construction time. However, the most fundamental distinction lies in the construction approach itself, as illustrated in Fig. 18. Both approaches follow four primary phases in a product's life cycle: production, construction, use, and end-of-life.

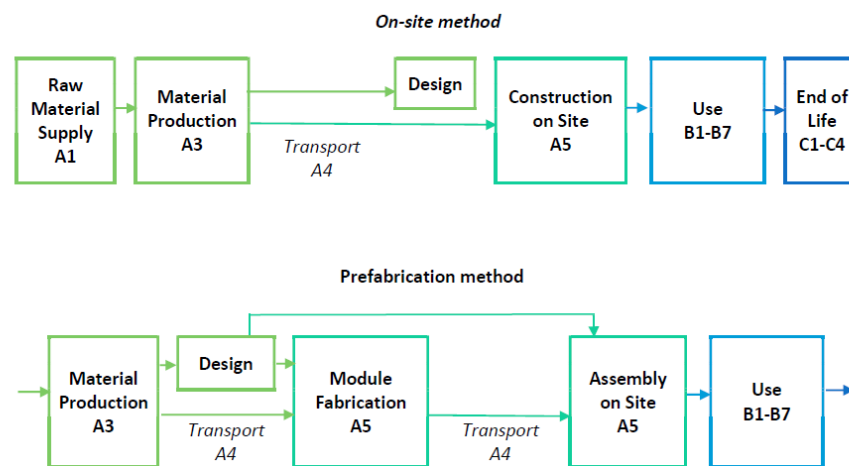


Fig. 18. Life Cycle of on-site and prefabricated building (Thomsen, R. F., 2022)

The use and end-of-life stages of both models are identical. However, there are sharp differences in the construction stage (A5). In the on-site building model, raw materials are supplied and then used to produce construction materials. These materials are delivered directly to the building site, where a comprehensive building design is developed. Construction takes place directly on-site, where all previously produced materials are assembled.

Similarly, in the prefabricated building model, raw materials are delivered to the location where they are processed into materials. However, in this case, the design process includes both separate building elements and the overall building assembly. After the design phase, prefabricated modules are manufactured in a factory, finished, and then delivered to the building site. While the modules

are being made, the building site is also being prepared. Once completed, the modules are installed on-site to finalize the building (Thomsen, 2022).

The studies listed in Table 2 have been referenced in the “Advantages of modular construction” section, particularly to demonstrate the potential of modular construction to reduce carbon emissions. They cover a range of building types, materials, and system boundaries across various geographic contexts. In the following section, a more detailed review of each study is presented to highlight their specific findings and relevance to the environmental benefits of modular construction (Li et al., 2022).

To evaluate the relative carbon footprints of PCBs and conventional cast-in-place buildings, this research created a building information modeling (BIM) based life-cycle carbon accounting system. The study examined five residential prefabricated high-rises in China, with a total floor area of 10,000 m² (from base to top). The analysis revealed that higher prefabrication rates generally reduced carbon emissions. PCBs overall emitted an average of 105.88 kg CO₂/(m²·a) compared to 130.79 kg Carbon /(m²·a) for conventional buildings. Research results underscore the environmental benefits of PCBs and support policies aimed at reducing the construction industry’s carbon footprint (Kamali et al., 2019).

This study employs a cradle-to-gate LCA to compare the environmental performance of conventional on-site construction methods with that of modular off-site construction methods. One conventional house and two modular dwellings in British Columbia were examined. In addition to carbon, these assessments also consider other environmental consequences, including acidification, eutrophication, ozone loss, and smog potential. The results show that Modular does not guarantee impact reduction, but it provides a great opportunity to reduce the environmental impact of construction. Implementing optimal strategies in design, material selection, transportation, and construction is a key point in reducing environmental impacts. In addition, the study’s analytic hierarchy process (AHP)-based framework provides a method for generating suitable environmental indices from LCA results. This framework helps address the challenges of comparing specific environmental impacts, and it can be applied in future studies to evaluate the environmental performance of various products, services, and processes (Hao et al., 2020). This study examines carbon emissions (CE) reduction during the materialization stage of a prefabricated official building in Jiangsu province, China, using a BIM-based approach. The

building has a total area of 40,408.84 m² and a construction area of 84,858.57 m², featuring a frame shear wall structure with a 70-year service life and a 50% adoption rate of prefabricated components. Findings show that prefabrication reduces CE by about 15% compared to conventional methods, mainly through materials production, transportation, and on-site construction (Jayawardana et al., 2023).

In this LCA of an office building in Sri Lanka, the authors compare the environmental performance of conventional and prefabricated building methods. Across all measured categories, prefabrication and environmental savings resulted in an 8.06% reduction in GHG emissions. Optimal savings occur with transportation distances under 120 km, and using green concrete could reduce GHG emissions by up to 12.05%. The study highlights the importance of integrated decision support systems for sustainable construction, with implications for policy, academia, and stakeholders in Sri Lanka (Pons & Wadel, 2011).

This cradle-to-grave LCA compares one non-prefabricated school and three industrialized, technically prefabricated schools made of concrete, steel, and wood. The analysis reveals that these technologies enhance building quality and mitigate environmental impacts, yet each method has its own weaknesses. An optimized prefabrication technology is recommended to fully close the materials cycle and further reduce resource consumption and waste generation (Wen et al., 2015).

Using an LCA technique, this study compares the assembly phase of Industrialized Building System (IBS) with conventional cast-in-situ construction for low-rise residential units in Iskandar Malaysia, Johor Bahru. Results show that IBS successfully lowers embodied energy (MJ) and GWP (kg CO₂-equivalent). There was an 11.70% drop in carbon emissions during the raw material phase and a 20.42% drop during the building phase (Du et al., 2019).

This study is an LCA that analyzes the carbon emissions of residential buildings by comparing prefabricated and conventional construction methods across four different levels of prefabrication. It evaluates cradle-to-site carbon emissions, covering material extraction, manufacturing, transportation, and construction phases. The findings show that prefabricated residential buildings produce approximately 18% fewer carbon emissions than conventional ones. However, increasing the prefabrication rate does not always result in lower emissions. The study highlights that selecting the appropriate prefabrication level is crucial for maximizing CO₂ eq reduction in residential construction (Al-Hussein et al., 2009).

Al-Hussein et al. (2009) examined the carbon emissions of traditional and modular buildings during their construction phases in 2009. To this end, they studied a four-story residential modular construction in Alberta, Canada, with 42 units. Transportation of materials, travel by workers, use of equipment, and heating during the winter were all individually catalogued as necessary construction activities for this building and a comparable conventional building. Consequently, we measured the amount of carbon dioxide gas released by each of these processes. However, we did not include in the carbon quantification the emissions associated with the embodied energy of the construction materials. Compared to on-site operations, this study found that modular methods reduced carbon emissions by 43%.

Prefabricated building components are examined in this study through an LCA to determine their economic, social, and environmental sustainability. It disregards contoured components, such as precast bay windows and balconies, in favor of uniform, prefabricated parts made using the assembly line technique, including wall panels, partitions, and laminates. To measure the effects, the research utilizes real-world data from various manufacturers across different provinces in China, employing 1 m³ of prefabricated components as the functional unit. Compared to traditional building methods, the results demonstrate that prefabrication rates of 50% and 30% significantly lower the potential for global warming by 31.78% and 13.94%, respectively (H. Gao et al., 2024).

A commercial residential prefabricated building (PB) and a traditional cast-in-situ building (TB) in China were analyzed for their carbon emissions (CEs) using an integrated LCA and BIM simulation. The results show that PBs have a 9.61% lower total carbon emissions intensity (CEI) than TBs, highlighting their advantage in reducing CE. The operation and maintenance stage is the largest contributor to emissions, with TBs emitting 11.02% more than PBs, while the materialization stage shows only a 3.32% difference between the two methods (Y. Gao et al., 2024).

This study examines greenhouse gas (GHG) emissions from a high-rise commercial and residential prefabrication project in Shenzhen City, China, through integrating BIM, Geographic Information System (GIS), and LCA. The project comprises six residential high-rises (91,200 m²), one commercial building, one kindergarten, and a prefabrication level of 17%. The research focuses on the use of prefabricated outside wall panels (1,875 units), balconies (930 units), and staircases (318 units) in residential buildings. With emissions of 269.16 kgCO₂eq/m³ as opposed to 393.63

kgCO₂eq/m³ in conventional construction, prefabricated buildings cut greenhouse gas emissions by 31.62% (Quale et al., 2012).

Quale et al. (2012) [35] performed a study on the environmental LCA of modular buildings. The researchers examined the environmental implications of conventional versus modular building methods during the construction process, measuring energy usage from start to finish. Each of the six buildings used in the case study (i.e., three residential modular and five conventional) was a two-story wood-frame home with a total floor space of 186 square meters. Three residential modular companies in the eastern US had their data collected from finished projects. This data included items such as utility bills, worker transportation, supplies, and trash information, as well as employee and construction schedules. It is physically impossible to find two identical copies of a building that were built using two distinct methods. When the modular construction specifications were compiled, the researchers requested that professional homebuilders supply data if they planned to use the same requirements to construct on-site buildings in the same area. Quantities of materials, transportation of materials, labor, energy used in the manufacturing process, transportation of modules, and on-site assembly were all factors used in estimating the embodied energy for modular case studies. Even with traditional structures, factors such as on-site energy usage, transportation costs (for both materials and labor), and the quantity of materials were all taken into account. Lastly, the amount of garbage produced throughout the construction process was measured for both buildings in the case study. Keep in mind that to evaluate the two construction styles, the authors solely considered the building materials that varied between the two. When calculating the amount of building waste, the net difference between the two techniques was again taken into account. Additionally, everyone believed that landfills handled all the trash. For energy quantification, the SimaPro database was utilized. Researchers were able to conduct assessments of the following effects using the Building for Environmental and Economic Sustainability (BEES) method: greenhouse gas emissions, non-cancer and carcinogen effects, acidification, eutrophication, criterion pollutants, ecotoxicity, water quality, smog, and ozone depletion. Comparing the conventional and modular cases, LCA studies for greenhouse gas emissions revealed that, generally speaking, modular structures had less detrimental effects on the environment. The average greenhouse gas emissions per square meter of modular buildings were found to be approximately 6 t of carbon less than those of conventional buildings. Moreover, conventional construction's greenhouse gas emissions were primarily attributable to on-site energy

consumption and labor transportation, highlighting areas for potential reduction in environmental impact. Compared to traditional buildings, the carbon footprint and other impacts were somewhat higher, ranging from 20 to 70%.

Table 2. Literature review on carbon emissions reductions in modular versus conventional construction

No.	Author	year	Country	Modular building Type	System boundary	Principal Structure
1	Li et al. (2022)	2022	China	High-rise residential	Cradle-to-gate	Concrete
2	Kamali et al. (2019)	2019	Canada	Single-family residential	Cradle-to-gate	wood
3	Hao et al. (2020)	2020	China	High-rise residential	Cradle-to-gate	Concrete
4	Jayawardana et al. (2023)	2023	Sri Lanka	Office building	Cradle-to-gate	Concrete
5	Pons & Wadel (2011)	2011	Spain	Educational	Cradle-to-grave	Concrete
6	Wen et al. (2015)	2015	Malaysia	low-rise residential	Cradle-to-end-of-construction	Concrete
7	Du et al. (2019)	2019	China	low-rise residential	Cradle-to-end-of-construction	Concrete
8	Al-Hussein et al. (2009)	2009	Canada	Multi-family Four-story residential	On-site-activities	Wood
9	Cheng et al. (2023)	2023	China	50% prefabrication Component	Cradle-to-gate	Concrete
10	Cheng et al. (2023)	2023	China	30% prefabrication Component	Cradle-to-gate	Concrete
11	H. Gao et al. (2024)	2024	China	Commercial Residential	Cradle-to-gate	Concrete
12	Y. Gao et al. (2024)	2024	China		Cradle-to-end-of-construction	Concrete
13	Quale et al. (2012)	2012	US	Single family Two-story residential	Cradle-to-end-of-construction	Wood/Steel (Modular) Concrete(conventional)

2.3.4.2.Integration of BIM and LCA

Building Information Modeling (BIM) is defined as “a collection of tools, procedures, and policies that enable numerous stakeholders to work together in a virtual environment to plan, design, construct, and manage an asset or facility” (BIM dictionary). It serves as a digital representation of a construction project, enabling the simulation of the entire building process with highly detailed models that include precise parametric objects that store critical information related to geometry, functionality, and attributes such as semantic, functional, and topographic details (Azhar, 2011; Potrč Obrecht et al., 2020).

Beyond the construction phase, BIM remains valuable for operations and maintenance, providing insights into spatial relationships, material properties, cost estimates, and project scheduling throughout the building’s lifecycle (Azhar, 2011). (Xu et al. 2022) identifies three distinct methods for integrating BIM and LCA, categorized based on how data is exchanged between BIM and LCA software (Fig. 19).

Basic Data Exchange (Type I): This technique retrieves quantitative information about materials from BIM files and sends it to external programs to calculate carbon emissions through basic multiplication. Tools like Revit, ArchiCAD, and Rhinoceros generate material data, which is then combined with LCA databases through Excel or custom-built scripts. While this approach is fast and straightforward, it is only suitable for basic LCA assessments due to its limited analytical capabilities.

Direct BIM Integration (Type II): This approach embeds carbon emissions factors directly into the BIM environment using plug-ins or application programming interfaces (APIs). It maximizes BIM’s potential as a centralized database and visualization tool. However, mapping emissions factors to BIM elements remains challenging due to inconsistencies in material classifications and definitions. Additionally, this method often relies on subjective input, which may lead to inaccuracies in the LCA process.

Advanced Integration with LCA Software (Type III): This method involves transferring BIM data directly into dedicated LCA software for a more precise and comprehensive assessment. By utilizing embedded databases, it enhances the connection between BIM’s visual modeling and LCA calculations, ensuring greater accuracy. Despite its advantages, interoperability challenges

between BIM and LCA tools continue to hinder seamless integration between these two software, and further development is needed in the future.

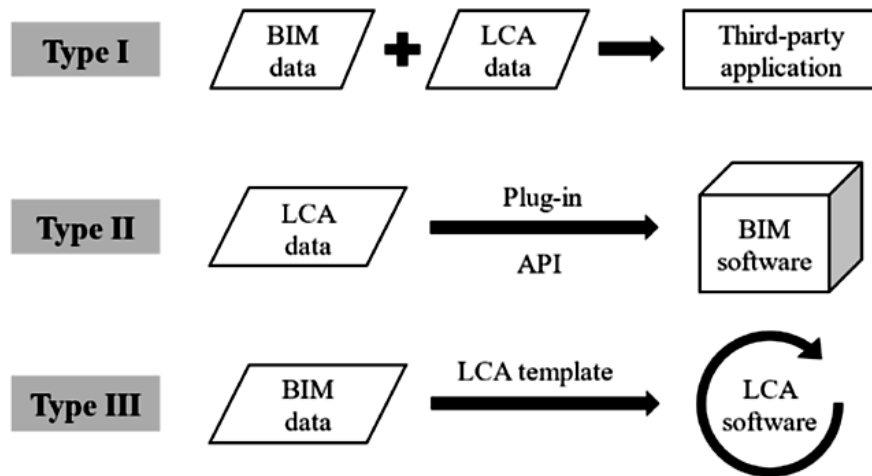


Fig. 19. Overview of BIM and LCA data exchange methods (Xu et al. 2022)

Since Revit is so integral to building design processes, it naturally became the most popular BIM technology. Various LCA software packages such as SimaPro, openLCA, and Athena Impact Estimator were utilized in previous studies (Ajayi et al., 2015; Jrade & Jalaei, 2013; Rezaei et al., 2019; Su et al., 2021).

Chapter 3: Case study - Cambridge Bay

The case study took place in Cambridge Bay, Nunavut, Canada. Cambridge Bay, situated in Nunavut, faces harsh Arctic climatic conditions that present unique challenges to building construction, energy efficiency, and environmental sustainability.

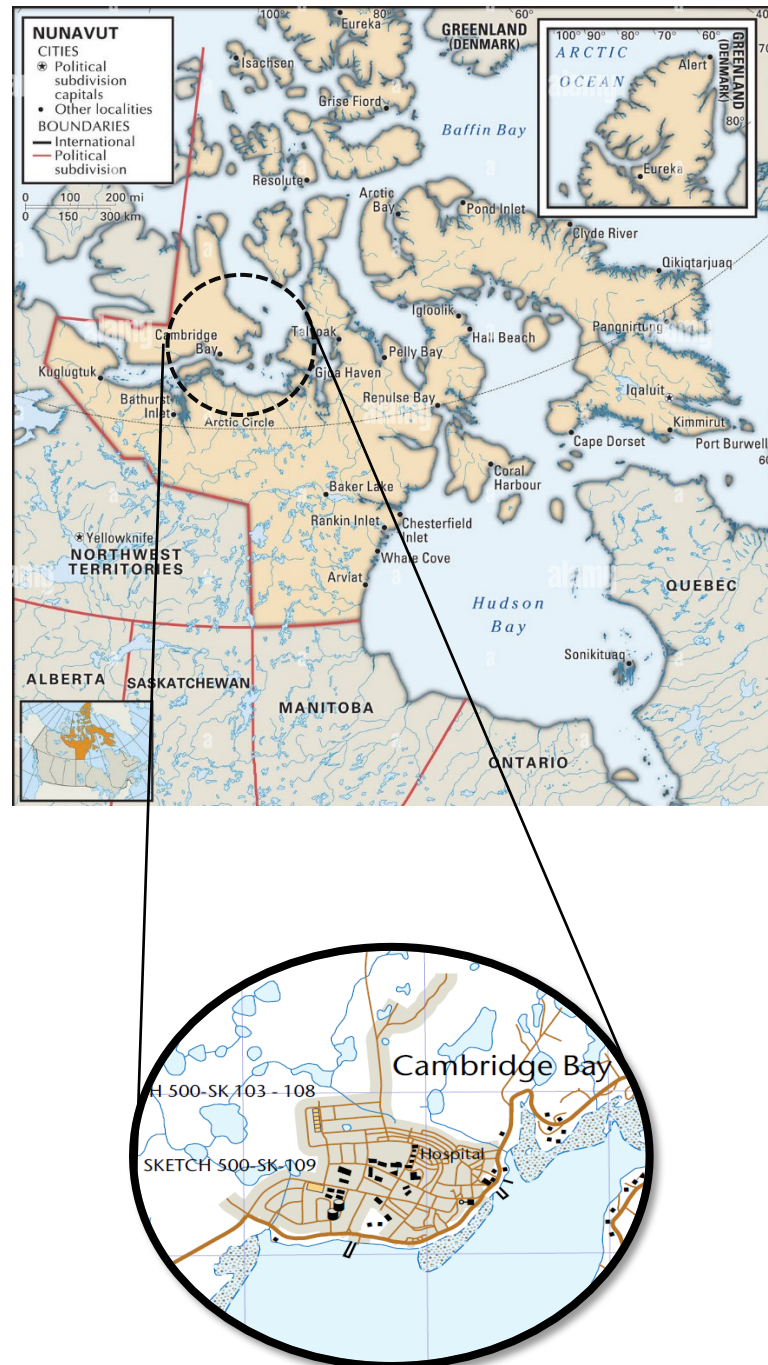


Fig. 20. Location of the case study site: Cambridge Bay, Nunavut

Cambridge Bay (Hamlet) had 1,760 residents in 2021, down 0.3% from the previous year. This Bay (Hamlet) had 571 occupied private homes in 2021, a 5.4% increase from 2016. The Bay (Hamlet) has a population density of 9.0 people per square kilometer and a land area of 195.78 km².

3.1. Cambridge Bay Climate

Cambridge Bay is climatically located in Canada's Arctic region. In July, the average daily maximum temperature is 13.3°C, and in February, it drops to -35.6°C, according to Environment and Climate Change Canada (Fig. 21) for the 1991-2020 climate period. In addition to the extreme temperature variations, Cambridge Bay experiences dry, cold Arctic conditions. The highest monthly precipitation occurs in July at approximately 28 mm, while winter months receive as little as 5 mm (Canada, 2025).

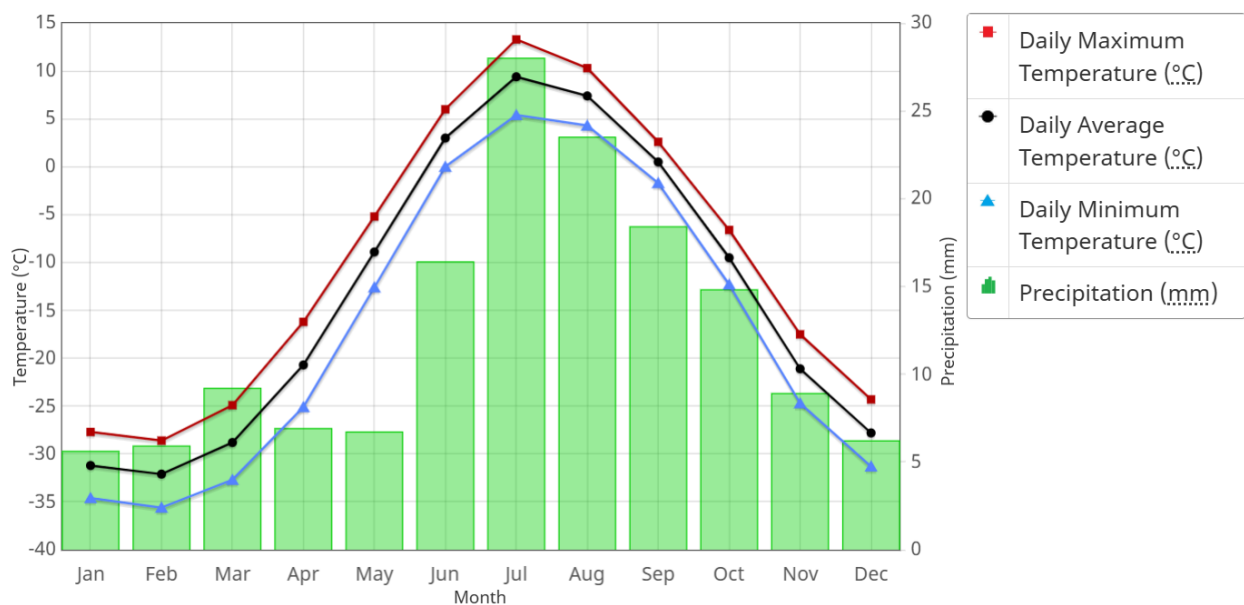


Fig. 21. Temperature and Precipitation Graph for 1991 to 2020 Canadian Climate Normal
Cambridge Bay

3.2. Energy Challenges and Carbon Emissions in Cambridge Bay

In terms of Energy, as mentioned in Chapter 2, Arctic communities are entirely reliant on diesel for their energy production. According to Statistics Canada (Fig. 22), a projection was made for integrating solar and wind energy into Nunavut's energy generation by 2023. However, this transition never happened, and Nunavut communities remain 100% reliant on diesel.

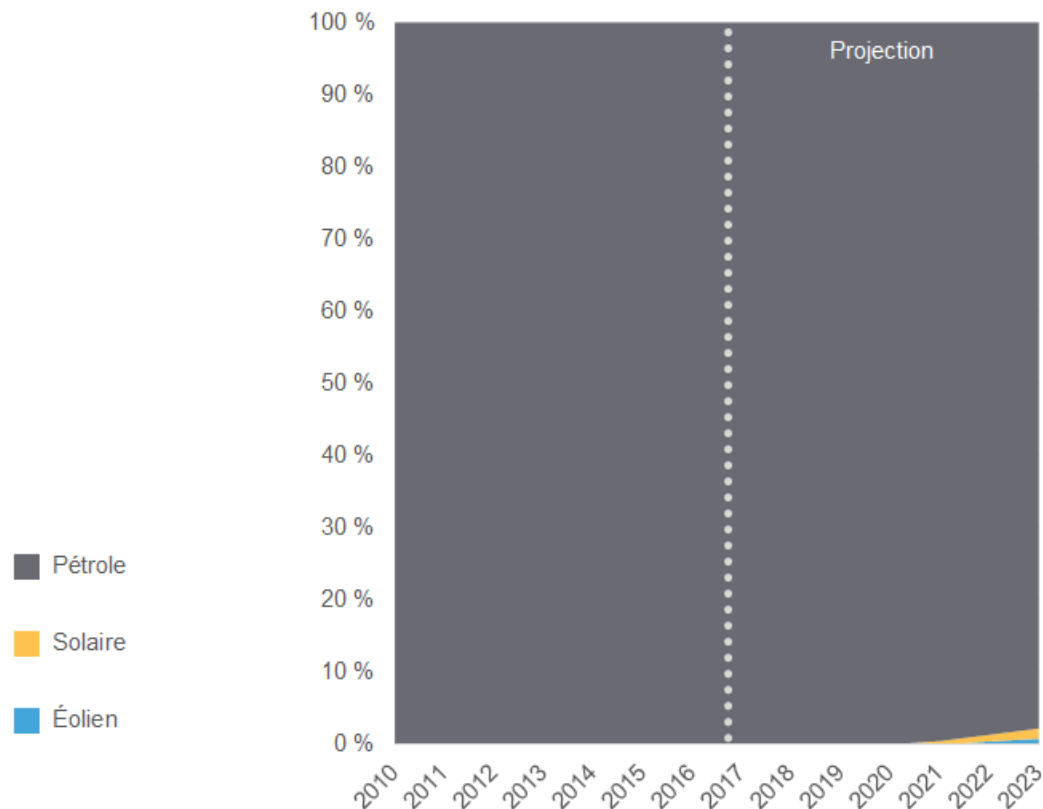


Fig. 22. Electricity Capacity and projections from 2010-2023 (Regulator, 2022)

On the other side, energy costs pose another major challenge in Nunavut. Electricity and fuel expenses consume a significant portion of household incomes, placing financial strain on community budgets. Many Arctic communities rely entirely on fossil fuels for electricity, heating, and transportation. These fuels, either sourced locally or transported by land, sea, or air, contribute to additional logistical difficulties and costs. Due to the prolonged winter season and extreme cold, energy consumption is significantly higher in northern communities than in southern ones. As a

result, a significant portion of community funds is allocated to maintaining fuel supplies and keeping generators operational.

This complete reliance on fossil fuels results in a high rate of carbon emissions from both electricity used in buildings and transportation.

3.3.Construction challenges in Cambridge Bay

Nunavut is currently facing a severe housing crisis, where many residents live in overcrowded conditions or have no access to adequate housing. Although the seriousness of this issue may not always be immediately apparent, it continues to impact communities across the region. There are four major issues affecting housing in Nunavut:

- a) **Housing shortage:** In 2016, Nunavut urgently required many new dwellings due to its severe housing situation. To close the housing gap with the rest of Canada, Nunavut would need to build an additional 3,000 homes, according to Nunavut Housing Corporation CEO Terry Audla. They had a long wait for their house to be built due to the shortage, which was already a significant problem.
- b) **Poor quality:** The housing shortage is further exacerbated by poor construction quality. Many homes in the Arctic lack essential features required for the harsh climate, such as durable materials designed for long-term resilience (Sultan, 2023). According to Statistics Canada, nearly one-third of households do not meet suitable housing conditions.
- c) **Overcrowding:** Nunavut also faces a serious overcrowding problem, with 38% of families living in overcrowded conditions. This rate is the second-highest rate in Canada, following Nunavik, where 53% of families are affected (Corporation, 2023).
- d) **Hidden homelessness** is another factor that increases housing wait times. Many individuals are forced to live with friends or family, which can lead to various health and social problems.
- e) **High Housing Costs:** The remoteness of Nunavut's communities, with no road connections, means they must rely solely on air travel and seasonal sealift for goods and construction materials. The high transportation costs make essential supplies, such as lumber and paint, far more expensive than in other parts of Canada. Additionally, the short summer shipping season further complicates supply logistics. Nunavut's construction sector also relies heavily on skilled workers from southern Canada to support the local

workforce, resulting in a high cost of transporting these workers and adding a significant financial burden to construction efforts (Corporation, 2023).

- f) Limited Construction time: Zachary Stuart Wontrop asserts that the construction time in Arctic regions is extremely limited. His findings emphasize that weather constraints significantly affect construction success, with June and July being the only suitable months for building (Fig. 23). Any construction outside this period increases the risk of delays and inefficiencies due to extreme cold, strong winds, and unpredictable precipitation. As a result, the short construction season presents a major challenge for infrastructure development in the Arctic, necessitating careful planning, prefabrication strategies, and weather-adaptive construction techniques to ensure project feasibility and success (Wontrop, 2023).

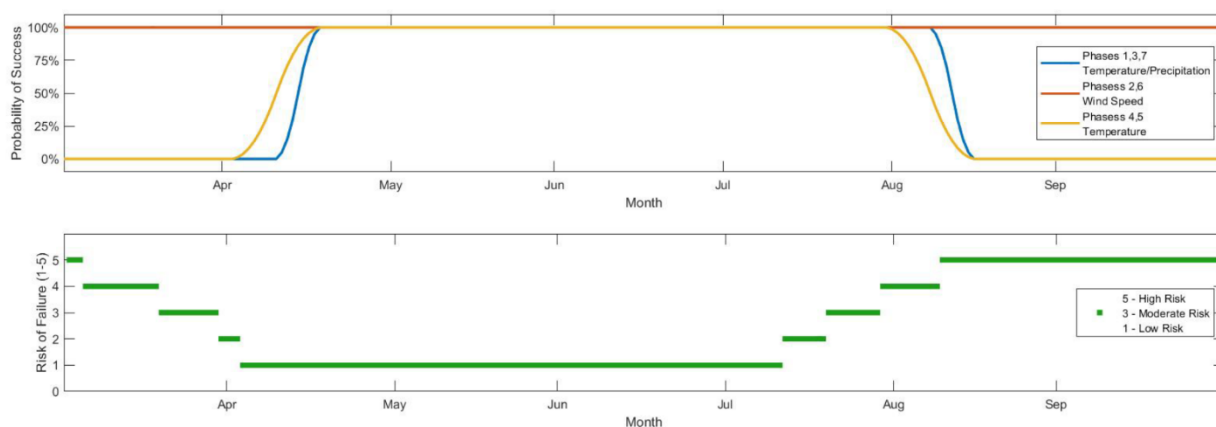


Fig. 23. Construction feasibility analysis for Clear Space Force Station, Alaska 9 (Wontrop, 2023)

- g) Coastal erosion and thawing permafrost: Climate change is one of the most significant contemporary concerns and stressors facing Aboriginal and northern communities across Canada. This stressor is more extreme in Canada's Arctic, where "in the Northern hemisphere, 1983 to 2012 was likely the warmest 30-year period of the last 1400 years". As shown in Fig. 24, a clear increasing trend in mean temperature is observed, rising from approximately -15°C in 1910 to an estimated 5°C by 2100.

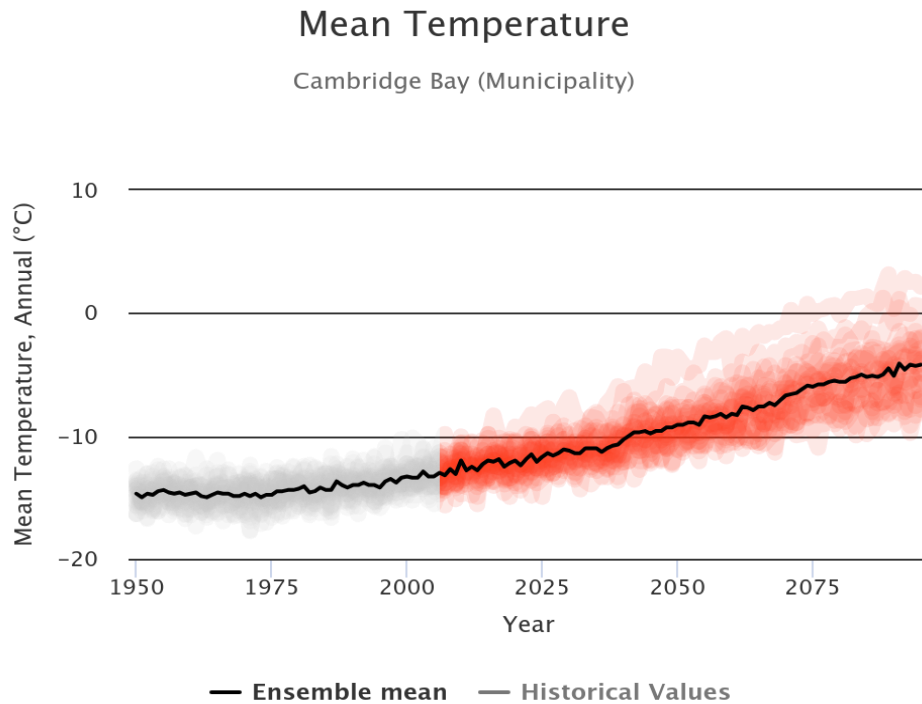


Fig. 24. Mean Temperature in Cambridge Bay (1950-2027) (Climate.ca)

Therefore, all Arctic communities, including those in Nunavut, which are primarily located along the coast in low-lying areas on permafrost, face extreme seasonal changes in wind, temperature, sea ice, and precipitation due to climate change. These shifts and severe weather events cause environmental instability that increases risks such as flooding, landslides, ground sinking due to thawing, and coastal erosion (Ford et al., 2010; Yukon Research Centre, 2014).

3.4.Arctic Modular Home Unit: Building overview

To address these challenges, the Modular Arctic Home Factory has introduced modular construction for remote Arctic communities. This approach aims to accelerate construction, alleviate housing shortages, mitigate overcrowding and hidden homelessness, and enhance building quality while reducing costs. Since modular homes are built in a controlled environment in a factory in Manitoba, there is no need to transport materials and skilled workers to the North, which significantly reduces the cost of housing in the region. Additionally, modular construction improves energy efficiency by implementing higher engineering standards in the building envelope, reducing energy consumption during the operational phase and potentially lowering energy costs and decreasing the rate of carbon emissions.

The Arctic Modular Home Factory originally operated as an on-site construction company in Cambridge Bay before transitioning to modular construction in 2020. With years of experience in on-site construction through its parent company, CHOU Consulting & Development Inc., it has pushed boundaries by pioneering modular off-site construction for the Arctic.

The building we want to analyze is its life cycle carbon footprint. It is a one-story home with three bedrooms, measuring 126 m² gross floor area, located in Cambridge Bay. It consists of three main modules: two main parts and one connecting part. The main parts are considered modular parts and were built in a factory in Manitoba, then shipped to Cambridge Bay by large Cargo from Montreal port. The connection part is built on-site while the other two modules are being assembled. The on-site construction takes only 16 days, which addresses the short construction time (Figs. 25-26).

Factory name	Arctic Modular Home
Founder	Stuart Rostant
Building type	Residential
Area	126 m ²
Story	One
Bedroom	Three

Table 3. General information of the case building



Fig. 25. 3D models of the Modular Unit

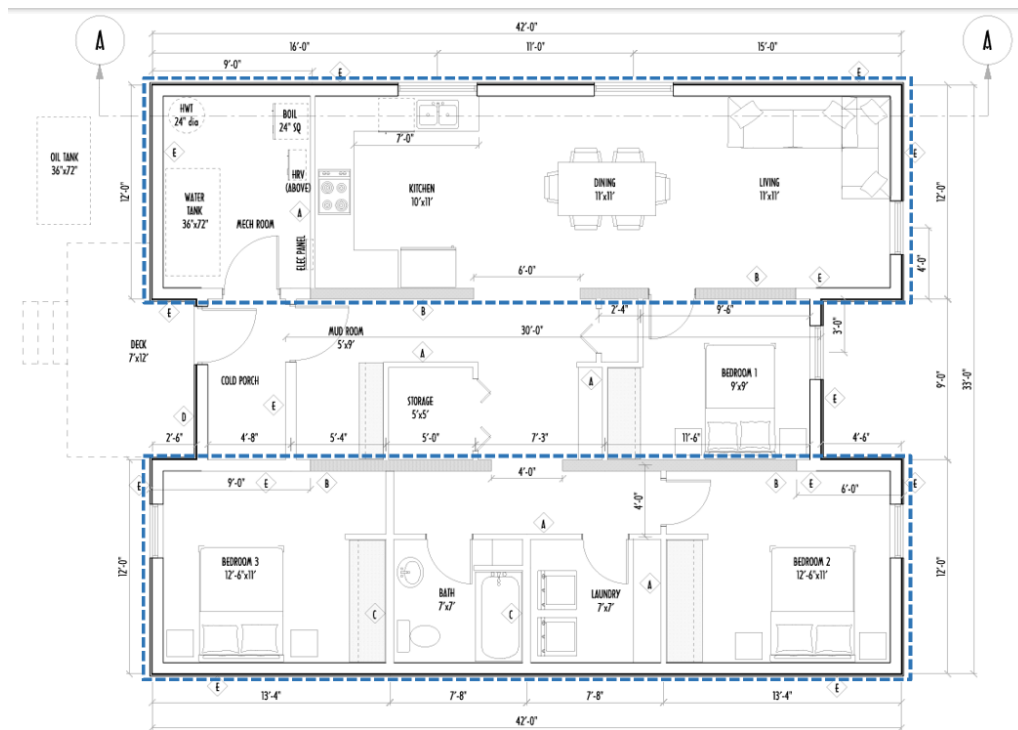


Fig. 26. Layout of the Modular Unit with the highlighted modular parts analyzed in this study

The two modules are fully furnished and equipped with a complete mechanical and electrical system. A new envelope technology, i.e., the Insulated Composite Envelope (ICE) from Greenstone Group, is used to enhance durability and withstand the harsh Arctic climate.

Chapter 4: Methodology

4.1.Goal and Scope of the Study

The purpose of this research is to assess the environmental impact of constructing a three-bedroom modular house in Cambridge Bay by calculating its life-cycle carbon footprint. This assessment will provide insights into the modular construction process in the Arctic, a topic that remains largely unexplored in academic research.

4.1.1. Functional Unit

All impact assessment calculations are based on the functional unit, which is a core feature of the LCA methodology. The success of the overall evaluation depends on this parameter; hence, its determination must occur early in the LCA, specifically during the objectives and scope phase. To enable a fair comparison and analysis of different systems or products, it is essential to establish a functional unit. This unit ensures consistency in evaluating various characteristics across multiple systems (Arzoumanidis et al., 2019).

For a better understanding of this study, since only the building envelope is analyzed, which consists of three components (i.e., roof, floor, and walls), the functional unit is defined as a 358 m² envelope, representing the total area of the envelope.

4.1.2. System Boundary

Fig. 27 illustrates the modular construction system boundary according to EN 15978; this study focuses on the cradle-to-end-of-building phase. Due to the remoteness of the area, assessing other stages such as the use phase and end-of-life was challenging. These stages require either an on-site evaluation or reliable data from the modular home factory. However, the remote location made on-site evaluation difficult, and the factory was unable to provide the necessary data for a comprehensive analysis. Therefore, data availability limits the system boundary to the Product Stage and Construction Phase.

The study's Life Cycle Carbon Assessment (LCCA) can help determine the amount of carbon dioxide emissions caused by modular in Cambridge Bay. Furthermore, it will shed light on the environmental impact, challenges, and practical considerations of modular construction in the Arctic, providing a more comprehensive picture of the subject.

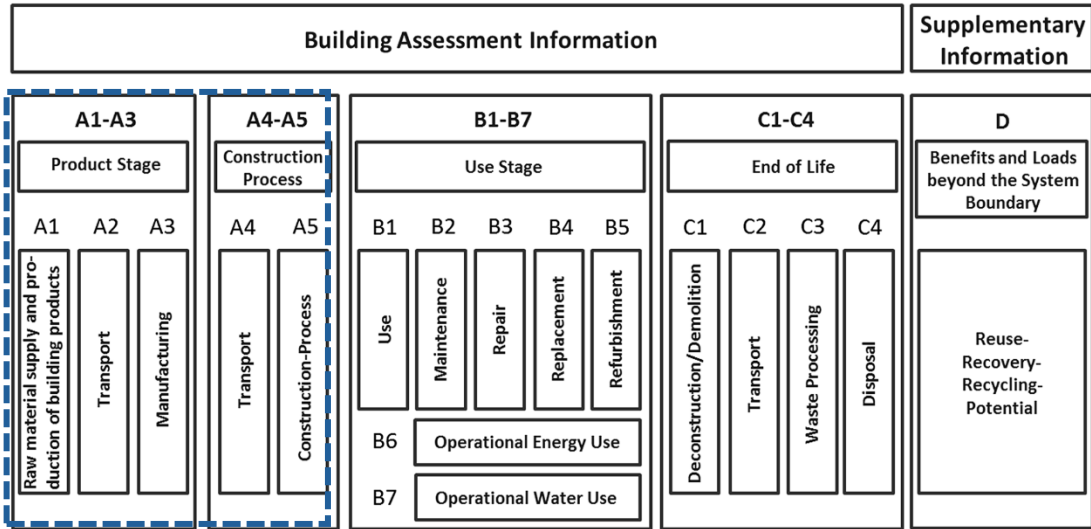


Fig. 27. The system boundary of this study is based on EN15978

Table 4. A functional equivalent set of LCA in this research

Building type	Single-family Residential
Location	Cambridge Bay - Nunavut
Structural System	One story - ICE Panel
Functional Unit	358 m ² envelope
System boundary	Cradle to End of Construction.

4.2.Life Cycle Inventory Analysis Levels

As shown in Fig. 28, the inventory analysis consists of five main categories, each corresponding to a phase of the defined system boundary. It begins with the Raw Material phase (A1), which includes the materials used in the unit's envelope, such as lumber, steel, drywall, and gypsum board, as specified in the BOQ. The first Transportation phase (A2) accounts for the fuel consumption involved in delivering the raw materials to the modular factory. In the Manufacturing phase (A3), electricity consumption for heating, lighting, and modular factory machinery, as well

as gas consumption, is considered. The second transportation phase (A4) focuses on fuel consumption for delivering modular components to the construction site by road and water, as well as for transporting skilled workers from southern Canada by air. Finally, the Construction phase (A5) assesses fuel consumption used for the electricity generator and construction equipment during the construction process. All these factors contribute to resource utilization, and the data is processed in SimaPro to generate the final Carbon emissions result.

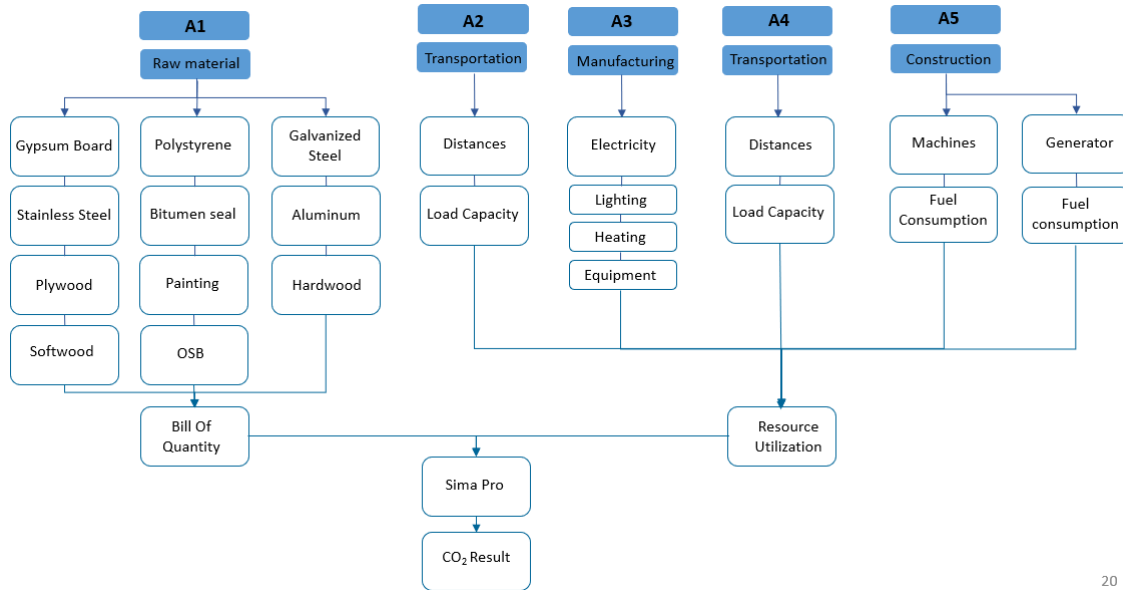


Fig. 28. Life Cycle Inventory Analysis flowchart

4.2.1. LCI Parameter for A1: Raw Material and BIM application

The inventory analysis for the Raw Material phase is conducted in three steps. The first step involves gathering information, which is done through emails and virtual meetings, as the Modular Arctic Home Factory is located in Manitoba. They provide all the layouts, detailed sections, and shop drawings of the envelope. As I discussed in the previous chapter, the home comprises two main Modules (1 and 2), which are considered the Modular part of this construction. The connection part is built on-site using a traditional construction method. The section of the modular unit (Fig. 29) illustrates the structural composition, insulation layers, and key assembly components of the roof, walls, floor, and foundation system. The section provides detailed measurements and material specifications essential for preparing the 3D model in Revit.

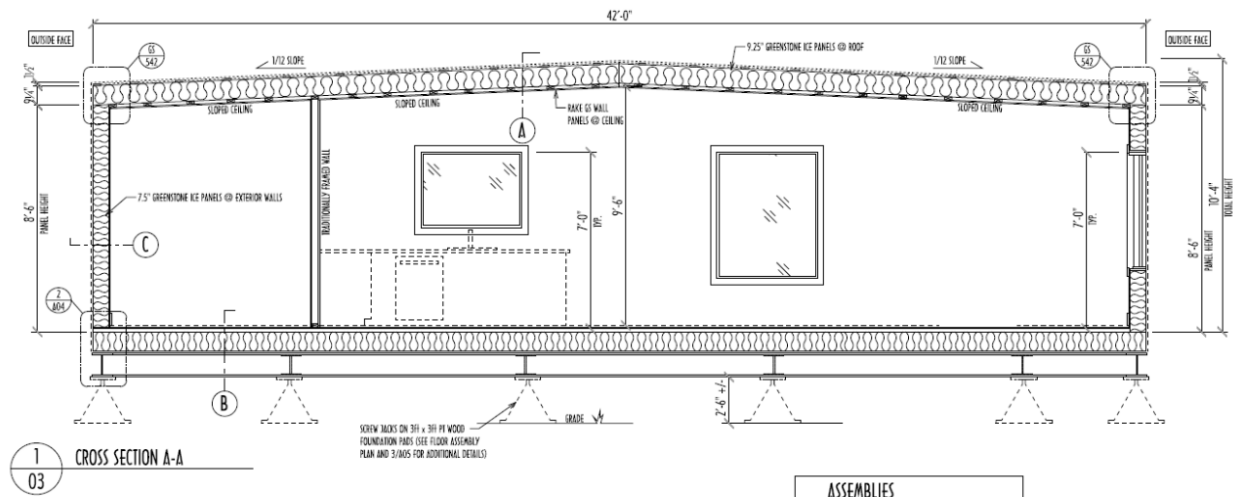


Fig. 29. Cross-section of the modular unit, showing structural components and material specifications

To get more details about the material used in the envelope, more detail of the envelope system is investigated through the shop drawings of the Insulated Composite Envelope (ICE) panels (Fig. 30). The ICE Panel is a specialized construction material that integrates EPS and galvanized steel, both widely recognized in the construction industry. This engineered combination creates a lighter yet stronger building envelope. Its innovative manufacturing process and connection design effectively prevent thermal bridging, making it one of the most energy-efficient building envelope solutions available today.

EPS is a rigid cellular plastic composed of up to 97% atmospheric air, ensuring consistent R-values without relying on trapped gases or emitting harmful substances. This stability prevents degradation over time. Galvanized steel, renowned for its high strength-to-weight ratio, enables versatile designs while being environmentally stable, fully recyclable, and highly **durability**.

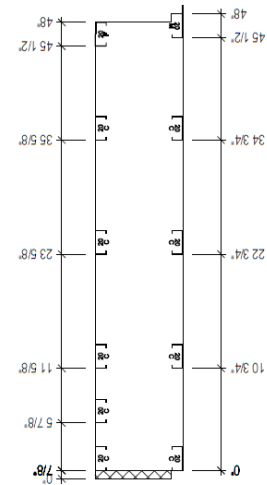
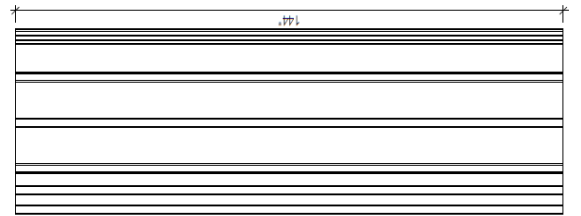
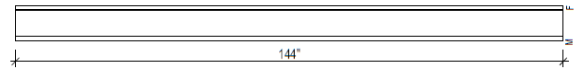
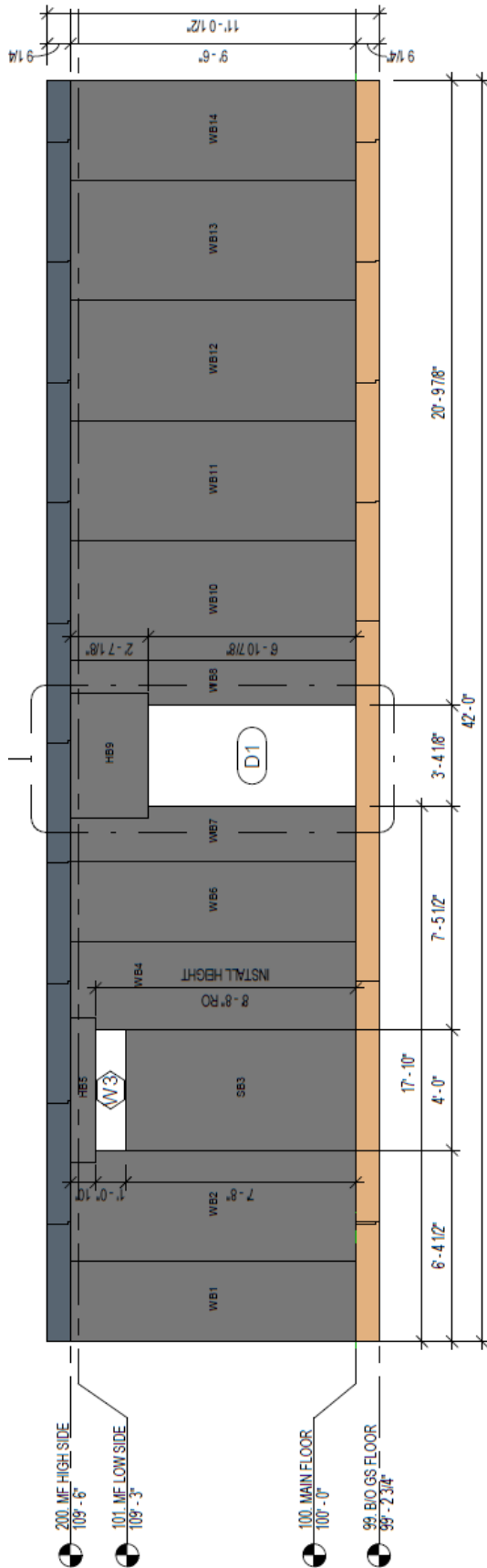


Fig. 30. A sample of provided shop drawings of the ICE Panel, showing the location and number of galvanized steel studs within the panel structure and openings

After collecting all necessary data, the second step is to model the units in Revit as a BIM model, ensuring an accurate representation of the design and construction details. This process allows for the automatic generation of the Bill of Quantity (BOQ), which improves material estimation, enhances precision, and reduces potential errors in inventory analysis (Figs. 31-33)

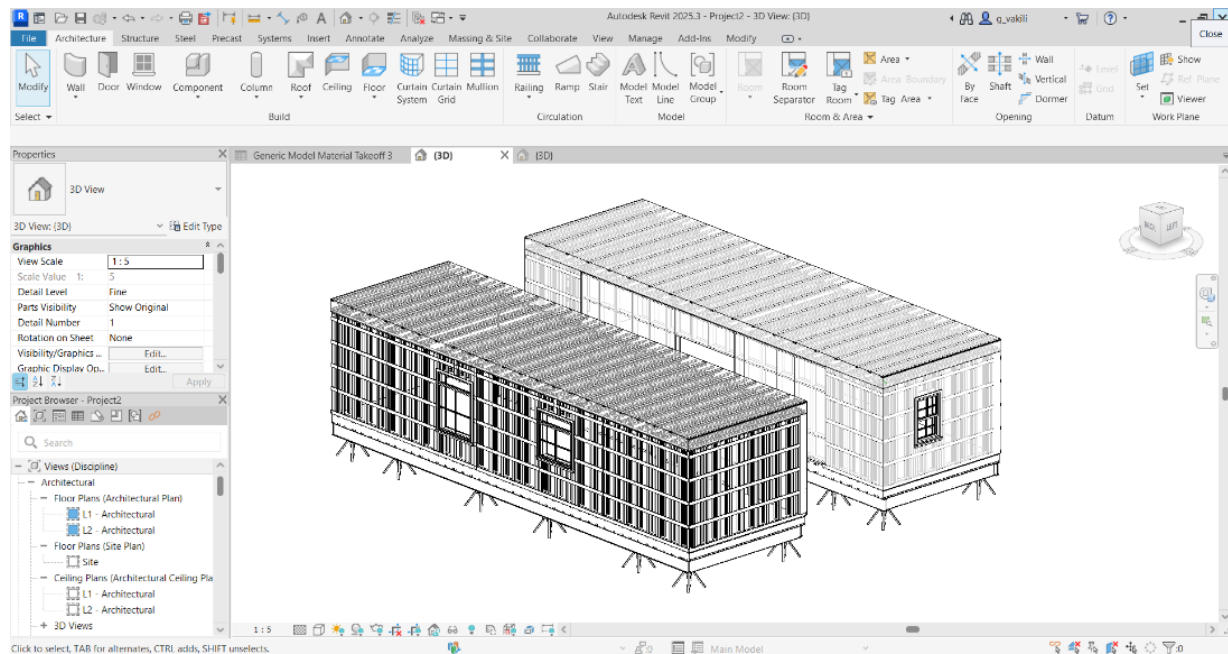


Fig. 31. 3D model of two modular units in Revit

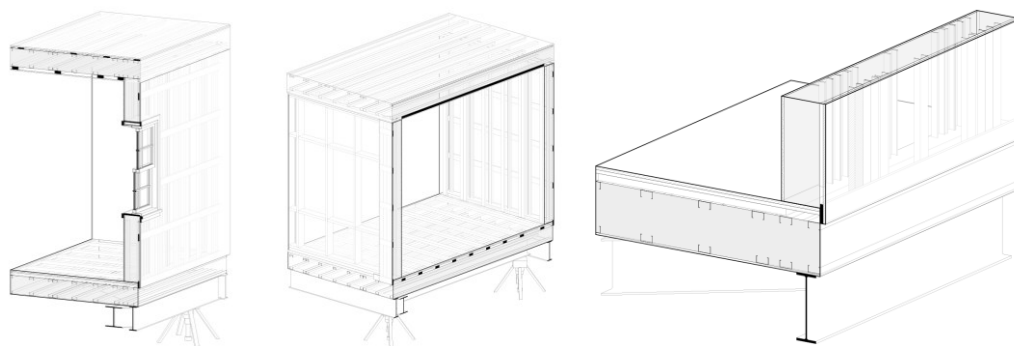


Fig. 32. 3D sections showing the detailed modeling of the envelope

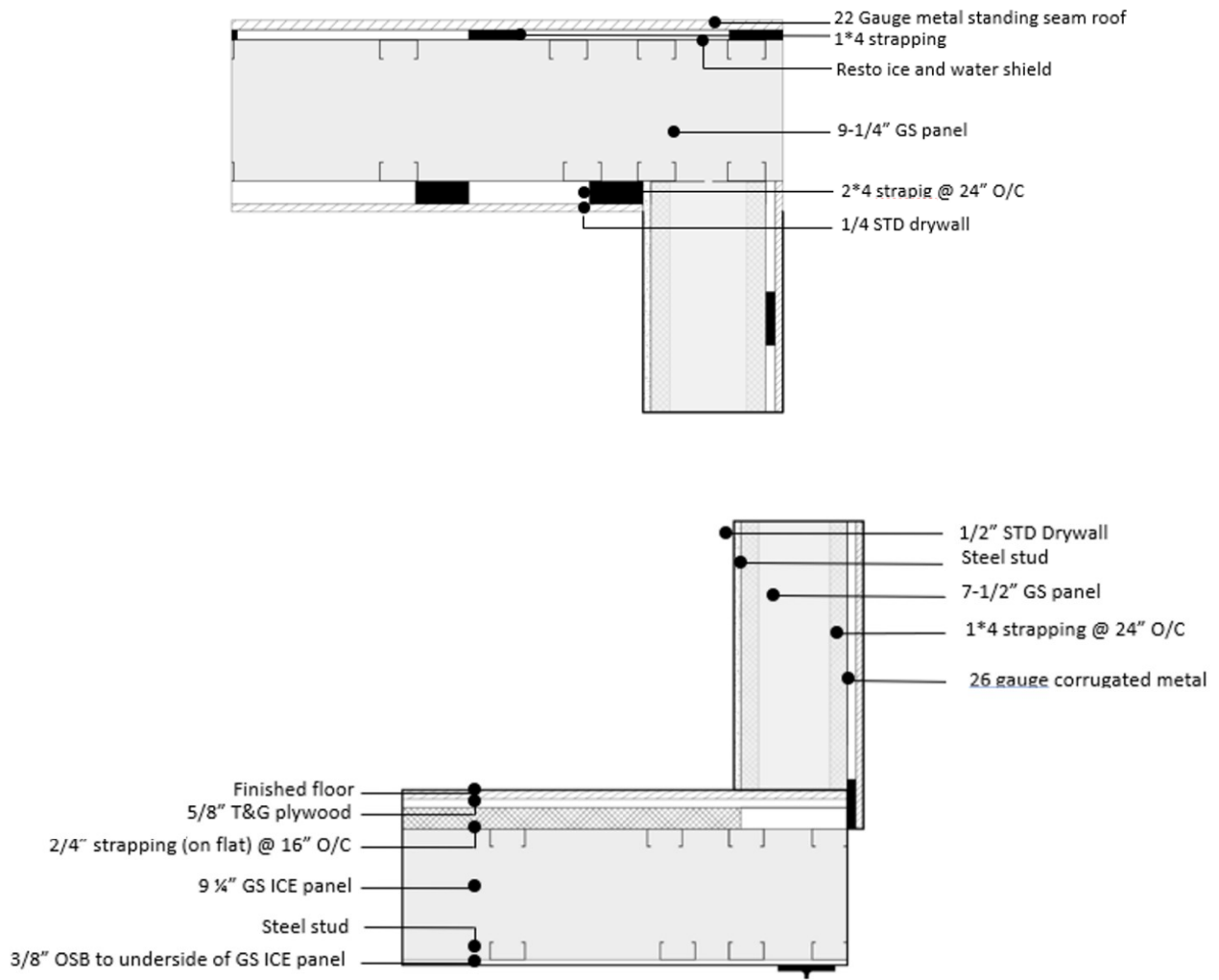


Fig. 33. Sections of Roof (left) and Floor and Walls (right) showing the detailed modeling of the envelope

Preparing the BOQ is the last stage. Two software tools are our mainstays for this task: Revit and Autodesk Takeoff. Some material quantities were extracted directly from the Revit model, while others required measurement using Autodesk Takeoff to ensure consistency in units with the SimaPro database. Materials that require takeoff include items such as gypsum board, insulation, aluminum, ICE panels, plywood sheathing, oriented strand board (OSB), parquet flooring, light-gauge steel, wood framing, furring strips, and various metal components, including galvanized steel and stainless steel (See Appendix A).

After generating the BOQ, among the three methods for transferring information from Revit to SimaPro (i.e., manual, semi-automated, and automated [A1]), this study employs the manual method due to the project's small size. However, for large-scale construction, this approach can be error-prone and may not be the most reliable option.

Table 5. Material Takeoff and LCI Mapping for SimaPro

	Material	Quantity	Unit	SimaPro
1	Gypsum fibreboard	2901.4	kg	Gypsum fibreboard GLO market for Alloc Rec, U
2	Polystyrene, extruded	1685.24	kg	Polystyrene, extruded {CA-QC} (Nahmens & Ikuma, 2012) polystyrene production, extruded, CO2 blown Alloc Def, U
3	Bitumen seal	91.68	kg	Bitumen seal, V60 {CA-QC} production Alloc Rec, U
4	Floor sheathing	1.58	m ³	Plywood, for outdoor use {CA-QC} production Alloc Def, U
5	Wood framing	0.38	m ³	Sawnwood, beam, hardwood, dried (u=10%), planed {CA-QC} planing, beam, hardwood, u=10% Alloc Def, U
6	Wooden Strapping	2.07	m ³	Sawnwood, beam, softwood, dried (u=10%), planed {CA-QC} planing, beam, softwood, u=10% Alloc Def, U
7	Oriented Strand Board	0.94	m ³	Residual wood, dry {CA-QC} plywood production, for outdoor use Alloc Def, U
8	Parquet floor	99.5	m ³	Engineered flooring US [EPD]*
9	Two coats of paint	32.47	kg	Alkyd paint, white, without solvent, in 60% solution state (Laboratory) market for Alloc Def, U
10	Light Gauge Structural	4003	kg	Galvanized steel US [EPD] *
11	Structural Framing	4560	kg	Stainless Steel US [EPD] *

4.2.2. LCI Parameter for A2 and A4: Transportation

Within the defined system boundary, transportation comprises two separate parts, namely A2 and A4. A2 transfers raw materials to the modular factory and A4 transfers complete units to the construction site in Cambridge Bay.

In this study, Phase A2 encompasses the transportation of main raw materials, such as ICE panels, from Brandon and Winnipeg to Reinfeld, where the modular construction factory is located (Fig. 36). Phase A4 involves transporting the fully assembled modular unit from Reinfeld to Montreal Port using two 50" trailers, while additional materials are transported separately on one 40" trailer. From Montreal Port, the two modular units and loose materials are shipped via a large cargo vessel operated by NEAS Inc. This shipping company provides transportation services to Arctic communities (Fig. 34).

Table 6 provides a thorough summary of the logistics required in transportation, including distance, vehicle types, and tonne-kilometer estimates.

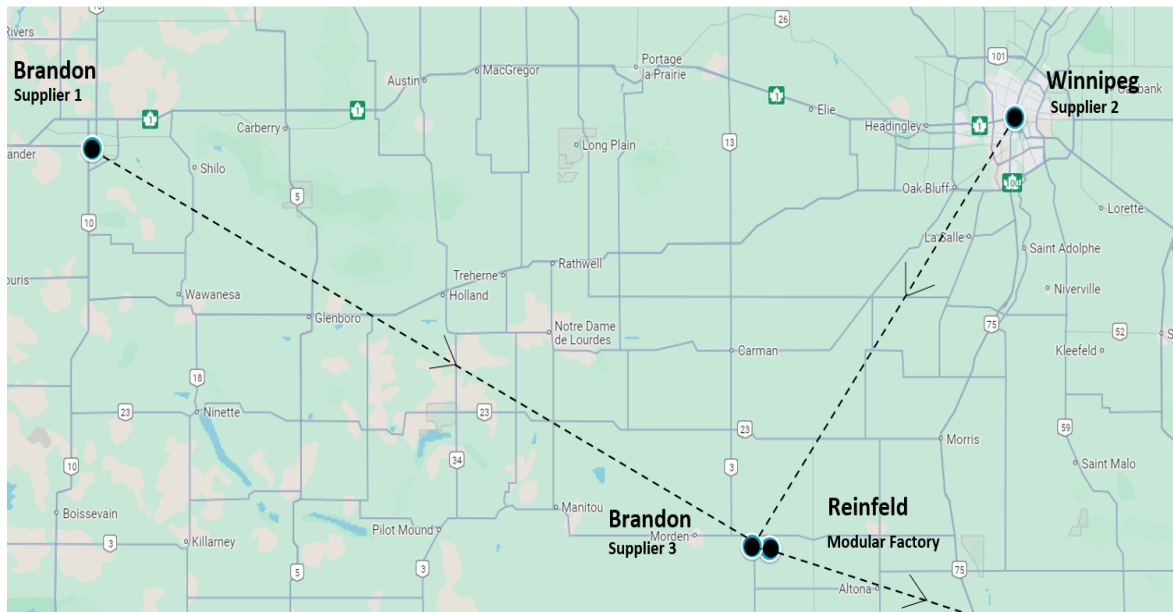


Fig. 34. Supplementary Transportation of Raw Materials (A2 Phase)



Fig. 35. Transportation of completed units from Reinfeld to Montreal port to Cambridge Bay



Fig. 36. Main transportation means used to ship the Units to Cambridge Bay (50' trailers and Large Cargo ship NSSI)

Table 6. Transportation Inventory LCI Mapping for SimaPro*

	Type	From	To	Distance	Machine type	Tonne	tkm	SimaPro
1	Supplier (ICE panel)	Brandon, MB	Rhine Feld, MB	226 km	50" Trailer	4.989	1127.514	Transport, freight, lorry 16-32 metric ton, EURO6 (Laboratory) market for Alloc Def, U
2	Supplier	Winnipeg	Rhine Feld, MB	118 km	40" flatbed truck	15.87	1872.66	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 (Laboratory) market for Alloc Def, U
3	Final Pod Module + Additional loose material	Rhine Feld, MB	6565 Bd Hébert, Montreal, QC	2345 km	2*50" Trailer 1*40" Trailer	20.865249	48928.90	Transport, freight, lorry 16-32 metric ton, EURO6 (Laboratory) market for Alloc Def, U
4	Shipping Modules + Additional loose material (NNSI)	6565 Bd Hébert, Montreal, QC	Cambridge Bay, NU	6491.26 km 3505 nm	Large Cargo	20.865249 +2.05	142807.71	Transport, freight, sea, transoceanic ship (Laboratory) market for Alloc Def, U
5	Transportation of six southern skilled workers to the site by airplane	Winnipeg	Cambridge Bay, NU	2181 km	airplane	6 person	13086	Transport, passenger, aircraft (Laboratory) market for Alloc Def, U

* The full list of calculation is provided in (Appendix B)

Certain transportation activities were excluded from the analysis due to inadequate data. For instance, information regarding employee commuting to and from the factory was not available. Additionally, loose lumber was added to the cargo shipment from a supplier located in Montreal; however, no data was provided on the weight of these materials, the distance traveled, or the type of vehicle used for transportation. As a result, these transport components were excluded from the assessment. Several forms of transportation in Cambridge Bay were excluded from the study because insufficient data were available. The use of tugboats to transport modular units from cargo ships to high-water marks was not included in the analysis because no information was provided regarding the distance traveled, fuel consumption, or the specific type of vessel involved.

4.2.3. LCI Parameter for A3: Manufacturing

In this section, two primary sources of carbon emissions are examined: electricity use and gas consumption during manufacturing processes. These emissions result from the energy required to operate machinery, process materials, and maintain factory operations. In the factory, each pod undergoes six stages, including mechanical work, electrical installation, envelope assembly, roofing, flooring, and interior finishing, such as painting. After these steps, the pods are stored in a waiting area before being loaded onto trailers (Fig. 37). According to the provided production schedule, it takes one month for two pods to complete all stages and be ready for shipment.

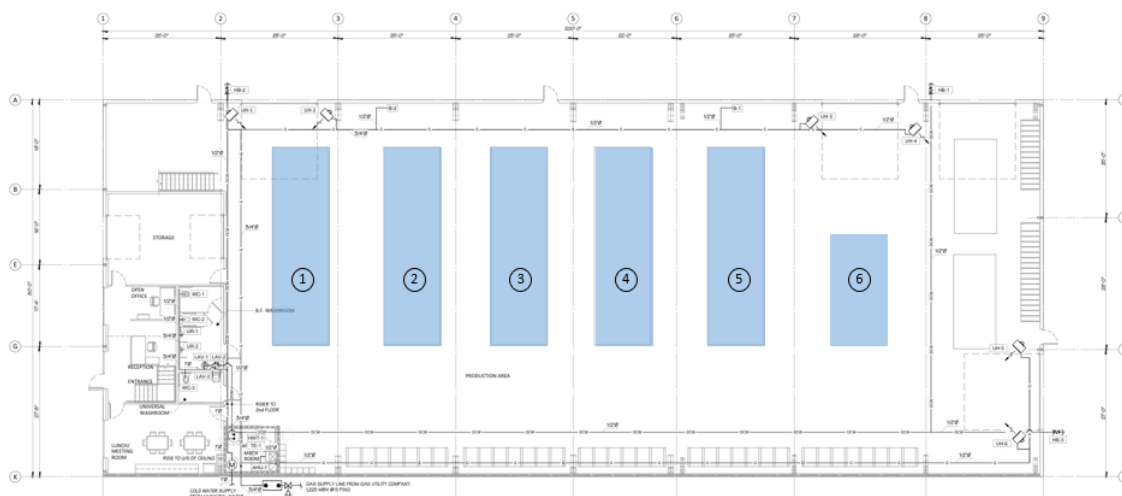


Fig. 37. Modular company layout and six working stages.

The electricity bill provided by the company does not accurately reflect the energy usage of a fully operational factory, as the facility is still relatively new. It only covers lighting and limited equipment usage within the factory. Regarding the equipment, most of it is powered by battery, except for the 5-tonne crane, which is used to move the GS panels and stud walls, as well as the plug-in heater used to dry the drywall mud. Additionally, a 20HP air compressor is used to move the pods. The office is not currently operational, but the Mechanical room equipment and the server room's IT electricity consumption are included in the bill.

In terms of gas consumption, the factory's boilers have not yet been operated. Currently, the building is heated using overhead heaters installed above the garage doors. While a gas bill has been provided, it does not represent the full future consumption. Gas usage is expected to increase significantly once the office becomes operational, as greater heating will be required during the winter months.

Based on the utility bills provided by the company, only half of its operational capacity is currently in use, with full operations expected within the next six months. Due to time constraints of this research project, the carbon emissions were assessed using the current utility bills, and the values were doubled to approximate the emissions under full operational conditions.

Table 7. Electricity Consumption and Gas Consumption for Modular Factory and LCI Mapping for SimaPro

	Category	Quantity	Unit	SimaPro
1	Electricity	3960	KWh	Electricity, low voltage {CA-MB} market for Alloc Def, S
2	Gas	16	MJ	Heat, central or small-scale, natural gas {RoW} market for heat, central or small-scale, natural gas Alloc Def, S

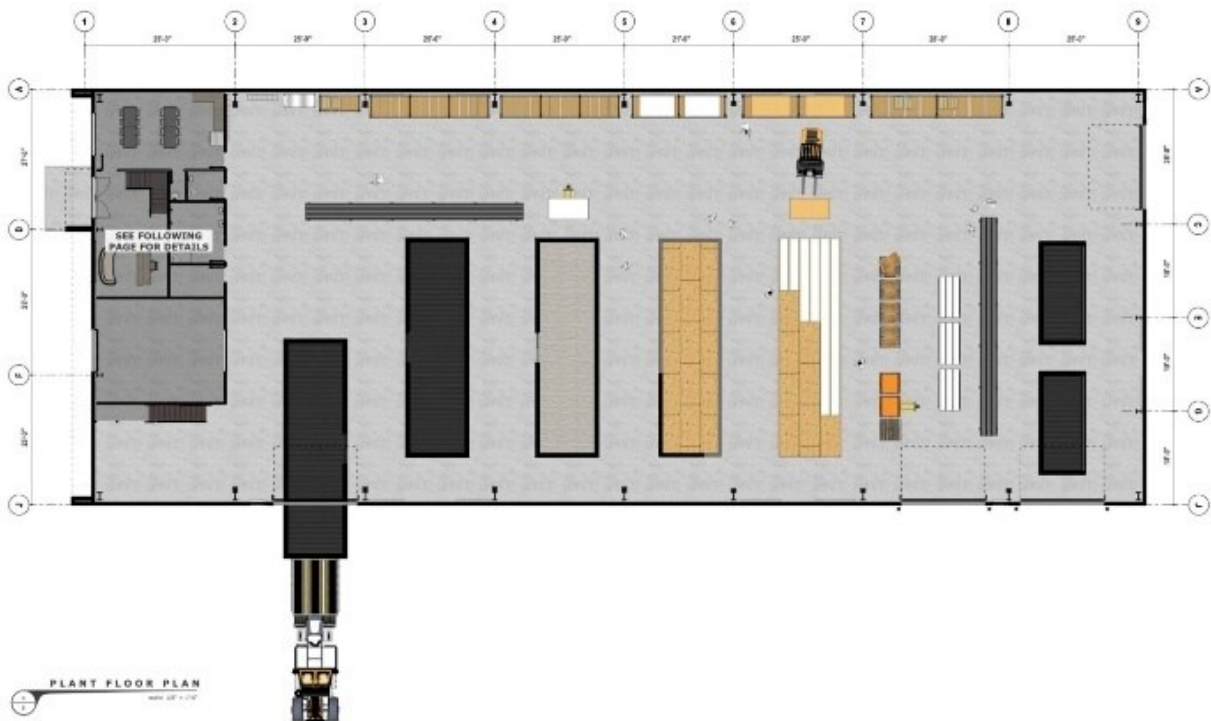


Fig. 38. Modular company layout and six working stages

4.2.4. LCI Parameter for A5: On-site Construction

On-site construction is the final phase of the defined system boundary for this project. The on-site assembly is not particularly complicated, as the entire unit was prepared in the factory, and only foundation preparation and unit assembly are performed on-site. In this phase, two types of emissions are evaluated: first, the fuel consumption of the small generator, and second, the fuel consumption of the machinery during this period. As discussed in the previous chapter, electricity in Cambridge Bay is generated exclusively by diesel. Therefore, for this project, a diesel generator is provided to supply power throughout the entire assembly process. Additionally, the total working hours and the type of vehicle are used to assess the fuel consumption of machines. The associated SimaPro data, along with the relevant calculations, are presented in Table 8 to provide a comprehensive assessment of energy use and emissions.

Table 8. Fuel Consumption and Energy Use for Machinery and Generator for on-site assembly and LCI Mapping for SimaPro*

	Type	Working hours	Model	Total fuel consumption(L)	Total fuel Energy (MJ)	SimaPro
Machines	Loader	6h	Cat980M	130.58	4673	Diesel, burned in building a machine (Laboratory) market for Alloc Def, U
	Small bobcat	4h	Bobcat S70	6	214.8	Diesel, burned in building a machine (Laboratory) market for Alloc Def, U
	Zoomboom	3h	JCB 525-60	21	751.8	Diesel, burned in building a machine (Laboratory) market for Alloc Def, U
Tools	Generator	-	Small generator	857	29,314.19	Diesel, burned in diesel-electric generating set, 18.5kW (Laboratory) market for Conseq, U

*The full list of bills is provided in (Appendix B).



Fig. 39. Moving the pods from the shore to the assembly site

4.3.LCA Software

4.3.1. SimaPro Characteristics

SimaPro is a versatile and user-friendly LCA program that facilitates the evaluation and enhancement of product and service sustainability through informed decision-making. It supports collaborative work, offers multiple impact assessment methods, and provides transparent results, with access to an extensive database, enabling in-depth analysis (Sustainability, 2024).

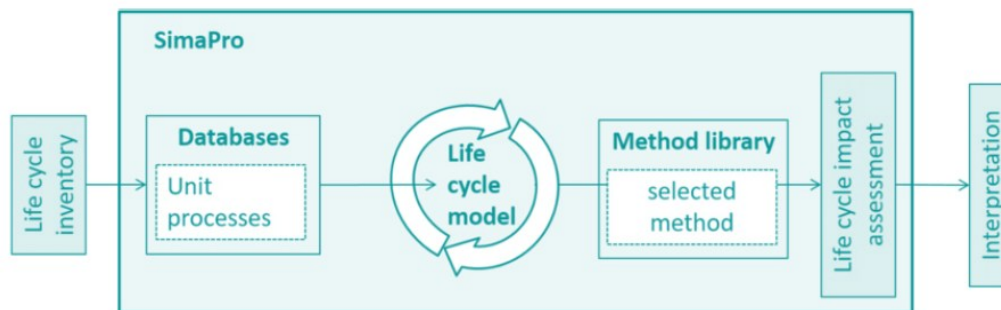


Fig. 40. LCA process in SimaPro (Almeida et al., 2018)

SimaPro provides various methods for conducting environmental impact assessments (SimaPro, 2021). For this study, the TRACI 2.1 V1.03/US-Canadian 2008 method was selected, as it is specifically developed for North American applications. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) was created by the U.S. Environmental Protection Agency as an independent software tool. Global warming, acidification, eutrophication,

smog, ozone layer depletion, land use, ecotoxicity, fossil fuel depletion, and the impact on human health (including cancer and non-cancer effects) are assessed. Because it measures outcomes in kilos of CO₂ equivalents, this study narrowly focuses on the category of global warming impacts (kgCO₂eq) (Sustainability, 2024).

Fig. 41 illustrates the global warming potential (GWP) of several greenhouse gases relative to carbon dioxide, using a reference value of 1, to define carbon dioxide equivalent. Carbon monoxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and trace gases, including hydrofluorocarbons (HFCs) and sulfur hexafluoride (SF₆), comprise the total emissions of greenhouse gases. GWP enables a consistent evaluation of their warming impacts over a century-long period. For example, the warming impact of 1 kilogram of methane is approximately 28 times that of 1 kilogram of CO₂, whereas the impact of SF₆ is 24,300 times more intense. These values highlight the vast variety in the climate impact of different greenhouse gases. Despite their relatively low GWPs, CO₂, CH₄, and N₂O account for almost 98% in terms of CO₂ eq (IPCC, 2021).

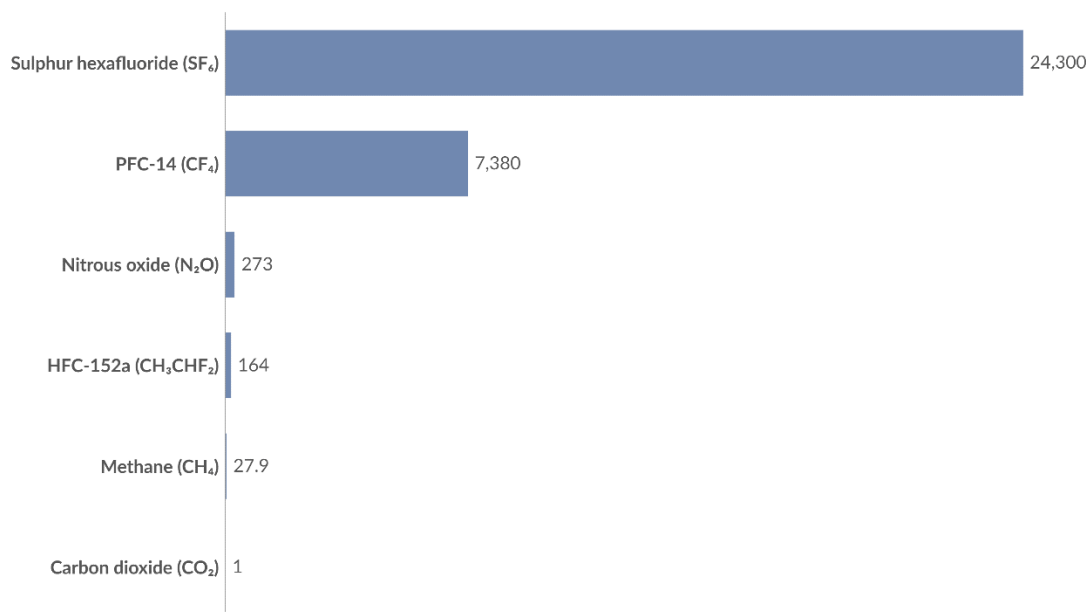


Fig. 41. Global warming Potential of greenhouse gases relative to CO₂ (IPCC, 2021)

Ecoinvent 3 database sources for SimaPro are utilized in this investigation. As a prominent source of life cycle inventory (LCI) data, Ecoinvent has played a crucial role in promoting eco-friendly practices across a wide range of businesses over the last decade. They help producers, politicians,

and shoppers make better, more environmentally friendly decisions with their extensive databases. Ecoinvent provides one of the most comprehensive global LCI resources available, spanning sectors such as energy, transportation, agriculture, chemicals, plastics, building and construction, packaging, forestry, textiles, metals, electronics, water supply, dairy, waste treatments, and recycling (Ecoinvent, 2024).

4.3.2. Simapro Inputs

The carbon footprint of the modular components throughout their entire life cycle was evaluated by extracting pertinent data from a database with three equivalents. In cases where suitable data were unavailable, Environmental Product Declarations (EPDs) were used instead. For example, EPDs related to galvanized steel, stainless steel, and engineered flooring were added to the SimaPro database (See Appendix C).

Chapter 5: Result Analysis

5.1.Life Cycle Interpretations

The final step of the LCA process involves conducting a comprehensive analysis of the results obtained using SimaPro LCA. Data interpretation, aimed at identifying important environmental consequences, assessing the relevance of the findings, and providing suggestions for enhancing the sustainability performance of the system under study, is the responsibility of this phase.

5.1.1. Raw Materials

The breakdown of carbon Emissions for raw materials is shown in the chart. Among the evaluated materials, stainless steel and galvanized steel exhibited the highest environmental impact, with emissions of 24,100 kg CO₂-eq and 11,500 kg CO₂-eq, respectively. Extruded polystyrene insulation also demonstrated a significantly high footprint (5,690 kg CO₂eq), largely due to its petrochemical-based production.

In contrast, wood-based products such as sawn wood (hardwood and softwood) and Oriented Standard Board (OSB) had the lowest emissions, ranging from 20.5 to 159 kgCO₂eq, highlighting their potential as low-carbon alternatives in building materials. Raw materials, such as gypsum board, aluminum cladding, and engineered flooring, had a moderate impact.

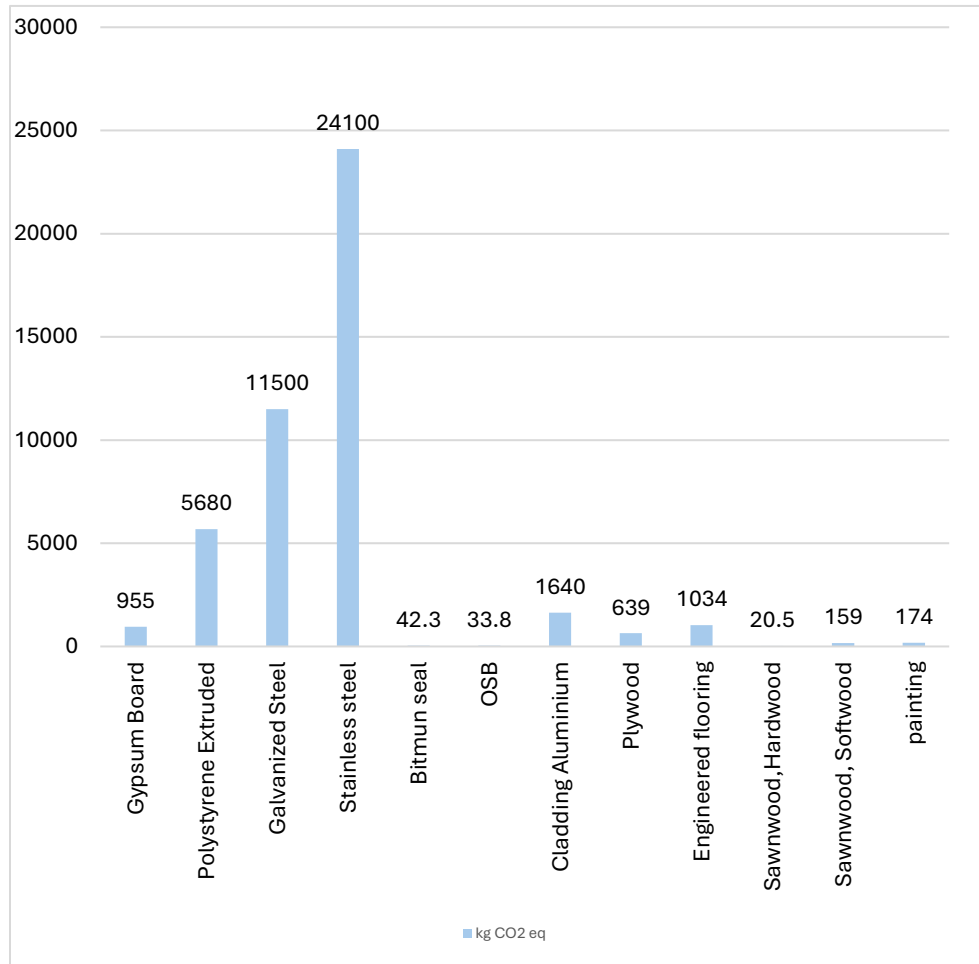


Fig. 42. Carbon emissions breakdown (kgCO₂eq) of raw materials

5.1.2. Transportation

Fig. 43 shows that the use of two 50'' trailers stands out as the highest emitter, producing 7,700 kg CO₂ eq, primarily due to the long-distance overland transport of two large, completed pods from Reinfeld to Montreal. Other notable contributors include 4' flatbed trucks (972 kg CO₂eq), large sea cargo (1,680 kg CO₂eq). Worker transportation also contributes 1,690 kg CO₂eq, highlighting the environmental impact of labor logistics in remote areas. The 50'' trailer for supplemental transport and the 40'' trailer both have shorter distances between the supplier and the plant, or between the supplier and the port; hence, they produce lower emissions of 186 kgCO₂eq and 387 kg CO₂ eq, respectively.

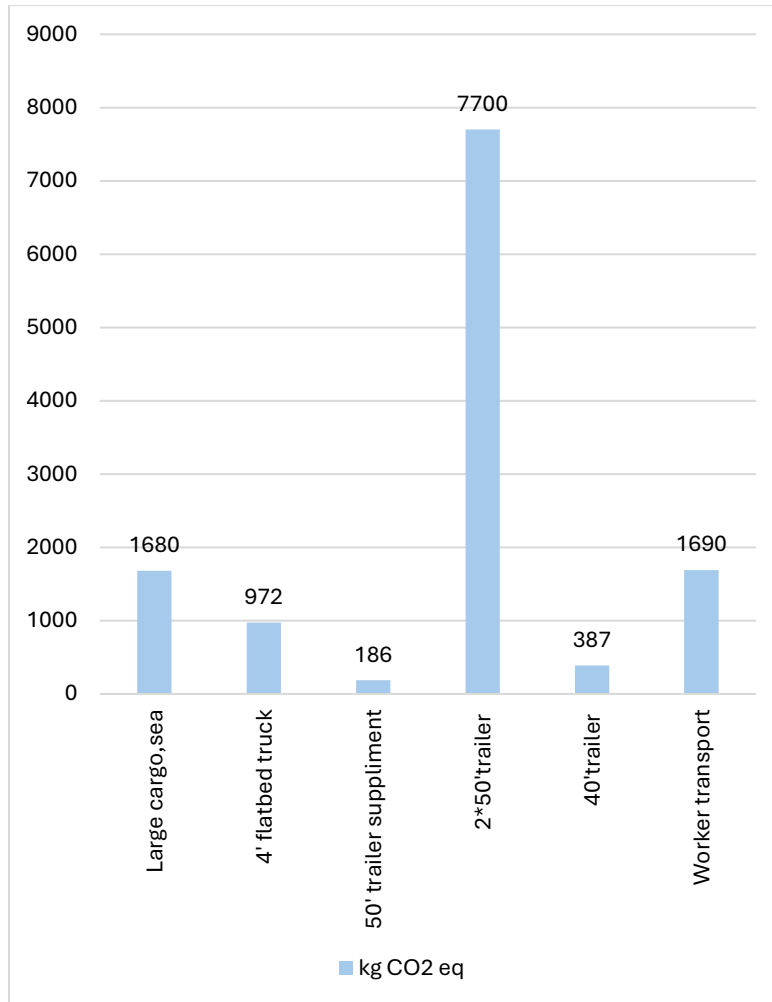


Fig. 43. Carbon emissions breakdown (kgCO₂eq) of Transportation

5.1.3. Manufacturing

Producing two pods requires very little power and gas because the factory is presently running at half capacity, the office portion is not in use, the boiler is awaiting permission, and most of the daily equipment is powered by batteries. The carbon emissions were increased to reflect the project's full functioning circumstances, though. Thus, as can be seen in Fig. 44, over 250 kg CO₂eq is contributed by gas consumption, whereas approximately 620 kgCO₂eq is attributed to electricity usage.

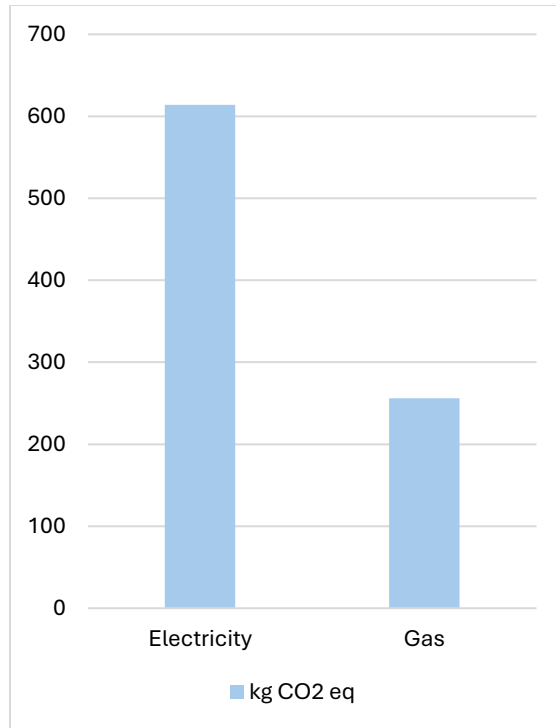


Fig. 44. Carbon emissions breakdown (kgCO₂eq) of Manufacturing

5.1.4. On-site Construction

During the installation procedure, the tiny generator is the primary source of electricity. Fig. 45 shows that this generator is the biggest contributor to carbon emissions, producing roughly 7,700 kgCO₂eq. Bobcats, Zoom Booms, and 980M Cats all produce comparatively small amounts of emissions, with each machine producing less than 500 kgCO₂eq. Although it produces somewhat higher emissions than the others, the 980M Cat loader is still significantly below the level of the generator.

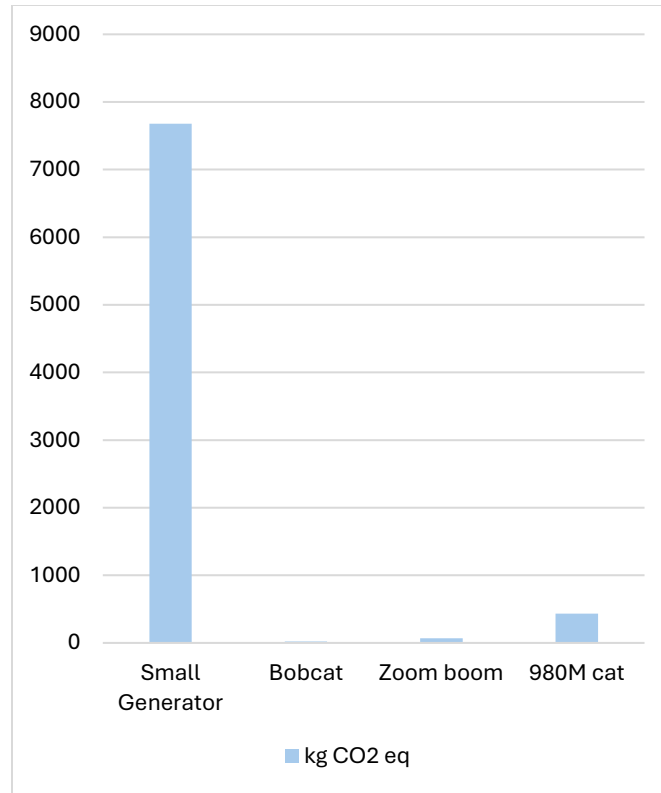


Fig. 45. Carbon emissions breakdown (kgCO₂eq) of on-site construction activities

5.1.5. Comparative Analysis

Table 9 presents the carbon emissions results for the product and construction stages individually. Due to limited access to reliable data from Cambridge Bay, it was not feasible to assess the remaining stages of the life cycle. Compared to the building stage, which accounts for 19,037 kgCO₂eq, the product stage accounts for a substantially greater amount of 71,173 kgCO₂eq. In this study, the difference is even more pronounced than in other life cycle studies, where the product stage typically accounts for the largest share of emissions. This is primarily due to the severe climatic conditions in Cambridge Bay, which led the designer to select highly durable materials such as aluminum, stainless steel, and galvanized steel, in addition to using thick insulation to resist the extreme cold.

Table 9. Carbon emissions in the product stage and the Construction stage of the LCA

Indicator	Unit	Life Cycle Stage				Supplementary	
		Product stage	Construction stage	Use stage	End of life stage	Benefits loads beyond the system boundary	and beyond the system boundary
		A1-A3	A4-A5	B1-B7	C1-C4	D	
GWP	KgCO ₂ eq	71,173	19,037	x	x	X	

Regarding the carbon emissions associated with each stage, the pie chart (Fig. 46) clearly illustrates that the raw material stage is the dominant contributor, accounting for 76% of the total emissions. Due to the severe weather conditions in Cambridge Bay and the requirement for long-term durability and insulation, high-impact materials such as galvanized steel, aluminum, and stainless steel were utilized. Transportation is the second highest contributor at 14%, primarily due to two major long-distance routes: first, transporting the fully assembled pods from Reinfeld to the Port of Montreal using two large trailers; and second, the large cargo shipment from Montreal to Cambridge Bay. It ranks third, representing 9% of the total emissions, slightly higher than the manufacturing stage, which accounts for 1%. This difference is largely due to the use of a gasoline-powered generator to supply electricity during installation, as the site lacks access to any power grid. The low contribution from manufacturing is due to the factory having only recently started operations. Due to the time constraints of this research project, emissions from this stage were calculated based solely on summer energy consumption. Emissions would likely be higher if winter heating demands were included.

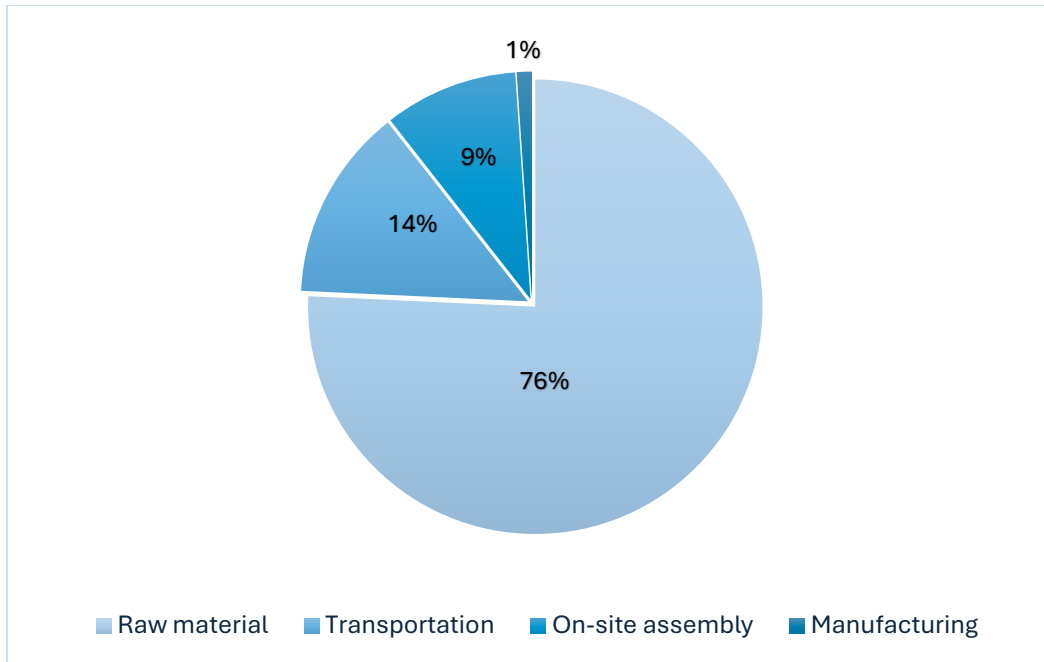


Fig. 46. Contribution of each life cycle phase to total CO2 emissions in modular building construction

5.2.Scenario Analysis (Consequential Analysis)

5.2.1. Alternative Raw Material Selection

In the raw material selection phase, stainless steel, galvanized steel, extruded polystyrene, and aluminum cladding were identified as the top four contributors to embodied carbon emissions. Among these, galvanized steel and extruded polystyrene are essential components of the ICE panels, which are designed according to manufacturer standards and building regulations for the Arctic zone. Moreover, due to their critical role in ensuring thermal insulation performance, these materials cannot be easily substituted, and complex calculations are required to determine whether alternative materials can be used.

In contrast, stainless steel, primarily used in structural elements such as beams, could potentially be replaced with Stainless Steel with higher recycled content, galvanized steel with higher recycled content, and wood – more sustainable and affordable materials with significantly lower carbon intensity. However, due to the harsh Arctic climate, the Arctic Modular Home Factory has opted to retain stainless steel for its exceptional strength, durability, and resistance to corrosion.

As shown in the figure, carbon emissions can be significantly reduced through material substitution. Replacing the stainless-steel structure with a version containing 70% recycled content nearly halves the emissions, reducing them from 24,100 kgCO₂eq to 12,800 kgCO₂eq. Using galvanized steel instead of stainless steel also reduces emissions to 12,900 kgCO₂eq, comparable to those of regular stainless steel. Additionally, galvanized steel with 28% recycled content further decreases emissions to 3,580 kgCO₂eq. The most substantial reduction is achieved by choosing a wood structure, which brings emissions down to just 241 kgCO₂eq (Fig. 48). The full list of EPDs is provided in Appendix C.

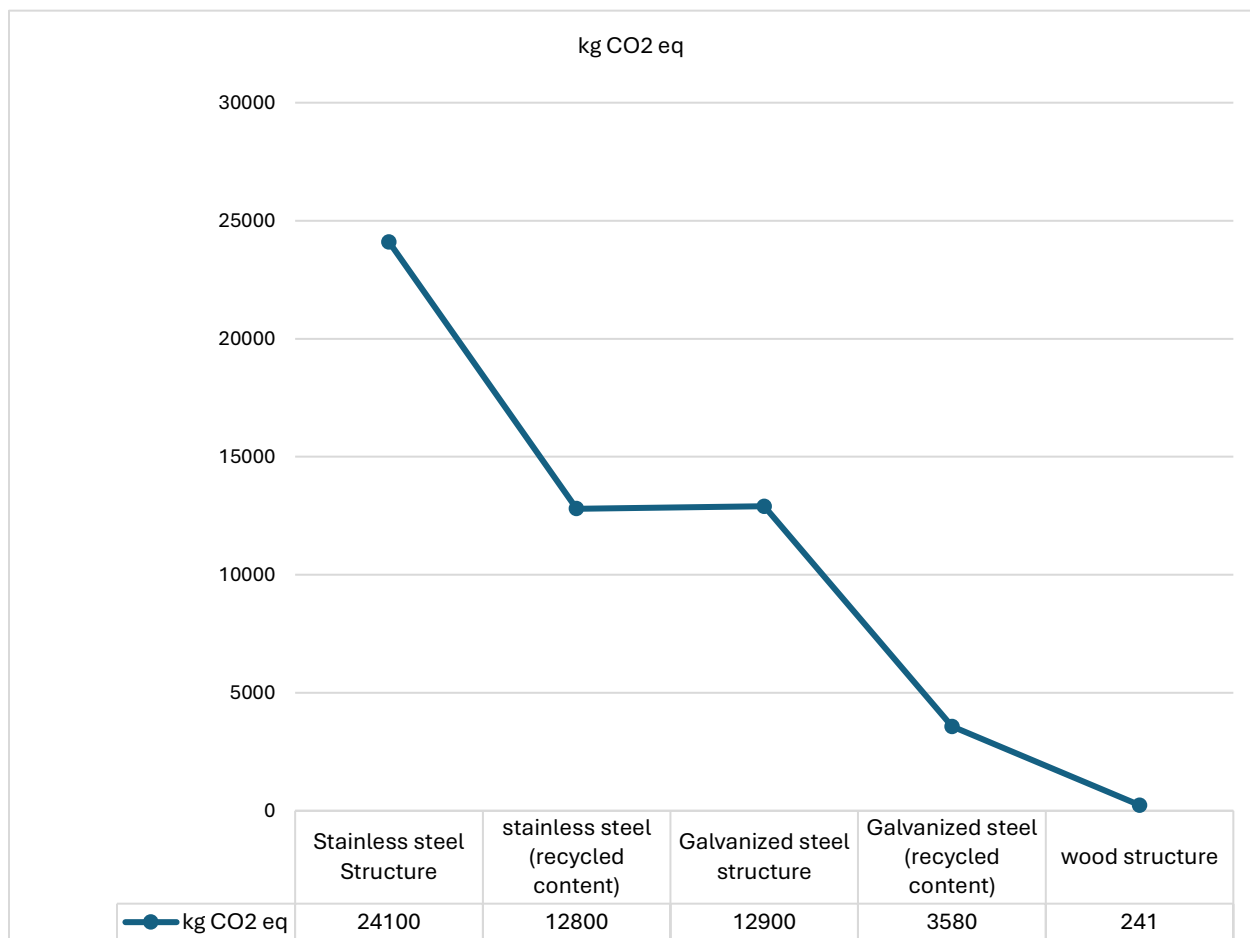


Fig. 47. Impact of material substitution on carbon reduction in the structure

For cladding material, three sustainable alternatives are suggested for Arctic regions, each offering significant carbon emissions reductions compared to aluminum cladding. As shown in Fig. 49, replacing aluminum cladding with fiber cement, equivalent to 1,640 kg CO₂ eq, leads to a reduction of approximately 550 kg CO₂eq. Using High-Pressure Laminate (HPL) board reduces emissions by 610 kgCO₂eq. The greatest reduction is achieved with wood, which lowers emissions by nearly 1,490 kgCO₂eq, making it the most sustainable choice. These alternatives not only improve environmental performance but also offer durability suitable for harsh Arctic climates. However, they are not as durable as aluminum and require more maintenance (See Appendix C).

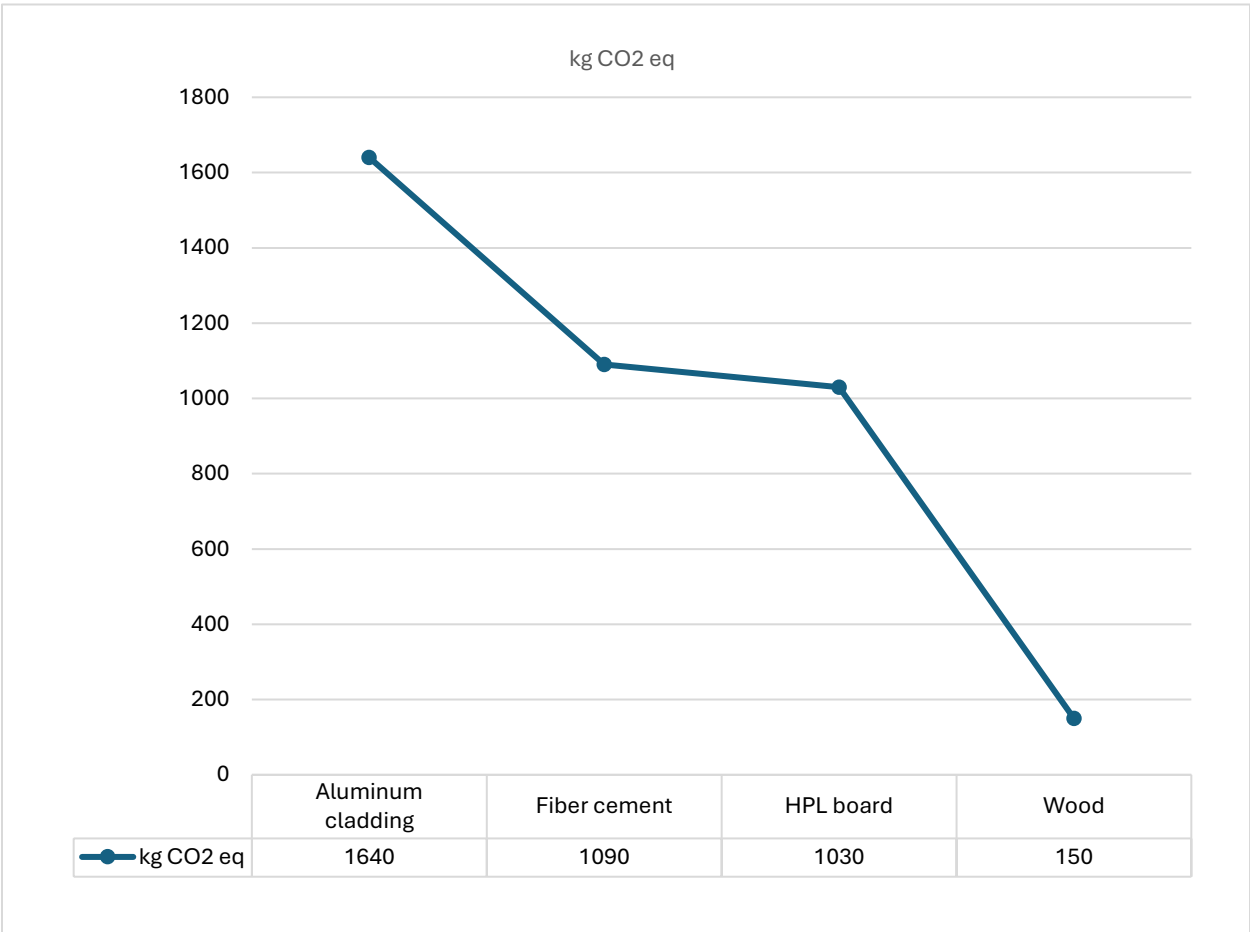


Fig. 48. Impact of material substitution on carbon reduction in the Cladding system

5.2.2. Port relocation

As shown in Fig. 50, relocating the shipping port from Montreal to Churchill in northern Manitoba improves two key aspects of the transportation phase. First, the overland distance from Reinfeld to the port becomes significantly shorter, reducing fuel use and emissions associated with transporting 50'' trailers. Second, the sea route from Churchill to Cambridge Bay is also shorter than from Montreal, making the overall transportation phase more efficient. By addressing both, the port relocation effectively targets the highest-emitting activities in this phase. As shown in Fig. 52, this strategic decision results in a threefold reduction in emissions, from approximately 12,700 kgCO₂eq to just 7,730 kgCO₂eq.

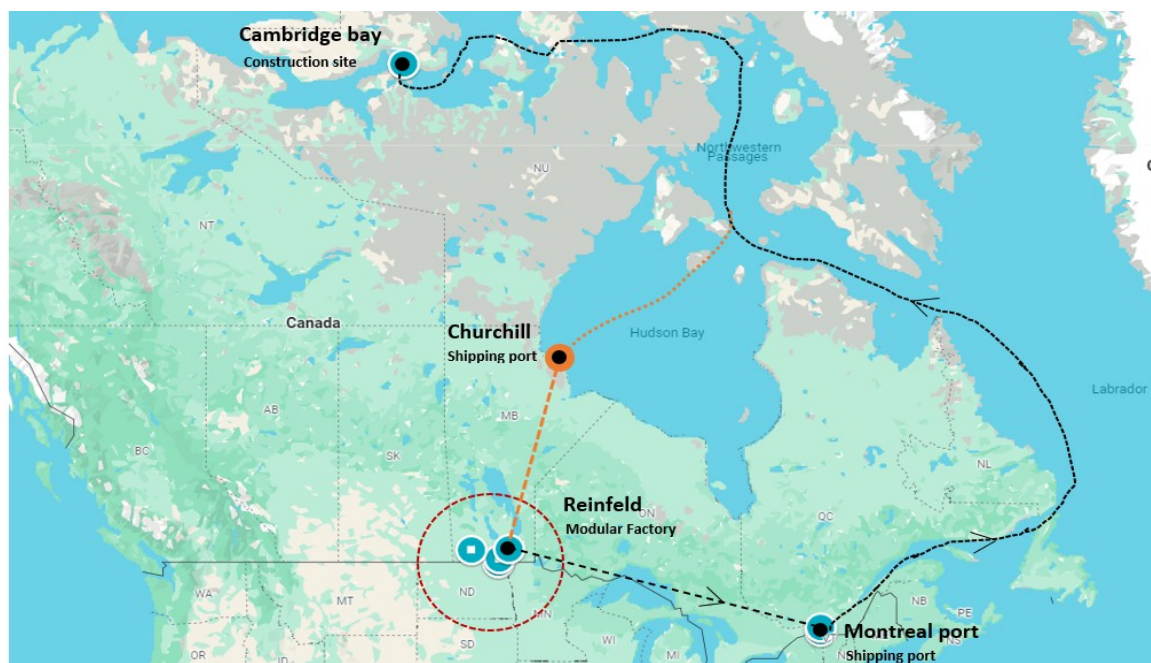


Fig. 49. Relocating the port from Montreal to Churchill port

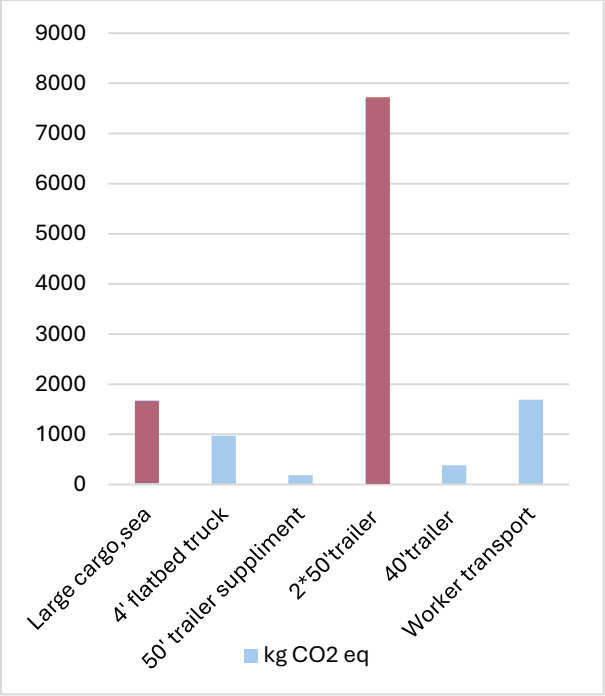


Fig. 50. First and Second Highest Contributors to Transportation CO2 Emissions

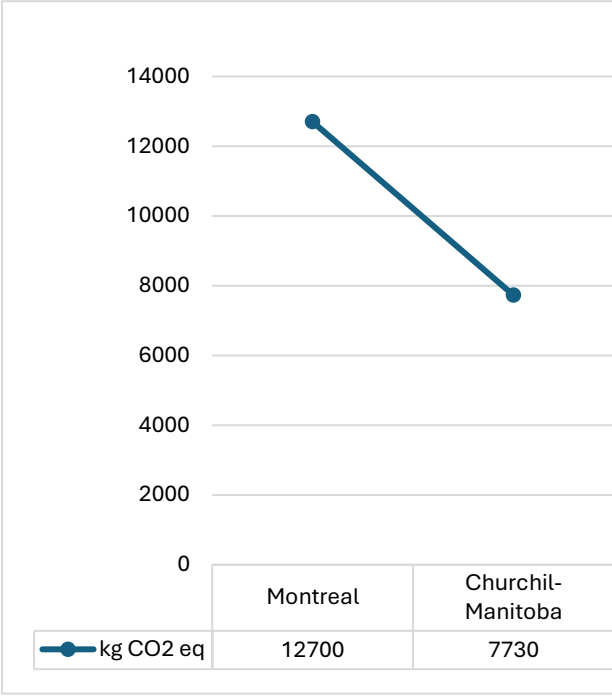


Fig. 51. Impact of relocating the port on carbon reduction in the Transportation phase

5.2.3. Local worker

The third improvement scenario, which involves employing local workers instead of flying in labor from the South, can eliminate approximately 12,700 kgCO₂eq associated with workforce air travel. This results in a significant reduction in overall emissions during the construction phase. In this revised approach, only the project manager and one skilled worker would need to be on-site for at least 10 units’ installation, and their travel-related emissions would be distributed between approximately ten homes. As illustrated in Fig. 52, for each unit, the worker’s travel will be reduced to 1,100 kg CO₂ eq.

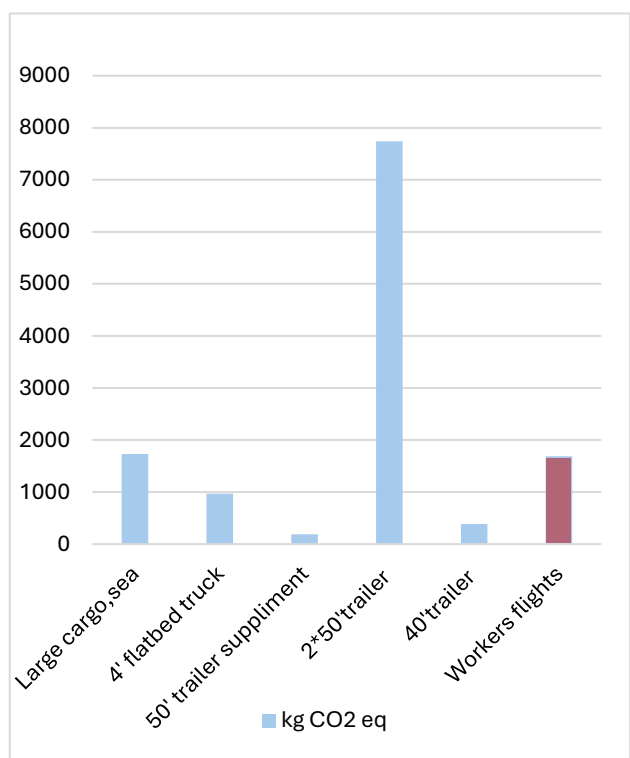


Fig. 52. Third Major Source of Transportation carbon Emissions

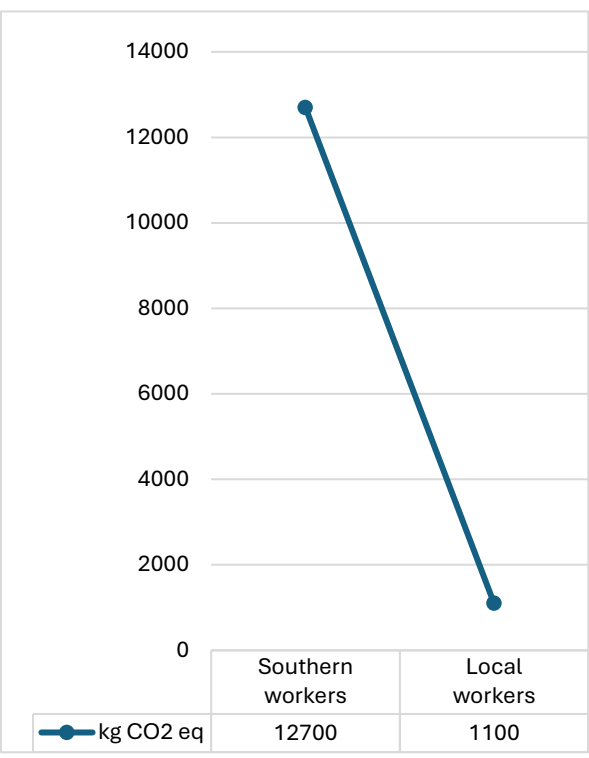


Fig. 53. Impact of using local workers on carbon reduction in Transportation phase

5.2.4. Modular Factory relocation

Relocating the modular factory from Manitoba to Montreal is the last improvement that has a significant impact on both the transportation and manufacturing phases of the project.

A2. Transportation

From a transportation perspective, establishing the factory closer to the final shipping port eliminates the need to ship the fully assembled modules over long distances. Previously, the complete units were transported from Reinfeld, Manitoba, to the Port of Montreal using two 50" trailers and one 40" trailer, a journey that contributed substantially to transportation-related Carbon emissions. By locating the factory in Montreal, long-haul trucking is eliminated, resulting in a considerable reduction in fuel use and associated carbon emissions. As illustrated in Fig. 53, the carbon emission of the transportation phase decreases threefold, from approximately 12,700 kgCO₂eq to 4,700 kgCO₂eq.

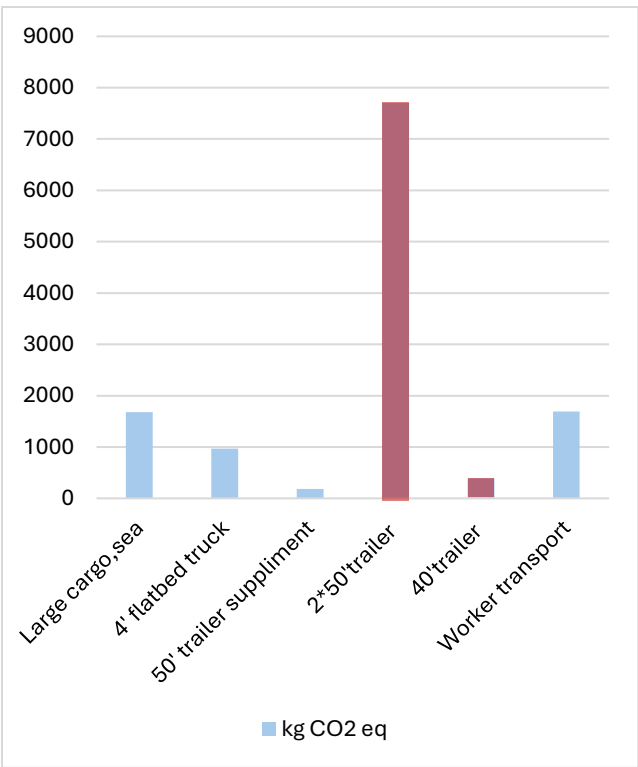


Fig. 54. Transportation carbon Contribution of Complete Module Shipping

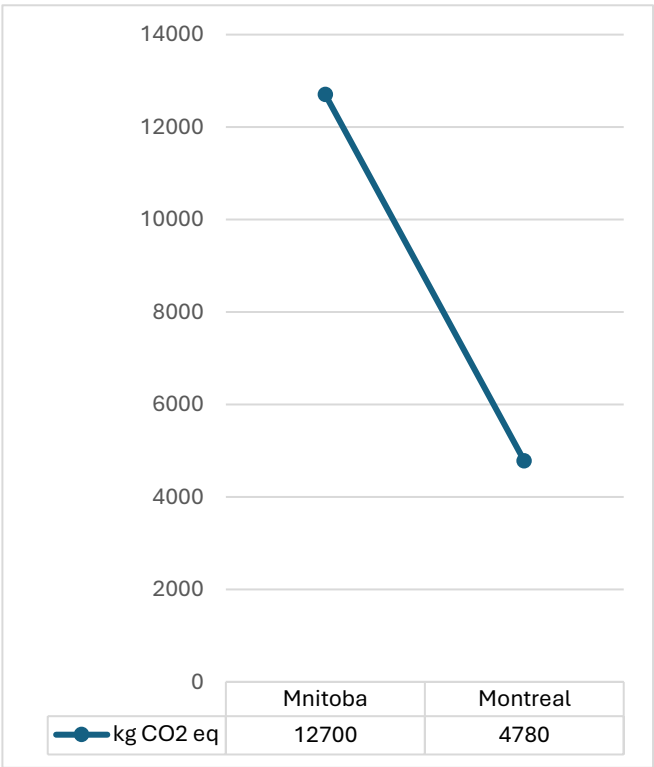


Fig. 55. Impact of relocating the modular factory on carbon reduction in Transportation phase

A3. Manufacturing Process

By relocating the factory to Montreal, where electricity is primarily generated from hydro power, a significant decrease in carbon emissions can be observed. As shown in Fig. 54, emissions drop from 614 kgCO₂eq in Manitoba to just 228 kgCO₂eq in Montreal.

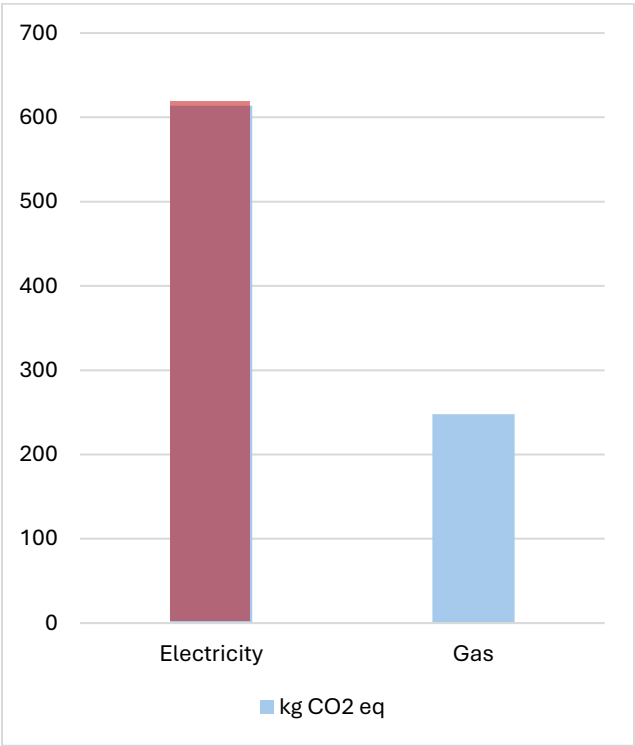


Fig. 56. Contribution of Electricity to carbon Emissions in the Manufacturing Phase

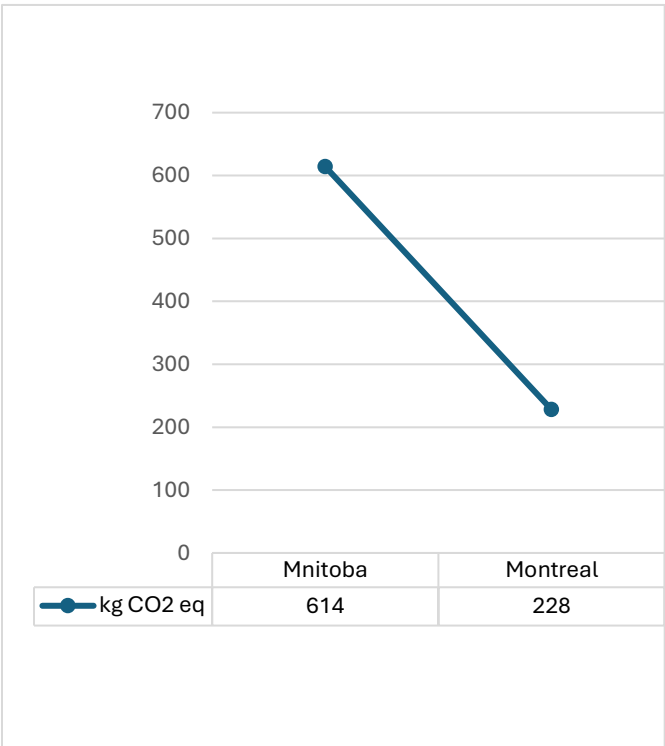


Fig. 57. Impact of relocating the modular factory on carbon reduction in electricity consumption of manufacturing

Chapter 6: Conclusions

6.1. Summary of contributions

This study examines the carbon emissions of modular homes in Cambridge Bay, a small town in northern Canada. The restoration project in Cambridge Bay encompasses fifty units, and although this research only looks at one, it is anticipated to soon expand to neighboring Nunavut villages. It is thus possible to extrapolate the results of this study to the full scope of the Cambridge Bay rehabilitation project. A standardized methodology vital to determining the environmental impacts of products and systems, LCA evaluates carbon emissions from cradle to end of life. The study's outcome is a scenario analysis that successfully lowers carbon emissions over the specified system boundaries.

- The results confirm that what other Modular LCA studies have found about the manufacture of raw materials is the single largest source of carbon emissions. However, in this case, the impact is even more pronounced due to the specific envelope configuration required to comply with Arctic building codes and withstand the region's extreme climate, as well as minimize long-term maintenance. The high carbon emission is largely attributed to the extensive use of polystyrene insulation and specific metal components used for the structural frame and cladding. In the development scenarios, alternative materials made from post-consumer recycled content were selected, leading to a substantial reduction in carbon emissions. This approach proves especially beneficial in Arctic contexts, where the use of durable materials is essential. Moreover, using wood or other emerging materials can significantly lower emissions in the material phase. While these alternatives may not always be as durable as metal material, their carbon-saving potential makes them valuable options in a sustainable design.
- In terms of transportation, a key finding of this study is that shipping the final modular units using two 50' trailers generates more carbon emissions than the long-distance marine shipment by cargo vessel. Besides, two development scenarios were identified that significantly reduce transportation-related emissions. The first involves reactivating the Port of Churchill, which would shorten the shipping distance by nearly half. The second

scenario considers relocating the manufacturing facility closer to the Port of Montreal, which would eliminate the need for long-haul road transportation entirely.

- The manufacturing phase is the least carbon-intensive stage of this project. However, if the result is generalized to the full-scale rehabilitation project in Cambridge Bay, even a 1% contribution from the manufacturing phase can translate into a significant amount of carbon that must be considered. The proposed development scenario for this phase involves relocating the factory to Montreal, where access to hydroelectric power could significantly reduce electricity-related emissions, especially in large-scale projects.
- With just 9% of total emissions occurring during the 16-day assembly phase, on-site building is one of the least carbon-intensive aspects of the project. However, when scaled to the entire rehabilitation project, this contribution becomes more significant. The primary source of electricity during this phase is a diesel generator, which cannot currently be replaced or improved due to the lack of access to any power grid in the area. Therefore, the only way to reduce carbon emissions in this phase is to maximize off-site preparation and minimize on-site assembly work.

6.2.Limitations

This study has two types of limitations that must be taken into consideration. The first category pertains to situations where data is unavailable, which forces the exclusion of certain data and places restrictions on the LCA's system boundary. The second concern is the failure to integrate LCA and BIM software effectively.

- Stages A1-A5 are the only ones covered by this study, which is the biggest drawback. Stages such as transportation, on-site building, and product stage (material extraction and production) are included. This constraint is due to the limited availability of data for the remaining life cycle stages. Collecting data for the phases after the modular units were assembled was difficult because these activities take place in a remote Arctic region. Additionally, the factory team was unable to provide information regarding the use, maintenance, or end-of-life stages.

- Since information on other parts, such as the mechanical and electrical systems, was lacking during the raw material phase, we had to settle for evaluating only the modular units' exteriors. In the Arctic, however, a building's envelope is more important than any other part. Environmental Product Declarations (EPDs) were also used for specific commodities due to a lack of data in the accessible databases.
- Finished unit delivery to the Montreal port and marine shipment units to the building site were all key components covered in the transportation stage assessment. However, because there was not enough solid evidence, we excluded a few minor transportation-related tasks, such as employees' daily commutes to and from the plant and any short-distance journeys required to bring in supplemental products or tools.
- Since utility bills were not available for the manufacturing phase, water usage was not included in the assessment. The study's power and gas bills represent consumption throughout the summer months. It is expected that consumption would be significantly higher during the winter; however, since the factory only began operating in March and due to time constraints, no winter utility data was available at the time of the study. Additionally, the factory is not yet operating at full capacity. According to the data provided, it is currently functioning at approximately 50% of its intended production level. Therefore, adjustments were made to estimate the carbon emissions associated with a fully operational facility.
- In the on-site assembly phase, several factors were excluded due to the challenges of data collection in the remote area. Since all activities take place in a distant Arctic region, gathering accurate and detailed information was particularly difficult. All available data for this phase was provided directly by the Modular Home Factory. However, some elements, such as short-distance transportation of construction vehicles and the process of pulling the pods from the high-water mark to the installation site, were not included in the assessment due to a lack of reliable data.

The second type of limitation is related to software, particularly concerning data limitations within SimaPro and integration of BIM and LCA software. In several cases, the lack of specific datasets required the use of Environmental Product Declarations (EPDs) or the selection of the closest

available alternatives to represent certain materials. This requirement introduces a level of approximation that can affect the accuracy of the results. Moreover, inconsistencies in material units between BIM software, such as Revit or Autodesk Takeoff, and SimaPro necessitated manual conversions and adjustments. The total accuracy of the evaluation was diminished, and the procedure was made more complicated by these extra processes. Due to the sheer volume of data and variety of materials used in large-scale projects, maintaining platform consistency and integration is already a serious challenge.

6.3.Future work

For future studies aimed at enhancing this research, the following suggestions have been identified:

Integration of BIM and LCA software: This study highlights the need for improved integration between BIM tools (such as Revit or Autodesk Takeoff) and LCA software. A key issue encountered was the discrepancy in material units and formats between the two systems, which required manual conversions and adjustments. This issue not only reduced workflow efficiency but also increased the potential for human error, especially in large-scale projects. Future work should focus on developing standardized unit mappings or automated translation tools to align BIM quantity take-offs with LCA input formats. Such advancements would enhance accuracy, reduce labor, and enable more seamless and scalable environmental assessments directly from BIM environments.

To enable broader industry adoption, the LCA process must become more streamlined, efficient, and user-friendly. While the current approach may suffice for small-scale projects, larger developments demand a more seamless workflow. Future work should focus on the development and refinement of LCA plug-ins directly within BIM software, such as Revit, allowing for real-time environmental assessments without the need for manual data transfer between platforms. Integrating LCA tools into the BIM environment would significantly accelerate the process, reduce human error, and support more sustainable decision-making from the earliest stages of design.

Refine the LCA: Future research should focus on broadening the system boundary to incorporate the modular construction's use, maintenance, and end-of-life phases, thereby enhancing the

environmental assessment's reliability and comprehensiveness. We can learn more about the effects of carbon if we include these periods of the life cycle. However, this requires access to detailed operational and maintenance data, which may only be obtainable through on-site data collection. The Modular Home Factory has expressed its willingness to support this effort by facilitating researcher access to the construction site; however, additional funding and logistical planning will be necessary to make this possible.

Enhancing Data Accuracy: For future studies, fostering early collaboration with industry partners is strongly recommended. Engaging stakeholders from the initial stages of the project can facilitate access to accurate and project-specific data, which is essential for producing realistic and reliable results. Such partnerships not only enhance data quality but also ensure that the study reflects real-world practices, thereby increasing the relevance and applicability of the research findings.

Life Cycle Cost Assessment: As future work, conducting a comprehensive cost assessment of this project and the associated development scenarios would provide valuable insights into their economic viability and help determine the feasibility of the proposed scenarios from a financial perspective

Sustainability: Acidification, eutrophication, human toxicity, and resource depletion are other environmental impact categories that should be considered in conjunction with carbon assessment to provide a more comprehensive view of the project's environmental performance. It is crucial to consider the social dimension in conjunction with the cost assessment to assess the sustainability of the planned development thoroughly. Evaluating factors such as local employment, community acceptance, and potential health and safety impacts would enable a more holistic sustainability analysis that considers all three pillars: People, Profit, and Planet (Mulligan, 2019).

Input-Output approach: To enhance the accuracy and completeness of the results, future studies could adopt a hybrid LCA approach by combining the process-based LCA with the input-output

LCA method. This integrated approach enables the consideration of broader system boundaries and indirect environmental impacts that may be overlooked in conventional process-based assessments. By leveraging the strengths of both methodologies, a hybrid LCA can improve data coverage, minimize system boundary truncation, and ultimately increase the reliability and robustness of the environmental impact results.

References

- (GlobalABC), U. N. E. P. U. a. G. A. f. B. a. C. (2024). Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector. <https://globalabc.org/resources/publications/beyond-foundations-2023-global-status-report-buildings-and-construction>
- (IEA), I. E. A. (2023). Share of buildings in total final energy consumption in 2022 and share of buildings in global energy and process emissions in 2022. <https://www.iea.org/reports/tracking-clean-energy-progress>
- (IPCC), I. P. o. C. C. (2021). Climate Change. C. U. Press. <https://www.ipcc.ch/report/ar6/wg1/>
- (UNEP), U. N. E. P. (2022). 2022 Global Status Report for Buildings and Construction. <https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction>
- Ahn, Y. H., & Kim, K.-T. (2014). Sustainability in modular design and construction: A case study of 'The Stack'. *International Journal of Sustainable Building Technology and Urban Development*, 5(4), 250-259.
- Ajayi, S. O., Oyedele, L. O., Ceranic, B., Gallanagh, M., & Kadiri, K. O. (2015). Life cycle environmental performance of material specification: a BIM-enhanced comparative assessment. *International Journal of Sustainable Building Technology and Urban Development*, 6(1), 14-24.
- Al-Hussein, M., Manrique, J. D., & Mah, D. (2009). North Ridge CO2 analysis report: comparison between modular and on-site construction. University of Alberta: Edmonton, AB, Canada.
- Almeida, J., Le Pellec, M., & Bengtsson, J. (2018). Reusable coffee cups life cycle assessment and benchmark. Edge: Joondalup, Australia.
- Arif, M., & Egbu, C. (2010). Making a case for offsite construction in China. *Engineering, Construction and Architectural Management*, 17(6), 536-548.
- Arzoumanidis, I., D'Eusanio, M., Raggi, A., & Petti, L. (2019). Cycle Assessment and Social Life Cycle. *Perspectives on Social LCA: Contributions from the 6th International Conference*,
- Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering*, 11(3), 241-252.

- Bertram, N., Mischke, J., & Sjödin, E. (2019). Modular construction: priorities for real-estate developers. McKinsey & Company.
- Bullard, C. W., Penner, P. S., & Pilati, D. A. (1978). Net energy analysis: Handbook for combining process and input-output analysis. *Resources and Energy*, 1(3), 267-313.
- Canada, E. a. C. C. (2023a). Greenhouse Gas Emissions. <https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/greenhouse-gas-emissions.html>
- Canada, E. a. C. C. (2023b). National Inventory Report 1990–2021: Greenhouse Gas Sources and Sinks in Canada – Part 3. Retrieved from <https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html>
- Canada, E. a. C. C. (2025). Canadian Climate Normals 1991–2020: Cambridge Bay. https://climate.weather.gc.ca/climate_normals/results_1991_2020_e.html?searchType=stnName_1991&txtStationName_1991=Cambridge+bay&searchMethod=contains&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=371000000&dispBack=1
- Canada, S. (2021). Household greenhouse gas emissions per capita, by province and territory, 2021. Government of Canada
- <https://www150.statcan.gc.ca/n1/daily-quotidien/231220/mc-c001-eng.htm>
- Cheng, Z., Zhang, T., Zhou, X., Li, Z., Jia, Y., Ren, K., Xu, T., Li, C., & Hong, J. (2023). Life cycle environmental and cost assessment of prefabricated components manufacture. *Journal of Cleaner Production*, 415, 137888.
- Corporation, N. H. (2023). Annual Report 2023-2024. Retrieved from <https://www.nunavuthousing.ca/publications>
- Crawford, R., & Treloar, G. (2004). Assessment of embodied energy analysis methods for the Australian construction industry.
- Division, U. N. S. (1999). Handbook of input-output table compilation and analysis. UN.
- Du, Q., Bao, T., Li, Y., Huang, Y., & Shao, L. (2019). Impact of prefabrication technology on the cradle-to-site CO₂ emissions of residential buildings. *Clean Technologies and Environmental Policy*, 21, 1499-1514.
- ecoinvent. (2024). Ecoinvent database. <https://ecoinvent.org/the-ecoinvent-database/#:~:text=The%20ecoinvent%20Database%20is%20a,of%20their%20products%20and%20services>

- Ford, J. D., Bell, T., & St-Hilaire-Gravel, D. (2010). Vulnerability of community infrastructure to climate change in Nunavut: a case study from Arctic Bay. *Community Adaptation and Vulnerability in Arctic Regions*, 107-130.
- Gao, H., Wang, D., Du, X., & Zhao, Z. (2024). An LCA-BIM integrated model for carbon-emissions calculation of prefabricated buildings. *Renewable and Sustainable Energy Reviews*, 203, 114775.
- Gao, Y., Wang, J., & Yiu, T. W. (2024). Multi-information integration-based life cycle analysis of greenhouse gas emissions for prefabricated construction: A case study of Shenzhen. *Environmental Impact Assessment Review*, 104, 107330.
- Gibb, A., & Pendlebury, M. (2006). Build offsite glossary of terms. Construction Industry Research & Information Association (CIRIA), London.
- Gibb, A. G. (1999). Off-site fabrication: prefabrication, pre-assembly and modularisation. John Wiley & Sons.
- Global, B. (2018). BRE Global Methodology for the Environmental Assessment of Buildings Using EN 15978:2011. B. G. Ltd. <https://www.greenbooklive.com>
- Hao, J. L., Cheng, B., Lu, W., Xu, J., Wang, J., Bu, W., & Guo, Z. (2020). Carbon emissions reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach. *Science of the Total Environment*, 723, 137870.
- Hatmoko, J. U. D., Wibowo, M. A., & Prasetyo, F. (2023). Carbon Emissions Analysis of Modular House Construction. *E3S Web of Conferences*,
- Hendrickson, C. T., Horvath, A., Joshi, S., Klausner, M., Lave, L. B., & McMichael, F. C. (1997). Comparing two life cycle assessment approaches: a process model vs. economic input-output-based assessment. *Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment. ISEE-1997*,
- Hossain, Y., & Marsik, T. (2019). Conducting life cycle assessments (LCAs) to determine carbon payback: A case study of a highly energy-efficient house in rural Alaska. *Energies*, 12(9), 1732.
- Huang, L., Krigsvoll, G., Johansen, F., Liu, Y., & Zhang, X. (2018). Carbon Emissions of global construction sector. *Renewable and Sustainable Energy Reviews*, 81, 1906-1916.

- Huovila, P., Ala-Juusela, M., Melchert, L., Pouffary, S., Cheng, C.-C., Ürge-Vorsatz, D., Koeppel, S., Svenningsen, N., & Graham, P. (2009). Buildings and Climate Change: Summary for decision-makers.
- ISO14040. (2006). Environmental management – Life cycle assessment – Principles and framework. In: International Organization for Standardization.
- ISO14044. (2006). Environmental management – Life cycle assessment – Requirements and guidelines. In: International Organization for Standardization.
- Jayawardana, J., Sandanayake, M., Jayasinghe, J., Kulatunga, A. K., & Zhang, G. (2023). A comparative life cycle assessment of prefabricated and traditional construction—A case of a developing country. *Journal of Building Engineering*, 72, 106550.
- Jrade, A., & Jalaei, F. (2013). Integrating building information modelling with sustainability to design building projects at the conceptual stage. *Building Simulation*,
- Kamali, M., & Hewage, K. (2016). Life cycle performance of modular buildings: A critical review. *Renewable and Sustainable Energy Reviews*, 62, 1171-1183.
- Kamali, M., Hewage, K., & Sadiq, R. (2019). Conventional versus modular construction methods: A comparative cradle-to-gate LCA for residential buildings. *Energy and Buildings*, 204, 109479.
- Khoshnava, S. M., Rostami, R., Ismail, M., & Rahmat, A. R. (2018). A cradle-to-gate based life cycle impact assessment comparing the KBFw EFB hybrid reinforced poly hydroxybutyrate biocomposite and common petroleum-based composites as building materials. *Environmental Impact Assessment Review*, 70, 11-21.
- Laboratory, G. M. (2025). Recent Monthly Mean CO₂ at Mauna Loa Observatory. National Oceanic and Atmospheric Administration (NOAA). <https://gml.noaa.gov/ccgg/trends/>
- Lawson, M., Ogden, R., & Goodier, C. I. (2014). *Design In Modular Construction* (Vol. 476). CRC press Boca Raton, FL.
- Li, X.-j., Xie, W.-j., Xu, L., Li, L.-l., Jim, C., & Wei, T.-b. (2022). Holistic life-cycle accounting of carbon emissions of prefabricated buildings using LCA and BIM. *Energy and Buildings*, 266, 112136.
- Mastrucci, A., Marvuglia, A., Popovici, E., Leopold, U., & Benetto, E. (2017). Geospatial characterization of building material stocks for the life cycle assessment of end-of-life scenarios at the urban scale. *Resources, Conservation and Recycling*, 123, 54-66.

- Mulligan, C. (2019). *Sustainable engineering: Principles and Implementation*. Crc Press.
- Nahmens, I., & Ikuma, L. H. (2012). Effects of lean construction on sustainability of modular homebuilding. *Journal of Architectural Engineering*, 18(2), 155-163.
- Navaratnam, S., Ngo, T., Gunawardena, T., & Henderson, D. (2019). Performance review of prefabricated building systems and future research in Australia. *Buildings*, 9(2), 38.
- Noordzy, G., Whitfield, R., Saliot, G., & Ricaurte, E. (2021). Modular construction. *The Journal of Modern Project Management*, 9(2).
- Omar, W. M. S. W. (2018). A hybrid life cycle assessment of embodied energy and carbon emissions from conventional and industrialised building systems in Malaysia. *Energy and Buildings*, 167, 253-268.
- Pan, W., & Goodier, C. (2012). House-building business models and off-site construction take-up. *Journal of Architectural Engineering*, 18(2), 84-93.
- Pervez, H., Ali, Y., & Petrillo, A. (2021). A quantitative assessment of greenhouse gas (GHG) emissions from conventional and modular construction: A case of developing country. *Journal of Cleaner Production*, 294, 126210.
- Pons, O., & Wadel, G. (2011). Environmental impacts of prefabricated school buildings in Catalonia. *Habitat International*, 35(4), 553-563.
- Potrč Obrecht, T., Röck, M., Hoxha, E., & Passer, A. (2020). BIM and LCA integration: A systematic literature review. *Sustainability*, 12(14), 5534.
- Quale, J., Eckelman, M. J., Williams, K. W., Sloditskie, G., & Zimmerman, J. B. (2012). Construction matters: Comparing environmental impacts of building modular and conventional homes in the United States. *Journal of Industrial Ecology*, 16(2), 243-253.
- Regulator, C. E. (2020). Canada's Renewable Power – Nunavut. <https://www.cer-rec.gc.ca/en/data-analysis/energy-commodities/electricity/report/canadas-renewable-power/provinces/renewable-power-canada-nunavut.html>
- Regulator, C. E. (2022). Renewable Electricity in Canada – Nunavut. <https://www.cer-rec.gc.ca/fr/donnees-analyse/produits-base-energetiques/electricite/rapport/electricite-renouvelable-canada/provinces/electricite-renouvelable-canada-nunavut.html>
- Rezaei, F., Bulle, C., & Lesage, P. (2019). Integrating building information modeling and life cycle assessment in the early and detailed building design stages. *Building and Environment*, 153, 158-167.

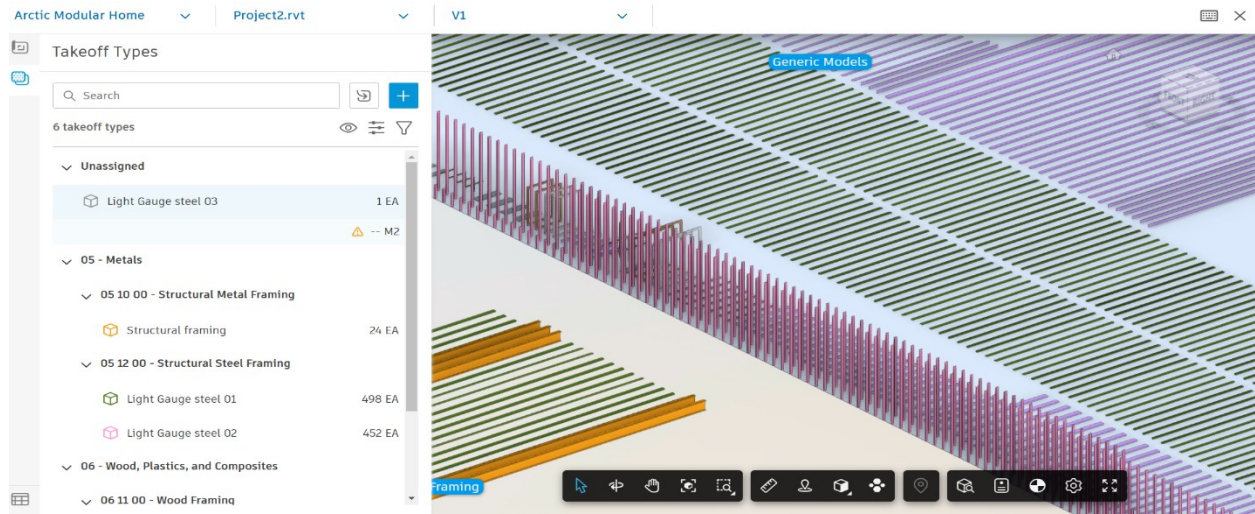
- Rezzag Lebza, M. (2022). Comparative analysis of life cycle GHG emissions of off-site Prefabricated modular volumetric construction and Panelized construction system for High rise wooden residential buildings in Norway: The potential of prefabricated wood Constructions as an efficient and sustainable building practice and their life cycle implications NTNU].
- Sandanayake, M., Luo, W., & Zhang, G. (2019). Direct and indirect impact assessment in off-site construction—A case study in China. *Sustainable Cities and Society*, 48, 101520.
- Su, S., Li, S., Ju, J., Wang, Q., & Xu, Z. (2021). A building information modeling-based tool for estimating building demolition waste and evaluating its environmental impacts. *Waste Management*, 134, 159-169.
- Sultan, A. (2023). Solving the housing crisis in Nunavut, Canada. *Scandinavian Journal of Public Health*, 51(7), 1023-1026.
- Sustainability, P. (2024). SimaPro – LCA software for informed changemakers. <https://simapro.com>
- Tavares, V., Lacerda, N., & Freire, F. (2019). Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The “Moby” case study. *Journal of Cleaner Production*, 212, 1044-1053.
- Thai, H. T., Ngo, T., & Uy, B. (2020, December). A review on modular construction for high-rise buildings. In *Structures* (Vol. 28, pp. 1265-1290). Elsevier.
- Thomsen, R. F. (2022). Use of prefabricated building construction method to reduce construction waste and Global Warming Potential from residential buildings in Denmark. *Building Energy Design*.
- Wang, H., Zhang, Y., Gao, W., & Kuroki, S. (2020). Life cycle environmental and cost performance of prefabricated buildings. *Sustainability*, 12(7), 2609.
- Wen, T. J., Siong, H. C., & Noor, Z. (2015). Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia. *Energy and Buildings*, 93, 295-302.
- Wontrop, Z. S. (2023). Arctic Construction Under Climatological Constraints: A Decision Support System for Expeditionary Construction Site Selection in the Arctic Environment.
- Xu, J., Teng, Y., Pan, W., & Zhang, Y. (2022). BIM-integrated LCA to automate embodied carbon assessment of prefabricated buildings. *Journal of Cleaner Production*, 374, 133894.

- Yoffe, H., Rankin, K. H., Bachmann, C., Posen, I. D., & Saxe, S. (2024). Mapping construction sector greenhouse gas emissions: a crucial step in sustainably meeting increasing housing demands. *Environmental Research: Infrastructure and Sustainability*, 4(2), 025006.
- Yukon Research Centre, H. o. C. B., and Canadian High Arctic Research Station. (2014). Cambridge Bay Energy and Emissions Inventory.
- Zenga, M., & Javor, A. (2008). *Modular Homes: The Future Has Arrived*. Cronos Books.
- Zhang, X., & Wang, F. (2016). Assessment of embodied carbon emissions for building construction in China: Comparative case studies using alternative methods. *Energy and Buildings*, 130, 330-340.

Appendices

Appendix A : Quantity Take-offs

- Autodesk Teke off



Name	Instances	Quantity	Unit	Length	Area	Classification 1	Code 1	Description 1
05 - Metals		974						
05 10 00 - Structural Metal Framing		24						
Structural framing -		24	0.57 M3	81.43M		05 10 00 - Structural Metal Framing	05 10 00	Structural Metal Framing
05 12 00 - Structural Steel Framing		950						
Light Gauge steel 01 -		498	0.38 M3	2006.90 M		05 12 00 - Structural Steel Framing	05 12 00	Structural Steel Framing
Light Gauge steel 02 -		452	0.13 M3	20865.249 M	0.00006231 m2	05 12 00 - Structural Steel Framing	05 12 00	Structural Steel Framing
06 - Wood, Plastics, and Composites		196						
06 11 00 - Wood Framing		196						
Wood framing -		34	0.38 M3			06 11 00 - Wood Framing	06 11 00	Wood Framing
06 11 00.B01 - 1 x _Furring Strips		162						
Wood Strapping -		162	2.07 M3			06 11 00.B01 - 1 x _Furring Strips	06 11 00.B01	1 x _Furring Strips

- Revit

<Roof Material Takeoff>				
A	B	C	D	E
Type	Material: Name	Material: Area	Material: Volume	Material: Unit weight
Generic - 9"	Air	1091 SF	2.74 m³	0.07 lb/ft³
Generic - 9"	Air	1091 SF	2.74 m³	0.07 lb/ft³
Generic - 9"	ICE panel	546 SF	11.91 m³	0.00 lb/ft³
Generic - 9"	ICE panel	546 SF	11.91 m³	0.00 lb/ft³
Generic - 9"	Metal - Stainless Steel	546 SF	0.81 m³	0.49 lb/ft³
Generic - 9"	Metal - Stainless Steel	546 SF	0.81 m³	0.49 lb/ft³
Generic - 9"	Resto water and ice shield	546 SF	0.04 m³	0.00 lb/ft³
Generic - 9"	Resto water and ice shield	546 SF	0.04 m³	0.00 lb/ft³
Generic - 9"	STD DRYWALL	546 SF	0.64 m³	68.67 lb/ft³
Generic - 9"	STD DRYWALL	546 SF	0.64 m³	68.67 lb/ft³

<Floor Material Takeoff>

A	B	C	D	E
Type	Material: Name	Material: Area	Material: Volume	Material: Unit weight
Floor 1	Plywood, Sheathing	1071 SF	1.58 m ³	34.46 lb/ft ³
Floor 1	Air	1071 SF	3.79 m ³	0.07 lb/ft ³
Floor 1	ICE panel	1071 SF	23.37 m ³	0.00 lb/ft ³
Floor 1	Parket floor	1071 SF	1.58 m ³	0.00 lb/ft ³
Floor 1	OSB (oriented strand board)	1071 SF	0.94 m ³	0.00 lb/ft ³

<Wall Material Takeoff>

A	B	C	D	E
Type	Material: Name	Material: Area	Material: Volume	Material: Unit weight
Ex-E	Air	337 SF	0.50 m ³	0.07 lb/ft ³
Ex-E	Air	105 SF	0.15 m ³	0.07 lb/ft ³
Ex-E	Air	52 SF	0.08 m ³	0.07 lb/ft ³
Ex-E	Air	59 SF	0.09 m ³	0.07 lb/ft ³
Ex-E	Air	95 SF	0.14 m ³	0.07 lb/ft ³
Ex-E	Air	367 SF	0.54 m ³	0.07 lb/ft ³
Ex-E	Air	95 SF	0.14 m ³	0.07 lb/ft ³
Ex-E	Air	54 SF	0.08 m ³	0.07 lb/ft ³
Ex-E	Air	59 SF	0.09 m ³	0.07 lb/ft ³
Ex-E	Air	98 SF	0.15 m ³	0.07 lb/ft ³
B	Air	95 SF	1.23 m ³	0.07 lb/ft ³
B	Air	93 SF	1.21 m ³	0.07 lb/ft ³
B	Air	95 SF	1.23 m ³	0.07 lb/ft ³
B	Air	95 SF	1.23 m ³	0.07 lb/ft ³
B	Air	17 SF	0.22 m ³	0.07 lb/ft ³
B	Air	17 SF	0.22 m ³	0.07 lb/ft ³
Ex-E	Aluminum	337 SF	0.40 m ³	169.18 lb/ft ³
Ex-E	Aluminum	105 SF	0.12 m ³	169.18 lb/ft ³
Ex-E	Aluminum	52 SF	0.06 m ³	169.18 lb/ft ³
Ex-E	Aluminum	59 SF	0.07 m ³	169.18 lb/ft ³
Ex-E	Aluminum	95 SF	0.11 m ³	169.18 lb/ft ³
Ex-E	Aluminum	367 SF	0.43 m ³	169.18 lb/ft ³
Ex-E	Aluminum	95 SF	0.11 m ³	169.18 lb/ft ³
Ex-E	Aluminum	54 SF	0.06 m ³	169.18 lb/ft ³
Ex-E	Aluminum	59 SF	0.07 m ³	169.18 lb/ft ³
Ex-E	Aluminum	98 SF	0.12 m ³	169.18 lb/ft ³
Ex-E	Gypsum Wall Board	327 SF	0.39 m ³	68.67 lb/ft ³
Ex-E	Gypsum Wall Board	102 SF	0.12 m ³	68.67 lb/ft ³
Ex-E	Gypsum Wall Board	52 SF	0.06 m ³	68.67 lb/ft ³
Ex-E	Gypsum Wall Board	59 SF	0.07 m ³	68.67 lb/ft ³
Ex-E	Gypsum Wall Board	92 SF	0.11 m ³	68.67 lb/ft ³
Ex-E	Gypsum Wall Board	92 SF	0.11 m ³	68.67 lb/ft ³
Ex-E	Gypsum Wall Board	52 SF	0.06 m ³	68.67 lb/ft ³
Ex-E	Gypsum Wall Board	57 SF	0.07 m ³	68.67 lb/ft ³
Ex-E	Gypsum Wall Board	96 SF	0.11 m ³	68.67 lb/ft ³
B	Gypsum Wall Board	189 SF	0.22 m ³	68.67 lb/ft ³
B	Gypsum Wall Board	186 SF	0.22 m ³	68.67 lb/ft ³
B	Gypsum Wall Board	189 SF	0.22 m ³	68.67 lb/ft ³
B	Gypsum Wall Board	189 SF	0.22 m ³	68.67 lb/ft ³
B	Gypsum Wall Board	34 SF	0.04 m ³	68.67 lb/ft ³
B	Gypsum Wall Board	34 SF	0.04 m ³	68.67 lb/ft ³
Ex-E	ICE panel	327 SF	5.80 m ³	0.00 lb/ft ³

Appendix B: Life Cycle Inventories

Raw Materials

- **Transportation:**

Calculation of the weight of the shipping package:

Cargo capacity: 12,754 MT, but the survey based on the NEAS shipping company, the heaviest cargo would be 8000MT or 8,000,000 kg

Unit weight: 20865.249 kg = 20.865 tonne

According to the document provided by NEAS, one of the shipments arrived in Cambridge Bay in 2022. Additionally, the exact distance traveled by the cargo from the Port of Montreal to Cambridge Bay is given in nautical miles (nm) and has been converted to kilometers (km) to match the data format required for assessment in SimaPro.

1nm = 1.852 kilometers

3505 nm $\times$ 1.852 = 6491.26 km

6491.26 km $\times$ 20.865 = 142807.71 tkm



SCHEDULE 2024 HORAIRE

2024 Sailing Schedule / Horaire de Transport 2024

September 26, 2024 / 26 Septembre 2024 @19:10

(Subject to weather and ice conditions / Assujetti aux conditions des glaces et aux conditions climatiques)

M/V AUJAQ	DESTINATION	ETA	Arrived	ETD	Sailed
	Loading / Chargement Becancour	11/08	✓	20/08	✓
A2N	Pond Inlet	28/08	✓	04/09	✓
	Arctic Bay	05/09	✓	07/09	✓
	Taloyoak	09/09	✓	13/09	✓
	Gjoa Haven	13/09	✓	16/09	✓
	Cambridge Bay	17/09	✓	21/09	✓
	Kugluktuk	22/09	✓	23/09	✓
	Pond Inlet	28/09		28/09	
	Becancour	05/10			

Book Online at [NEAS.ca](https://www.neas.ca)

Port of Montreal to Port of Cambridge Bay: 3505 nautical miles

find start port:

Port of Montreal

find destination port:

Port of Cambridge Bay

start typing to see the suggestions

calculate

?

TIME AT SEA

DISTANCE: **3505** nm SPEED: **14** knots DAYS AT SEA: **10.4**

+

-

- **Manufacturing**

Electricity consumption:

Electricity - General service small 3 phase / Électricité - Service général triphasé - petite puissance									
Meter number / N° de compteur	Service / Pour la période From / Du	To / Au	Days / Jours	Meter readings / Relevés du compteur Previous / Précédent		Present / Nouveau	Multiplier / Multiplicateur	kW.h / kWh	Reading type / Type de relevé
1555808	Mar 20 MAR/25	Apr 22 AVR/25	33	276	342		120	7,920	Actual Réel
Basic Charge / Redevance de base								\$ 33.69	
Energy Charge / Frais d'énergie								7,920.000 kW.h x \$0.09485	751.21
Demand / Consommation de pointe									
Measured / Consommation mesurée		.302 x 120		36.240 kV.A					
Subtotal / Total partiel								784.90	
7.00% Prov Tax / Taxe prov.								54.94	
5.00% GST / TPS								39.24	
Electricity charges / Frais d'électricité									879.08

Natural Gas - Large Commercial / Gaz Naturel - Commercial - grand											
Meter number / N° de compteur	Service / Pour la période From / Du	To / Au	Days / Jours	Meter readings / Relevés du compteur Previous / Précédent		Present / Nouveau	Usage / Consommation	Base pressure adj/Facteur de ajustement de la pression de base	Metric conversion factor/Facteur de conversion métrique	Cubic metres (m³) / Mètres cubes (m³)	Reading type / Type de relevé
946437	Mar 22 MAR/25	Apr 22 AVR/25	31	1	32	31	x	1.00000	x	2.832784 = 87.816	Estimated Estimatif
Basic Charge / Redevance de base										\$ 85.00	
Gas Commodity (Centra) / Gaz - prix du produit						87.816 m³	x	\$ 0.06670		5.86	
Delivery / Livraison						87.816	x	0.09070		7.96	
Subtotal / Total partiel										98.82	
7.00% Prov Tax / Taxe prov.										6.92	
5.00% GST / TPS										4.94	
Federal Carbon Charge / Redevance fédérale sur le carbone - 25.495 m³ x \$ 0.1525										3.89	
5.00% GST on Federal Carbon Charge / TPS sur Redevance fédérale sur le carbone										0.19	
Natural gas charges / Frais de gaz naturel										114.76	

The electricity bill for the period from March 20 to April 22 shows a total consumption of 7,920 kWh. During this time, four pods were under construction and were completed. Assuming each pod consumed approximately the same amount of energy, we can calculate the electricity used per pod as follows:

$$7,920 / 2 = 3960 \text{ KWH for two pods}$$

Besides, based on the data provided by the factory, only half of the factory has been operated yet, so we doubled this consumption to get closer to the real consumption of a fully operated factory.

Gas Consumption:

4 pods are finished per month.

$$87.816 \text{ m}^3 / 2 = 43.90 \text{ m}^3 \text{ for two pods}$$

Natural Gas

Unit	Equivalent to
1.0 Cubic metres (m ³)	0.0373 Gigajoules (GJ) (Based on 1000 Btu/cf)

[https://apps.cer-rec.gc.ca/Conversion/conversion-tables.aspx?utm_source=chatgpt.com#s1ss2]

$$43.90 \times 37.3 = 1,637.47 \text{ MJ}$$

Besides, based on the data provided by the factory, only half of the factory has been operated yet, so we doubled this consumption to get closer to the real consumption of a fully operated factory.

- **On-site assembly**

For the Loader, Small Bobcat, and the Zoom Boom, we have the working hours. However, for all Generators, the factory provides the amount of Fuel used to run it from the starting point to the

end of assembly. Besides, in SimaPro, the related database is Diesel burned in the Building machine, and we need to put the MJ

Small Generator:

Gasoline has an energy content of about 34.2 MJ per liter.

Total energy = $857.14 \text{ liters} \times 34.2 \text{ MJ/liter} = 29,314.19 \text{ MJ}$.

Bob Cat (Bobcat S70):

A Bobcat S70 consumes approximately 1.5 liters per hour under moderate load. [

<https://www.bobcat.com/na/en/equipment/loaders/skid-steer-loaders/s70>]

$$1.5 \text{ L} \times 4 \text{ h} = 6 \text{ L}$$

$$6 \text{ L} \times 35.8 \text{ MJ/L} = 214.8 \text{ MJ}$$

Loader (Cat 980M):

The average fuel consumption of the loader is 5.75 Gallon per hour. [<https://wheelercat.com/wp-content/uploads/2023/01/Cat-Performance-Handbook-from-VST-fuel-consumption-2022-12-09T21-20-09.pdf>]

$$\text{Total Fuel consumption: } 5.75 \text{ g} \times 6 \text{ h} = 34.5 \text{ gallon}$$

$$\text{Convert to Litre: } 34.5 \times 3/875 = 130.58 \text{ L}$$

$$\text{Using an average Energy content of 35.8 MJ per litre for diesel: } 130.58 \text{ L} \times 35.8 \text{ MJ/L} = 4673 \text{ MJ}$$

Zoom Boom (JCB 525-60):

Average Fuel Consumption of a Zoom Boom is 7 liters per hour. [

<https://plantclassifieds.com/fuel-consumption-jcb-525-60/>]

Total Fuel Consumption : $7 \text{ liters/hour} \times 3 \text{ hours} = 21 \text{ liters}$

Total Energy consumption : $21 \text{ liters} \times 35.8 \text{ MJ/liter} = 751.8 \text{ MJ}$

Appendix C: Life Cycle Carbon Inventories

Raw Material Input

In SimaPro, there were no available datasets for galvanized steel, stainless steel, or engineered flooring, nor any closely related materials. Therefore, I downloaded the corresponding EPDs and used the data provided in them.

- **Stainless steel:**



1. GENERAL INFORMATION

MANUFACTURER	Montanstahl AG
PROGRAMME USED	The International EPD® System. For more information see www.environdec.com
EPD REGISTRATION NUMBER/DECLARATION NUMBER	EPD-IES-0017172
PRODUCT / PRODUCT FAMILY NAME AND MANUFACTURER REPRESENTED	Hot rolled stainless steel profiles, manufactured by Montanstahl AG.
PRODUCT DESCRIPTION AND USE	Hot rolled stainless steel profiles destined primarily for the use in the sector of construction, general industry, automotive.
DECLARATION ISSUED	2024-10-17
VALID UNTIL	2029-10-16
OWNER OF DECLARATION	Montanstahl AG, Via Gerrette 2 Zona Industriale 5 CH-0855 Stabio, Switzerland. Tel. +41 (0)91 041 08 00, info@montanstahl.com
EPD PREPARED BY	Ergo s.r.l. www.ergosrl.net
SCOPE	The LCA is based on 2023 production data for hot rolled stainless steel profiles manufactured by Montanstahl manufacturing plant in Switzerland. This EPD covers information modules production stage A1-A3, end-of life stages C1-C4 and resource recovery stage D (cradle to gate with module C1-C4, module D) according to EN 15804:2012+A2:2019/AC:2021.
FUNCTIONAL UNIT / DECLARED UNIT	The declared unit (DU) is 1 metric ton of hot rolled stainless steel profiles plus packaging.

CEN standard EN 15804 served as the core Product Category Rules-PCR	
PCR:	PCR 2019:14 Construction products and construction services, Version 1.3.4.
Product group classification:	The UN CPC code of the product is 412* Products of iron or steel*
PCR review was conducted by:	The Technical Committee of the International EPD® System. Chair: Claudia A. Peña. email: info@environdec.com
Independent verification of the declaration and data, according to ISO 14025:	☐ EPD process certification ☒ EPD verification
Third party verifier:	RINA Services S.p.A. Via Corsica 12, Genova - Italy Tel +39 010 -5385306 - www.rina.org ACCREDIA Registration number: 0002-VV
Accredited or approved by:	The International EPD System
Procedure for follow-up of data during EPD validity involves third party verifier:	☐ Yes ☒ No

The EPD owner has the sole ownership, liability, and responsibility for the EPD.

Impact Category	Unit	Product stage	End of life stage				Benefits and loads beyond the system boundary
		A1-A3	C1	C2	C3	C4	D
Climate change (GWP) – total	kg CO ₂ eq	5.28E+03	8.42E-01	1.19E+01	1.47E+01	4.64E+00	-6.31E+02
Climate change (GWP) – fossil	kg CO ₂ eq	5.21E+03	8.13E-01	1.19E+01	1.45E+01	1.47E+00	-6.31E+02
Climate change (GWP) – biogenic	kg CO ₂ eq	7.27E+01	2.77E-02	3.62E-03	1.31E-01	3.16E+00	-6.58E-02
Climate change (GWP) – Land use, LULUC	kg CO ₂ eq	4.35E+00	1.87E-03	2.34E-04	1.68E-02	1.14E-05	-2.72E-01
Ozone depletion	kg CFC11eq	6.44E-05	1.36E-08	2.59E-07	2.32E-07	3.55E-09	-2.31E-05
Acidification	mol H+eq	2.71E+01	4.32E-03	3.01E-02	1.14E-01	2.10E-03	-2.37E+00
Eutrophication, aquatic freshwater	kg P eq	1.73E+00	6.84E-04	8.17E-05	3.09E-03	1.63E-05	-2.85E-01
Eutrophication, aquatic marine	kg N eq	5.13E+00	9.69E-04	1.17E-02	4.84E-02	2.07E-03	-5.61E-01
Eutrophication, terrestrial	mol N eq	5.33E+01	9.09E-03	1.23E-01	5.18E-01	1.08E-02	-5.77E+00
Photochemical ozone formation	kg NMVOC eq	1.88E+01	2.84E-03	4.88E-02	1.54E-01	3.16E-03	-3.07E+00

$$0.57 \text{ m}^3 * 8000 \text{ kg/m}^3 = 4560 \text{ kg}$$

Montanstahl AG. (2024). *Environmental Product Declaration: Hot rolled stainless steel profiles* (EPD No. EPD-IES-0017172). The International EPD® System. Retrieved from <https://www.environdec.com>

- **Galvanized steel:**

ENVIRONMENTAL PRODUCT DECLARATION



United States Steel

Galvanized Steel Coil
Carbon Steel Sheets



ASTM INTERNATIONAL

According to ISO 14025
and ISO 21930:2017

EPD PROGRAM AND PROGRAM OPERATOR NAME, ADDRESS, LOGO, AND WEBSITE	ASTM INTERNATIONAL 100 BARR HARBOR DRIVE P.O. BOX C700 WEST CONSHOHOCKEN, PA 19428-2959, USA HTTPS://WWW.ASTM.ORG/	 ASTM INTERNATIONAL
GENERAL PROGRAM INSTRUCTIONS AND VERSION NUMBER	ASTM Program Operator Rules, Version: 8.0, Revised 04/29/20	
MANUFACTURER NAME AND ADDRESS	United States Steel Corporation, One North Broadway, Gary, IN 46402	
DECLARATION NUMBER	EPD 809	
DECLARED PRODUCT & FUNCTIONAL UNIT OR DECLARED UNIT	Galvanized Steel Coil, 1 metric ton	
REFERENCE PCR AND VERSION NUMBER	Part A: Life Cycle Assessment Calculation Rules and Report Requirements, UL Environment, UL 10010, v3.2, 2018; and Part B: Designated Steel Construction Product EPD Requirements, UL Environment, UL 10010-34, v2.0, 2020	
DESCRIPTION OF PRODUCT APPLICATION/USE	Galvanized steel coil used in automotive, construction, appliance, energy, containers, and packaging industries	
PRODUCT RSL DESCRIPTION (IF APPL.)	N/A	
MARKETS OF APPLICABILITY	North America	
DATE OF ISSUE	1/19/2024	
PERIOD OF VALIDITY	5 years	
EPD TYPE	Product-specific	
RANGE OF DATASET VARIABILITY	Site-specific, mean	
EPD SCOPE	Cradle-to-gate	
YEAR(S) OF REPORTED PRIMARY DATA	2021	
LCA SOFTWARE & VERSION NUMBER	LCA for Experts v10.7	
LCI DATABASE(S) & VERSION NUMBER	LCA for Experts 2023.1	
LCIA METHODOLOGY & VERSION NUMBER	TRACI 2.1, IPCC 2013 (AR5)	
The PCR review was conducted by:		Dr. Tom Gloria, Chair, Industrial Ecology Associates
This declaration was independently verified in accordance with ISO 14025: 2008, ISO 21930:2017 and PCR.		Tim Brooke, ASTM International
☐ INTERNAL ☒ EXTERNAL		
This life cycle assessment was conducted in accordance with ISO 14044 and the reference PCR by:		Trinity Consultants, Inc.
This life cycle assessment was independently verified in accordance with ISO 14044 and the reference PCR by:		Lindita Bushi, PhD., Athena Sustainable Materials Institute

PARAMETER	UNIT	A1	A2	A3	Total
GWP 100 (excl. biogenic carbon)	kg CO ₂ eq.	5.38E+02	5.63E+01	2.29E+03	2.88E+03
ODP	kg CFC 11 eq.	7.42E-06	7.27E-13	4.80E-09	7.43E-06
AP	kg SO ₂ eq.	1.87E+00	6.34E-01	3.81E+00	6.31E+00
EP	kg N eq.	8.47E-02	2.99E-02	5.64E+00	5.76E+00
SFP	kg O ₃ eq.	2.85E+01	1.28E+01	7.32E+01	1.14E+02
ADP _{FOSSIL}	MJ, LHV	8.31E+02	9.87E+01	3.76E+03	4.69E+03

$$0.51 \text{ m}^3 * 7850 \text{ kg/m}^3 = 4003.5 \text{ kg}$$

$$0.57 \text{ m}^3 * 7850 \text{ kg/m}^3 = 4474.5 \text{ kg}$$

ASTM International. (n.d.). *Environmental Product Declaration: Hot-dip galvanized steel coils (EPD No. SCS-EPD-06247)*, U.S. Steel Corporation. SCS Global Services. Retrieved April 21, 2025, from <https://www.astm.org/products-services/certification/environmental-product-declarations.html>

- **Wood Engineered Flooring**

Declared unit: 1m² wood flooring products

Environmental impact descriptive parameters															
Results per functional unit															
Indicator	Unit	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	D
GWP-total	kg CO ₂ eq.	1.04E+01	2.73E+00	1.89E+00	ND	ND	ND	ND	ND	ND	ND	0.00E+00	1.67E-01	5.03E-02	-4.50E-01
GWP-fossil	kg CO ₂ eq.	2.52E+01	2.73E+00	1.50E+00	ND	ND	ND	ND	ND	ND	ND	0.00E+00	1.67E-01	5.00E-02	-4.95E-01
GWP-biogenic	kg CO ₂ eq.	1.49E+01	6.96E-04	3.84E-01	ND	ND	ND	ND	ND	ND	ND	0.00E+00	4.78E-05	4.66E-05	4.50E-02
GWP-luluc	kg CO ₂ eq.	1.37E-01	1.65E-03	6.90E-03	ND	ND	ND	ND	ND	ND	ND	0.00E+00	8.61E-05	1.62E-04	5.91E-05
ODP	kg CFC 11 eq.	3.15E-07	4.09E-08	1.63E-08	ND	ND	ND	ND	ND	ND	ND	0.00E+00	2.50E-09	6.46E-10	-6.75E-09
AP	mol H ⁺ eq.	1.40E-01	3.44E-02	7.51E-03	ND	ND	ND	ND	ND	ND	ND	0.00E+00	5.92E-04	2.61E-04	6.56E-04
EP-freshwater	kg P eq.	1.67E-03	2.06E-05	8.46E-05	ND	ND	ND	ND	ND	ND	ND	0.00E+00	1.58E-06	1.03E-06	-6.54E-06
EP-marine	kg N eq.	2.85E-02	9.06E-03	1.66E-03	ND	ND	ND	ND	ND	ND	ND	0.00E+00	1.92E-04	9.25E-05	-7.62E-04
EP-terrestrial	mol N eq.	3.10E-01	9.96E-02	1.79E-02	ND	ND	ND	ND	ND	ND	ND	0.00E+00	2.06E-03	9.93E-04	-9.08E-03
POCP	kg NMVOC eq.	1.05E-01	2.95E-02	6.14E-03	ND	ND	ND	ND	ND	ND	ND	0.00E+00	7.96E-04	2.97E-04	-1.99E-03
ADP-minerals&metals*	kg Sb eq.	4.00E-05	6.61E-06	2.12E-06	ND	ND	ND	ND	ND	ND	ND	0.00E+00	5.34E-07	2.93E-09	-9.92E-07
ADP-fossil*	MJ	2.84E+02	3.66E+01	1.47E+01	ND	ND	ND	ND	ND	ND	ND	0.00E+00	2.35E+00	6.76E-01	-7.60E+00
WDP*	m ³	3.86E+00	1.37E-01	1.99E-01	ND	ND	ND	ND	ND	ND	ND	0.00E+00	1.04E-02	1.47E-03	-6.38E-03
GWP-GHG ¹	kg CO ₂ -eq	2.57E+01	2.73E+00	1.59E+00	ND	ND	ND	ND	ND	ND	ND	0.00E+00	1.67E-01	5.03E-02	-4.50E-01

Interwood International Limited. (2024). *Environmental Product Declaration: Engineered wood flooring – CANICA®* (EPD No. EPD-IES-0017657). The International EPD® System. Retrieved from <https://www.environdec.com>

- **Stainless Steel (70% Post-consumer material)**

Results per declared unit								
Indicator		Unit	A1-A3	C1	C2	C3	C4	D
Global warming potential	Fossil	kg CO ₂ eq.	2,76E+03	0,00E+00	1,92E+01	2,74E+01	3,13E-01	-1,13E+02
	Biogenic	kg CO ₂ eq.	4,28E+01	0,00E+00	5,59E-04	-7,06E-01	4,31E-05	-4,56E-01
	Land use & land use change	kg CO ₂ eq.	2,69E+00	0,00E+00	7,78E-03	2,58E-02	1,61E-04	-2,66E-01
Global warming potential – Total		kg CO ₂ eq.	2,80E+03	0,00E+00	1,92E+01	2,67E+01	3,13E-01	-1,14E+02
Ozone layer depletion potential		kg CFC 11 eq.	7,17E-02	0,00E+00	2,84E-07	2,92E-07	9,04E-09	-1,29E-06
Acidification potential		mol H ⁺ eq.	7,78E+00	0,00E+00	4,39E-02	2,92E-01	2,22E-03	-9,77E+00
Eutrophication potential	Freshwater	kg P eq.	7,62E-01	0,00E+00	1,52E-03	1,48E-02	2,60E-05	-8,33E-02
	Marine	kg N eq.	1,78E+00	0,00E+00	1,02E-02	6,48E-02	8,44E-04	-1,91E-01
	Terrestrial	mol N eq.	2,10E+01	0,00E+00	1,10E-01	7,30E-01	9,22E-03	-2,09E+00
Photochemical ozone formation		kg NMVOC eq.	6,07E+00	0,00E+00	6,15E-02	2,15E-01	3,30E-03	-1,26E+00
Abiotic depletion potential	Minerals & metals	kg Sb eq.	2,44E-01	0,00E+00	6,26E-05	1,60E-03	4,89E-07	-1,21E-02
	Fossil	MJ	1,85E+04	0,00E+00	2,64E+01	1,18E+02	4,74E-01	-8,24E+02
Water deprivation potential		m ³	1,57E+03	0,00E+00	1,22E+00	4,55E+00	3,35E-01	-3,45E+02

EPD International AB. (2024). *Environmental Product Declaration: Hot rolled duplex stainless steel* (EPD No. EPD-IED-0017270). The International EPD® System.

<https://www.environdec.com>

- **Galvanized Steel (26.8% Post-consumer material)**

Mandatory impact category indicators according to EN 15804+A2:2019

Results per 1 metric tonne of XCarb® recycled and renewably produced Cold Rolled Coils							
Indicator	Unit	A1-A3	C1	C2	C3	C4	D
GWP-fossil	kg CO ₂ eq.	7,99E+02	4,16E+01	2,60E+01	1,34E+00	2,96E-01	-3,05E+01
GWP-biogenic	kg CO ₂ eq.	3,40E-01	2,22E-02	1,04E-02	9,82E-03	0,00E+00	1,80E-01
GWP-luluc	kg CO ₂ eq.	3,72E-01	3,73E-01	2,45E-01	1,04E-03	9,33E-04	-4,06E-03
GWP-total	kg CO ₂ eq.	8,00E+02	4,20E+01	2,63E+01	1,36E+00	2,97E-01	-3,03E+01
ODP	kg CFC 11 eq.	8,98E-08	1,54E-11	3,45E-12	2,20E-11	7,64E-13	4,09E-11
AP	mol H ⁺ eq.	2,56E+00	2,95E-01	1,92E-01	3,30E-03	2,13E-03	-7,46E-02
EP-freshwater	kg P eq.	5,23E-04	1,50E-04	9,69E-05	4,80E-06	6,05E-07	-7,11E-06
EP-marine	kg N eq.	7,34E-01	1,45E-01	9,51E-02	9,70E-04	5,51E-04	-1,20E-02
EP-terrestrial	mol N eq.	8,03E+00	1,61E+00	1,05E+00	1,04E-02	6,06E-03	-1,07E-01
POCP	kg NMVOC eq.	2,11E+00	2,79E-01	1,82E-01	2,63E-03	1,66E-03	-4,87E-02
ADP-minerals& metals*	kg Sb eq.	7,87E-04	2,77E-06	1,76E-06	1,95E-07	1,39E-08	-1,73E-04
ADP-fossil*	MJ	8,93E+03	5,81E+02	3,61E+02	2,71E+01	4,00E+00	-3,03E+02
WDP*	m ³	1,88E+02	6,23E-01	3,20E-01	2,66E-01	3,30E-02	-2,06E+00
Acronyms	GWP-fossil = Global Warming Potential fossil fuels; GWP-biogenic = Global Warming Potential biogenic; GWP-luluc = Global Warming Potential land use and land use change; ODP = Depletion potential of the stratospheric ozone layer; AP = Acidification potential, Accumulated Exceedance; EP-freshwater = Eutrophication potential, fraction of nutrients reaching freshwater end compartment; EP-marine = Eutrophication potential, fraction of nutrients reaching marine end compartment; EP-terrestrial = Eutrophication potential, Accumulated Exceedance; POCP = Formation potential of tropospheric ozone; ADP-minerals&metals = Abiotic depletion potential for non-fossil resources; ADP-fossil = Abiotic depletion for fossil resources potential; WDP = Water (user) deprivation potential, deprivation-weighted water consumption						

* Disclaimer: The results of this environmental impact indicator shall be used with care as the uncertainties of these results are high or as there is limited experience with the indicator.

We discourage the use of the results of modules A1-A3 without considering the results of module C.

ArcelorMittal Europe – Flat Products. (2023). *Environmental Product Declaration: XCarb® recycled and renewably produced Cold Rolled Coils* (EPD No. S-P-11266, Version 1.1). The International EPD® System. <https://www.environdec.com>

- **Fiber cement Cladding**

Environmental Impacts for 1 m ² of Hiden High density fibre cement board									
Impact indicators	Unit	A1-A3	A4	A5	C1	C2	C3	C4	D
GWP-fossil	kg CO ₂ eq.	1.15E+01	2.55E+00	3.81E-03	0.00E+00	1.13E-01	0.00E+00	2.44E-01	0.00E+00
GWP-biogenic	kg CO ₂ eq.	-2.62E+00	5.27E-03	9.14E-02	0.00E+00	2.33E-04	0.00E+00	2.54E+00	0.00E+00
GWP-luluc	kg CO ₂ eq.	1.14E-02	8.14E-05	5.06E-06	0.00E+00	3.60E-06	0.00E+00	1.31E-04	0.00E+00
GWP-total	kg CO ₂ eq.	8.90E+00	2.55E+00	9.52E-02	0.00E+00	1.13E-01	0.00E+00	2.79E+00	0.00E+00
ODP	kg CFC -11 eq.	1.86E-11	1.27E-13	7.11E-15	0.00E+00	5.62E-15	0.00E+00	6.49E-13	0.00E+00
AP	Mole of H ⁺ eq.	7.32E-02	1.83E-02	2.30E-05	0.00E+00	8.08E-04	0.00E+00	1.82E-03	0.00E+00
EP-freshwater	kg P eq.	5.82E-05	4.00E-07	2.14E-07	0.00E+00	1.77E-08	0.00E+00	1.20E-06	0.00E+00
EP-marine	kg N eq.	1.79E-02	8.96E-03	3.12E-05	0.00E+00	3.96E-04	0.00E+00	4.88E-04	0.00E+00
EP-terrestrial	Mole of N eq.	1.94E-01	9.83E-02	8.86E-05	0.00E+00	4.35E-03	0.00E+00	5.34E-03	0.00E+00
POCP	kg NMVOC eq.	4.98E-02	1.76E-02	5.49E-05	0.00E+00	7.80E-04	0.00E+00	1.69E-03	0.00E+00
ADP-minerals & metals*	kg Sb eq.	3.92E-07	3.05E-08	1.45E-10	0.00E+00	1.35E-09	0.00E+00	9.86E-09	0.00E+00
ADP-fossil*	MJ	9.44E+01	3.32E+01	5.44E-02	0.00E+00	1.47E+00	0.00E+00	3.14E+00	0.00E+00
WDP*	m ³ world equiv.	8.97E-01	5.41E-03	4.03E-04	0.00E+00	2.39E-04	0.00E+00	2.60E-02	0.00E+00
Acronyms	GWP-fossil = Global Warming Potential fossil fuels; GWP-biogenic = Global Warming Potential biogenic; GWP-luluc = Global Warming Potential land use and land use change; ODP = Depletion potential of the stratospheric ozone layer; AP = Acidification potential, Accumulated Exceedance; EP-freshwater = Eutrophication potential, fraction of nutrients reaching freshwater end compartment; EP-marine = Eutrophication potential, fraction of nutrients reaching marine end compartment; EP-terrestrial = Eutrophication potential, Accumulated Exceedance; POCP = Formation potential of tropospheric ozone; ADP-minerals & metals = Abiotic depletion potential for non-fossil resources; ADP-fossil = Abiotic depletion for fossil resources potential; WDP = Water (user) deprivation potential, deprivation-weighted water consumption								

Ramco Industries Limited. (2025). *Environmental Product Declaration: Hiden – High Density Fiber Cement Board* (EPD No. EPD-IES-0017244). The International EPD® System. <https://www.environdec.com>

- **High Pressure Laminate Board**

Results per declared unit							
Indicator	Unit	A1-A3	C1	C2	C3	C4	D
NATURCLAD - W S 8 mm							
GWP-fossil	kg CO ₂ eq.	2,55E+01	0,00E+00	8,98E-02	9,62E-02	1,43E-02	-6,87E+00
GWP-biogenic	kg CO ₂ eq.	-1,11E+01	0,00E+00	3,72E-05	9,57E+00	1,66E+00	-2,41E-02
GWP-luluc	kg CO ₂ eq.	8,12E-02	0,00E+00	3,20E-05	2,16E-04	3,83E-06	-7,39E-03
GWP-total	kg CO ₂ eq.	1,45E+01	0,00E+00	8,99E-02	9,67E+00	1,67E+00	-6,90E+00
ODP	kg CFC 11 eq.	2,27E-06	0,00E+00	2,04E-08	8,05E-09	2,03E-09	-8,28E-07
AP	mol H ⁺ eq.	1,25E-01	0,00E+00	2,58E-04	5,31E-04	4,85E-04	-1,98E-02
EP-freshwater	3- eq. kgPO ₄	4,43E-03	0,00E+00	2,20E-06	3,04E-05	8,80E-07	-9,14E-04
EP-freshwater	kg P eq.	1,44E-03	0,00E+00	7,18E-07	9,91E-06	2,87E-07	-2,98E-04
EP-marine	kg N eq.	2,95E-02	0,00E+00	5,11E-05	7,11E-05	2,28E-04	-2,69E-03
EP-terrestrial	mol N eq.	2,81E-01	0,00E+00	5,71E-04	8,71E-04	2,58E-03	-3,42E-02
POCP	kg NMVOC eq.	1,22E-01	0,00E+00	2,19E-04	2,27E-04	6,78E-04	-1,05E-02
ADP-minerals&metals*	kg Sb eq.	3,20E-04	0,00E+00	2,48E-06	3,71E-07	8,91E-08	-2,87E-05
ADP-fossil*	MJ	5,43E+02	0,00E+00	1,36E+00	1,95E+00	1,62E-01	-1,24E+02
WDP	m ³ eq	2,50E+01	0,00E+00	3,84E-03	2,19E-02	5,00E-03	-1,08E+00

Parklex Prodema Int. S.L.U. (2016). *Environmental Product Declaration: HPL boards with natural wood finish NATURCLAD – W and NATURHARDPANEL – W* (EPD No. S-P-00975, Rev. 2023-10-11). The International EPD® System. <https://www.environdec.com>