

Life Cycle Assessment of Modular Housing for Northern Quebec Communities

By

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Abstract

Life Cycle Assessment of Prefabricated Modular Housing for Northern Quebec Communities

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This study presents a life cycle assessment (LCA) of a prefabricated modular dwelling delivered to northern communities in Nunavik, Québec. The analysis combines a cradle-to-site assessment (A1–A5) with selected use-stage impacts (B1–B7) to provide a more comprehensive understanding of environmental performance over the building life cycle.

Using SimaPro 9.5 with the ecoinvent 3.7 database, and following ISO 14040/44 and EN 15804 standards, the study evaluates greenhouse gas emissions using the IPCC 2013 GWP 100-year method. The cradle-to-site results show that material production (A1) is the dominant contributor, accounting for approximately 80% of total emissions, with steel and aluminum responsible for over 90% of A1–A3 impacts. Transport to site (A4), including multimodal truck and sealift logistics, contributes approximately 13%, reflecting the significant challenges of remote northern delivery. Manufacturing (A3) and installation (A5) represent smaller but non-negligible shares.

In addition, selected use-stage impacts (B1–B7) were assessed to capture operational and maintenance-related emissions over a 50-year service life. While these stages contribute less than the initial embodied impacts, they provide important insight into long-term performance and system durability in northern Canada conditions.

Scenario analysis demonstrates that material substitution, particularly replacing structural steel with engineered timber, can reduce cradle-to-site emissions by approximately 20%. Improvements in transport efficiency and logistics optimization offer an additional 5–10% reduction.

Overall, the results highlight that both material selection and logistics play critical roles in the environmental performance of modular housing in remote regions. The framework developed in this study provides a transparent and reproducible basis for supporting low-carbon design and policy decisions in northern construction.

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CHAPTER 1. INTRODUCTION

1.1 Background

Construction in remote and northern regions is often associated with significant logistical, climatic, and environmental constraints. Transporting materials over long distances, limited access for seasonal sealift operations, and the challenges posed by harsh sub-Arctic weather conditions directly affect both project delivery timelines and environmental performance. These constraints influence the selection of materials, energy requirements, and the emissions associated with transportation, on-site assembly, and long-term operation. Within this context, it is commonly assumed that material production stages (A1–A3) constitute the largest share of embodied environmental impacts. However, transport to the site (A4) and installation activities (A5) can account for a substantial portion of cradle-to-site ecological burdens and, in some cases, may approach or exceed the impacts generated during upstream manufacturing.

Prefabricated modular construction has been promoted as an efficient delivery model for remote communities because it shortens site schedules, improves quality control, and enhances worker safety. However, once volumetric modules are transported over long distances and through multimodal corridors, typically combining trucking, marine sealift, and local handling in northern Canada, the environmental impact profile shifts. Transport (A4) often becomes a major contributor due to heavy loads and extended routes, while installation activities (A5) may reflect reliance on diesel-powered cranes, generators, and temporary site energy. For this reason, logistics and installation processes must be treated with the same methodological rigour as material production when assessing the environmental performance of modular housing in northern contexts.

Life Cycle Assessment (LCA) provides a systematic framework for quantifying environmental impacts across the stages of a building's life cycle. In accordance with ISO 14040/14044 and the modular structure defined in EN 15804 and EN 15978, this research adopts an expanded system boundary that integrates both cradle-to-site stages (A1–A5) and use-stage modules (B1–B7). While earlier studies frequently isolate embodied impacts during production and delivery or focus solely on operational energy use, a whole life cycle perspective is required to understand trade-offs between upfront embodied carbon, long-term operational energy demand, and maintenance and replacement requirements, particularly in cold and remote regions where energy use dominates lifetime emissions.

The Nunavik region of northern Québec provides a representative setting for this analysis. Communities such as Kuujuaq, Inukjuak, and Salluit are disconnected from the southern road network, depend on seasonal marine resupply for heavy goods, and rely on aviation for year-round passenger transport. Prefabricated modules manufactured in southern Québec must therefore pass through complex multimodal supply chains before reaching their final destinations. These conditions make Nunavik an appropriate context for examining how routing, mode choice, load

efficiency, climate severity, and site practices influence both embodied and operational life cycle impacts.

Against this background, this thesis undertakes a whole life cycle assessment of prefabricated modular housing deployed in three northern Québec communities. The analysis integrates cradle-to-site impacts (A1–A5) with use-stage modules (B1–B7), including operational energy demand, maintenance, repair, and replacement over the building service life. Modelling is performed in SimaPro 9.5 using the ecoinvent 3.7 database as background data. Climate change impacts are quantified using the IPCC 2013 Global Warming Potential (100-year horizon), complemented by a limited set of additional midpoint indicators to support interpretation and identify potential trade-offs. Baseline results are combined with scenario analyses to reflect realistic decision options for low-carbon modular housing in northern environments.

1.1.1 Climate Change Context in Canada:

Over the past five decades, Canada has experienced warming at a rate that exceeds the global average. According to long-term climate observations, Canada has warmed at approximately twice the rate of the global average, while northern regions such as the Arctic and sub-Arctic have experienced warming nearly three times faster. Since 1948, average winter temperatures in northern Canada have increased by more than 3.5 °C, and seven of the ten warmest years on record have occurred within the past two decades.

This rapid warming has led to widespread permafrost thawing, sea ice loss, and shorter ice seasons, all of which directly impact the feasibility of construction, material durability, and the long-term resilience of community infrastructure in northern regions.

The evolution of Canada’s climate policy mirrors this scientific trajectory. Initial commitments began with Canada’s participation in the United Nations Framework Convention on Climate Change (1992) and later the Kyoto Protocol (1998), which targeted a 6% reduction below 1990 emission levels by 2012. Although Canada withdrew from Kyoto in 2011 after exceeding its targets, the federal government progressively adopted more ambitious goals under the Paris Agreement (2015) and the Net-Zero Emissions Accountability Act (2021). The current national target aims for a 40–45% reduction below 2005 levels by 2030 and net-zero emissions by 2050. These evolving policies highlight how climate change has transitioned from a scientific concern to a national planning priority, particularly relevant for northern housing and infrastructure, where warming already disrupts traditional construction practices, increases operational energy demand, and challenges long-term building performance.

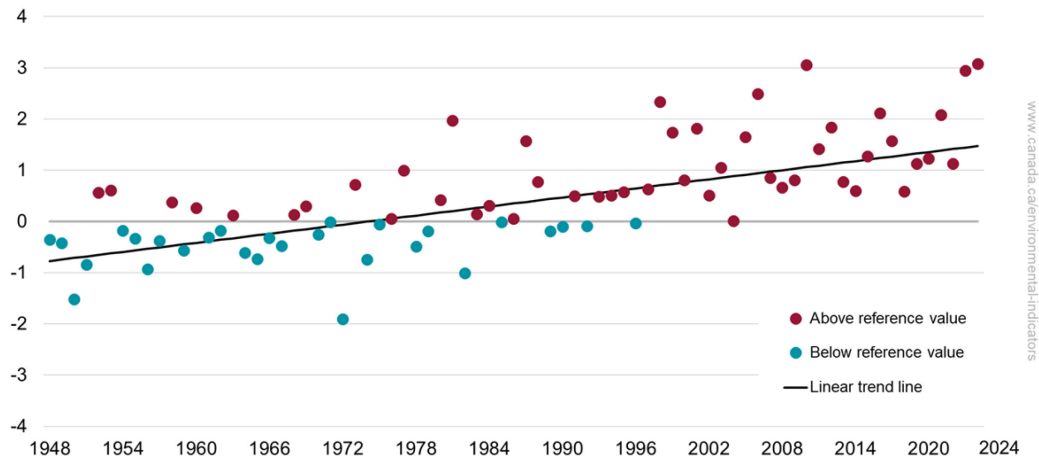


Figure 1: Annual average temperature departures in Canada, 1948–2023

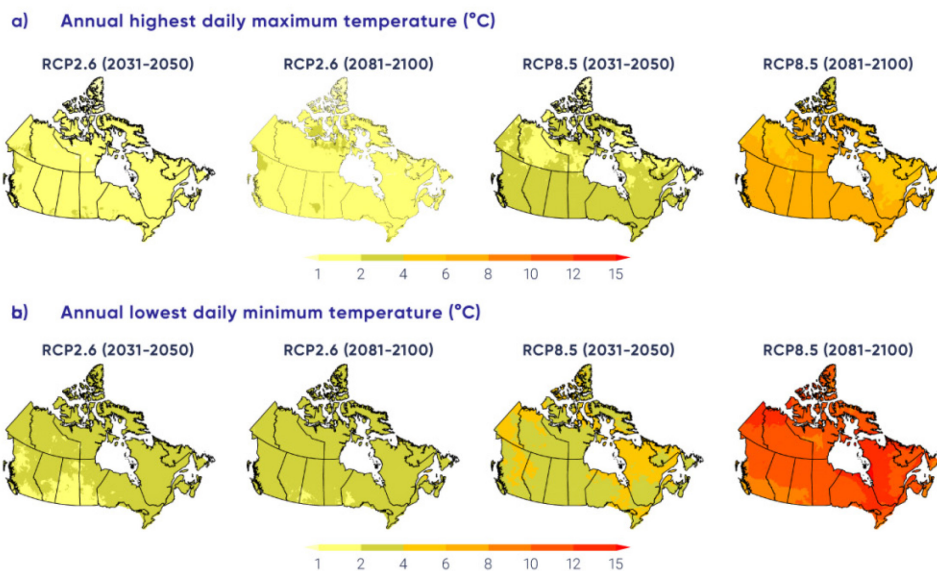


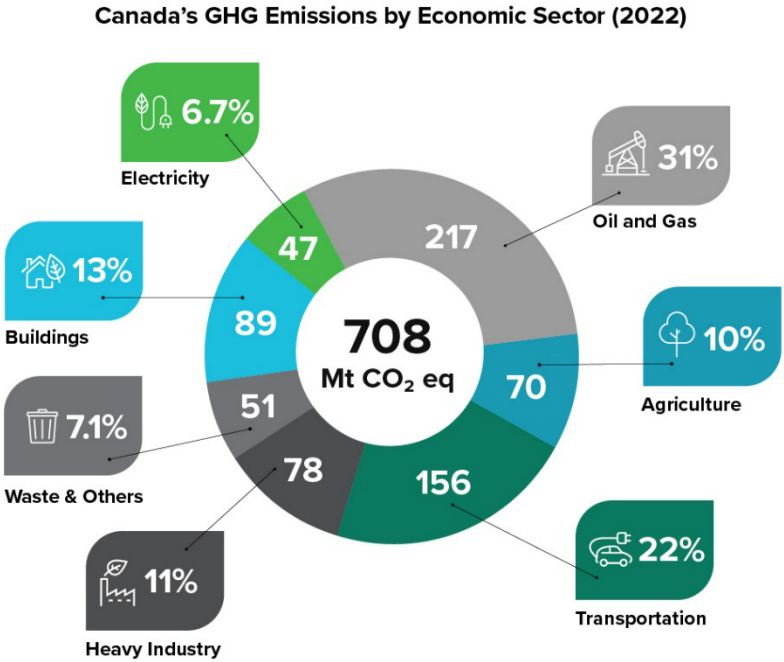
Figure 2: Projected changes in extreme temperatures across Canada under low (RCP2.6) and high (RCP8.5) greenhouse gas emission scenarios

1.1.2 National CO₂ Emissions and Sectoral Distribution (1990–2023):

Over the last 50 years, Canada’s greenhouse gas (GHG) emissions have followed a pattern of growth, stabilization, and recent decline. In 1990, total national emissions were approximately 606 Mt CO₂, rising to a peak of 759 Mt CO₂ in 2005, and then gradually declining to around 694 Mt CO₂ in 2023. Although the overall reduction since 2005 represents about –8.5%, Canada remains one of the world’s highest per-capita emitters, averaging nearly 17 t CO₂ per person roughly double the global average.

The moderate national decline reflects structural changes such as the phase-out of coal-fired electricity, increased renewable energy deployment, and efficiency improvements across multiple sectors. From a sectoral perspective, oil and gas production and transportation remain the dominant sources of emissions. In 2023, the oil and gas sector accounted for roughly 30% ($\approx 208 \text{ Mt CO}_2$) of national emissions, followed by transportation ($\approx 157 \text{ Mt}$, 23%), buildings ($\approx 83 \text{ Mt}$, 12%), heavy industry ($\approx 78 \text{ Mt}$, 11%), agriculture ($\approx 69 \text{ Mt}$, 10%), and electricity generation ($\approx 49 \text{ Mt}$, 7%). Together, oil and gas and transportation represent more than half of Canada’s total GHG footprint.

Historically, emissions from these two sectors have increased by more than 30–70% since 1990, while electricity-related emissions have fallen substantially due to cleaner grids in provinces such as Québec, British Columbia, and Manitoba. Although Canada contributes only about 1.4% of global GHG emissions, its energy-intensive economy, cold climate, and dispersed population result in disproportionately high emissions per capita. This context underscores the importance of domestic decarbonization efforts particularly within the building and transport sectors, as integral components of Canada’s broader strategy to reduce both embodied and operational emissions in the built environment.



* National Inventory Report 1990-2022: Greenhouse Gas Sources and Sinks in Canada

Figure 3: Canada’s GHG emissions by sector in 2022

1.2 Problem Statement

Housing construction in remote and northern regions presents a complex set of environmental challenges driven by both material-related and logistics-related factors. Embodied emissions associated with conventional construction materials can be substantial, particularly when high-impact products are used in energy-intensive building envelopes. At the same time, the transportation of prefabricated volumetric modules over long distances and seasonal, multimodal supply chains introduce additional carbon burdens that are often comparable to, or greater than, those arising from material production alone. Together, material selection and transport and installation processes emerge as critical drivers of cradle-to-site environmental impacts in northern modular housing.

In northern regions such as Nunavik, these challenges are further intensified by severe logistical constraints. Most northern communities are not connected to the southern road network and rely almost exclusively on long-distance transportation systems combining trucking and seasonal marine sealift. This sealift transportation is typically available only for a limited window of approximately two to three months per year. As a result, the delivery of modular housing units and construction materials must be carefully scheduled within this narrow period. Outside this seasonal shipping window, transportation options are extremely limited and often depend on air transport, which is both economically and environmentally costly. Furthermore, the Northern areas construction season itself is very short due to extreme climatic conditions. Building installation and site activities can only be carried out during a limited time frame, which often requires rapid assembly, intensive equipment use, and additional workforce travel. These logistical constraints increase the overall environmental footprint of construction activities and make transportation-related emissions a particularly important component of northern housing projects.

In practice, mitigating these impacts may involve substituting lower-carbon materials, optimizing transport routes and load efficiency, or increasing reliance on locally based labour and site-specific adaptations. However, each of these strategies carries implications for cost, constructability, scheduling, and long-term performance. The environmental trade-offs associated with such decisions remain insufficiently quantified, particularly in the context of northern communities where logistical constraints and climatic conditions differ fundamentally from those in southern regions. Despite the growing interest in prefabricated modular construction as a low-carbon building strategy, relatively limited research has been conducted on the environmental performance of modular housing in northern regions. Existing life cycle assessment studies of modular housing predominantly emphasize production stages (A1–A3), often underrepresenting the significance of transport (A4) and installation (A5) in remote settings. In parallel, fully comprehensive cradle-to-grave assessments (A1–C4 or Module D) are rarely achievable for northern settlements due to limited availability of reliable data on building use, maintenance, repair, replacement, and end-of-life scenarios. As a result, many analyses either rely on simplified assumptions or exclude critical life cycle stages, limiting their decision relevance.

This combination of logistical complexity, long-distance seasonal transportation, data constraints, and fragmented system boundaries constitutes a key problem for environmental assessment of northern modular housing. Without a transparent, reproducible, and standards-compliant framework that integrates material production, logistics-intensive construction stages, and realistically modelled use-stage processes, decision-makers lack the analytical basis needed to evaluate decarbonization strategies and to balance upfront embodied emissions against long-term operational and maintenance impacts in the northern communities.

1.3 Research Objectives

The overarching aim of this thesis is to conduct a transparent and standards-compliant whole life cycle assessment of prefabricated modular housing deployed in northern Québec communities. By integrating cradle-to-site stages (A1–A5) with use-stage modules (B1–B7), the study seeks to clarify where, how, and why environmental burdens arise across the building life cycle under remote and cold-climate conditions.

The specific objectives of this research are to:

1. Model representative case studies of prefabricated modular housing in multiple northern Québec communities using SimaPro and the ecoinvent database, in accordance with ISO 14040/44 and the modular structure defined in EN 15804 and EN 15978.
2. Quantify and compare stage-wise life cycle contributions across production, transport, installation, and use stages (A1–A5 and B1–B7), identifying dominant processes and materials responsible for greenhouse gas emissions.
3. Analyze the key drivers of life cycle impacts under northern conditions, including material selection, logistics routes and load efficiency, site installation practices, climate severity, and operational energy demand.
4. Evaluate trade-offs between upfront embodied emissions and long-term operational and maintenance impacts, highlighting life cycle hotspots and sensitivities specific to remote modular housing.
5. Develop and test improvement scenarios that explore practical strategies to reduce life cycle impacts, such as material substitution, logistics optimization, workforce localization, and operational energy efficiency measures.
6. Provide decision-relevant insights for policymakers, housing agencies, and designers seeking to decarbonize modular housing in northern regions while maintaining technical feasibility and contextual realism.

1.4 Scope and Limitations

This study adopts a whole life cycle assessment framework in accordance with ISO 14040/14044 and the modular structure defined in EN 15804 and EN 15978. The system boundary integrates cradle-to-site stages (A1–A5) with use-stage modules (B1–B7), allowing the analysis to capture both logistics-intensive construction impacts and long-term operational performance. The functional unit is defined as one prefabricated modular dwelling deployed in northern Québec, modelled across three representative communities, Kuujuaq, Inukjuak, and Salluit, to reflect variation in climate conditions, logistics routes, and energy supply contexts.

Life cycle inventory modelling was carried out in SimaPro 9.5 using the ecoinvent 3.7 database as background data. Climate change impacts were quantified using the IPCC 2013 Global Warming Potential (100-year time horizon), supplemented by a limited set of midpoint indicators to support interpretation and identify potential trade-offs between life cycle stages.

Several limitations should be acknowledged. First, detailed manufacturer-specific information, including complete bills of materials and process-level energy data, was not fully available. As a result, material compositions, production processes, and factory energy use were modelled using a combination of secondary datasets, industry literature, and conservative assumptions. While this approach follows standard LCA practice, it introduces uncertainty into absolute impact values.

Second, comprehensive and site-specific logistics data for the multimodal supply chains serving northern Québec communities were limited. Information on routing, distances, vessel characteristics, load factors, and backhauls was therefore compiled from public sources, published transport studies, and regional logistics documentation. Although these assumptions are considered representative of typical northern delivery conditions, variations in routing or utilization rates could influence transport-related results.

Third, modelling of use-stage modules (B1–B7) relied on generalized assumptions regarding building operation, maintenance intervals, repair activities, and component replacement, informed by available guidelines and literature for cold-climate construction. Empirical data on long-term building performance in remote northern settlements remain scarce, and future access to measured operational and maintenance data would improve the accuracy.

Finally, due to the combined reliance on secondary data and scenario-based assumptions, numerical results presented in later chapters should be interpreted as indicative rather than exact. To address this uncertainty, key parameters were tested through scenario and sensitivity analyses, enabling evaluation of how results respond to plausible variations in design, logistics, and operational conditions.

Despite these limitations, the study provides a transparent and reproducible assessment framework tailored to northern modular housing. By explicitly documenting assumptions and examining their

influence on outcomes, the analysis remains decision-relevant and offers meaningful insight into material, logistics, and operational trade-offs across the building life cycle.

1.5 Thesis Structure

The remainder of this thesis is organized into five chapters. Chapter 2 reviews the existing literature on life cycle assessment in the construction sector, with particular emphasis on prefabricated building systems, cold-climate housing, and environmental assessment of northern and remote communities. This review establishes the theoretical and methodological context for the study and identifies key gaps addressed by the research.

Chapter 3 outlines the methodological framework adopted in this thesis. It describes the goal and scope definition, system boundaries, functional unit, data sources, life cycle inventory modelling, and impact assessment methods used to evaluate whole life cycle impacts in accordance with ISO and EN standards.

Chapter 4 presents the case studies of prefabricated modular housing deployed in three northern Québec communities, Kuujuaq, Inukjuak, and Salluit. This chapter details the modelling assumptions, life cycle inventories, and baseline results across cradle-to-site (A1–A5) and use-stage modules (B1–B7), highlighting location-specific differences in logistics and operational performance.

Chapter 5 explores scenario and sensitivity analyses to assess how variations in material selection, logistics configurations, installation practices, and operational parameters influence life cycle outcomes. These analyses are used to examine trade-offs and identify key drivers of environmental impacts under northern conditions.

Finally, Chapter 6 synthesizes the main findings of the thesis, discusses their implications for policy, design, and housing delivery in northern regions, and outlines limitations and directions for future research.

CHAPTER 2. Literature Review

2.1. Building Sector Emissions in Canada

The building and construction sector represents a major source of greenhouse gas (GHG) emissions in Canada and plays a central role in national decarbonization strategies. According to Canada's National Inventory Report (2023), direct emissions from residential and commercial buildings amounted to approximately 83 Mt CO₂, corresponding to about 12% of total national emissions. When upstream electricity generation associated with space heating, cooling, and building operation is included, the contribution of the building sector rises to roughly 17–18%, making it the third-largest emitting sector after oil and gas production and transportation.

Historically, building-related emissions in Canada have increased moderately since 1990, driven primarily by population growth, expanding floor area, and rising demand for residential and institutional space. These trends have been partially offset by improvements in building codes, insulation levels, appliance efficiency, and the progressive decarbonization of electricity grids in provinces such as Québec, British Columbia, and Manitoba. Nevertheless, fossil fuel combustion for space and water heating remains the dominant source of direct building emissions, accounting for more than 95% of sectoral GHG output.

Beyond operational energy use, the environmental footprint of buildings is increasingly shaped by embodied emissions associated with construction materials and processes. Cement, steel, and insulation products contribute disproportionately to life cycle greenhouse gas emissions, with cement production alone responsible for approximately 8% of global CO₂ emissions. Similar patterns are observed within Canadian construction supply chains, raising concern about the growing share of embodied carbon in new buildings as operational energy becomes cleaner.

At the global scale, the building and construction sector accounts for nearly 37% of energy-related CO₂ emissions (UNEP, 2023), highlighting the need for integrated mitigation strategies that address both operational and embodied impacts. In the Canadian context, approaches such as material substitution (e.g., engineered timber, recycled steel, and low-carbon concrete), improved envelope performance, and the adoption of prefabricated and modular construction methods have been identified as promising pathways for reducing life cycle emissions.

Policy initiatives increasingly reflect this dual focus. The Canada Green Buildings Strategy (2022) emphasizes electrification, high-performance envelopes, and the integration of whole life cycle carbon assessment into building design and procurement. While electrification and heat pump deployment are central mitigation strategies in southern regions, their applicability is more limited in northern and remote communities, where diesel-based energy systems and logistical constraints persist. In these contexts, high-efficiency prefabricated housing, enhanced insulation standards, and reduced on-site construction intensity offer some of the most immediate opportunities for lowering both operational and embodied emissions.

Taken together, these trends underline the importance of evaluating building emissions across the full life cycle and within their geographic context. For northern and remote regions of Canada, where logistics, material transport, and energy supply differ fundamentally from southern conditions, conventional assumptions about emission drivers may not hold. This reinforces the need for life cycle assessment approaches that explicitly account for location-specific construction and operational realities.

2.2 Overview of LCA in Construction

Life Cycle Assessment (LCA) is widely recognized as the reference methodology for evaluating the environmental performance of buildings across their life cycle. The ISO 14040 and ISO 14044 standards define the core phases of an LCA, including goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. In the construction sector, these principles are operationalized through the modular framework introduced in EN 15804, which structures environmental impacts into discrete life cycle stages to improve transparency and comparability.

Within this framework, the product and construction process stages are divided into A1 (raw material supply), A2 (transport to manufacturer), A3 (manufacturing), A4 (transport to site), and A5 (installation). This modularization allows practitioners to isolate the contribution of individual processes and to identify stages where mitigation measures may be most effective. While early building LCAs often focused primarily on material production (A1–A3), subsequent research has shown that transport and installation stages can represent a substantial share of total impacts, particularly in projects characterized by long supply chains or challenging site conditions.

To address these complexities, several national and international guidance documents have extended the application of ISO and EN standards to whole-building assessments. Frameworks such as the RICS Whole Life Carbon Assessment guidance (2024) and the NRC Whole-Building Life Cycle Assessment Guidelines (2022) emphasize consistent definition of functional units, transparent reporting of system boundaries, and explicit modelling of transport modes, load factors, site energy use, and construction waste. These requirements are intended to reduce methodological variability and improve the decision relevance of LCA results.

For remote and northern construction projects, adherence to such guidance is particularly important. In these contexts, emissions associated with logistics-intensive transport (A4) and on-site installation activities (A5) can rival or exceed those from material production, challenging assumptions derived from studies conducted in more accessible regions. As a result, LCAs that omit or simplify these stages risk underestimating total impacts and misrepresenting the effectiveness of proposed mitigation strategies. This has reinforced the need for context-sensitive

LCA approaches that explicitly account for geographic, logistical, and climatic conditions when assessing the environmental performance of buildings.

2.3 Prefabrication and Modular Construction

Prefabricated and modular construction has been widely promoted as a means of improving construction efficiency, enhancing quality control, and reducing on-site waste and labour intensity. By shifting a substantial portion of construction activities to controlled factory environments, prefabrication can limit material losses, improve dimensional accuracy, and shorten on-site installation periods. These advantages have made modular construction particularly attractive for projects facing tight schedules, labour shortages, or challenging site conditions.

However, the environmental performance of prefabricated systems is strongly context-dependent. Early studies by Kamali and Hewage (2016) showed that off-site fabrication can significantly reduce material waste and associated embodied emissions, while cautioning that long-distance transportation of modules may offset these benefits. More recent work has reinforced this finding. Greer et al. (2023) demonstrated substantial variability in embodied carbon outcomes for modular housing, driven by differences in module design, structural systems, and delivery distances. Similarly, Wang et al. (2021) found that increasing factory prefabrication intensity reduced impacts in production stages (A1–A3) but led to higher transport-related emissions (A4) due to heavier and less flexible shipments.

Comparable trade-offs have been reported in European contexts. Meireles et al. (2024) observed that prefabricated wall systems reduced overall life cycle impacts in Portugal, yet increased the relative contribution of transport, particularly where production facilities were distant from construction sites. These findings underline a recurring pattern in the literature: prefabrication is not inherently low-carbon, but rather shifts the distribution of environmental impacts across life cycle stages.

Taken together, existing studies suggest that the carbon performance of modular construction depends less on the prefabrication approach itself and more on factors such as module weight, material selection, logistics configuration, transport distance, and regional supply conditions. In remote and northern regions, where delivery routes are long and multimodal, these factors become especially influential. As a result, evaluating prefabricated housing systems requires life cycle assessment approaches that explicitly account for transport and installation processes, rather than assuming net environmental benefits based solely on reduced on-site activity.

2.3.1 Technical Characteristics of Modular Construction

Modular construction systems are based on standardized volumetric units that are manufactured off-site and transported to the construction location as largely completed assemblies. As described by Lawson (2007), modular buildings can be composed of several system typologies, including fully enclosed four-sided load-bearing modules, partially open-sided units, open-sided corner-

supported systems, hybrid modular-panel configurations, and non-load-bearing pods such as prefabricated bathroom units. These typologies offer varying levels of structural capacity and spatial flexibility, with four-sided load-bearing modules being the most commonly adopted in residential, student housing, and hotel developments due to their structural robustness and straightforward stacking logic.

A defining characteristic of modular construction is the set of dimensional constraints imposed by transportation requirements. Typical internal module widths range from approximately 3.0 to 3.6 m, while external transport widths are generally limited to about 4.0 m. Module lengths commonly vary between 6 and 10 m. Road transport regulations impose additional constraints, including notification requirements for loads exceeding 2.9 m in width and escort vehicles for loads wider than approximately 4.3 m. These restrictions directly influence logistics planning and contribute to transport-related life cycle impacts (A4), particularly for long-distance or multimodal delivery routes.

Vertical dimensions further constrain modular design. Maximum allowable transport heights, typically around 4.95 m, limit the integration of roof assemblies and mechanical systems within individual modules. In addition, modular construction often results in deeper floor-ceiling assemblies compared to conventional buildings. Because each module incorporates its own structural framing, insulation layers, service cavities, and lifting reinforcements, floor-ceiling depths commonly range from 300 to 450 mm for standard modules and may reach 750–900 mm in frame-supported hybrid systems. These deeper assemblies can influence thermal bridging, envelope continuity, and operational energy performance (B6), effects that are particularly relevant in cold-climate regions such as Nunavik, where space heating dominates annual energy demand.

From a performance perspective, modular buildings typically achieve high levels of thermal, acoustic, and fire resistance due to the controlled conditions of factory fabrication. Lawson (2007) reports that façade U-values on the order of $0.2 \text{ W/m}^2\cdot\text{K}$ can be attained using insulated sheathing systems combined with mineral wool. Airborne sound insulation values frequently exceed 63 dB, surpassing typical regulatory requirements by 5–10 dB, while impact sound transmission levels below 30 dB are commonly achieved. Fire resistance ratings of up to 90 minutes can be provided through the use of multiple layers of fire-rated gypsum board and non-combustible insulation materials. These characteristics make modular construction well suited to applications requiring stringent envelope performance, occupant comfort, and fire safety.

The maximum achievable height of modular buildings depends largely on the adopted structural and bracing strategy. Unbraced single-line modular arrangements are generally limited to three storeys, whereas additional gable or cross-bracing can increase feasible heights to five storeys. When combined with stabilizing cores, modular systems can reach between seven and twelve storeys, depending on module configuration and wind loading conditions. In larger or mixed-use developments, modular units are frequently integrated with steel or concrete podiums and hybrid

structural frames, which provide lateral stability and enable greater architectural flexibility at lower levels.

2.4 Embodied Impacts of A1–A3

Material production stages (A1–A3) are consistently identified in the literature as major contributors to embodied greenhouse gas emissions in modular and prefabricated housing systems. These stages include raw material extraction, processing, and manufacturing, and are strongly influenced by structural material choice, envelope composition, and the level of industrialization. Several studies report substantial embodied carbon reductions when conventional concrete or steel systems are replaced with timber-based or hybrid solutions. Andersen et al. (2021), for instance, demonstrated that timber structures can reduce greenhouse gas emissions by approximately 30–50% compared to reinforced concrete or steel alternatives. In modular applications, factory-controlled production further enables material optimization and reduced waste generation.

Nevertheless, embodied impacts remain highly sensitive to material selection. Dani et al. (2025) analyzed a structural insulated panel (SIP)-based modular dwelling in New Zealand and reported embodied emissions of approximately 285 kg CO₂e/m², with oriented strand board (OSB) and foam insulation cores dominating A1–A3 impacts. Broader reviews of modular construction systems (Wang et al., 2024) confirm that steel framing, concrete foundations, and high-performance insulation materials consistently emerge as production-stage hotspots.

Importantly, literature increasingly highlights interactions between material choices and downstream life cycle stages. Strategies aimed at reducing A1–A3 impacts, such as thicker insulation layers or heavier structural systems, often increase module mass and volume, thereby influencing transport-related emissions in A4. As a result, material substitutions cannot be evaluated in isolation, and embodied carbon reductions must be assessed in conjunction with logistics implications.

2.5 Transport and Installation Impacts (A4–A5)

Transport to site (A4) and installation activities (A5) represent critical contributors to cradle-to-site emissions in modular construction, particularly for projects involving long-distance or constrained delivery routes. Multiple studies have shown that A4 emissions can equal or exceed A1–A3 impacts when modules are transported over extended distances or require specialized logistics. Wang et al. (2021) and Greer et al. (2023) reported cases in which transport-related emissions dominated cradle-to-site impacts due to heavy module weights, oversized loads, and limited load factors. Hemmati et al. (2024) further demonstrated that partial loads, limited backhauls, and the use of escort vehicles can substantially increase A4 emissions beyond values typically assumed in generic databases. Recent professional guidance, including IStructE (2024) and RICS (2024), therefore requires explicit reporting of transport routes, modes, distances, load factors, and backhaul assumptions.

Installation impacts (A5) include crane operation, temporary power generation, on-site equipment use, worker accommodation, and construction waste management. Although frequently simplified in LCAs, measured data indicate that these impacts can be significant. Hemmati et al. (2024) reported installation-stage emissions ranging from 27 to 33 kg CO₂/m² based on equipment duty-cycle monitoring, substantially higher than commonly used default values. Fanis et al. (2022) similarly concluded that construction-stage emissions are often underestimated, particularly in projects relying on diesel-powered equipment. In remote construction contexts, accurate modelling of A4 and A5 requires detailed representation of logistics chains, equipment runtime, fuel types, and site practices rather than reliance on generic assumptions

2.6 Operational Impacts in Northern Housing (B1–B7)

In northern and the northern regions, operational impacts frequently dominate whole life cycle emissions due to extreme climatic conditions and carbon-intensive energy systems. Use-stage modules (B1–B7), and particularly operational energy use (B6), are strongly influenced by space heating demand, ventilation requirements, and the absence of grid-connected electricity.

In Nunavik and Nunavut, all communities rely on isolated diesel-based power plants for electricity generation and on heating oil for space heating. According to Environment and Climate Change Canada, Nunavut generated approximately 0.7 Mt CO₂e in 2023 only a small fraction of national emissions but exhibited among the highest per capita emission levels due to its small population and complete dependence on imported fossil fuels. Stationary energy use, including building heating and power generation, accounts for approximately 80–85% of regional emissions, with the remainder dominated by aviation and marine transport.

Under these conditions, building energy performance becomes a critical determinant of life cycle impacts. High-performance envelopes reduced thermal bridging, and improved airtightness can significantly reduce heating demand. Prefabricated modular construction is well-suited to achieving these performance levels due to factory-controlled fabrication and reduced on-site variability. Studies conducted in cold-climate contexts suggest that enhanced modular envelopes can reduce heating energy consumption by 30–40%, directly lowering diesel use and associated emissions. Despite these advantages, empirical data on long-term operational performance, maintenance, and replacement in remote northern communities remain limited. Consequently, many LCAs rely on generalized assumptions for B1–B7 modules, introducing uncertainty into whole life cycle results and reinforcing the need for transparent sensitivity analysis

2.7 Modular Construction as a Decarbonization Enabler in Remote Regions

Modular construction has been widely discussed in the literature as a potential enabler of decarbonization in the building sector. Off-site fabrication under controlled factory conditions reduces material waste, improves construction precision, and shortens on-site installation time.

Studies report waste reductions of 45–70% relative to conventional construction, translating directly into avoided embodied emissions (Teng et al., 2018).

Comparative LCAs indicate that prefabricated buildings can achieve 10–30% lower embodied emissions than conventional counterparts, with greater reductions observed when low-carbon materials such as engineered timber, recycled steel, or alternative binders are used (Kamali & Hewage, 2017; Pervez, 2022). However, these benefits are highly context-dependent and may be offset by increased transport emissions in logistics-intensive projects.

In remote northern regions, modular construction offers additional advantages by minimizing on-site labour, reducing exposure to harsh weather, and enabling rapid installation during short construction windows. While transport emissions at the A4 stage are unavoidable, the literature suggests that gains achieved through improved manufacturing efficiency and reduced operational energy demand can outweigh these increases over the building life cycle when systems are properly designed

2.8 Synthesis of Literature Gaps and Relevance to This Thesis

The reviewed literature reveals a consistent imbalance in life cycle stage coverage. Production impacts (A1–A3) are extensively studied, whereas transport and installation stages (A4–A5) are frequently simplified or omitted, despite their demonstrated importance in remote projects. Operational impacts (B6) are often assessed separately from embodied emissions, limiting the ability to evaluate whole life cycle trade-offs.

Data gaps remain particularly pronounced for multimodal Arctic logistics, equipment duty cycles, and long-term operational performance in isolated communities. Interactions between material substitution, module mass, transport intensity, and operational energy demand are rarely quantified within a single assessment framework.

This thesis addresses these gaps by conducting a standards-compliant life cycle assessment of prefabricated modular housing in northern Québec. By integrating detailed modelling of cradle-to-site stages with use-stage impacts and explicitly accounting for location-specific logistics and energy systems, the research aims to clarify key emission drivers and to identify realistic decarbonization pathways for northern housing.

Table 1: Summary of key life cycle assessment studies on prefabricated and modular construction and their relevance to this thesis.

Author(s)	Year	Software Method	Scope	Region Context	Key Findings	Relevance
Kamali & Hewage	2016	Various (SimaPro, GaBi)	A1–A5	Canada/General	Prefabrication reduces waste but transport may offset benefits	Early recognition of logistics as potential carbon burden
Andersen et al.	2021	Mixed (GaBi, SimaPro)	A1–A3	Scandinavia	Timber buildings show 30–50% lower GHGs vs steel/concrete, but biogenic carbon reporting inconsistent	Highlights material substitution potential; underlines need for consistent reporting
Wang et al.	2021	SimaPro + ecoinvent	A1–A5	China	Higher prefabrication reduces A1–A3 but increases A4 transport	Demonstrates trade-off between factory efficiency and transport
Greer et al.	2023	GaBi	A1–A5	EU/US	Large variability in embodied carbon outcomes for modular housing	Supports thesis focus on transport intensity and context
Fnais et al.	2022	Review (mixed data)	Various	Global	Found systematic under-reporting of A4/A5; high uncertainty	Frames methodological gap directly motivating this thesis
Hemmati et al.	2024	Measured site data	A5	Middle East	Duty-cycle monitoring shows A5 emissions much higher than defaults	Provides rare empirical evidence; supports generator/crane

						modelling in Nunavik
Meireles et al.	2024	OpenLCA	A1–A5	Portugal	Prefabricated wall assemblies had lower A1–A3 but high A4 contribution	Emphasises importance of including transport in prefabrication LCAs
Berges-Alvarez et al.	2024	IFC–BIM LCA workflow	Design stage	Spain	Demonstrated BIM–LCA pipelines for modular buildings	Informs thesis digitalisation scenarios (BIM–LCA integration)
Dani et al.	2025	LCAQuick	A1–A5	New Zealand	SIP modular dwelling ~285 kg CO ₂ e/m ² upfront; OSB + foam insulation dominated	Relevant for SIP-based modular envelopes and insulation impacts

CHAPTER 3. Methodology

This chapter describes the methodological framework adopted to conduct a life cycle assessment (LCA) of prefabricated modular housing deployed in northern Québec. The assessment integrates cradle-to-site stages (A1–A5) with use-stage modules (B1–B7), in accordance with ISO 14040/14044 and the modular structure defined in EN 15804 and EN 15978. The approach is designed to capture both logistics-intensive construction impacts and operational energy performance under cold-climate and remote-context conditions.

All modelling was carried out using SimaPro v9.5 with the ecoinvent v3.7 database (cut-off system model). Assumptions, dataset selections, and calculation rules were systematically documented to ensure transparency and reproducibility.

In accordance with ISO 14044, this thesis does not present comparative assertions disclosed to the public. Any future comparative publication based on this work would require an independent critical review

3.1 Methodological Framework

The assessment follows the four phases of LCA defined in ISO 14040/14044: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. Life-cycle stages are structured using the EN 15804 modular framework, allowing impacts to be reported consistently across production (A1–A3), transport and installation (A4–A5), and use stages (B1–B7).

Modelling was performed in SimaPro v9.5 using ecoinvent v3.7 (cut-off) as the background database. All foreground processes, dataset mappings, geographic scopes, and system-model selections were recorded in a dataset register to support reproducibility.

Climate change impacts were quantified using the IPCC 2013 Global Warming Potential (100-year horizon), expressed in kilograms of CO₂ (kg CO₂), consistent with EN 15804 and RICS (2024) Whole Life Carbon Assessment guidance. To support interpretation and identify potential trade-offs, a limited set of midpoint indicators from ReCiPe 2016 was also calculated, including Cumulative Energy Demand (CED), Particulate Matter Formation, and Human Toxicity

3.2 Goal and Intended Application

The primary goal of this study is to quantify life-cycle greenhouse gas emissions associated with prefabricated modular housing delivered to northern Québec communities and to identify key drivers of both embodied and operational impacts. Particular emphasis is placed on understanding how material selection, multimodal logistics, site installation practices, and operational energy use interact under remote and cold-climate conditions.

The intended audience includes building designers, modular manufacturers, housing agencies, and researchers seeking decision-relevant evidence to support low-carbon housing strategies in northern regions. Results are intended for comparative interpretation within the defined system boundary rather than for public product comparison.

3.3 Scope and System Boundary

The system boundary encompasses both cradle-to-site stages (A1–A5) and use-stage modules (B1–B7):

1. **A1–A3:** Raw material supply, transport to factory, and prefabrication
2. **A4:** Transport of modular units to site via multimodal logistics
3. **A5:** On-site installation activities
4. **B1–B7:** Use-stage processes, with emphasis on operational energy use (B6)

End-of-life stages (C1–C4) and benefits beyond the system boundary (Module D) are excluded due to the lack of reliable data for northern settlements.

Allocation followed the ISO hierarchy (avoidance → physical causality → economic allocation). Minor flows below 1% were excluded where the cumulative cut-off did not exceed 5%. Foreground data represent current practices (2024–2025), while background data were sourced from ecoinvent v3.7 using Canadian or regional proxies where available.

3.4 Functional Unit and Reference Flow

The functional unit is defined as one prefabricated modular dwelling delivered, installed, and operated in northern Québec. For cradle-to-site modelling, the reference dwelling has a footprint of 16 × 24 ft (~36 m²).

Reference flows include material quantities for structural components, envelope systems, finishes, insulation, glazing, and fixings. These were derived from a partial factory bill of materials and supplemented with literature and technical documentation where manufacturer data were incomplete.

3.5 Case Context and Assumptions

The modular dwelling is designed for northern conditions and installed on elevated jack or pile foundations (0.6–1.2 m clearance) to accommodate permafrost-sensitive soils. The envelope incorporates low U-values, continuous air and vapour barriers, and a ventilated rainscreen façade suitable for cold-climate performance.

Only attributes relevant to the life-cycle inventory were retained in the model, including material quantities (A1–A3), shipped mass and logistics parameters (A4), installation energy and waste (A5), and operational energy demand (B6).

3.6 Data Quality Objectives

Data quality objectives were defined as follows:

1. **Temporal:** 2024–2025
2. **Geographical:** Québec production; northern Québec operation
3. **Technological:** Prefabricated modular construction and diesel-based northern energy systems
4. **Completeness and consistency:** Mass balance, unit coherence, and dataset traceability
5. **Uncertainty:** Addressed through scenario design, $\pm 20\%$ sensitivity testing, and optional Monte Carlo simulation

3.7 Life Cycle Inventory (LCI)

The life cycle inventory (LCI) quantifies all relevant material, transport, energy, and operational flows within the defined system boundary. The system boundary of this study includes cradle-to-site stages (A1–A5) as well as use-stage modules (B1–B7), consistent with EN 15804 and EN 15978. However, the level of inventory detail varies across modules in response to data availability and their relative contribution to life cycle impacts in northern and remote contexts.

Consistent with common practice in building LCAs, detailed quantitative modelling was performed for stages known to dominate impacts, while other stages were included using simplified, literature-informed assumptions. In particular, operational energy use (B6) was modelled explicitly, as it represents the primary driver of use-stage emissions in cold-climate, diesel-dependent northern communities. Other use-stage modules (B1–B5 and B7) were included at a simplified level and are addressed qualitatively in the interpretation of results.

A1 – Raw material supply

Material quantities were derived from detailed material take-offs of the prefabricated modular dwelling, including structural components, envelope assemblies, insulation, finishes, glazing, and fixings. These quantities were matched to appropriate ecoinvent v3.7 datasets based on material composition and regional production. Typical fabrication waste factors of 5–10% were applied to account for off-cuts and material losses during manufacturing, in line with values reported in the literature for modular construction.

A2 – Transport to prefabrication facility

Inbound transportation of materials from suppliers to the prefabrication facility was modelled using ecoinvent road freight datasets. Transport distances were estimated based on supplier locations and verified using publicly available mapping tools. Modelling assumptions included representative truck classes, fuel types, and an average load factor of 80%, which was varied by $\pm 20\%$ in sensitivity analyses to reflect uncertainty and variability in supplier logistics.

A3 – Prefabrication and manufacturing

Energy consumption associated with factory prefabrication was modelled using representative electricity and fuel inputs corresponding to typical modular manufacturing operations in Québec. Material off-cuts and rejected components generated during production were included as waste flows within the system boundary. Where manufacturer-specific energy data were unavailable, proxy values from literature and background datasets were used, with assumptions documented explicitly.

A4 – Transport to site

Transport of the prefabricated modules from southern Québec to northern Québec communities was modelled as a multimodal logistics chain. This included road transport from the factory to the port of departure, marine sealift to the northern region, and local handling and positioning upon arrival. Each transport segment was represented using ecoinvent datasets corresponding to vehicle or vessel class, distance travelled, and fuel type. Assumptions regarding load factors, routing, and auxiliary operations were documented and tested through scenario analysis.

A5 – On-site installation

Installation activities included fuel consumption by on-site equipment such as cranes, loaders, telehandlers, generators, and welding tools. Equipment runtime was estimated based on typical duty cycles reported in the literature and contractor documentation for modular installation in remote settings. Construction waste generated during assembly, estimated at 5–10% of selected materials, was included within the A5 inventory.

B1–B5 and B7 – Use-stage processes (simplified)

Use-stage processes related to building use, maintenance, repair, replacement, and operational water use (B1–B5 and B7) were included at a simplified level. Due to limited empirical data for long-term building performance in northern Québec communities, these modules were modelled using generalized assumptions derived from cold-climate building literature and standards. Their contribution is discussed qualitatively in later chapters rather than treated as primary quantitative drivers.

B6 – Operational energy use

Operational energy use (B6) was modelled in detail, reflecting its dominant contribution to life cycle emissions in northern contexts. Energy demand was estimated based on cold-climate heating requirements and typical envelope performance for prefabricated modular housing. Electricity generation and space heating were represented using diesel-based energy supply profiles characteristic of isolated northern Québec communities. This module provides the primary quantitative basis for assessing use-stage impacts and for evaluating trade-offs between embodied and operational emissions

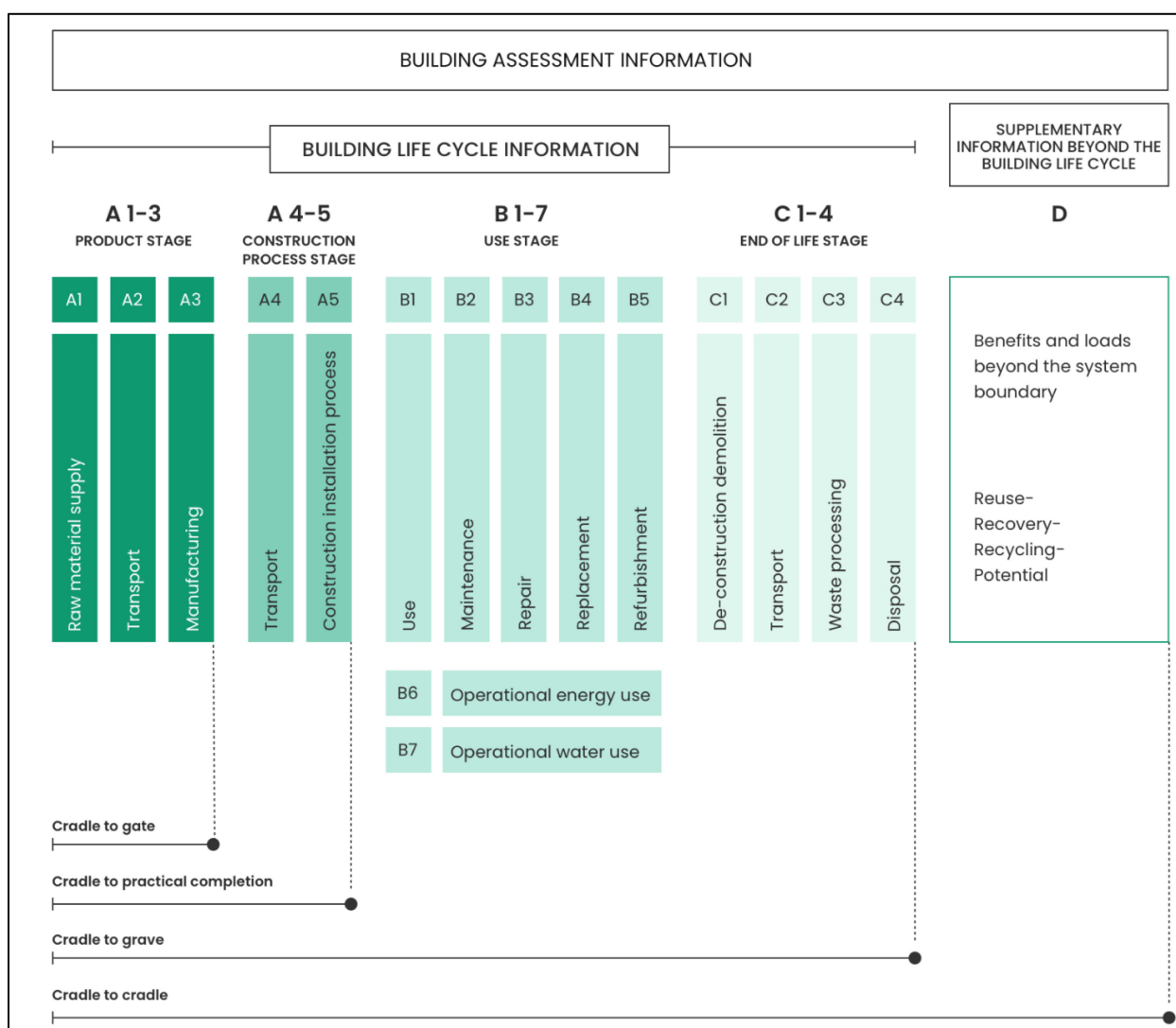


Figure 4: General structure of the LCA framework applied in this study (ISO 14040/44)

3.8 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase translates the life cycle inventory data associated with each assessed stage into quantifiable environmental impacts. In this study, LCIA was conducted for both cradle-to-site stages (A1–A5) and use-stage modules (B1–B7), with particular emphasis on operational energy use (B6), reflecting the importance of heating-dominated performance in northern and remote contexts. All impact calculations were performed in SimaPro v9.5 using background data from the ecoinvent v3.7 database (cut-off by classification), ensuring transparency and consistency across modules.

Primary indicator:

The principal impact indicator applied in this assessment is the IPCC 2013 Global Warming Potential (GWP, 100-year time horizon), expressed in kilograms of carbon dioxide equivalent (kg CO₂ e). This metric quantifies the radiative forcing effects of greenhouse gas emissions over a 100-year period and is fully aligned with EN 15804, EN 15978, and the RICS (2024) Whole Life Carbon Assessment guidance. Using GWP 100a as the primary indicator enables comparison with national benchmarks and international building LCA studies.

Secondary indicators:

To support interpretation and to assess potential trade-offs beyond climate change, a limited set of midpoint indicators from ReCiPe 2016 (Hierarchist perspective) was also calculated. These indicators include Cumulative Energy Demand (CED), Particulate Matter Formation, and Human Toxicity. Together, they provide complementary insight into energy intensity, local air-quality implications, and broader human health impacts associated with material production, logistics, and operational energy use.

Outputs and interpretation:

Stage-disaggregated impact results were generated for all assessed modules (A1–A5 and B1–B7). Contribution analyses were used to identify dominant processes within and across life cycle stages, such as material production, long-distance transport, on-site installation, and operational energy demand. Hotspot visualizations and comparative breakdowns support interpretation of these results. The LCIA outputs form the quantitative basis for the scenario and sensitivity analyses presented in Chapter 5, where alternative material choices, logistics configurations, and

operational assumptions are evaluated as potential pathways for reducing life cycle greenhouse gas emissions in northern modular housing.

3.9 Scenario Design

To examine how key design, logistics, and operational choices influence overall life cycle performance, a set of alternative scenarios was developed and modelled using SimaPro v9.5. Scenarios were constructed to isolate individual decision variables while maintaining all other parameters consistent with the baseline model. This approach enables clear attribution of observed changes in environmental impacts to specific assumptions or interventions.

The objective of the scenario analysis is not to prescribe optimal solutions, but rather to test the sensitivity of life cycle results to realistic variations in material selection, logistics configuration, and operational conditions that are particularly relevant in northern and remote construction contexts. Scenarios were designed to address both cradle-to-site stages (A1–A5) and use-stage impacts (B1–B7), with emphasis placed on stages identified in the literature as dominant contributors under cold-climate conditions.

The following scenarios were evaluated:

1. Transport load-factor optimization (A4)

Transport efficiency was assessed by varying assumed load factors for both road freight and marine sealift operations within $\pm 20\%$ of the baseline value (80%). This scenario reflects common logistical constraints in northern supply chains, including partial loads, limited backhauls, and seasonal shipping windows. The analysis quantifies how changes in transport utilization affect A4 emissions and overall cradle-to-site impacts.

2. Material substitution in production stages (A1–A3)

Alternative material configurations were modelled to explore potential reductions in embodied greenhouse gas emissions during raw material supply and manufacturing. Tested substitutions included replacing expanded polystyrene (EPS) insulation with graphite-enhanced EPS, substituting mineral wool with cellulose insulation, and interchanging plywood with oriented strand board (OSB). These scenarios evaluate trade-offs between embodied emissions, material mass, and downstream transport implications, while maintaining equivalent thermal and structural performance.

3. Workforce travel and localization (A4)

Given that skilled labour is frequently transported by air from southern Québec to northern

communities, a dedicated scenario examined the effect of excluding or reducing worker travel. This scenario represents the potential benefits of workforce localization or regional training initiatives and captures the influence of air travel emissions on transport-related life cycle impacts.

4. Operational energy sensitivity (B6)

To reflect uncertainty in building operation under northern climatic conditions, a sensitivity scenario was developed for operational energy use. Heating energy demand was varied within $\pm 20\%$ of the baseline to account for differences in envelope performance, occupant behaviour, and climatic variability. This scenario assesses the robustness of life cycle conclusions with respect to use-stage emissions, which are expected to dominate long-term impacts in diesel-dependent energy systems

3.10 Quality Assurance

Given the limited availability of complete primary data from modular manufacturers and regional contractors, a mixed-data approach was adopted, combining verified sources with clearly documented assumptions. Material quantities, transport distances, and system configurations were cross-checked against design drawings, supplier documentation, and publicly available logistics information. Where manufacturer-specific data were unavailable, representative values from peer-reviewed literature and ecoinvent v3.7 datasets were applied.

Internal consistency checks were conducted within SimaPro v9.5 to ensure coherence between modelled material quantities and total transported mass, with acceptable deviations maintained within $\pm 5\text{--}10\%$. Units, dataset references, and geographic scopes were reviewed to ensure compatibility across all assessed life cycle stages (A1–A5 and B1–B7). All scenarios were implemented within the same modelling framework to ensure that only the intended variables were modified between runs.

While some parameters rely on proxy or secondary data, the modelling strategy prioritizes transparency, traceability, and reproducibility over numerical precision. This approach ensures that results remain representative of current northern modular construction practices while explicitly acknowledging uncertainty inherent to remote project contexts.

3.11 Ethical Considerations

This research does not involve human participants, personal data, or community-level surveys. All information used in the life cycle modelling, such as material quantities, transport routes, fuel types, and energy system characteristics, was derived from publicly available datasets, manufacturer specifications, or published technical and scientific sources.

Regional contextual information related to northern Québec communities, including logistics infrastructure, sealift schedules, and climatic conditions, was obtained from publicly accessible

documents and reports in accordance with institutional research ethics guidelines. Care was taken to avoid the disclosure of identifiable, sensitive, or proprietary community information, and the research was conducted with respect for Indigenous and northern contexts.

3.12 Limitations

Limitations

Several limitations affect the scope and precision of the results presented in this study:

1. A complete, manufacturer-verified bill of materials was not available for the modular dwelling. As a result, certain parameters, such as component masses, fabrication waste rates, and factory energy use, were estimated using literature values, technical datasheets, and comparable modular projects.
2. Transport distances and routing for multimodal delivery to northern Québec communities were estimated using public mapping tools, sealift operator schedules, and logistics reports, introducing uncertainty in the modelling of A4 emissions.
3. Seasonal and operational variability in northern logistics, including weather-related delays, lighterage operations, and fluctuations in vessel load factors, could not be fully represented within the model.
4. Long-term empirical data on building operation, maintenance, and replacement in northern communities remain limited, necessitating simplified assumptions for several use-stage modules (B1–B5 and B7).

Accordingly, results should be interpreted as indicative rather than exact. Their primary value lies in supporting comparative analysis, identifying dominant emission drivers, and informing decision-making related to low-carbon housing strategies in northern and remote regions

CHAPTER 4. Life Cycle Assessment of a Prefabricated House in Kuujjuaq, Nunavik

This chapter presents the life cycle assessment results for a prefabricated modular housing unit deployed in Kuujjuaq, a remote community in Nunavik, northern Québec. While the overall assessment framework of this thesis integrates both cradle-to-site stages (A1–A5) and use-stage modules (B1–B7), the primary analytical focus of this chapter is on the cradle-to-site phase, where material production, logistics, and installation processes are most strongly influenced by the constraints of northern construction.

The analysis follows the requirements of ISO 14040/14044 and the modular structure defined in EN 15804. Results are reported for raw material supply, transport to the prefabrication facility, factory manufacturing, long-distance transport to site, and on-site installation (A1–A5). Operational energy use (B6) is referenced where relevant to contextualize embodied impacts and to highlight trade-offs with use-stage performance, and is examined in greater detail in subsequent chapters

4.1 Case study: Nunavik building

4.1.1 Goal and Scope

The goal of this case study is to evaluate the life cycle environmental impacts associated with the delivery and installation of a prefabricated modular housing unit in Kuujjuaq, Nunavik, under remote and cold-climate conditions. While the broader assessment framework of this thesis integrates both cradle-to-site stages (A1–A5) and use-stage modules (B1–B7), this section focuses primarily on the cradle-to-site phase in order to quantify greenhouse gas emissions up to the point of occupancy and to identify stage-specific emission hotspots.

The functional unit is defined as one prefabricated modular dwelling unit (16 × 24 ft) delivered, installed, and operated in Kuujjuaq, Nunavik. In this chapter, results are reported primarily for cradle-to-site stages (A1–A5).

The system boundary follows the modular structure defined in EN 15804 and includes:

1. A1: Raw material extraction and processing
2. A2: Transport of raw materials to the prefabrication facility in Napierville, Québec
3. A3: Prefabrication of structural and envelope assemblies
4. A4: Long-distance transport by truck and seasonal sealift, including near-shore lighterage
5. A5: On-site installation, including equipment energy use, temporary power, construction waste, and optional worker transport

6. Use-stage modules (B1–B7) are included in the overall life cycle framework of the thesis, with operational energy use (B6) addressed explicitly in later analysis. End-of-life stages (C1–C4) and benefits beyond the system boundary (Module D) are excluded due to the lack of reliable region-specific data for northern settlements.

4.1.2. Assumptions and Limitations

Due to the limited availability of complete primary data for construction projects in remote northern regions, a number of assumptions were required to develop the life cycle inventory for the Kuujjuaq case study. These assumptions were selected to be representative of typical modular construction and logistics practices in Nunavik and are consistent with values reported in the literature.

Material losses during factory prefabrication and on-site installation were assumed to range between 5% and 10%, reflecting common industry practice for modular construction and prior LCA studies. Transport efficiency for both road freight and marine sealift segments was modelled using an average load factor of 80%. This assumption reflects typical northern supply chains, where containers and vessels are rarely utilized at full capacity and return trips frequently operate with partial or no backhaul.

On-site installation was assumed to occur over a three-day period, involving a crew of six workers operating eight-hour shifts. Equipment use during installation included a diesel generator (approximately 40 operating hours), a telehandler (approximately 6 hours), a loader (approximately 6 hours), and welding equipment (approximately 2 hours). Fuel consumption was calculated based on equipment power ratings and operating hours, converted to energy units, and modelled in SimaPro using diesel combustion datasets.

All on-site equipment was assumed to operate exclusively on diesel fuel, consistent with current practice in isolated northern communities. Electricity used during prefabrication was modelled using Québec's low-carbon grid mix. Transport distances were estimated based on supplier locations using publicly available mapping tools and sealift operator schedules. The marine transport leg was modelled using marine distillate fuels (MGO or VLSFO), in line with International Maritime Organization regulations governing fuel use in Arctic waters effective from 2024.

As an optional and separately reported component, crew metabolic energy expenditure was included in the inventory using an average range of 2,500–3,000 kcal per worker per day. While this element is not standard practice in all building LCAs, it has been considered in selected northern construction studies and is reported transparently to avoid conflation with core construction emissions.

Several limitations should be acknowledged when interpreting the results of this case study. Use-stage modules (B1–B7) and end-of-life stages (C1–C4) are not quantified in detail within this chapter, as reliable region-specific data for long-term operation, maintenance, and disposal in northern settlements remain scarce. Transport emission factors for sealift operations and fuel use for on-site equipment rely on representative values rather than measured data. Seasonal variability in logistics schedules, weather-related delays, and installation timing could not be fully captured. In addition, some material quantities were estimated using proxy data where manufacturer-specific information was unavailable.

All impact results presented in this chapter are calculated using the IPCC 2013 Global Warming Potential (100-year time horizon) as the primary indicator, expressed in kilograms of CO₂, in accordance with EN 15804 and RICS guidance. Selected ReCiPe 2016 midpoint indicators were used solely to support interpretation and are not reported as primary outcomes. These assumptions and limitations do not undermine the validity of the hotspot analysis but instead highlight areas where improved access to region-specific data would strengthen future life cycle assessments of northern modular housing.

4.1.3. System Description

The system analyzed in this study consists of a single prefabricated modular housing unit manufactured in southern Québec and delivered to the community of Kuujjuaq in Nunavik. The unit represents a typical Northern residential module with a footprint of 16 × 24 ft and is designed to meet the thermal and structural requirements of subarctic climates. The building envelope is based on structural insulated panels (SIPs) for walls and roof assemblies, supplemented with mineral wool insulation and OSB and plywood finishes. These materials were selected to provide high thermal resistance, airtightness, and durability under prolonged cold-weather exposure.

The delivery of the modular unit follows a multimodal logistics corridor characteristic of northern Québec construction. First, the completed module is transported by truck from the prefabrication facility to the Port of Sainte-Catherine in southern Québec. From there, it is shipped by marine sealift to Kuujjuaq during the limited ice-free navigation season, typically between July and October. Marine transport is modelled using marine distillate fuels, consistent with current International Maritime Organization regulations governing fuel use in northern waters. Upon arrival in the region, the module is unloaded through near-shore lighterage operations along the Koksoak River, as large vessels cannot berth directly at the community. Final positioning and handling within Kuujjuaq are performed using local equipment.

Once delivered, the modular unit is installed on elevated pile foundations, which are standard practice in Nunavik to minimize permafrost disturbance, accommodate snow accumulation, and improve airflow beneath the structure. On-site installation relies on diesel-powered equipment, including a telehandler, loader, and portable generator, as well as temporary power supply and

limited welding activities. These processes reflect typical construction practices in remote northern communities where grid electricity is unavailable or unreliable during installation.

Construction waste generated during installation, including packaging materials and minor off-cuts from fitting and connections, is modelled as 5–10% of material inputs, in line with assumptions used elsewhere in this thesis. Waste is assumed to be managed through prevailing northern disposal practices, primarily landfill, with limited recycling available for selected materials such as metals. Worker transport and metabolic energy use are not included in the baseline system description but are addressed separately in sensitivity analyses to maintain transparency and comparability with standard building LCA practice.

4.1.4. System Components

The prefabricated modular unit analysed in this study is composed of a combination of structural, envelope, and finishing components typical of modular housing designed for northern and subarctic conditions. The system configuration reflects current practice in prefabricated construction for Nunavik, where durability, thermal performance, and constructability under constrained logistics are primary design drivers.

Structural components include the primary load-bearing elements of the module, such as floor and roof framing, wall structural cores, and connection hardware required for lifting, transport, and on-site assembly. These elements are designed to resist transport-induced stresses, snow loads, and wind exposure while remaining compatible with modular stacking and pile-supported foundations.

The building envelope comprises wall and roof assemblies based on structural insulated panels (SIPs), supplemented with mineral wool insulation, vapour and air barrier layers, exterior sheathing, and interior linings. Envelope components were selected to achieve high thermal resistance, reduced air leakage, and robust moisture control, which are critical for minimizing heat loss and maintaining long-term performance in cold-climate, heating-dominated contexts.

Finishing components include interior wall finishes, floor layers, exterior cladding elements, windows, doors, and associated fixings. While these elements contribute less to overall structural capacity, they represent a non-negligible share of material mass and embodied emissions and are therefore included explicitly in the life cycle inventory.

Material quantities and mass estimates for all system components were derived primarily from manufacturer specifications, technical drawings, and available design documentation for the modular unit. Where complete primary data were unavailable, secondary sources and literature values were used to supplement or adjust component masses to ensure internal consistency of the inventory. All mass estimates were checked against the total shipped weight of the module to maintain coherence between material production (A1–A3) and transport modelling (A4).

The level of component detail included in the inventory reflects the objective of this chapter, which is to establish a robust cradle-to-site baseline for embodied impacts. Components with negligible mass or impact contribution were aggregated where appropriate, while major material categories were retained explicitly to enable meaningful contribution and hotspot analyses in subsequent sections.

4.1.5 System Product

The product system examined in this study consists of a single prefabricated modular dwelling manufactured in southern Québec and transported to Kuujjuaq for installation under remote northern conditions. The unit represents a complete residential module delivered to site in a near-finished state, consistent with current modular housing practices in Nunavik.

The product includes all major assemblies required for structural integrity, enclosure, and interior functionality. These comprise the primary structural frame, wall and roof structural insulated panels (SIPs), thermal insulation layers (including mineral wool), exterior and interior sheathing (such as plywood and gypsum board), fenestration systems, interior finishes, and the connection components necessary for lifting, transport, and on-site assembly.

All components included within the product system boundary are those typically required for the deployment of a modular dwelling in northern communities and are considered integral to the delivered unit at the point of installation. Temporary construction equipment, site infrastructure, and operational energy use are treated separately within the life cycle inventory and impact assessment stages, in accordance with the modular structure defined in EN 15804.

This definition of the product system ensures consistency between material production (A1–A3), transport to site (A4), and installation activities (A5). It provides a clear basis for the cradle-to-site impact results presented in the following sections.

4.1.6 Functional Unit

The functional unit adopted in this study is defined as one prefabricated modular dwelling with a footprint of 16 × 24 ft, fully delivered and installed in the community of Kuujjuaq, Nunavik. This definition reflects a complete and deployable housing unit at the point of occupancy and provides a consistent reference for quantifying life cycle environmental impacts.

By expressing all results relative to a single modular unit, the assessment enables coherent comparison of alternative material configurations, transport assumptions, and installation scenarios within the defined system boundary. This functional unit is maintained consistently across the cradle-to-site analysis presented in this chapter and supports alignment with the broader whole-life framework adopted in the thesis.



Figure 5: Prefabricated Unit (16 × 24 ft)

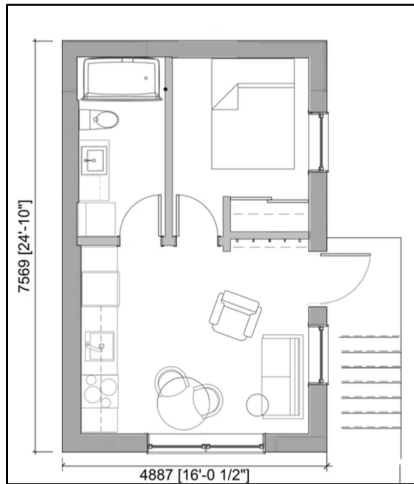


Figure 7: plan of modular unit (16 × 24 ft)

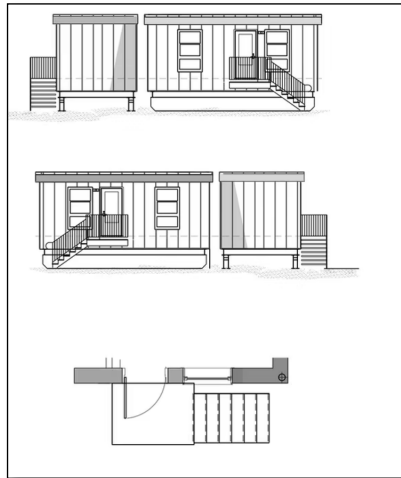


Figure 6: Elevation of modular unit

4.1.7 System Boundary

The system boundary applied in this case study is defined in accordance with the modular structure of EN 15804 and adopts a cradle-to-site scope for the primary quantitative analysis. The boundary includes raw material extraction and processing (A1), transport of materials to the prefabrication

facility (A2), factory-based manufacturing and assembly (A3), long-distance transport to Kuujjuaq via truck and seasonal sealift (A4), and on-site installation activities (A5).

This boundary captures the life cycle stages most directly influenced by the logistical, climatic, and infrastructural constraints of northern construction and therefore represents the focus of the results presented in this chapter.

Use-stage modules (B1–B7) are included in the overall life cycle framework of the thesis and are considered conceptually in relation to embodied impacts; however, they are not quantified in detail within this case study chapter due to the limited availability of reliable, region-specific data for long-term building operation and maintenance in Nunavik settlements. End-of-life stages (C1–C4) and benefits beyond the system boundary (Module D) are likewise excluded for the same reason.

The adopted system boundary is illustrated in Figure 8, which situates the cradle-to-site analysis within the broader building life cycle structure defined by ISO 14040/44 and EN 15804.

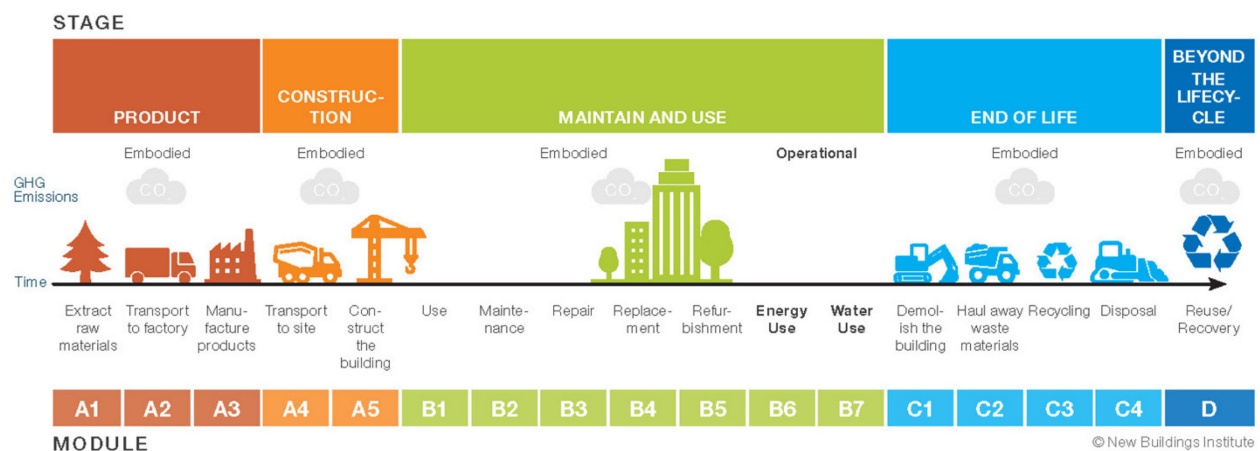


Figure 8: System boundary of the life cycle assessment framework applied in this study

4.1.8 Limitations:

The results of this case study should be interpreted within the context of the defined system boundary and the data constraints inherent to construction projects in remote northern regions. Although the broader methodological framework of this thesis considers both cradle-to-site (A1–A5) and use-stage (B1–B7) modules, the quantitative analysis presented in this chapter is limited to cradle-to-site stages. As a result, long-term operational, maintenance, and end-of-life impacts are not reflected in the numerical results discussed here.

Several modelling assumptions introduce uncertainty. Where project-specific supplier information or measured data were unavailable, background processes were represented using average datasets from the ecoinvent database. Transport modelling, particularly for the sealift and local site

operations, relied on estimated fuel use, equipment types, and duty cycles rather than continuous monitoring data. In addition, seasonal variability in northern logistics, such as weather-related delays, changes in vessel utilization, or installation scheduling could not be fully captured within the model.

These limitations do not undermine the validity of the stage-level comparisons or hotspot identification presented in this chapter. Instead, they highlight the sensitivity of cradle-to-site impacts to logistics assumptions and data availability and point to areas where improved access to region-specific transport, construction, and operational data would allow future life cycle assessments of northern modular housing to achieve higher resolution and confidence.

4.2 A1 – Raw Material Supply and Processing

Stage A1 represents the upstream environmental impacts associated with the extraction and primary processing of materials used in the prefabricated modular dwelling. For the 16×24 ft unit analysed in this study, material inputs are dominated by structural and envelope components designed to meet the thermal and durability requirements of northern Québec.

The primary contributors at this stage include structural steel elements used in the module frame and connections, insulation materials within wall and roof assemblies, gypsum-based boards for interior partitions, and glazing systems composed of glass and aluminum frames. Additional materials such as galvanized steel for exterior stairs and railings, plywood and oriented strand board (OSB) for sheathing, and resilient interior finishes (e.g., PVC flooring) were also included. While some of these materials represent a smaller share of total mass, their inclusion ensures a comprehensive representation of the production-stage impacts.

Material quantities were derived from available factory documentation, design drawings, and manufacturer datasheets. Where quantities were specified in volumetric terms, they were converted to mass using standard material densities to ensure consistency across the life cycle inventory. Each material was then linked to a representative background process in the ecoinvent v3.7 database and modelled in SimaPro v9.5 using the cut-off system model.

Results for the A1 stage highlight the strong influence of material choice on embodied greenhouse gas emissions. High-mass and energy-intensive materials, particularly structural steel and insulation products, emerge as the dominant contributors to A1 impacts. This finding is consistent with the literature on modular construction and underscores the importance of material substitution strategies explored later in the scenario analysis. All impacts reported for this stage are expressed in kilograms of CO₂ (kg CO₂), calculated using the IPCC 2013 Global Warming Potential (100-year time horizon) method

4.2.1 Shared geometry (basis for quantity take-off)

- Module footprint: $7.30 \text{ m} \times 4.90 \text{ m} \rightarrow \text{floor area} = \mathbf{35.77 \text{ m}^2}$

- Wall height = **2.50 m**
- Floor + roof area = **71.54 m²**
- External wall area (interior face) = **62.25 m²**
- Two internal partitions = **50.0 m²** (both sides)

These geometric bases were used to calculate all volumes and masses; full derivations are provided in the appendix.

4.2.2 Material quantities

1. Steel, low alloy (structural): 4,710 kg
2. Polyurethane rigid foam (insulation core): 318.1 kg (*replace with EPS dataset if panels are EPS*)
3. PVC (vinyl flooring): 232.5 kg
4. Wood chips (partition cavity fill): 323.4 kg
5. Sawnwood, softwood (framing, blocks): 0.339 m³
6. Flat glass (windows): 72.0 kg
7. Aluminium (window + door frames): 121.2 kg
8. Galvanized steel (stairs/rails/platform): 141.3 kg
9. Gypsum fibreboard (interior faces):
 - Option A (no ceiling): 1,193 kg
10. Softwood T&G ceiling (alternative to Option B): 0.572 m³

Input/output	Parameters		
Name	Status	Comment	
A1 raw material material	None		
Materials/Assemblies	Amount	Unit	Distribution
Steel, low-alloyed, hot rolled {RER} production Cut-off, U	4710	kg	Undefined
Polyurethane, rigid foam {RoW} production Cut-off, U	318.1	kg	Undefined
Polyvinylchloride, bulk polymerised {GLO} market for Cut-off, U	232.5	kg	Undefined
Flat glass, uncoated {RER} production Cut-off, U	72	kg	Undefined
Aluminium, wrought alloy {GLO} market for Cut-off, U	121.2	kg	Undefined
Galvanized steel sheet, at plant/RNA	300	kg	Undefined
Sawnwood, softwood, dried (u=10%), planed {RoW} market for Cut-off, U	1.8	m3	Undefined
Polyethylene, low density, granulate {GLO} market for Cut-off, U	60	kg	Undefined
Steel, low-alloyed {GLO} market for Cut-off, U	30	kg	Undefined
Adhesive, for metal {RoW} market for adhesive, for metal Cut-off, U	30	kg	Undefined
Add			
Processes		Amount	Unit
Add			
Image			
Add			

Figure 9: Raw material in SIMA Pro A1

4.2.3 Inventory-to-dataset mapping (ecoinvent v3.7)

Table 2: Raw material for A1

#	Material / Assembly	Amount	Unit	SimaPro dataset
1	Steel, low-alloy (structural chassis and beams)	4710	kg	Steel, low-alloyed, hot rolled {RER} production Cut-off, U
2	Polyurethane rigid foam (spray insulation)	318.1	kg	Polyurethane, rigid foam {RoW} production Cut-off, U
3	PVC vinyl flooring	232.5	kg	Polyvinylchloride, bulk polymerised {GLO} market for Cut-off, U
4	Flat glass (windows)	72	kg	Flat glass, uncoated {RER} production Cut-off, U

5	Aluminium (window/door frames + stairs/rails/platform)	261.2	kg	Aluminium, wrought alloy {GLO} market for Cut-off, U
6	Exterior cladding (coil-coated / galvanized steel panels)	300	kg	Galvanized steel sheet, at plant/RNA
7	Softwood tongue-and-groove boards (interior walls + ceiling)	1.8	m ³	Sawnwood, softwood, dried (u=10%), planed {RoW} market for Cut-off, U
8	Gypsum plasterboard (bathroom walls and ceiling only)	300	kg	Gypsum plasterboard {RoW} production Cut-off, U
9	Air/water barrier membranes (bitumen + LDPE proxy)	60	kg	Polyethylene, low density, granulate {GLO} market for Cut-off, U
10	Fasteners + adhesives/sealants (steel + PU proxies)	30	kg	a) Steel, low-alloyed {GLO} market for Cut-off, U (15 kg) b) Adhesive, for metal {RoW} market for adhesive, for metal Cut-off, U (15 kg)

4.2.4 Quality assurance and reproducibility

Data provenance: All material masses were derived from geometric take-offs and density values and cross-checked against manufacturer specifications and technical datasheets.

Mass balance: The total A1 mass (sum of all material inputs plus 5–10% allowance for cut-offs and construction waste) reconciles with the A4 shipped module mass within ± 5 –10%.

Uncertainty treatment: A ± 10 –20% sensitivity range was applied to the dominant contributors (steel, polyurethane insulation, aluminum).

Dataset consistency: All background processes were selected from ecoinvent 3.7 and implemented in SimaPro 9.5 under the cut-off system model.

4.2.5 A1 results

Table 3: Direct CO₂ Emissions of Main Materials in A1 (Raw materials) from SIMA PRO

Material	CO ₂ fossil (kg)	CO ₂ biogenic (kg)	CO ₂ land transformation (kg)	Total (kg)
Steel, low-alloyed	~8,100	–	–	~8,100
Steel, galvanized sheet	~2,500	–	–	~2,500
Flat glass, uncoated	~626	–	–	~626
Polyurethane, rigid foam	~135	–	–	~135
Polyvinylchloride (PVC, bulk)	~106	–	–	~106
Polyethylene, low density (LDPE)	~85	–	–	~85
Adhesive, for metal	~36	–	–	~36
Sawnwood, softwood (dried, planed)	–	~191	~177	~368
Plywood, at plant	–	~170	~165	~335
Total	≈12,700	≈361	≈13.3	≈13,074

The cradle-to-gate A1 impacts amount to approximately 13.1 t CO₂ for the baseline inventory (SimaPro 9.0, 2025). Contribution analysis shows that steel (low-alloy and galvanized) dominates the total, accounting for ~82% of emissions. Aluminum components (frames, stairs, and rails) contribute ~11%, while wood products (sawnwood and plywood) represent ~5%. Other inputs, including flat glass, polyurethane foam, PVC, LDPE, and adhesives, each contribute less than 3% of total CO₂ releases. These findings confirm that steel and aluminium are the primary drivers of embodied carbon in the A1 stage, together responsible for over 90% of the total. In contrast, wood products and minor materials have comparatively small impacts. Accordingly, future mitigation strategies should prioritize options such as recycled steel, lightweight aluminium alternatives, and optimized wood sourcing to achieve the most significant reductions in cradle-to-gate emissions.

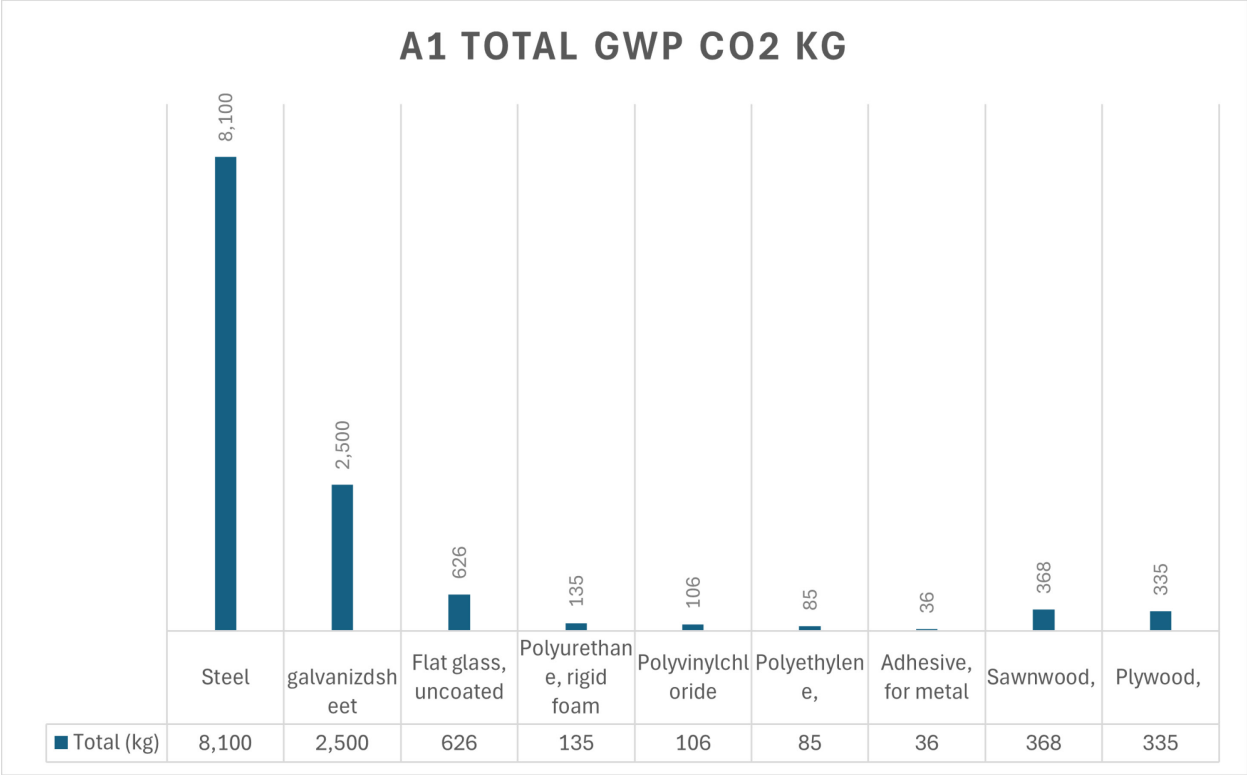


Figure 10: Contribution of materials to A1 stage greenhouse gas emissions.

4.3 A2 Transport to the factory

The A2 stage represents the upstream transportation of all materials included in the A1 inventory from their respective suppliers to the modular prefabrication facility located in Napierville, Québec. This stage captures inbound logistics associated with raw materials and semi-finished products prior to factory manufacturing. All transport processes were modelled in SimaPro v9.5 using road freight datasets from ecoinvent v3.7, representing EURO 6 lorries in the 16–32 t capacity range. These datasets were selected to reflect typical regional freight transport conditions in Québec. Transport distances were estimated using GIS-based road mapping tools and converted into tonne-kilometres based on the transported mass of each material. For materials originally quantified by volume, such as timber-based products, standard density values were applied to derive transportable masses. The total inbound transport demand for all materials amounts to approximately 2,803 tonne-kilometres. When assessed using the IPCC 2013 Global Warming Potential (100-year time horizon), this corresponds to an estimated impact of about 0.17 t CO₂ (≈174 kg CO₂). In comparison with the production stage (A1), the contribution of A2 to overall cradle-to-site emissions is minor, reflecting the relatively short transport distances and the dominance of material manufacturing impacts.

As expected, the majority of A2 emissions is associated with the transport of structural steel, which represents the largest share of transported mass. All other materials contribute only marginally to

the total A2 impact. These results confirm that, for this case study, inbound logistics to the factory play a secondary role in the overall life cycle profile when compared to raw material production and long-distance transport to the site.



Figure 11: Nunavik Modular factory facility in Napierville, Québec.

4.3.1. Goal & scope

The goal of this sub-section is to model the inbound logistics associated with materials included in the A1 inventory, from their respective supplier regions in Québec to the modular prefabrication facility located in Napierville. The scope of A2 is limited to supplier-to-factory road transportation only. Long-distance delivery of the prefabricated module to Kuujuaq is excluded from this stage and reported separately under A4, in accordance with the EN 15804 modular structure.

4.3.2. Data sources & key assumptions

1. Background datasets: ecoinvent v3.7 (cut-off system model), implemented in SimaPro v9.5.
2. Vehicle class: Road transport was modelled using a single representative freight lorry class (16–32 t, EURO 6), selected to reflect typical regional haulage conditions in Québec and to maintain consistency across materials.
3. Transport distances: Road distances between supplier regions and the Napierville prefabrication facility were estimated using GIS-based routing tools and entered into the model as tonne-kilometres (t·km).
4. Material masses: Transported masses were taken directly from the A1 inventory. For materials originally quantified by volume, standard density values were applied. For

example, softwood tongue-and-groove ceiling boards were converted using a density of $500 \text{ kg}\cdot\text{m}^{-3}$ ($1.8 \text{ m}^3 \approx 900 \text{ kg}$)

4.3.3. Modelling approach

Inbound transport for each material was modelled as a separate A2 process. For each entry, transport demand was calculated as the product of material mass (kg) and transport distance (km), yielding kilogram-kilometres (kg·km), which were subsequently converted to tonne-kilometres (t·km). All inbound logistics were represented using the sameecoinvent process (*Transport, freight, lorry 16–32 t, EURO 6*) to ensure methodological consistency and to avoid introducing unnecessary variability in the absence of supplier-specific vehicle data.

4.3.4. Results (A2)

- Total transport work: $\approx 2,803 \text{ t}\cdot\text{km}$
- Total A2 climate impact: $\approx 174 \text{ kg CO}_2$

Table 4: Summary of material origins, transport distances for stage A2

#	Material	Mass	Origin	Distance to Napierville (km)	Mode
1	Steel, low-alloy (structural)	4,710 kg	Val-d’Or, QC (steel fabricator)	~525 km	Truck 16–32t
2	Polyurethane rigid foam (spray insulation)	318.1 kg	Montréal, QC (chemical supplier)	~40 km	Truck 16–32t
3	PVC vinyl flooring	232.5 kg	Sherbrooke, QC	~190 km	Truck 16–32t
4	Flat glass (windows)	72 kg	Saint-Georges, QC	~250 km	Truck 16–32t
5	Aluminium (frames, stairs, rails)	261.2 kg	Laval, QC (extrusion plant)	~60 km	Truck 16–32t
6	Galvanized steel sheet (cladding proxy)	300 kg	Montréal, QC (coil-coating facility)	~40 km	Truck 16–32t
7	Softwood T&G boards	1.8 m ³ (~900 kg)	Mont-Tremblant, QC (sawmill)	~160 km	Truck 16–32t

8	Gypsum plasterboard (bathroom)	300 kg	Québec City, QC (gypsum board plant)	~260 km	Truck 16–32t
9	Air/water barrier membranes (LDPE proxy)	60 kg	Montréal, QC (polymer distributor)	~40 km	Truck 16–32t
10	Fasteners + adhesives	30 kg	Granby, QC (hardware supply)	~100 km	Truck 16–32t

Inventory:

Table 5: Transport inventory for materials (A2 stage)

	Material	Mass (kg)	Distance (km)	Amount (kg·km)	Unit	Transport dataset (same for all)
1	Steel, low-alloy (structural)	4,710	525	2,472,750	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
2	Polyurethane rigid foam	318.1	40	12,724	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
3	PVC vinyl flooring	232.5	190	44,175	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
4	Flat glass (windows)	72	250	18,000	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
5	Aluminium (frames + stairs/rails)	261.2	60	15,672	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
6	Galvanized steel sheet (cladding)	300	40	12,000	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
7	Softwood T&G boards	900	160	144,000	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}

8	Gypsum plasterboard (bathroom)	300	260	78,000	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
9	Air/water barrier membranes (LDPE proxy)	60	40	2,400	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
10	Fasteners + adhesives (steel + adhesive)	30	100	3,000	kgkm	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}
	Total			174 kg CO₂		

Input/output		Parameters					
Name	Status	Comment					
A2 transport to site	None						
Materials/Assemblies	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Add							
Processes	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	2472750	tkm	Undefined				Steel, low-alloy (structural)
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	12724	tkm	Undefined				Polyurethane rigid foam
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	44175	tkm	Undefined				PVC vinyl flooring
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	18000	tkm	Undefined				Flat glass (windows)
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	15672	tkm	Undefined				Aluminium (frames + stairs/rails)
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	12000	tkm	Undefined				Galvanized steel sheet (cladding)
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	144000	tkm	Undefined				Softwood T&G boards
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	78000	tkm	Undefined				Gypsum plasterboard (bathroom)
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	2400	tkm	Undefined				Air/water barrier membranes (LDPE proxy)
Transport, freight, lorry 16-32 metric ton, euro6 (RoW) market for transport, freight, lorry 16-32 metric ton, EURO6 Cut-off, U	3000	tkm	Undefined				Fasteners + adhesives (steel + adhesive)
Add							
Image							

Figure 12: SimaPro setup for A2 transport-to-site processes and material-specific freight inputs

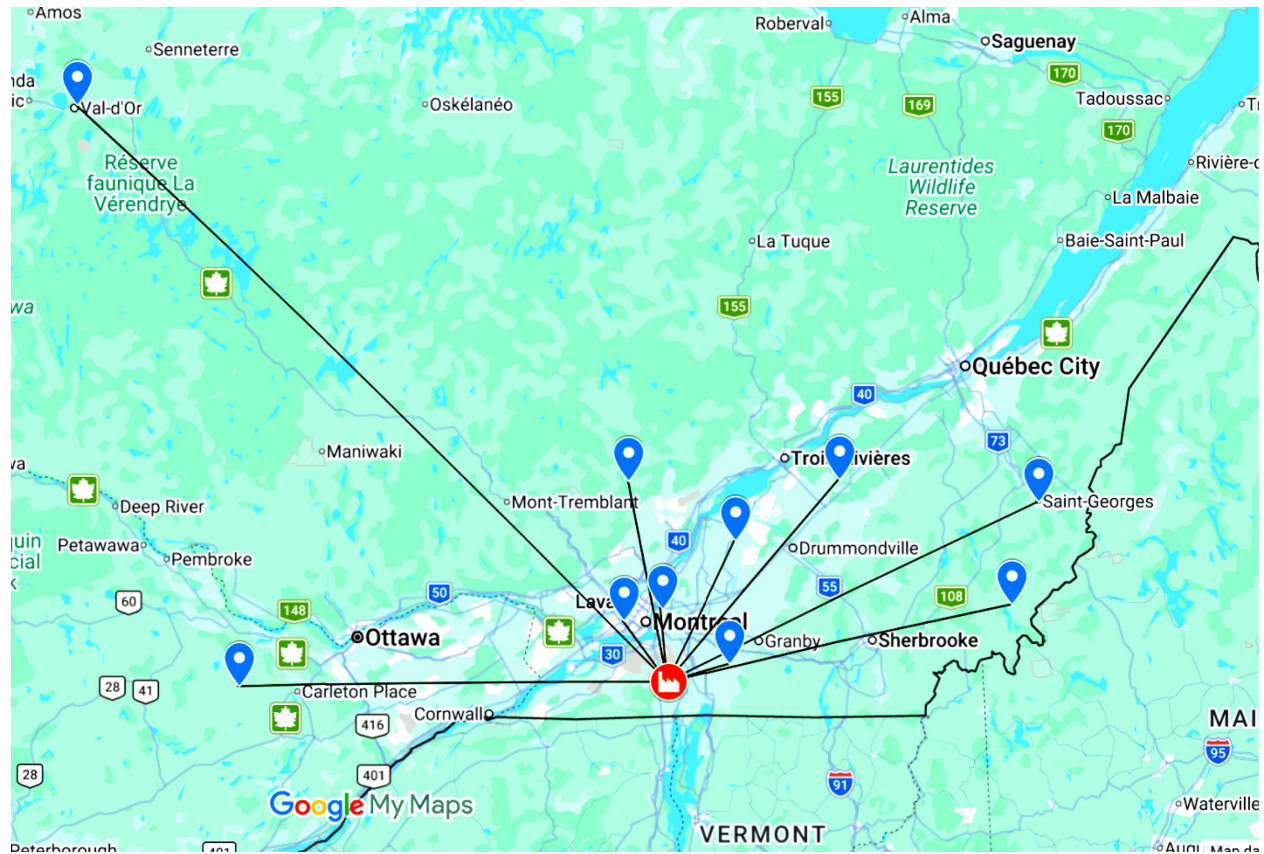


Figure 13: The supplier's factories for the unit

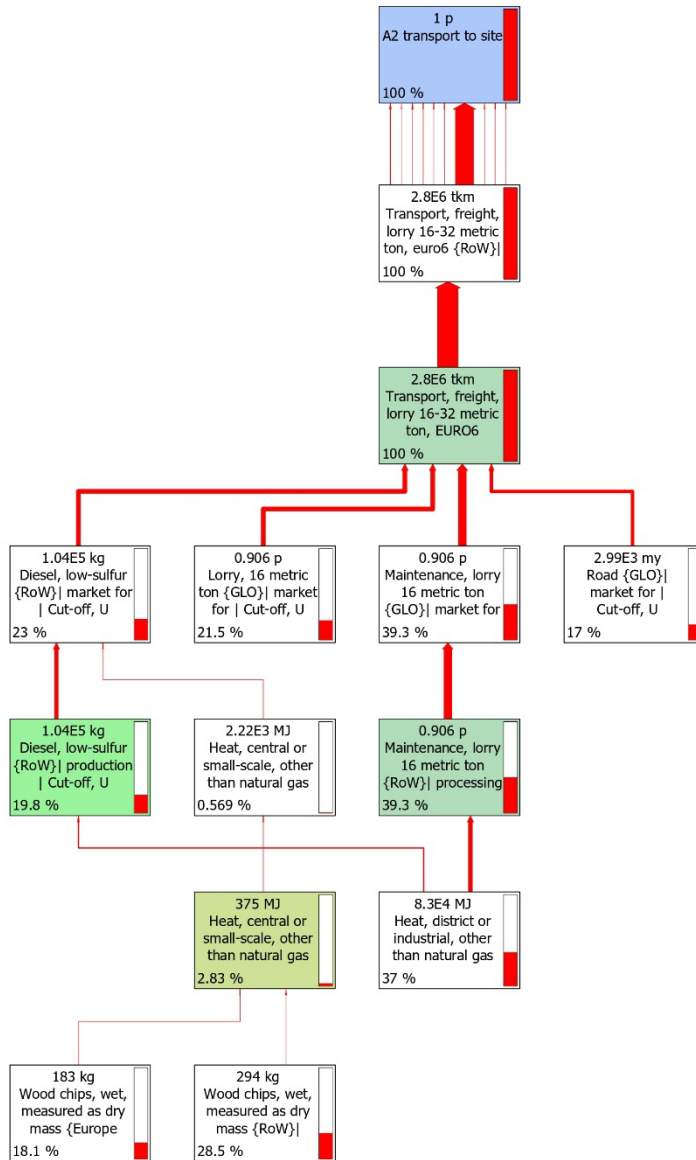


Figure 14: Global warming potential (GWP) of materials during the A2 transport stage

4.3 A3. Manufacturing

This stage accounts for the energy and fuel consumption associated with the off-site prefabrication of one modular housing unit at the manufacturing facility in Napierville, Québec. The A3 module represents factory-based processes required to assemble the structural frame, envelope systems, and primary building components prior to delivery to site, in accordance with the EN 15804 system boundary.

- **Factory Description**

The prefabricated modular unit is manufactured at an industrial facility located in Napierville, Québec. The facility has an approximate floor area of 6,000 m² and operates as a light industrial production space dedicated to modular housing. Each production cycle yields one complete floor module with dimensions of 16 × 24 ft (≈36 m²). Manufacturing activities include cutting and framing, installation of structural insulated panels (SIPs), placement of insulation layers, mounting of windows and doors, application of interior and exterior sheathing, and preliminary electrical and plumbing preparation

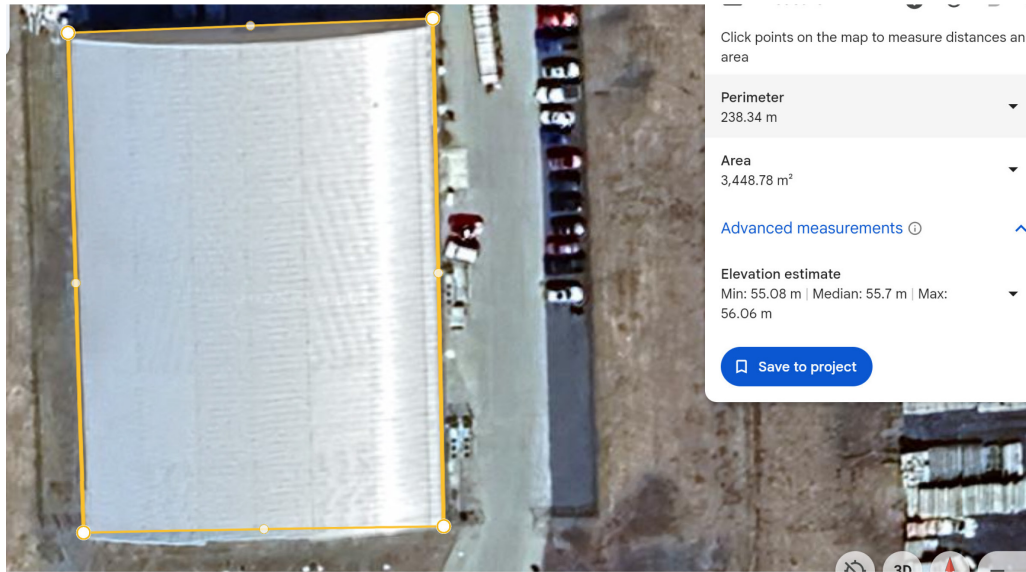


Figure 15: Satellite measurement of the Nunavik Modular facility area (≈3,449 m²) using Google Earth.

4.3.1. Goal and scope

The A3 module captures all direct energy and fuel inputs required for the factory-based manufacturing of one modular unit. Included processes comprise diesel-powered handling and lifting operations, electricity use for machinery, lighting, and small tools, and natural gas consumption for space heating and insulation curing, where applicable. Packaging materials, waste treatment beyond internal handling, and the embodied impacts of factory buildings and equipment are excluded, consistent with EN 15804 guidance.



Figure 16: Street view of the Nunavik Modular manufacturing facility in Napierville, Québec.

4.3.2. Data sources and assumptions

All background processes were modelled in SimaPro v9.5 using the ecoinvent v3.7 database (cut-off system model). Energy inputs were represented using regionally appropriate datasets and proxy values where site-specific measurements were unavailable:

- **Diesel consumption** was modelled using the dataset “*diesel, burned in building machine {GLO}*”, representing forklifts, loaders, telehandlers, and small generators used for material handling and assembly.
- **Electricity consumption** was modelled using “*electricity, low voltage {CA-QC}*”, reflecting Québec’s predominantly hydroelectric grid.
- **Natural gas use** for space heating and insulation curing was modelled using “*heat, district or industrial, natural gas {CA-QC}*”.

Energy quantities were estimated based on industrial benchmarks for modular prefabrication facilities and scaled to a single-unit production cycle. All assumptions were documented to ensure transparency and reproducibility.

Human labour metabolism (supplementary item)

For completeness, human labour metabolism was estimated as a supplementary item based on an average daily energy expenditure of approximately 2,500–3,000 kcal per worker per day, assuming a production crew of 15 workers over a three-day manufacturing period. This contribution is reported separately and is not included in the baseline A3 life cycle inventory totals, as human metabolism is not typically considered within EN 15804-compliant building LCAs. Its inclusion serves to contextualize the relative magnitude of factory energy and fuel emissions and is discussed qualitatively in the interpretation and sensitivity analysis.

4.3.3. Inventory

Per functional unit (one modular unit), the following energy inputs were included:

Table 6: Energy sources and associated GWP contributions for the A3

Source process	Amount (MJ / proxy)	GWP (kg CO ₂)	Notes
Diesel, burned in building machines	673 MJ	≈ 414	Diesel consumption from forklifts, telehandlers, lifting equipment, welding, and on-site assembly operations. Dominant contributor to A3 impacts.
Electricity, low voltage (CA-QC)	294 MJ	≈ 188	Electricity use for lighting, small tools, and semi-automated machinery. Modelled using Québec's low-carbon electricity mix.
Natural gas, industrial heating (CA-QC)	244 MJ	≈ 27	Space and process heating within the manufacturing facility. Minor contribution relative to diesel and electricity.
Subtotal A3 (energy only)	–	≈ 629	Energy-related manufacturing impacts modelled directly in SimaPro.
Human labour (reported separately)	manual	≈ 30	Literature-based estimate (≈ 0.05–0.1 kg CO ₂ per FTE·h × estimated labour hours). Reported for completeness, but excluded from percentage breakdown.
Total A3 (energy + labour)	–	≈ 659	Matches SimaPro inventory profile with supplementary labour reporting.

4.3.4. Results

Applying the IPCC 2013 GWP (100-year time horizon), the manufacturing stage (A3) captures the direct energy use and supporting activities associated with factory prefabrication of the modular unit.

Diesel combustion in mobile construction machinery, including forklifts, lifting equipment, and welding generators operating within the plant, emerges as the dominant contributor, accounting for approximately two-thirds of total A3 emissions ($\approx 66\%$), or about 414 kg CO₂ per unit. Electricity consumption (≈ 294 MJ), modelled using Québec’s low-carbon electricity mix (CA-QC), contributes close to 30% of manufacturing-stage emissions (≈ 188 kg CO₂). Although Québec’s grid is largely hydropower-based, the upstream processes included in the ecoinvent background dataset explain the non-negligible contribution observed at this stage. Industrial natural gas use for space and process heating within the factory (≈ 244 MJ) plays a comparatively minor role, contributing roughly 4% of A3 impacts (≈ 27 kg CO₂), which is consistent with the limited thermal requirements of modular manufacturing. To account for non-energetic contributions, a small proxy for human labour (≈ 30 kg CO₂ per unit) was included based on values reported in the literature. This contribution is reported separately for transparency and does not alter the relative ranking of energy-related hotspots. Overall, the A3 stage contributes approximately 659 kg CO₂ per modular unit. These results confirm that diesel fuel use and electricity consumption during factory operations represent the principal emission hotspots at the manufacturing stage, while natural gas heating and labour-related emissions remain secondary contributors.

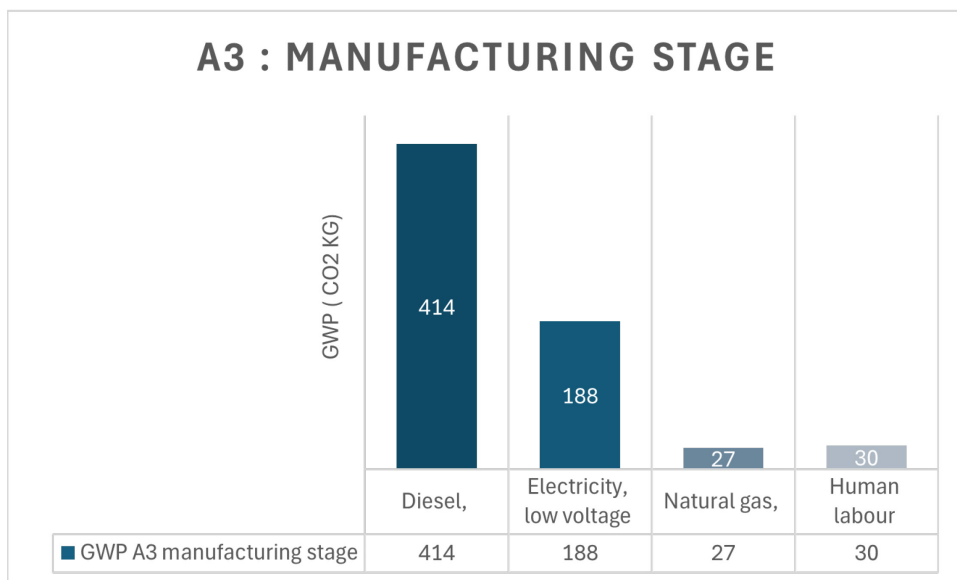


Figure 17 Contribution of Energy to co2 emission in the A3 stage (IPCC 2013 GWP 100)

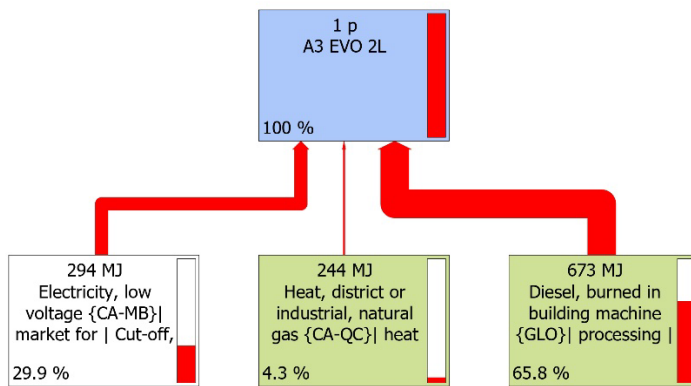


Figure 18 Sima pro contribution of energy-related GWP in A3 Manufacturing stage

4.4. A4 - Transportation to Northern Communities (Cradle-to-Site)

Module A4 quantifies the greenhouse gas emissions associated with transporting one standardized prefabricated modular housing unit from the manufacturing facility in southern Québec to northern construction sites.

In line with the thesis framework, the upstream life-cycle stages (A1–A3) and on-site installation activities (A5) are identical for all cases. Variability within Module A4 arises exclusively from differences in transport distance and routing to alternative northern destinations.

Three representative destinations, Kuujjuaq, Salluit, and Inukjuak, are assessed within the same A4 system boundary to reflect the range of logistics corridors currently served by the manufacturer.



Figure 19: On-site placement of prefabricated housing module using heavy machinery



Figure 20: 3 different destinations

4.4.1. Goal and scope

The goal of Module A4 is to assess the cradle-to-site transport impacts associated with delivering one prefabricated modular housing unit from the factory in Napierville, Québec, to northern construction sites. The functional unit remains one complete modular housing unit, consistent with previous life-cycle stages.

Module A4 includes:

1. Long-haul road transport from the factory to the southern port of departure.
2. A4 varies only by destination
3. Same vehicle types, same mass, same crew
4. Seasonal marine sealift to northern ports.
5. Local handling and short-distance trucking at the destination.
6. Passenger air transport for skilled southern workers is required during installation.

Packaging activities and on-site lifting or crane operations are excluded from this module and accounted for in Module A5.

4.4.2. Data sources and assumptions

The following assumptions apply to all destinations:

- **Module mass:** approximately 10 tonnes per unit (rounded for transport modelling);
- **Road freight (south):** lorry 16–32 t, EURO5 (ecoinvent, RoW);
- **Marine transport:** transoceanic cargo ship (ecoinvent, GLO) used as a proxy for sealift operations.
- **Local road freight:** lorry 3.5–7.5 t, EURO5 (ecoinvent, RoW);
- **Air transport:** six skilled workers flown from Montréal to the destination (round trip);
- **Databases:** eco-invent v3.7 (cut-off), modelled in SimaPro v9.5;
- **Distances:** derived from NEAS (2024) routing and shipping information

4.4.3 Transport to Kuujjuaq (Nunavik)

The A4 module includes all transport activities required to deliver the prefabricated housing module from the manufacturing facility in Napierville, Québec, to the construction site in three Nunavik communities: Kuujjuaq (baseline), Salluit, and Inukjuak.

The multimodal logistics chain is identical in structure for all destinations:

1. Road freight (factory → Port of Montréal)
2. Marine sealift (Port of Montréal → northern destination)
3. Local delivery (destination port → construction site)
4. Passenger air travel for skilled installation workers

All results are calculated using **IPCC 2013 GWP100** in SimaPro and reported in **kg CO₂**

Transport Inventory (per functional unit)

Table 7: A4 Results – Kuujjuaq

Segment	Distance (km)	Load	Transport work
Factory → Port of Montréal	54.6	10 t	546 t·km
Montréal → Kuujjuaq (sealift)	1,550	10 t	15,500 t·km
Port → Construction site	2	10 t	20 t·km
Skilled workers (air travel)	1,450	6 pax	8,700 p·km

Table 8: Emission of each segment in CO₂

Segment	Emissions (kg CO ₂)
Road freight (south)	290
Marine sealift	1,240
Local trucking	8
Skilled worker flights	542
Total A4	2,080 kg CO ₂

Interpretation

Marine transport dominates due to the significantly larger tonne-kilometre demand relative to the short local delivery segment. Aviation contributes notably due to high emission intensity per passenger-kilometre.

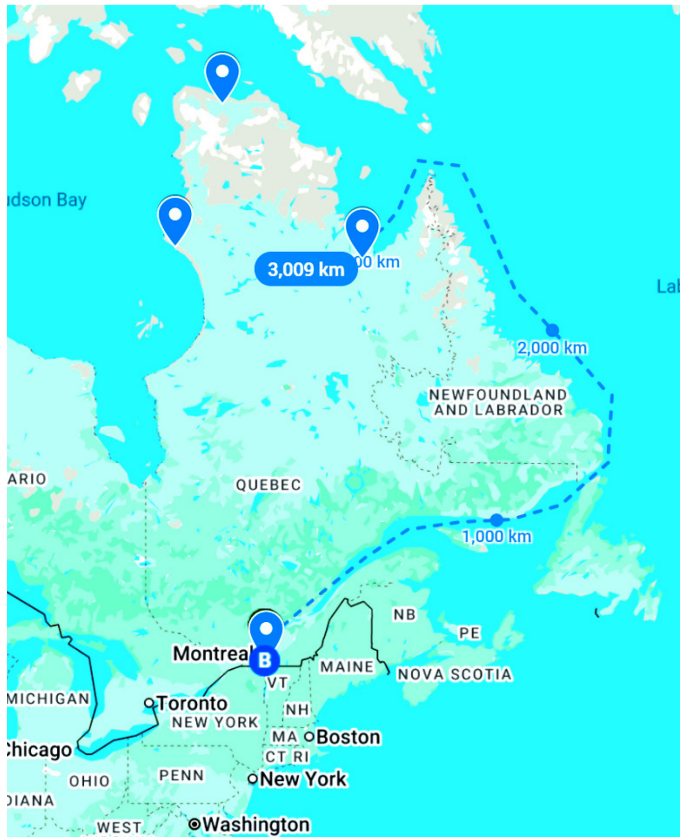


Figure 21: transportation from Quebec to Kuujuaq

Input/output	Parameters	
Name	Status	Comment
A4 EVO 2L Transport	None	
Materials/Assemblies	Amount	Unit
Add		
Processes	Amount	Unit
Transport, freight, lorry 16-32 metric ton, EUROS (RoW) transport, freight, lorry 16-32 metric ton, EUROS Cut-off, S	5000	tkm
Transport, freight, sea, transoceanic ship (GLO) market for Cut-off, S	32600	tkm
Transport, freight, lorry 3.5-7.5 metric ton, euro5 (RoW) market for transport, freight, lorry 3.5-7.5 metric ton, EUROS Cut-off, S	5100	tkm
Transport, passenger, aircraft (GLO) market for Cut-off, S	9540	personkm
Add		
Image		

Figure 22: Sima pro result for A4

4.4.4 Transport to Salluit

Salluit is located further northwest than Kuujjuaq, increasing the marine transport requirement along the Hudson Strait corridor.

Transportation to Salluit:

The sensitivity of the transport phase (A4), the first alternative destination considered was Salluit, a northern community located further northwest of Kuujjuaq in Nunavik. Like Kuujjuaq, Salluit is served by the NEAS seasonal sealift network, but its greater distance from southern Québec increases overall shipping requirements.

The transport chain in this scenario mirrors the baseline configuration. Prefabricated modules are first moved by heavy-duty truck from the Napierville factory to the Port of Montréal, then transported by marine vessel through the Hudson Strait to Salluit. Upon arrival, the modules are transferred to smaller local trucks for final on-site delivery. In addition, six skilled workers are flown from Montréal to Salluit to supervise installation and commissioning.

Transport distances and modes were derived from NEAS (2024) routing data to ensure realistic logistics assumptions. All other factors, including vehicle types, payloads, and handling procedures, remain identical to the baseline case. This configuration allows the scenario to isolate the influence of destination distance on cradle-to-site emissions while maintaining consistent operational conditions.

Table 9: Results – Salluit Transport Inventory

Segment	Distance (km)	Load	Transport work
Factory → Port of Montréal	54.6	10 t	546 t·km

Montréal → Salluit (sealift)	3,574	10 t	35,740 t·km
Port → Construction site	51	10 t	510 t·km
Skilled workers (air travel)	1,450	6 pax	8,700 p·km

Table 10: Emission of each segment in CO₂

Segment	Emissions (kg CO ₂)
Road freight (south)	290
Marine sealift	1,720
Local trucking	75
Skilled worker flights	445
Total A4	2,530 kg CO₂

Interpretation

The extended marine distance increases sealift emissions substantially. Sealift remains the dominant contributor, followed by aviation.

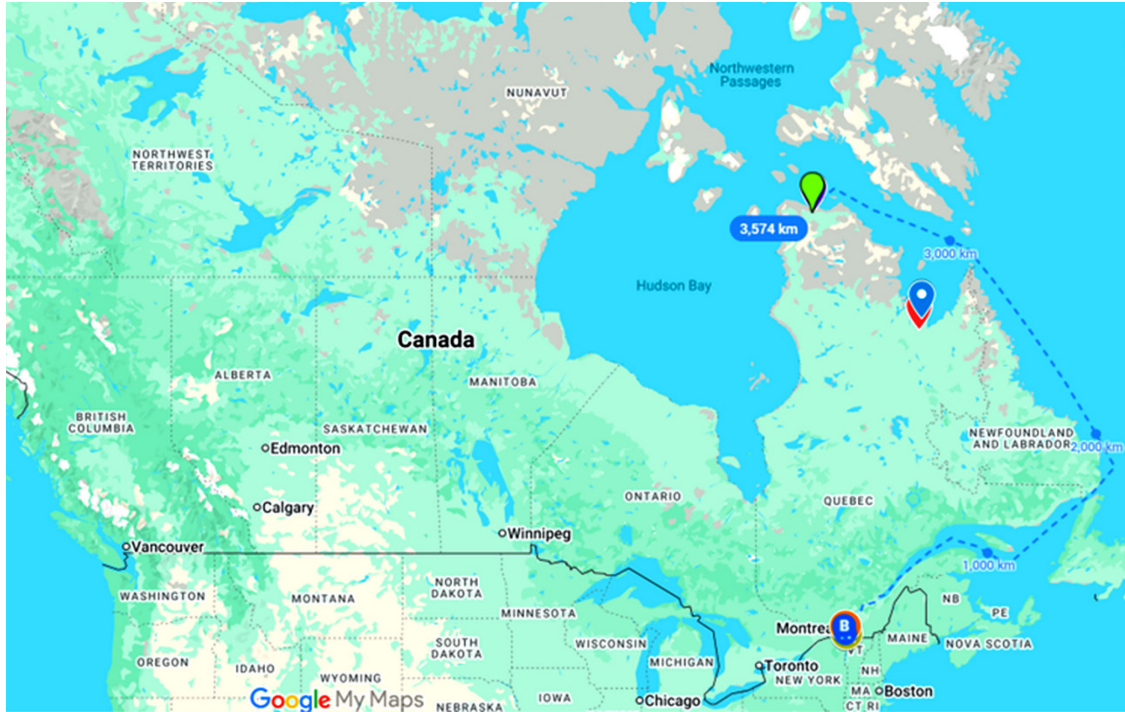


Figure 23: Transportation to Salluit

4.4.5 Transport to Inukjuak

Inukjuak is located along the eastern coast of Hudson Bay. Unlike Kuujuaq and Salluit, port infrastructure limitations require additional offshore handling via barge before final on-site delivery.

In the second scenario, the delivery destination is changed from Kuujuaq to Inukjuak, another northern community in Nunavik that is regularly supplied by the regional construction company. Inukjuak is located on the eastern coast of Hudson Bay, farther west than Kuujuaq, and is accessible only seasonally by marine sealift and small aircraft. These geographic and operational conditions result in a slightly different logistics chain compared to the base case.

As in the other scenarios, prefabricated modules are first transported by heavy-duty truck from the Napierville factory to the Port of Montréal. From there, the sealift route follows the Hudson Bay corridor instead of the Hudson Strait, extending the marine distance and requiring additional cargo handling operations. Upon arrival at the Inukjuak port, modules are typically unloaded onto barges or smaller vessels before being transferred ashore and delivered to the site by local truck.

Like Kuujuaq and Salluit, six skilled workers are flown from Montréal to Inukjuak to oversee installation, although this flight covers a shorter distance compared to the other Nunavik routes. Including Inukjuak in the scenario analysis provides a realistic representation of common northern housing deliveries, while also illustrating how sealift dependency and additional barge handling can influence the embodied carbon profile of modular construction logistics.

Table 11: Transport Inventory - Inukjuak

Segment	Distance (km)	Load	Transport work
Factory → Port of Montréal	54.6	10 t	546 t·km
Montréal → Hudson Bay (sealift)	2,300	10 t	23,000 t·km
Offshore → Shore (barge transfer)	3	10 t	30 t·km
Shore → Construction site	1.5	10 t	15 t·km
Skilled workers (air travel)	1,230	6 person	7,380 p·km

Table 12: Emission of each segment in CO₂

Segment	Emissions (kg CO ₂)
Road freight (south)	290
Marine sealift	1,480
Barge handling	6
Local trucking	6
Skilled worker flights	448
Total A4	2,230 kg CO₂

Interpretation

Sealift remains the dominant contributor due to long-distance marine transport. Barge handling and local trucking contribute marginally due to very short transport distances. Air travel continues to represent the second most influential source of emissions.

The comparative results clearly demonstrate the strong sensitivity of the A4 module to marine transport distance. Since all three scenarios share identical assumptions for module weight,

transport modes, vehicle classes, and worker logistics, differences in A4 emissions are primarily driven by variations in sealift distance.

Salluit exhibits the highest total A4 emissions (2,530 kg CO₂), which is consistent with its more northerly location along the Hudson Strait corridor. The extended marine route significantly increases tonne-kilometre demand, thereby amplifying overall transport emissions. In contrast, Kuujjuaq presents the lowest A4 impact (2,080 kg CO₂) due to its comparatively shorter sealift distance and minimal local delivery requirements. Inukjuak (2,230 kg CO₂) falls between the two, reflecting an intermediate marine distance and additional handling requirements associated with limited port infrastructure.

These findings confirm that, within northern modular construction logistics, marine transport distance is the dominant determinant of cradle-to-site transport emissions. Consequently, project location within Nunavik can alter A4 emissions by more than 20%, even when construction specifications and transport configurations remain unchanged.

Table 13:A4 results between different cities

Destination	Total A4 (kg CO₂)
Kuujjuaq	2,080
Salluit	2,530
Inukjuak	2,230

The results confirm that A4 emissions increase with marine distance. Salluit exhibits the highest transport emissions due to extended sealift requirements, while Kuujjuaq represents the lowest among the three communities.

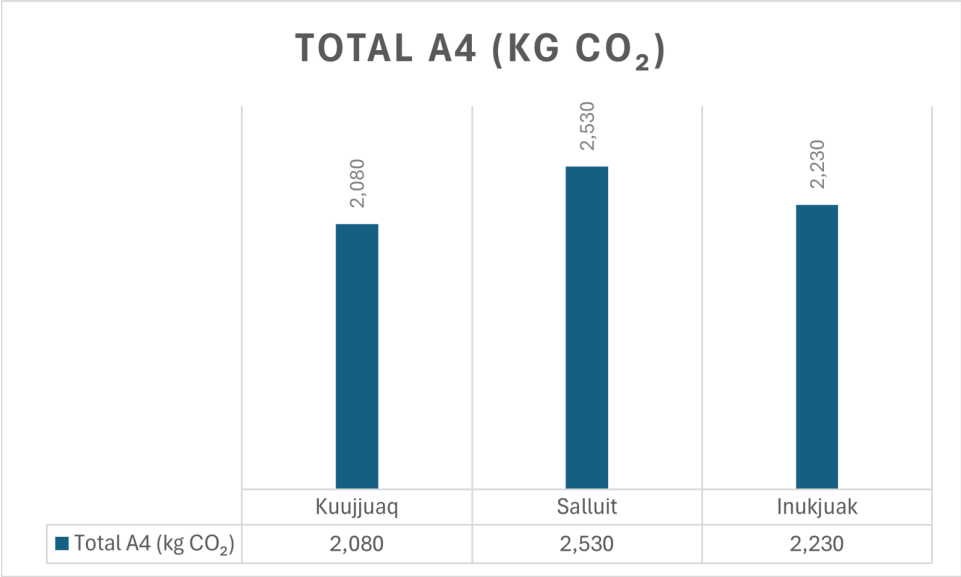


Figure 24: A4 comparison column charts

4.5. A5. Construction / Installation

The A5 stage represents the on-site installation of one prefabricated modular housing unit at the destination site. While the majority of material processing and assembly activities occur off-site (Modules A1–A3), additional operations are required once the module arrives on-site.

These activities include crane operation for lifting and positioning the unit, telehandler use for minor adjustments, and temporary electricity demand for site lighting, power tools, and ventilation. In some cases, temporary space heating is required to maintain acceptable working conditions during installation. To ensure consistency with the upstream life-cycle stages, installation activities are assumed to be identical across all destination sites. As a result, Module A5 is modelled independently of geographic location, allowing transport-related variability to be isolated within Module A4. Human labour metabolism is included as a minor but measurable source of emissions to provide a complete representation of on-site installation activities

4.5.1. Goal and scope

The goal of Module A5 is to quantify the greenhouse gas emissions associated with the on-site installation of one prefabricated modular housing unit.

The functional unit remains one complete modular unit, consistent with previous life-cycle stages. Module A5 includes fuel and electricity use for lifting, positioning, and temporary site operations, as well as space heating where required. Human labour metabolism is reported as a supplementary contribution.

Installation activities are assumed to be uniform across all destination sites, and therefore independent of transport distance or regional context. Packaging disposal and infrastructure-related impacts are excluded, in accordance with EN 15804 system boundaries.



Figure 25. A5 installation of one prefabricated unit

4.5.2. Data sources and assumptions

Databases: ecoinvent v3.7 (cut-off), modelled in SimaPro v9.5

Diesel fuel:

“Diesel, burned in building machine {GLO}” for crane and telehandler operation

Electricity:

“Electricity, low voltage {CA-QC}” for temporary site electricity (lighting, tools, ventilation)

Natural gas:

“Heat, natural gas, boiler condensing modulating {CA}” to represent temporary space heating

Human labour:

6 workers × 3 days, approximated at 2 kg CO₂ per worker per day → 36 kg CO₂ total (manual input)

Waste:

Minor packaging and off-cut waste excluded (<2% of module mass)

4.5.3. Inventory (per functional unit)

Table 14: Inventory of on-site installation processes A5

Process	Purpose	Amount	Unit	Notes
Diesel, burned in the building machine {GLO}	Crane & telehandler operation	2.33	GJ	≈ 65 L diesel
Electricity, low voltage {CA-QC}	Lighting, tools, ventilation	1.71	GJ	≈ 475 kWh
Heat, natural gas, boiler condensing {CA}	Temporary site heating	1.14	GJ	≈ 30 m ³
Human labour (manual input)	Worker metabolism	36	kg CO ₂	6 workers × 3 days

4.5.4. Results

The on-site installation stage (A5) generates a total of approximately 443 kg CO₂ per unit. Diesel consumption associated with crane and telehandler operation is the dominant contributor, accounting for about 52% of total A5 emissions. Temporary electricity use contributes approximately 26%, while natural gas used for space heating represents around 14%.

Human labour metabolism contributes approximately 8% of total A5 emissions and remains a secondary factor relative to energy use. Overall, Module A5 contributes less to total cradle-to-site emissions than Modules A1 and A4 but exceeds the impacts of A2 and is comparable in magnitude to A3. These results confirm that, despite the advantages of prefabrication, on-site installation remains reliant on diesel-powered equipment. This highlights potential mitigation opportunities through the adoption of electric or hybrid lifting equipment and reduced reliance on temporary fossil-based heating.

Table 15:A5 total co2 emission

Source	Energy (GJ)	GWP (kg)	Share
Diesel (crane & telehandler)	2.33	230	52%
Electricity (tools, lighting, ventilation)	1.71	117	26%
Natural gas (temporary heating)	1.14	60	14%
Human labour metabolism	,	36	8%
Total A5	5.18	443	100%

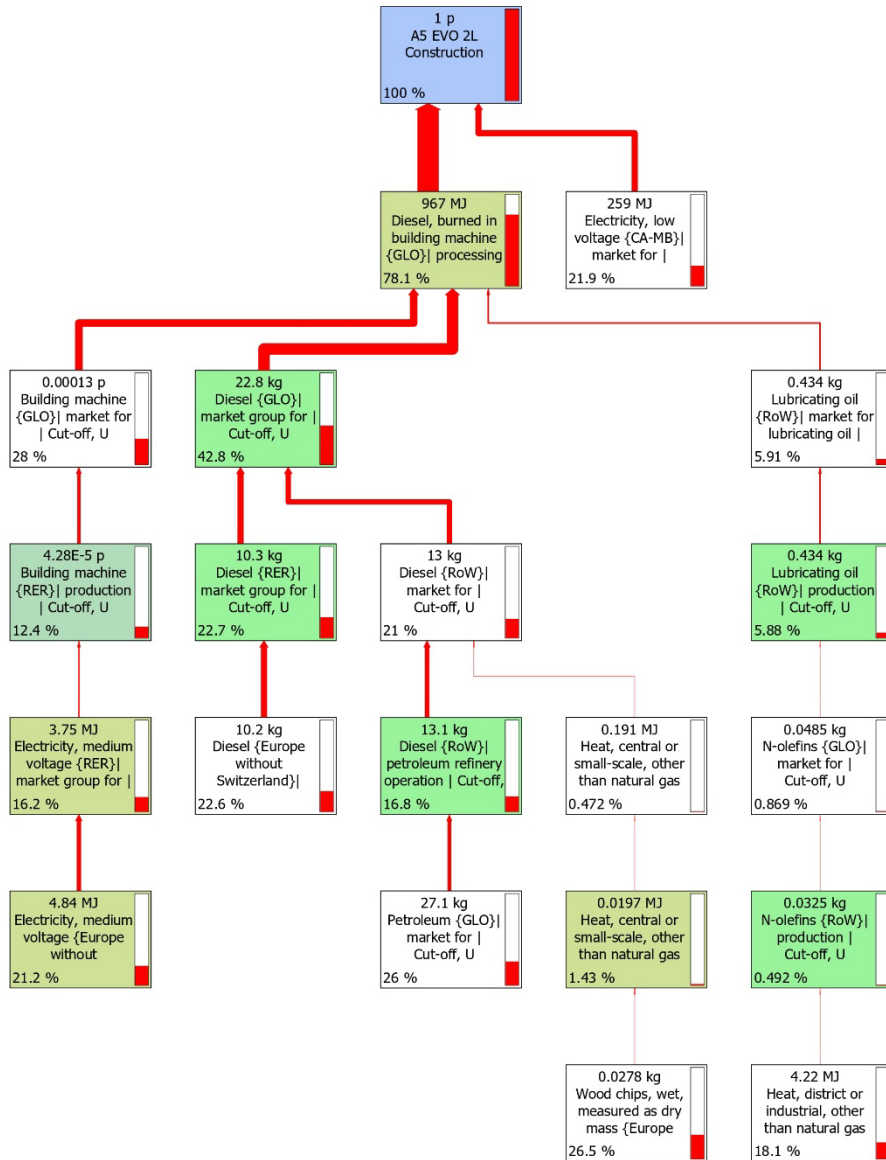


Figure 26: A5 Sima pro Diagram

4.6 Discussion and synthesis of cradle-to-site results (A1–A5)

This section synthesizes the cradle-to-site life cycle assessment results (Modules A1–A5) for one prefabricated modular housing unit delivered to three Nunavik communities: Kuujuaq, Salluit, and Inukjuak. These modules include material production (A1), supplier transport (A2), factory manufacturing (A3), multimodal transport to site (A4), and on-site installation (A5).

Across all scenario's, embodied emissions are dominated by upstream material production, while transportation to remote destinations represents the second most influential stage. 4.6.1 Contribution of each life-cycle stage

4.6.1 Stage Contributions

A1 – Raw material production

Emissions from material production amount to:

13,100 kg CO₂

This stage represents approximately 78–80% of total cradle-to-site emissions across all destinations. Structural steel is the primary contributor within this module.

A2 – Transport to factory

Supplier transport contributes:

174 kg CO₂

This represents roughly 1% of total emissions and reflects relatively short southern Québec supply distances.

A3 – Manufacturing (factory operations)

Factory energy use contributes:

659 kg CO₂

Diesel-powered material handling and welding dominate this stage, followed by electricity consumption under Québec's low-carbon grid.

A4 – Transport to site (multimodal + crew travel)

Transport emissions vary by destination:

- **Kuujuuaq:** 2,080 kg CO₂
- **Salluit:** 2,530 kg CO₂
- **Inukjuak:** 2,230 kg CO₂

Marine sealift is the dominant contributor within A4, followed by passenger air travel for skilled installation crews. Southern trucking and short-distance local delivery contribute comparatively minor shares.

A5 – On-site installation

On-site installation contributes:

443 kg CO₂

Diesel-powered cranes and telehandlers account for over half of these emissions, with temporary electricity, space heating, and worker metabolism contributing smaller shares.

Table 16: A1-A5 results

	Name	CO ₂ (kg CO ₂)
A1	Raw material	13,100
A2	Transport to factory	174
A3	Manufacturing	659
A4-K	Transport to site – Kuujjuaq	2,080
A4-S	Transport to site – Salluit	2,530
A4-I	Transport to site – Inukjuak	3,750
A5	On-site installation	443

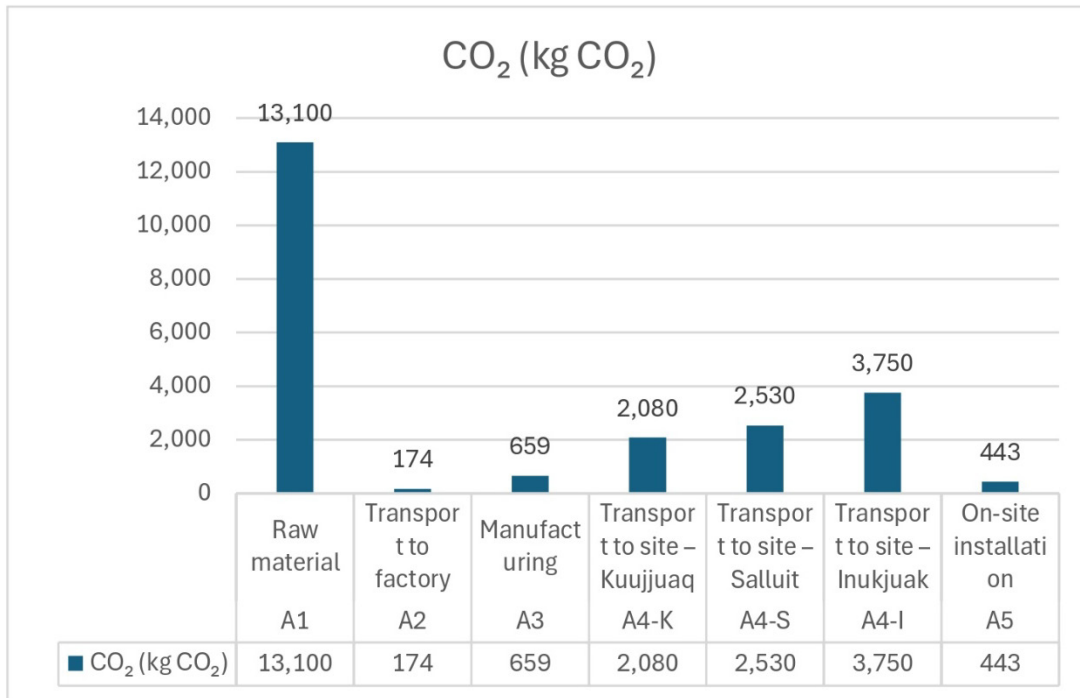


Figure 27: Column chart of (A1-A5) for different destinations

Table 17: Comparison of A1-A5 in 3 different destinations.

Stage	Name	Indicator	Kuujuuaq	Salluit	Inukjuak
A1	Raw material supply & processing	kg CO ₂	13,100	13,100	13,100
A2	Transport to the factory	kg CO ₂	174	174	174
A3	Manufacturing (factory energy)	kg CO ₂	659	659	659
A4	Transport to site	kg CO ₂	2,080	2,530	3,750
A5	On-site installation	kg CO ₂	443	443	443
Total A1–A5	Cradle-to-site	kg CO ₂	16,456	16,906	18,126

4.6.2 Sensitivity and Uncertainties

While the overall trends observed across Modules A1–A5 remain robust, several key sources of uncertainty should be acknowledged.

First, material quantities, particularly structural steel, represent the most influential parameter in the entire cradle-to-site system. With A1 accounting for approximately 13,100 kg CO₂ (\approx 78–80% of total emissions across all destinations), a \pm 10–20% variation in steel mass would shift total cradle-to-site emissions by several tonnes. This confirms that material specification decisions dominate uncertainty propagation within the system.

Second, transport modelling assumptions introduce variability in Module A4. Although marine sealift distances were based on representative routing data, real-world emissions may vary due to vessel loading efficiency, backhauling conditions, weather delays, and seasonal shipping windows in Nunavik. Passenger air travel assumptions, including aircraft type, occupancy rate, and whether trips are modelled as one-way or round-trip, also influence A4 outcomes. However, even under variation, marine sealift remains the dominant transport contributor.

Third, energy mix assumptions affect results in A3 (manufacturing) and A5 (installation). The use of Québec’s hydro-dominated electricity grid results in comparatively low electricity-related emissions. Applying a Canadian-average electricity mix would increase electricity contributions in these modules by a factor of approximately five to ten, though total cradle-to-site emissions would still remain material-dominated.

Finally, human labour metabolism contributes a minor share (approximately 30–40 kg CO₂ per unit). As its inclusion is optional in building LCAs and does not materially affect stage ranking or total outcomes, it does not influence the primary conclusions of this study.

4.6.3 Benchmarking with Literature

The cradle-to-site embodied emissions calculated in this study range from:

1. **16,456 kg CO₂ (Kuujuuaq)**
2. **16,606 kg CO₂ (Inukjuak)**
3. **16,906 kg CO₂ (Salluit)**

These values fall within the range reported in previous literature for modular housing systems.

Bilec et al. (2006) reported cradle-to-site emissions between 12 and 18 t CO₂ for steel-framed modular housing units of comparable size. Similarly, Rauf and Crawford (2019) identified values ranging from 14 to 20 t CO₂ for hybrid timber–steel modular dwellings in cold-climate regions. Häkkinen and Wirtanen (2011) further observed that transportation may account for 10–15% of total embodied emissions in remote construction projects, aligning closely with the 13–15% contribution of A4 observed in the present study.

Overall, these comparisons confirm that the results obtained here are realistic, technically plausible, and consistent with the expected embodied carbon intensity of modular housing delivered to remote northern communities.

4.6.4 Implications

The results highlight several implications for prefabricated modular housing deployment in the northern regions.

First, material production dominates embodied emissions, indicating that material substitution, particularly reducing structural steel intensity in favour of engineered timber or hybrid structural systems offers the greatest mitigation potential. Even moderate reductions in steel mass would produce substantially larger emission savings than optimization in later life-cycle stages.

Second, transport logistics remain a critical sensitivity factor in northern contexts. While not exceeding material impacts, A4 emissions vary meaningfully between destinations (≈ 450 kg difference between the lowest and highest cases). Improvements in vessel efficiency, optimized sealift scheduling, and reduced reliance on air travel for installation crews could further decrease cradle-to-site impacts.

Finally, although on-site installation (A5) represents a smaller share of total emissions ($\sim 3\%$), it remains an opportunity for improvement. Transitioning from diesel-powered cranes and telehandlers to electric or hybrid equipment would reduce direct construction emissions and improve local air quality in remote communities.

4.7 Introduction to the Use Stage in Building Life Cycle Assessment

In building Life Cycle Assessment (LCA), the use stage (Modules B1–B7) represents all environmental impacts occurring after construction and before end-of-life. According to internationally recognized LCA standards for buildings (e.g., EN 15978 and EN 15804), this stage captures impacts associated with building operation, maintenance, repair, replacement, refurbishment, operational energy consumption, and operational water use over the defined Reference Study Period.

Unlike the product and construction stages (A1–A5), which quantify embodied emissions prior to occupancy, the use stage reflects long-term operational and performance-related impacts that accumulate throughout the building's service life. For residential buildings in cold climates, such as those located in Nunavik, the use stage may be influenced by harsh environmental conditions, maintenance logistics, and energy demand patterns.

In this study, the use stage is evaluated over a 50-year reference study period, consistent with common practice in building LCA literature. Modules B1 through B7 are assessed in accordance with standard methodological guidance and adapted to the specific characteristics of the prefabricated modular housing unit examined.

4.7.1.B1-Use of the Building (Emissions in Use)

Module B1 accounts for direct emissions occurring during the normal use of the building that are not related to operational energy or water consumption. According to EN 15978, such emissions may include on-site fuel combustion, refrigerant leakage from cooling systems, or other emission-generating processes located within the building system boundary.

In the prefabricated modular dwelling assessed in this study, no direct on-site emissions occur during the use phase. The building utilizes a glycol-based hydronic radiant floor distribution system. In the EnergyPlus model, space heating demand is represented as delivered thermal energy (reported as “District Heating Water”), indicating that heat is supplied from an external source rather than generated through on-site fuel combustion. Furthermore, the dwelling is not equipped with refrigerant-based cooling systems or other emission-producing equipment within the building boundary.

Accordingly, in line with EN 15978 and common residential building LCA practice, Module B1 is assumed to contribute 0 kg CO₂ per year, and therefore 0 kg CO₂ over the 50-year reference study period. All impacts associated with operational energy use, including space heating and electricity consumption, are accounted for separately under Module B6 (Operational Energy Use).

4.7.2.B2- Maintenance Stage

1. Scope and Assumptions (50-year service life)

Module B2 represents the routine maintenance activities required to preserve the functional and aesthetic performance of the prefabricated modular dwelling over a 50-year reference service life. The unit is located in Nunavik's subarctic climate, where low temperatures, wind exposure, and moisture impose specific durability requirements on envelope materials and building systems.

Maintenance activities considered in this stage exclude full component replacements, which are reported under Module B4, and focus instead on consumables, coatings, and minor elements that require periodic intervention. Based on manufacturer documentation, standard practice for cold-climate buildings, and values reported in the literature, the following maintenance operations were included:

1. Periodic top-up of glycol in the radiant floor heating loop every five years,
2. Repainting of exterior steel cladding every fifteen years,
3. Resealing of façade joints and window gaskets every ten years,
4. Minor annual touch-ups of anti-corrosion protective coatings,
5. Partial replacement of LED light sources and corroded fasteners over the study period.

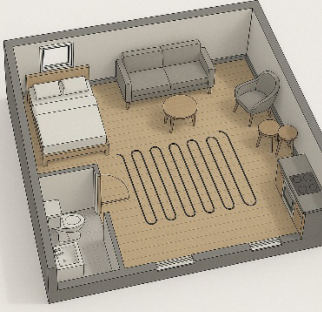

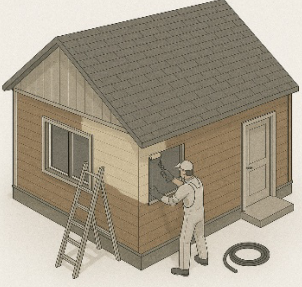

These activities were modelled in SimaPro v9.5 using representative datasets from ecoinvent v3.7 (cut-off). Where direct datasets were unavailable, proxy processes were applied (e.g., polymer production for sealants and gaskets, coating processes for paints, and chemical proxies for glycol-based fluids). All assumptions were applied consistently across the 50-year lifespan.

Results:

The total embodied greenhouse gas emissions associated with maintenance activities amount to approximately 870 kg CO₂ over 50 years. The dominant contributors are the periodic glycol refilling of the heating system and the repainting of the steel façade, which together account for nearly 80% of the B2 impact.

Although maintenance emissions remain small compared to the cradle-to-site impacts (A1–A5), their inclusion ensures a complete life-cycle perspective and improves the robustness of the cradle-to-grave assessment in accordance with EN 15978 system boundaries.

Table 18: B2 Maintenance Modelling (50-year service life)

	Code	Activity	Frequency (50 y)	System Component
	B2-Glycol	Top-up of glycol fluid in radiant floor system	Every 5 yrs (10×)	Mechanical – radiant heating loop
	B2-Recoat	Repainting steel façade (two coats)	Every 15 yrs (yrs 15, 30, 45)	Building envelope – steel cladding
	B2-Gasket	Replacement of door / window gaskets	Every 10 yrs (5×)	Openings – windows & doors
	B2-Sealant	Renewal of joints / sealants (PU or silicone)	Every 10 yrs (5×)	Envelope – façade joints & openings



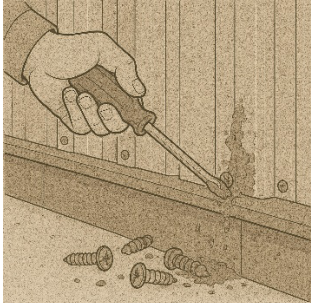
	B2-LED	Partial replacement of LED light sources	Every 10–12 yrs (≈ 10 units)	Electrical – lighting system
	B2-Touch-up	Minor anti-corrosion paint repairs	Annual small applications	Envelope – steel façade
	B2-Fasteners	Replacement of corroded fasteners	Once in 50 yrs	Connections – façade / structure

Table 19:B2 – Maintenance (50-year service life)

	Product	Frequency (in 50 y)	Sima pro dataset name	Quantity	CO ₂ (kg)
1	Glycol heating fluid (top-up)	Every 5 years (10×)	Hydraulic fracturing fluid {GLO} production,	0.20 m ³ (≈ 222 kg) (total for 10 cycles)	≈ 550
2	Façade paint (recoating, 2 coats)	Every 15 years (3×)	Laminating service, foil, with acrylic binder {CA-QC}	198 m ² (total for 3 cycles)	≈ 155
3	Window/door gaskets (EPDM)	Every 10 years (5×)	Extrusion, plastic film {RoW}	3.9 kg (total for 5 cycles)	≈ 11
4	Joint sealant (PU / silicone)	Every 10 years (5×)	Polymer foaming {CA-QC}	18 kg (total for 5 cycles)	≈ 72
5	Minor paint touch-up	Small annual repairs	Laminating service, foil, with acrylic binder {CA-QC}	3.5 m ²	≈ 3

6	LED light sources (partial replacement)	Every 10–12 years	Lamp, LED	1 kg (~10 pcs)	≈ 60
7	Corroded fasteners (steel)	Once every 50 years	Steel, low alloy	1 kg	≈ 2
Total					≈853–870

B2 – Maintenance stage description

The B2 stage represents the routine maintenance and partial replacement activities required throughout the 50-year service life of the prefabricated modular unit. Based on the manufacturer’s technical documentation and standard maintenance cycles for building systems in cold climates, this stage includes the top-up of glycol in the radiant floor heating loop every five years, repainting of the steel façade every fifteen years, resealing of façade joints and window gaskets every ten years, and minor annual anti-corrosion paint touch-ups. In addition, partial replacement of LED light sources and corroded fasteners were considered over the study period. These maintenance operations were modelled in SimaPro v9.5 using representative datasets from Ecoinvent 3.7 (cut-off, U). Proxy processes were selected for materials with no direct dataset (e.g., hydraulic fracturing fluid for glycol, polymer foaming for polyurethane sealant, plastic film extrusion for EPDM gaskets, and laminating service with acrylic binder for paint). The total embodied carbon of these recurring activities was estimated at approximately 0.86 t CO₂ over 50 years, with the glycol refilling and façade recoating accounting for nearly 80 % of the total maintenance impact. Although these operations represent a relatively small share compared to the cradle-to-site emissions (A1–A5), their inclusion ensures a complete cradle-to-grave assessment consistent with EN 15978 system boundaries

Total CO₂ emission B2: 870 kg over 50 years

4.7.3.B3 – Repair Stage (50-year service life)

The B3 stage includes localized repair works that restore the function of components during the 50-year service life of the modular unit. These repairs differ from maintenance (B2) because they occur only after a failure or physical damage, not as regular preventive actions. For buildings located in Northern climates such as Nunavik, the most common repair needs arise from corrosion of façade panels, minor leaks in radiant floor loops, and small electrical or fastening failures due to thermal stress and freeze–thaw cycles. All repair actions were modelled in SimaPro v9.5 using Ecoinvent 3.7 (cut-off, U) datasets corresponding to the material replaced and its re-installation. The inventory assumed one or two repair events per component during the 50-year service life.

Table 20: B3 Repair Stage (50-year service life)

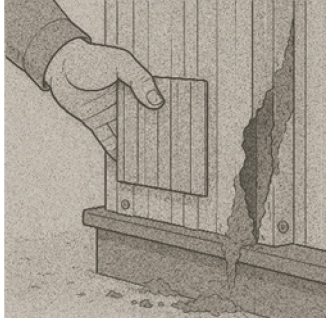
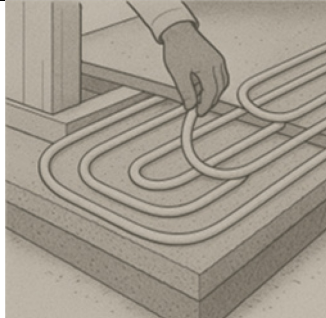
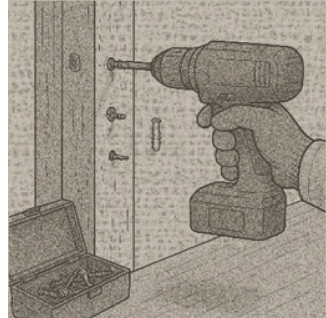
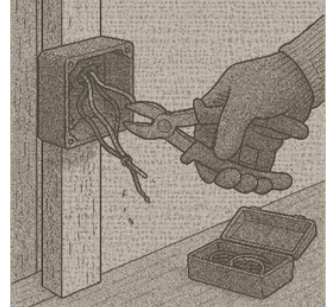
#	Code	Activity	Frequency (50 y)	System Component
	B3- steel cladding	Localized repair of damaged or corroded exterior steel cladding (cut-out and patch replacement)	Every 25 years → 2× total	Building envelope, exterior steel cladding
	B3- PEX tubing	repair of hydronic radiant floor heating loop (replacement of damaged PEX tube section)	Once in 50 years → 1×	Mechanical system , radiant floor heating (PEX loop)
	B3 - wall fasteners & anchors	Replacement/repair of interior wall fasteners and anchors (corroded or loose steel fasteners reinstalled or replaced)	Once in 50 years → 1×	
	B3	Localized repair of damaged electrical wiring segment (removal and replacement of ~21 m cable inside walls)	Once in 50 years → 1×	Electrical system, internal wiring and junction boxes

Table 21:-B3 Repair Modelling (50-year service life)

Component repaired	Frequency (50 y)	Quantity	SimaPro dataset used	CO ₂ emission (kg)
Exterior steel cladding (localized repair)	2	47 kg	`steel, low-alloyed {RER}	steel production, converter, low-alloyed
Radiant floor loop (PEX tubing)	1	5 kg	`polyethylene, high density, granulate {RER}	production
Interior wall fasteners/anchors	1	1 kg	`steel, low-alloyed {RER}	steel production, converter, low-alloyed
Electrical wiring segment	1	21 m	`cable, three-conductor cable {GLO}	production
Subtotal (PEX + wiring)	-	-	-	≈ 75.4
Total (B3)				≈ 171

B3 – Repair Stage:

The B3 repair stage accounts for localized corrective actions carried out during the 50-year service life of the modular housing unit. Unlike regular maintenance (B2), which involves periodic preventive activities, the B3 stage represents reactive interventions, minor repairs undertaken only when a partial failure or physical damage occurs. In northern conditions such as Nunavik, the most common repair needs are associated with façade corrosion, small leaks in the radiant floor heating loop, loosening of interior fasteners, and minor electrical wiring failures caused by freeze–thaw cycles and material fatigue.

The repair inventory was modelled in SimaPro v9.5 using Ecoinvent 3.7 “Cut-off, U” datasets for each replaced component. Four representative repair actions were included: localized replacement of steel façade panels (47 kg steel), small-scale repair of PEX radiant floor tubing (5 kg HDPE equivalent), re-anchoring of interior fasteners (1 kg steel), and replacement of a short electrical cable segment (≈ 21 m). The model estimated total emissions of ≈ 171 kg CO₂, of which the steel façade repair contributed the most (≈ 92 kg CO₂), followed by combined PEX tubing and wiring repairs (≈ 75 kg CO₂). Fastener replacements contributed less than 5 kg CO₂.

Overall, the B3 repair stage represents less than 1 % of the cradle-to-site (A1–A5) embodied emissions, confirming the high durability and reparability of the prefabricated modular design. Including this stage ensures a comprehensive cradle-to-grave system boundary in accordance with EN 15978, and demonstrates that maintenance and repair requirements for northern modular housing are minimal compared with material production and transportation stages.

4.7.4. B4 – Replacement Stage

The B4 stage includes the complete replacement of components whose service life is shorter than the building’s 50-year reference life. Unlike B2 (maintenance) or B3 (localized repair), this stage assumes full removal and substitution of elements that reach the end of life, such as flooring, windows, interior finishes, and mechanical equipment. Replacements were modelled in SimaPro v9.5 using Ecoinvent 3.7 “Cut-off, U” datasets corresponding to each product type.

Table 22: B4 Replacement Modelling (50-year service life)

Component replaced	Frequency (50 y)	Quantity	SimaPro dataset used	CO ₂ emission (kg)
Vinyl flooring (PVC)	Every 25 years (2×)	72 kg	`Polyvinylchloride, bulk polymerized {RER}	polyvinylchloride production, bulk polymerization
Interior drywall panels	Every 25 years (2×)	300 kg	`Gypsum plasterboard {RER}	gypsum plasterboard production
Mechanical pump (circulation)	Every 20 years (2× + partial 3rd)	1 p	`Pump station {Row}	construction
Windows (aluminum triple-pane)	Every 30 years (1–2×)	5.8 m ²	`Window frame, aluminum, U=1.6 W/m ² K {Row}	production
Exterior door (aluminium/composite)	Every 30 years (1–2×)	0.022 m ³ (~60 kg eq.)	`Aluminum, wrought alloy {RER}	aluminum production, wrought alloy
Lighting fixtures (LED)	Every 10–12 years (≈ 5×)	10 pcs (≈ 1 kg)	`Ultraviolet lamp {GLO}	ultraviolet lamp production, for water disinfection
Total repair:				1 205 kg CO₂

Name: b4 Status: None Comment:


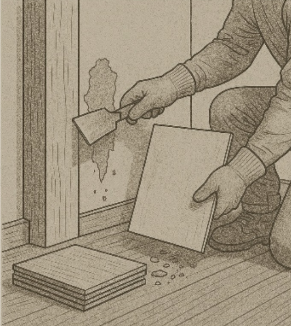
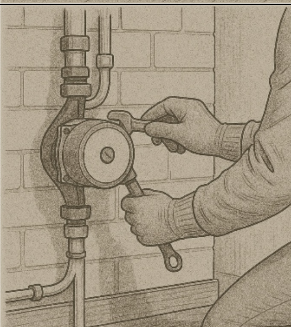

Materials/Assemblies	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Polyvinylchloride, bulk polymerised {RoW} polyvinylchloride production, bulk polymerisation Cut-off, U	72	kg	Undefined				
Gypsum plasterboard, technology mix of plasterboard production, production mix at factory, 12.5 mm tl	300	kg	Undefined				
Pump station {RoW} construction Cut-off, U	1	p	Undefined				
Window frame, poly vinyl chloride, U=1.6 W/m2K {RoW} production Cut-off, U	5.76	m2	Undefined				
Plywood, for outdoor use {CA-QC} production Cut-off, U	0.10	m3	Undefined				
Ultraviolet lamp {GLO} ultraviolet lamp production, for water desinfection Cut-off, U	10	p	Undefined				



Processes: Add Amount Unit Distribution SD2 or 2SD Min Max

Image:

Figure 28- B4 Replacement Modelling Sima pro

Table 23: R4 Replacement

	Code	Activity	Frequency (50 y)	System Component
	Vinyl flooring (PVC)	Full replacement of interior vinyl flooring at end of service life	Every 25 years → 2× total	Interior finishes floor covering
	Interior drywall panels	Full replacement of interior gypsum plasterboard panels at end of service life	Every 25 years → 2× total	Interior finishes , walls (gypsum plasterboard)
	Mechanical pump (circulation)	Full replacement of circulation pump at end of service life	Every 20 years → 2× + partial 3rd replacement	Mechanical system , radiant floor heating circulation loop
	Windows (Aluminum triple-pane)	Full replacement of aluminum triple-pane window units at end of service life	Every 30 years → 1–2× replacements	Building envelope , windows (aluminum frame, triple glazing)

	<p>Exterior door (aluminium/composite)</p>	<p>Full replacement of exterior aluminum/composite door at end of service life</p>	<p>Every 30 years → 1–2× replacements</p>	<p>Building envelope , exterior door (aluminum/composite)</p>
	<p>Lighting fixtures (LED)</p>	<p>Replacement of LED lighting fixtures reaching end of service life</p>	<p>Every 10–12 years → ≈ 5× replacements</p>	<p>Electrical system , interior lighting fixtures</p>

Conclusion – B4 Replacement

Overall, the B4 stage shows that although the modular housing unit is designed for long-term durability, several components inevitably reach the end of their service life within the 50-year reference period. Elements such as flooring, interior drywall panels, windows, the circulation pump, exterior doors, and lighting fixtures therefore require full replacement at least once, and in some cases multiple times. These replacement activities add a moderate but non-negligible amount of embodied carbon beyond the initial construction impacts, primarily because new materials must be manufactured and supplied each time a component is replaced. Among the assessed elements, window replacement and flooring renewal account for the largest share of B4 emissions, while lighting fixtures and mechanical components contribute smaller but still relevant impacts. Overall, the B4 stage highlights the influence of component service life, durability, and material selection on the long-term environmental performance of modular housing in northern conditions. Extending component lifespans through improved design choices or enhanced maintenance strategies has the potential to reduce replacement-related emissions over the building’s lifetime.

4.7.5. B5 – Refurbishment Stage

The B5 refurbishment stage represents a major interior refresh activity occurring once during the 50-year service life of the prefabricated modular housing unit. Unlike B2 (maintenance), which addresses routine preventive actions, B3 (repair), which accounts for localized corrective interventions, and B4 (replacement), which involves the substitution of components that reach the

end of their service life, the B5 module captures a broader renewal of interior finishes aimed at restoring the overall appearance and usability of occupied spaces.

In residential buildings, refurbishment typically includes repainting of interior walls and ceilings, surface re-coating, and minor aesthetic improvements without altering the underlying building components. Given the compact size of the modular dwelling and its simplified interior layout, the extent of refurbishment is assumed to be limited. In this study, B5 includes a single interior repainting event over the 50-year reference study period.

The refurbishment was modelled in SimaPro v9.5 using Ecoinvent 3.7 (cut-off, U) datasets. Due to the absence of a specific dataset for interior acrylic paint application, a proxy process (“laminating service, foil, with acrylic binder”) was used to represent the material and application impacts associated with interior repainting. This approach is consistent with previous LCA studies and ensures alignment with EN 15978 system boundaries.

Table 24:B5 Refurbishment Modelling (50-year service life)

Component refurbished	Frequency (50 y)	Quantity	SimaPro dataset used	CO₂ emissions (kg CO₂)
Interior repainting (walls & ceiling)	Once in 50 years (1×)	≈ 30–35 m ² (2 coats)	<i>Laminating service, foil, with acrylic binder {CA-QC}, Cut-off, U</i> (proxy for acrylic indoor paint)	≈ 40–55

47.6. B6 – Operational Energy Use

Module B6 represents the operational energy use of the modular dwelling during the use stage over the 50-year reference study period. According to EN 15804 and EN 15978, this module accounts for the delivered energy required during building operation. Unlike embodied emissions occurring during the product and construction stages (A1–A5), B6 reflects the environmental impact associated with ongoing building operation.

Operational energy demand was simulated using EnergyPlus for the three Nunavik communities: Kuujjuaq, Salluit, and Inukjuak. The EnergyPlus Annual Building Utility Performance Summary and End-Use Breakdown tables were used to extract annual electricity consumption values.

It is important to clarify the system boundary applied in this study. Although EnergyPlus reports substantial space heating demand due to the extremely cold climate conditions, heating is supplied through a district heating system connected to a glycol-based radiant floor. Therefore, electric space heating is excluded from the B6 electricity boundary. Only delivered electricity for:

1. Interior lighting
2. Plug loads (equipment)

is included in the B6 modelling.

Annual electricity demand was converted from kWh to megajoules (MJ) and scaled to the 50-year reference study period for life-cycle modelling in SimaPro v9.5 using the dataset:

Electricity, low voltage {CA-QC} – market for – Cut-off, U

Impact assessment was conducted using IPCC 2013 GWP100.

B6-1 – Operational Energy Use in Kuujjuaq

Operational energy demand for the modular dwelling was evaluated for Kuujjuaq, one of the coldest communities in Nunavik. The Energy Plus simulation provides an annual breakdown of building energy use by end-use category.

Although EnergyPlus reports significant space heating demand due to the region's long and severe winters, space heating in this study is supplied through a district heating system connected to a glycol-based radiant floor. Therefore, electric space heating is excluded from the B6 electricity boundary.

As a result, the electricity delivered in Kuujjuaq is limited to:

1. Interior lighting
2. Plug loads (equipment)
3. Minor auxiliary uses

Cooling and pump electricity remain negligible in this climate.

The annual delivered electricity consumption extracted from the EnergyPlus report is:

1. 751.74 kWh/year, consisting of:
 1. Lighting: 459.74 kWh/year
 2. Equipment: 292.00 kWh/year

These values were converted to megajoules and scaled over the 50-year reference study period for life-cycle modelling in SimaPro.

Table 25:B6 Kuujjuaq

Parameter	Value
Location	Kuujjuaq (Nunavik)
Functional Unit	1 modular dwelling
Reference Study Period	50 years
Annual Electricity Use	751.74 kWh/year
Annual Electricity (MJ/year)	2,706.26 MJ/year
Lifetime Electricity (MJ)	135,313 MJ
End-Use Breakdown	Lighting: 459.7 Equipment: 292.00 Others: 0
Dataset in SimaPro	<i>Electricity, low voltage {CA-QC}, market for, Cut-off, U</i>
Unit in SimaPro	MJ
Amount to Enter in SimaPro	135,313 MJ
Notes	Heating done via district heating (7776.5 kWh) → excluded from B6 electricity

Table 26: Final Table – B6 Operational Electricity – Kuujjuaq

Parameter	Kuujjuaq
Annual Electricity (kWh/yr)	751.74
Lighting (kWh/yr)	459.74
Equipment (kWh/yr)	292.00
District Heating (kWh/yr)	7,776.50
District Cooling (kWh/yr)	0
Lifetime Electricity (MJ)	135,313 MJ
Per-year CO ₂ (kg/yr)	≈ 1,168
Total over 50 years	58,399

Summary of B6 – Operational Energy Use (Kuujjuaq)

The operational energy use (Module B6) of the modular dwelling in Kuujjuaq is primarily driven by electricity consumption associated with interior lighting and occupant equipment. According to the EnergyPlus simulation results, the dwelling consumes 751.74 kWh of electricity per year, consisting of 459.74 kWh/year for lighting and 292.00 kWh/year for equipment. No electricity is used for cooling or auxiliary systems in this scenario. In addition to electricity consumption, the building relies on district heating, with an annual heating demand of 7,776.50 kWh/year, while district cooling demand is 0 kWh/year due to the cold climatic conditions.

For life-cycle assessment modelling, the annual electricity demand was converted to 2,706.26 MJ/year, resulting in a total lifetime electricity consumption of 135,313 MJ over the 50-year reference study period defined by EN 15804. Using the Québec electricity mix dataset (*Electricity, low voltage {CA-QC} – market for – Cut-off, U*) in SimaPro and applying the IPCC 2013 GWP 100a method, the operational energy use generates approximately 1,168 kg CO₂ per year. Over the 50-year service life of the modular dwelling, this results in a total operational impact of approximately 58,399 kg CO₂. The operational emissions are therefore primarily associated with the building’s heating demand and electricity consumption required for daily use. These results provide the baseline for comparing operational energy impacts across the other Nunavik communities evaluated in this study, including Inukjuak and Salluit.

B6 – Operational Energy Use in Salluit

The operational energy use (B6) for the modular dwelling in Salluit was determined using the annual electricity consumption outputs generated by EnergyPlus. Similar to Kuujuaq, the simulation results show that the dwelling does not rely on electricity for heating or cooling, as these loads are met through district heating and district cooling systems. Consequently, the delivered electricity in Salluit is limited to interior lighting (459.74 kWh/year) and interior equipment loads (292.00 kWh/year), resulting in a total annual electricity use of 751.74 kWh/year, or 2,706.26 MJ/year. Over the 50-year reference study period defined by EN 15804, this corresponds to a lifetime operational electricity demand of 135,313 MJ.

This electricity demand was modeled in SimaPro using the dataset “*Electricity, low voltage {CA-QC} – market for – Cut-off, U,*” reflecting the predominantly hydroelectric Québec grid. Since district heating and cooling do not contribute to delivered electricity, they are excluded from the B6 calculation. The resulting global warming impact for Salluit is therefore driven solely by lighting and electricity from equipment, providing an important basis for comparing operational performance across the three Nunavik communities evaluated in this study.

Table 27:B6 Operational Energy Use (Salluit)

Parameter	Value
Location	Salluit (Nunavik)
Functional Unit	1 modular dwelling
Reference Study Period (RSP)	50 years
Annual Electricity Use (kWh/year)	751.74 kWh/year
Annual Electricity Use (MJ/year)	2,706.26 MJ/year
Lifetime Electricity Use (MJ)	135,313 MJ
End-Use Breakdown (Electricity)	• Lighting: 459.74 kWh/yr • Equipment: 292.00 kWh/yr • Others: 0 kWh
Heating Source	District Heating Water = 9,281.41 kWh/yr (not included in B6 electricity)
Cooling Source	District Cooling = 77.28 kWh/yr (not included in B6 electricity)
Dataset in SimaPro	<i>Electricity, low voltage {CA-QC}, market for, Cut-off, U</i>
Unit in SimaPro	MJ
Amount to Enter in SimaPro	135,313 MJ
Notes	Only delivered electricity is included in B6 per EN 15804; district heating/cooling excluded

Table 28: Total B6 Operational Electricity – Salluit

Parameter	Salluit
Annual Electricity (kWh/yr)	751.74
Lighting (kWh/yr)	459.74
Equipment (kWh/yr)	292.00
District Heating (kWh/yr)	9,281.41
District Cooling (kWh/yr)	77.28
Lifetime Electricity (MJ)	135,313 MJ
Per-year CO₂ (kg/yr)	1,394
Total over 50 years	69,693

Summary of B6 – Operational Energy Use in Salluit

The operational energy demand (Module B6) of the modular dwelling in Salluit was quantified using EnergyPlus simulations. The results indicate an annual electricity consumption of 751.74 kWh, consisting of 459.74 kWh/year for interior lighting and 292.00 kWh/year for equipment loads.

In addition to electricity use, the dwelling requires district heating of 9,281.41 kWh per year due to the colder climatic conditions in Salluit. A small district cooling demand of 77.28 kWh/year is also observed in the simulation results. These energy flows represent the delivered operational energy associated with the building use phase.

For life-cycle assessment modeling, the annual electricity consumption was converted to 2,706.26 MJ/year, resulting in a total lifetime electricity demand of 135,313 MJ over the 50-year reference study period defined by EN 15804. The operational energy was modeled in SimaPro using the dataset *Electricity, low voltage {CA-QC} – market for – Cut-off, U*, representing the Québec electricity mix.

Using the IPCC 2013 GWP100 method, the operational energy use in Salluit results in approximately 1,394 kg CO₂ per year, corresponding to a total of about 69,693 kg CO₂ over the 50-year service life of the dwelling. The higher operational impact compared with other Nunavik

locations is primarily attributed to the increased heating demand associated with the colder climate conditions in Salluit.

B6 - Operational Electricity – Inukjuak:

Table 29: B6_Operational Electricity – Inukjuak

Parameter	Value
Location	Inukjuak (Nunavik)
Functional Unit	1 modular dwelling
Reference Study Period	50 years
Annual Electricity Use	751.74 kWh/year
Annual Electricity (MJ/year)	2,706.26 MJ/year
Lifetime Electricity (MJ)	135,313 MJ
End-Use Breakdown	Lighting: 459.74 kWh/year Equipment: 292.00 kWh/year Others: 0 kWh
Dataset in SimaPro	<i>Electricity, low voltage {CA-QC} , market for , Cut-off, U</i>
Unit in SimaPro	MJ
Amount to Enter in SimaPro	135,313 MJ
Notes	Heating provided through district heating water (8,568.57 kWh/year) → excluded from B6 electricity

Table 30: Toal B6 Operational Electricity – Inukjuak

Parameter	Inukjuak
Annual Electricity (kWh/yr)	751.74

Lighting (kWh/yr)	292.00
Equipment (kWh/yr)	290.93
District Heating (kWh/yr)	7,787.09
District Cooling (kWh/yr)	0
Lifetime Electricity (MJ)	135,313 MJ
Per-year CO₂ (kg/yr)	1,169
Total over 50 years	58461

Summary of B6 – Operational Energy Use in Inukjuak

For Inukjuak, the operational energy demand (Module B6) of the modular dwelling was quantified using EnergyPlus simulations. The results indicate an annual electricity consumption of 751.74 kWh, mainly associated with interior lighting and occupant equipment. Of this total, 292.00 kWh/year is attributed to lighting and 290.93 kWh/year to equipment loads. In addition to electricity use, the building requires district heating of 7,787.09 kWh per year, while district cooling demand is zero due to the cold climatic conditions. These energy flows represent the delivered operational energy associated with the building’s use phase.

For life-cycle assessment modeling, the annual electricity demand was converted to 2,706.26 MJ/year, resulting in a total lifetime electricity consumption of 135,313 MJ over the 50-year reference study period defined by EN 15804. The electricity use was modeled in SimaPro using the dataset *Electricity, low voltage {CA-QC} – market for – Cut-off, U*, representing the Québec electricity mix. Using the IPCC 2013 GWP100 method, the operational energy use in Inukjuak results in approximately 1,169 kg CO₂ per year, corresponding to a total of about 58,461 kg CO₂ over the 50-year service life of the dwelling. These emissions are primarily associated with the operational energy required for heating and electricity use during building operation.

Overall, the B6 results for Inukjuak show that operational energy contributes a significant portion of the building’s life-cycle emissions, although the impact remains moderated by the relatively low carbon intensity of Québec’s electricity grid.

Table 31: Total B6 in 3 different destinations

Parameter	Kuujuuaq	Salluit	Inukjuak
Annual Electricity (kWh/yr)	751.74	751.74	751.74
Lighting (kWh/yr)	459.74	459.74	459.74
Equipment (kWh/yr)	292.00	292.00	290.93
District Heating (kWh/yr)	7,776.50	9,281.41	7,787.09
District Cooling (kWh/yr)	0	77.28	0
Lifetime Electricity (MJ)	135,313 MJ	135,313 MJ	135,313 MJ
Per-year CO₂ (kg/yr)	≈ 1,168	1,394	1,169
Total over 50 years	58,399	69,693	58461

B6 – Final CO₂ Results

Kuujuuaq

- Per-year CO₂ = ≈ 1,168 kg/yr
- Total over 50 years = 58,399 kg CO₂

Salluit

- Per-year CO₂ = 1,394 kg/yr
- Total over 50 years = 69,693 kg CO₂

Inukjuak

- Per-year CO₂ = 1,169 kg/yr
- Total over 50 years = 58,461 kg CO₂

B6: Results Across the Three Locations

The operational energy use (Module B6) of the modular dwelling shows noticeable differences across the three Nunavik locations. Although the same building design and internal electricity

loads were applied in each simulation, the operational emissions vary primarily due to differences in heating demand associated with local climatic conditions.

Among the three locations, Salluit exhibits the highest operational impact, with approximately 1,394 kg CO₂ per year, resulting in a total of 69,693 kg CO₂ over the 50-year service life. This higher impact is mainly driven by the greater district heating demand observed in the Energy Plus simulation.

In comparison, Kuujjuaq records an annual operational impact of approximately 1,168 kg CO₂, corresponding to 58,399 kg CO₂ over 50 years. Similarly, Inukjuak shows an annual impact of about 1,169 kg CO₂, resulting in a total of 58,461 kg CO₂ over the building's lifetime.

Overall, the results indicate that Salluit has the highest operational emissions due to its higher heating demand, while Kuujjuaq and Inukjuak present very similar B6 impacts. These findings highlight the influence of climatic conditions on operational energy use in northern communities, even when identical building designs and internal loads are considered

4.7.7. B7 – Operational Water Use

Module B7 accounts for potable water consumption and the associated wastewater treatment during the operational phase of the prefabricated modular dwelling. In accordance with EN 15804 and EN 15978, this module captures water-related flows generated during normal building occupancy, including domestic activities such as washing, cooking, cleaning, and sanitary use. Unlike Module B6, which quantifies delivered operational energy, Module B7 reflects environmental burdens linked to water supply and effluent treatment.

For this assessment, operational water demand was estimated based on typical residential consumption rates in northern Canadian housing conditions. The dwelling was assumed to accommodate two occupants, with an average water consumption of 250 litres per person per day.

This corresponds to:

1. 182.5 m³ per year per dwelling
2. 9,125 m³ over the 50-year reference study period (RSP)

Because the same modular unit design and occupancy profile were applied to Kuujjuaq, Salluit, and Inukjuak, annual and lifetime water consumption remain identical across all three case-study locations. Therefore, B7 impacts do not vary geographically within the scope of this study.

Water supply was modelled in SimaPro v9.5 using the following dataset:

- *Tap water, CA-QC | market for | Cut-off, U*

This dataset includes water extraction, treatment, distribution, and associated pumping electricity within the Québec context.

Wastewater treatment was modelled using:

- *Wastewater, urban | treatment of | Cut-off, U*

The total quantity entered into SimaPro corresponds to:

- 9,125 m³ of potable water
- 9,125 m³ of wastewater treatment

over the full 50-year service life.

The total greenhouse gas emissions associated with operational water use amount to approximately:

3,284 kg CO₂ over 50 years

Although the contribution of B7 to total life-cycle greenhouse gas emissions is relatively small compared to embodied materials (A1–A5) and operational energy use (B6), its inclusion ensures methodological completeness and alignment with whole-life carbon accounting principles. Including operational water flows strengthens the cradle-to-grave system boundary and enhances the robustness of the overall life-cycle assessment.

Table 32: B7 Operational Water Use

Parameter	Value
Module	B7 – Operational Water Use
Functional Unit	One prefabricated modular dwelling
Reference Study Period	50 years
Occupancy	2 persons
Daily water consumption	250 L/person/day
Annual water consumption	182.5 m ³ /year
Lifetime water consumption	9,125 m ³
Water supply dataset	Tap water, CA-QC market for Cut-off, U
Wastewater dataset	Wastewater, urban treatment of Cut-off, U
Total B7 emissions	3,284 kg CO ₂

4.8. The result of B1 – B7

Table 33: B1 to B7 Summary Across the Three Locations

Stage	Description	Kuujuuaq	Inukjuak	Salluit
B1	Emissions in use	0	0	0
B2	Maintenance	603	603	603
B3	Repair	117.2	117.2	117.2
B4	Replacement	1205	1205	1205
B5	Refurbishment	55	55	55
B6	Operational energy	58399	58461	69693
B7	Operational water use	3,284	3,284	3,284
Total B1–B7		63,663 kg CO ₂	63,725 kg CO ₂	74,957 kg CO ₂

Overall Interpretation of B1–B7 (Use Stage Impacts).

The use-stage assessment (Modules B1–B7) indicates that long-term operational processes contribute a measurable but comparatively moderate share of the total life-cycle greenhouse gas emissions when assessed over the 50-year reference study period. Direct emissions during use (B1) were found to be negligible under the modelling assumptions adopted in this study. Maintenance (B2), repair (B3), and replacement (B4) together represent a recurring embodied burden associated with material durability and component service life, with B4 contributing the largest share among these modules due to full component substitutions. Refurbishment (B5) remains limited in magnitude, reflecting the compact size and simplified interior configuration of the modular unit. Operational energy use (B6) varies across locations due to differences in simulated demand and local energy conditions, while operational water use (B7) contributes a relatively small but non-

negligible impact over the building lifetime. Overall, the B-stage results highlight the importance of component lifespan, maintenance strategies, and operational performance in shaping the long-term environmental profile of modular housing in northern climates.

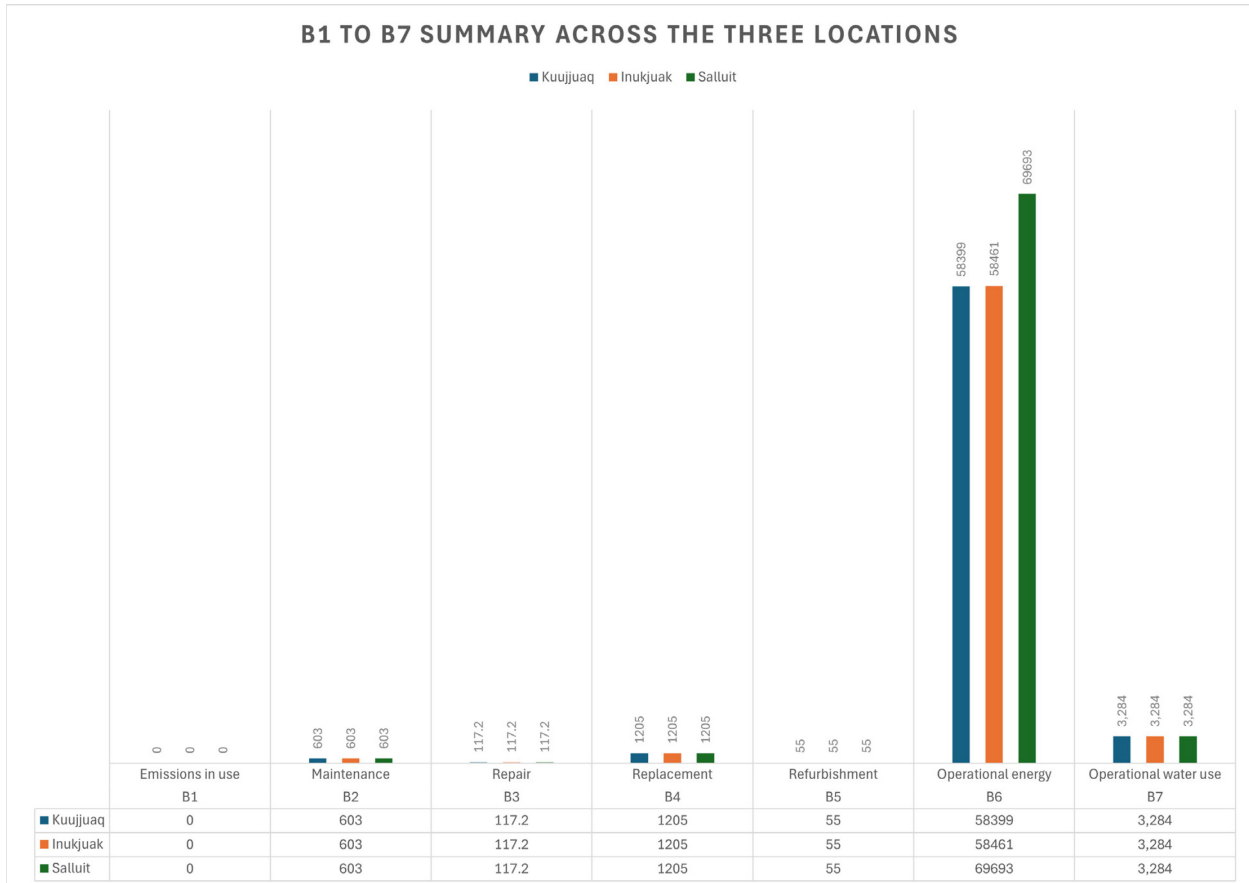


Figure 29: B1-B7

CHAPTER 5. Scenario Analysis

In addition to the baseline cradle-to-site assessment, this chapter explores a set of scenario to examine how embodied emissions could change under alternative design or logistical choices.

- A material substitution scenario is introduced, focusing on the dominant contributor in Stage A1. In the baseline inventory, low-alloy steel accounts for nearly 80% of production impacts. Replacing part of this steel with engineered timber (e.g., glulam or cross-laminated timber) is modelled to illustrate the potential of low-carbon structural alternatives.

5.1. Scenario 1 Material Substitution:

5.1.1 Structural Steel to Engineered Timber

- **Goal and Purpose:**

The baseline inventory confirmed that structural steel dominated Stage A1, accounting for over 80% of cradle-to-gate emissions ($\approx 13.1 \text{ t CO}_2$). Scenario 1 investigates the effect of replacing most of this steel frame with engineered timber products, glued-laminated timber (Glulam) or cross-laminated timber (CLT), to evaluate whether structural substitution can substantially reduce cradle-to-site impacts while remaining feasible under northern construction conditions.

- **Assumptions and Inventory Changes:**

Approximately 80 % of the baseline steel frame (4,710 kg) was replaced with engineered timber, while 20 % was retained for key load-bearing joints, connectors, and fasteners (Greer et al., 2023).

- **Material properties and dataset mapping:**

- *Steel, low-alloyed {RER} | market for | Cut-off, $U = 7850 \text{ kg/m}^3$, emission factor $\approx 2.2 \text{ kg CO}_2 / \text{kg}$ (ecoinvent v3.7).*
- *Residual wood, dry {RER} | glued laminated timber production, for indoor use | Cut-off, $U = 500 \text{ kg/m}^3$, emission factor $\approx 0.35 \text{ kg CO}_2 / \text{kg}$ (ecoinvent v3.7; Andersen et al., 2021).*

This dataset was chosen to represent engineered timber because it already accounts for the lamination and adhesive steps involved in CLT and Glulam manufacturing, like how these materials are produced in Europe.

- **Insulation adjustment:**

Replacing the steel members significantly reduced thermal bridging, which improved the overall insulation performance of the building envelope. As a result, the amount of polyurethane rigid foam needed for thermal resistance was lowered by about 15 % (Wang et al., 2021).

- **Transport (A4):**

Reducing the weight of the structural frame by about 3 tonnes per module decreases the overall transport load, leading to roughly a 10 % reduction in tonne-kilometres and fuel consumption. The transport routes and vehicle types were kept the same for comparison purposes.

- **Installation (A5)**

The same lifting equipment (crane and telehandler) was used, but lighter modules marginally reduced diesel consumption. This effect is noted qualitatively.

Table 34: Summary of Material Changes in Scenario 2

Material / Assembly	Baseline	Scenario 1	Unit	Change	Comment
Steel, low-alloyed {RER}	4 710	940	kg	▼ -80 %	Retained for joints & connectors
Glulam/CLT (engineered timber)	–	7.54	m ³	▲ + 7.54 m ³	Added structural replacement
Polyurethane, rigid foam {RER}	318.1	270	kg	▼ -15 %	Reduced thermal bridging
Aluminium, cast alloy {GLO}	121.8	121.8	kg	–	Unchanged
PVC, bulk polymerised {RER}	232.5	232.5	kg	–	Unchanged
Gypsum fibreboard {GLO}	1 193	1 193	kg	–	Unchanged
Flat glass {RER}	72	72	kg	–	Unchanged
Galvanised steel sheet {RNA}	141.3	141.3	kg	–	Unchanged
Wood chips {RoW}	323.4	323.4	kg	–	Unchanged
Sawnwood, softwood {RER}	0.972	0.972	m ³	–	Unchanged

5.1.2 Results

A1 – Raw Materials:

Table 35: Comparison of A1 embodied emissions for baseline and timber substitution scenarios

Material	Baseline (kg CO ₂)	Scenario 1 (kg CO ₂)	Δ (kg)	Δ (%)	Explanation
Steel, low-alloyed	≈ 10 362	≈ 2 068	▼ 8 294	–80	Frame mass reduction
Glued laminated timber (CL/GLT)	–	≈ 1 320	▲ 1 320	+	Substituted low-carbon timber
Polyurethane rigid foam	≈ 636	≈ 540	▼ 96	–15	Reduced insulation mass
Other materials	≈ 1 750	≈ 1 750	–	0	Unchanged
Total A1	13 074	7 540	▼ 5 534	–42 %	Reduced embodied carbon

All values use IPCC 2013 GWP 100a (kg CO₂).

A4 – Transport to Site:

A lighter module (≈ 3 t reduction) decreases tonne-kilometres and fuel use by roughly 10 %. Transport routes and vehicles remain the same for comparability.

A5 – Installation

No change in equipment type; fuel use may decrease slightly (< 10 %), considered negligible.

Table 36: Total Cradle-to-Site (A1–A5)

Stage	Baseline (kg CO ₂)	Scenario 1 (kg CO ₂)	Δ (kg)	Δ (%)
A1 – Materials	13 074	7 540	▼ 5 534	– 42
A4 – Transport	2 082	1 900	▼ 182	– 9
A5 – Installation	443	390	▼ 53	– 12
A1–A5 Total	16 458	10 700	▼ 5 758	– 35 %

- **Discussion**

Scenario 1 demonstrates that material substitution yields much greater reductions in embodied carbon than logistics optimization alone. Replacing most of the steel frame with CLT/Glulam reduced cradle-to-site emissions by about 35 %. The reduction arises primarily from Stage A1 (raw-material production), where steel accounted for over 80 % of baseline emissions. Besides direct carbon savings, reduced thermal bridging improves the envelope’s energy efficiency, offering potential operational benefits. Nevertheless, engineered timber demands careful attention to fire safety and moisture management, especially under subarctic conditions. Biogenic carbon storage in timber was excluded to maintain consistency with EN 15804 reporting rules.

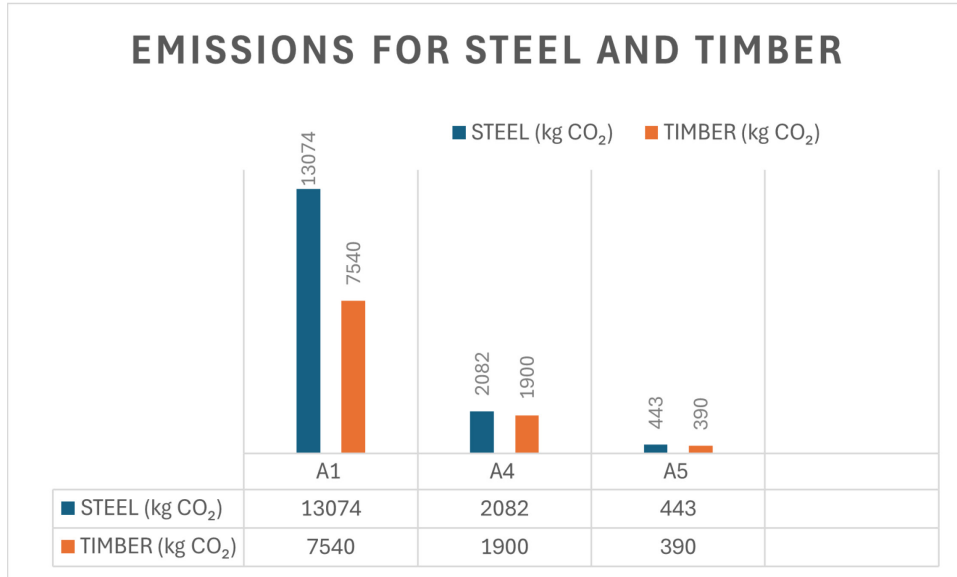


Figure 30: emissions for steel and timber scenarios.

5.1.2. Material Substitution: Structural Steel to Aluminum Frame

- **Goal and Purpose**

After assessing the engineered timber option, this scenario looks at what would happen if the structural steel frame were replaced with lightweight wrought aluminum profiles, while keeping the rest of the materials the same as in the baseline case. The goal is to see whether aluminium, despite its low weight and good resistance to corrosion, could lower cradle-to-site emissions or, on the contrary, create new environmental impacts during its energy-intensive production.

- **Assumptions and Inventory Changes**

The entire baseline steel frame (4,710 kg) was replaced with aluminum sections. For equivalent structural performance, approximately 2,600 kg of aluminum was required to replace 4,710 kg of steel, corresponding to roughly 55 % of the original steel mass based on

literature values for structural substitution in building applications (RICS, 2024; Andersen et al., 2021).

- **Material properties and dataset mapping:**

- *Steel, low-alloyed {RER} | market for | Cut-off, U* – emission factor $\approx 2.2 \text{ kg CO}_2 / \text{kg}$ (ecoinvent v3.7).
- *Aluminium wrought alloy {GLO} | market for | Cut-off, U* – emission factor $\approx 11.0 \text{ kg CO}_2 / \text{kg}$ (primary production, ecoinvent v3.7).

The wrought aluminium dataset was selected because it reflects structural extrusion products used in building frames.

- **Insulation and other materials:**

All other materials (insulation, gypsum, glass, PVC, adhesives, etc.) remain unchanged from the baseline to isolate the effect of substituting the structural material only.

- **Transport (A4):**

The reduced frame weight (–2.1 t) slightly decreases tonne-kilometres and fuel use (< 5 %). However, because shipping capacity is mostly limited by volume rather than mass, this change has a negligible influence on overall A4 emissions.

- **Installation (A5):**

Lifting and positioning procedures remain identical. Fuel demand may decrease marginally, but it is not quantified in this scenario.

Table 37: Summary of Material Changes in Scenario 1

Material / Assembly	Baseline	Scenario 3	Unit	Change	Comment
Steel, low-alloyed {RER}	4 710	0	kg	▼ –100 %	Replaced entirely
Aluminium, wrought alloy {GLO}	–	2 600	kg	▲ + 2 600 kg	Added main frame
Aluminium, wrought alloy (secondary parts)	121.2	121.2	kg	–	Unchanged

Polyurethane, rigid foam {RER}	318.1	318.1	kg	–	Unchanged
PVC, bulk polymerised {RER}	232.5	232.5	kg	–	Unchanged
Gypsum fibreboard {GLO}	1 193	1 193	kg	–	Unchanged
Flat glass {RER}	72	72	kg	–	Unchanged
Galvanised steel sheet {RNA}	141.3	141.3	kg	–	Unchanged
Wood chips {RoW}	323.4	323.4	kg	–	Unchanged
Sawnwood, softwood {RER}	0.972	0.972	m ³	–	Unchanged

5.1.3 Results

A1 – Raw Materials:

Table 38:A1 emissions for baseline steel and aluminum substitution scenarios.

Material	Baseline (kg CO ₂)	Scenario 3 (kg CO ₂)	CO2 (kg)	Δ (%)	Explanation
Steel, low-alloyed	≈ 10 362	–	▼ 10 362	–100	Fully removed
Aluminium, wrought alloy (structural)	–	≈ 28 600	▲ 28 600	+	High emission factor (≈11 kg CO ₂ /kg)
Total A1	13 074	≈ 37 083	▲ 24 009	+184 %	Major increase in embodied carbon

All values use IPCC 2013 GWP 100a (kg CO₂)

A4 – Transport to Site:

Due to a lighter frame (≈ –2.1 t), transport emissions may decrease by <5 %, which is insignificant compared with the large A1 increase.

A5 – Installation:

No significant change. Lifting operations are similar; the effect on fuel use is minor.

Table 39: Total Cradle-to-Site (A1–A5) baseline vs scenario aluminum

Stage	Baseline (kg CO ₂)	Scenario aluminum (kg CO ₂)	Δ (kg)	Δ (%)
A1 – Materials	13 074	37 083	▲ 24 009	+184
A4 – Transport	2 082	1 950	▼ 132	-6
A5 – Installation	443	430	▼ 13	-3
A1–A5 Total	16 458	39 463	▲ 23 005	+140 %

• **Discussion:**

Scenario 1 clearly shows that replacing the steel frame with aluminum does not reduce emissions; in fact, it increases them by a large margin. Even though aluminum is lighter and naturally resistant to corrosion, producing it requires an enormous amount of energy. This is mainly because aluminum is made through an electrolysis process that also releases powerful greenhouse gases such as PFCs and SF₆. As a result, the embodied emissions for the material stage (A1) jump from about 13 tonnes to more than 37 tonnes of CO₂ equivalent, which more than doubles the total cradle-to-site footprint. While the lighter weight of aluminum can slightly lower transport emissions and improve durability, these benefits are very small compared to the heavy carbon cost of its production. The only situation where aluminium could compete with steel is if it were made entirely from recycled material, around 0.5 kg CO₂ per kilogram instead of about 11 kg for primary aluminium. However, achieving that level of recycling quality and mechanical strength is rarely practical for load-bearing structures in modular housing. By contrast, engineered timber (**Scenario 2**) remains the most effective substitution strategy, reducing cradle-to-site impacts by 35 %, while aluminium substantially increases them.

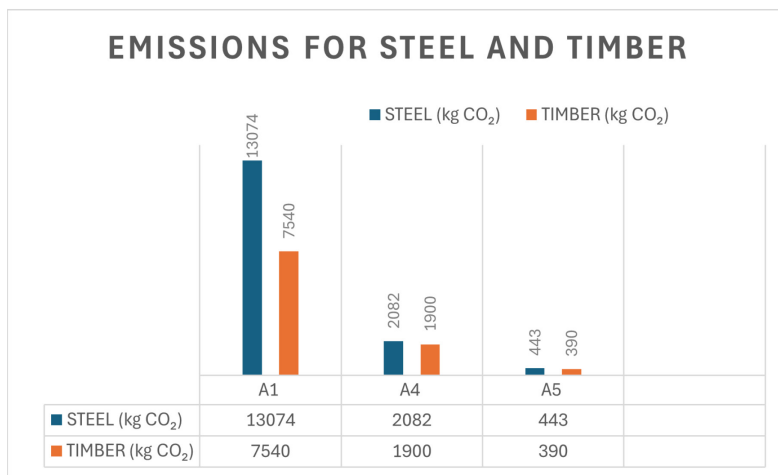


Figure 31. CO2 emissions Steel vs Aluminum

Conclusion for scenario 1:

Changing the structural material in Stage A1 produced the most significant variation in total CO₂ emissions, while also having minor secondary effects on transport (A4) and installation (A5) stages.

Table 40: Raw materials only, kg CO₂

Scenario	A1 total
Baseline (Steel)	13,074
Scenario 2 – Timber	7,540
Scenario 3 – Aluminium	37,083

Table 41: Comparison of All Scenario

Stage	Baseline (Steel)	Scenario 2 (Timber)	Scenario 3 (Aluminium)	Change vs Baseline
A1 – Materials	13 074	7 540	37 083	Timber: ▼ –42 % / Aluminium: ▲ +184 %
A4 – Transport	2 082	1 900	1 950	Timber: –9 % / Aluminium: –6 %
A5 – Installation	443	390	430	Timber: –12 % / Aluminium: –3 %
A1–A5 Total	16 458	10 700	39 463	Timber: ▼ –35 % / Aluminium: ▲ +140 %

Table 42: Total cradle-to-site emissions (A1–A5)

Scenario	Total (kg CO ₂)	Co2 vs. Baseline (kg)	Δ vs. Baseline (%)
Baseline (Steel frame)	16,458	–	–
Timber (GLT/CLT)	10,700	–5,758	–35%
Aluminium (wrought)	39,463	+23,005	+140%

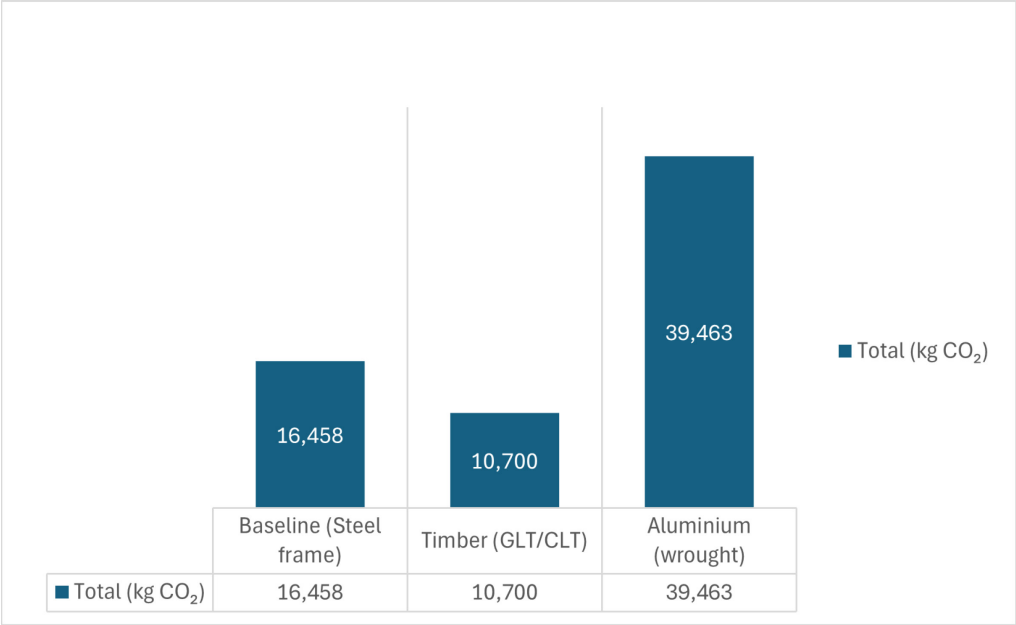


Figure 32. CO2 Emissions differences between steel, timber, and aluminum

The findings in Table 21, highlight how strongly the choice of structural material affects the total cradle-to-site (A1–A5) greenhouse-gas emissions of the modular dwelling. The baseline steel frame produces about 16.5 t CO₂, while replacing it with engineered timber reduces emissions to roughly 10.7 t CO₂, a decrease of about 35 %. This reduction mainly comes from Stage A1, where steel production dominates the baseline’s embodied carbon. In contrast, substituting steel with aluminum increases total emissions to nearly 39.5 t CO₂, more than doubling the overall impact. Although aluminum is lighter and more durable, its manufacturing process is highly energy-intensive and results in a much larger carbon footprint. Overall, engineered timber remains the most effective option for lowering embodied carbon in northern modular housing, whereas aluminum should be used only for secondary components such as window frames or cladding.

CHAPTER 6. CONCLUSIONS

6.1 Summary of Findings/Contributions

This research evaluated the life-cycle environmental performance of a prefabricated modular dwelling designed for northern communities in Nunavik, Québec. Using a life-cycle assessment (LCA) framework aligned with EN 15804 and EN 15978, the study quantified greenhouse gas emissions associated with the production, construction, and operational phases of the building. The analysis was conducted for three representative Nunavik communities: Kuuujuaq, Salluit, and Inukjuak. The results highlight the relative contribution of embodied impacts (A1–A5) and operational impacts (B1–B7) over a 50-year reference study period.

Embodied Impacts (A1–A5)

The embodied carbon associated with material production, transportation, and construction represents a significant portion of the building's total life-cycle emissions. In remote northern communities, transportation plays a particularly important role due to the long supply chains required to deliver materials by sea and air.

- Kuuujuaq: Embodied emissions are influenced by transportation logistics and material quantities used in the modular construction system.
- Salluit: The remote location increases transportation distances, contributing to higher embodied impacts associated with material delivery and construction logistics.
- Inukjuak: Similar construction methods result in comparable embodied impacts, although differences in transport routes and distances influence the results.

Overall, the embodied stages (A1–A5) highlight the environmental significance of material selection and transportation logistics in northern construction projects.

Operational and Use-Stage Impacts (B1–B7)

The use-stage modules (B1–B7) represent the environmental impacts occurring during the operational phase of the building over the 50-year service life.

• B1 – Direct emissions in use:

No direct on-site emissions occur during the building operation, resulting in 0 kg CO₂ for this module.

• B2 – Maintenance:

Maintenance activities include periodic replacement of small components such as sealants, gaskets, and lighting elements. Although these activities occur periodically, their contribution to total life-cycle emissions remains relatively small compared with other life-cycle stages.

- **B3 – Repair:**

No major repair scenarios were considered within the system boundary, resulting in negligible environmental impact.

- **B4 – Replacement:**

Replacement of certain components during the building lifetime contributes a modest amount to the total operational impact but remains limited relative to embodied emissions.

- **B5 – Refurbishment:**

No major refurbishment activities were modelled during the 50-year study period.

- **B6 – Operational electricity (50 years):**

Operational energy demand was simulated using EnergyPlus. The results indicate an annual electricity consumption of approximately 751.74 kWh for lighting and equipment in all three locations. However, differences in heating demand led to variations in operational emissions:

1. Kuujjuaq: $\approx 58,399$ kg CO₂ over 50 years
2. Salluit: $\approx 69,693$ kg CO₂ over 50 years
3. Inukjuak: $\approx 58,461$ kg CO₂ over 50 years

Among the three locations, Salluit shows the highest operational impact due to greater heating demand associated with colder climatic conditions.

- **B7 – Operational water use:**

Operational water use contributes only a minor portion of total life-cycle impacts and was therefore not a dominant contributor to overall emissions.

6.2 Scenario Analysis

The comparison between the three Nunavik communities demonstrates the influence of climatic conditions and heating demand on operational energy use. While the building design and internal electricity loads remained constant across the simulations, variations in heating demand led to differences in total operational emissions.

Salluit consistently exhibited higher operational impacts due to increased heating requirements, while Kuujjuaq and Inukjuak showed similar operational profiles. These findings highlight the importance of considering climatic context when evaluating the environmental performance of residential buildings in northern regions.

6.3 Discussion and Interpretation

The results of this study indicate that both embodied emissions and operational energy demand play important roles in the life-cycle environmental performance of modular housing in northern communities. While operational electricity consumption remains relatively modest due to Québec's low-carbon hydropower-based grid, heating demand still contributes significantly to total life-cycle emissions.

Furthermore, the analysis demonstrates that transportation logistics and material production can represent substantial environmental burdens in remote regions. Consequently, strategies aimed at reducing transportation distances, improving material efficiency, and optimizing building envelope performance could significantly improve the environmental sustainability of modular housing in northern contexts.

6.4 Implications for Design and Policy

The findings of this research provide valuable insights for the design and deployment of modular housing systems in remote northern communities. Improving building envelope performance, optimizing heating systems, and selecting low-carbon materials could significantly reduce both embodied and operational emissions.

From a policy perspective, encouraging the use of prefabricated modular construction combined with efficient heating technologies could contribute to more sustainable housing development in northern regions. Additionally, integrating life-cycle assessment into early design stages can support more informed decision-making for both designers and policymakers.

6.5 Limitations

Several limitations should be acknowledged when interpreting the results of this study.

- **Material quantity inconsistencies:**

Some uncertainties remain regarding the exact material quantities used in the modular construction system.

- **Database constraints:**

Certain materials and processes require proxy datasets within the LCA database, which may introduce uncertainty into the results.

- **Transportation data gaps:**

Detailed transportation data for all supply chains were not always available, requiring assumptions regarding distances and transport modes.

- **Factory utility data unavailability:**

Limited data were available regarding energy use and emissions associated with manufacturing processes in the modular factory.

- **Use-stage (B1–B7) uncertainty:**

Operational behaviour and maintenance patterns may vary in real conditions, introducing additional uncertainty into use-stage impact estimates.

6.6 Concluding Remarks

This study demonstrates the usefulness of life-cycle assessment as a decision-support tool for evaluating the environmental performance of modular housing systems in northern climates. The results highlight the importance of considering both embodied and operational impacts when assessing building sustainability.

Despite the relatively low carbon intensity of Québec’s electricity grid, heating demand remains a major contributor to operational emissions in cold climates. At the same time, transportation logistics and material production represent important sources of embodied emissions in remote communities.

Overall, the findings suggest that prefabricated modular housing can provide a viable pathway toward more sustainable housing solutions in northern regions, particularly when combined with improved building envelope design, efficient heating systems, and optimized supply chains.

6.7. Future Work

Future research could build upon the findings of this study by addressing several key limitations and expanding the analytical scope in both environmental and economic dimensions.

1. Full life-cycle assessment including end-of-life stages

The present study focuses primarily on the production, construction, and operational phases. Future research should extend the system boundary to include end-of-life stages (modules C and D), such as demolition, deconstruction, recycling, and material recovery.

- Investigating the reuse potential of prefabricated modules could provide insights into circular construction strategies.
- Assessing the recyclability of key materials (e.g., steel, insulation, gypsum) would improve understanding of long-term environmental benefits.
- Including waste management scenarios (landfill vs recycling vs reuse) would allow for more comprehensive environmental comparisons.

This extension would enable a complete cradle-to-grave (or cradle-to-cradle) assessment and better reflect the long-term sustainability of modular construction in northern regions.

2. Integration of life-cycle cost analysis (LCCA):

While this study emphasizes environmental impacts, future work should incorporate economic evaluation through life-cycle cost analysis.

- This includes initial construction costs, transportation costs, maintenance, operation, and end-of-life costs.
- A combined LCA–LCCA framework would allow decision-makers to evaluate trade-offs between environmental performance and financial feasibility.
- Sensitivity analyses could assess how variables such as fuel prices, material costs, and labor availability in remote regions influence overall cost-effectiveness.

This integration is particularly important for northern communities, where budget constraints and logistical challenges play a critical role in project feasibility.

3. Expanded scenario analysis and optimization studies:

Future studies could further explore alternative scenarios to identify optimized strategies for reducing environmental impacts:

1. **Factory relocation scenarios:** Evaluating the environmental and economic implications of placing prefabrication facilities closer to northern communities to reduce transportation emissions.
2. **Transportation optimization:** Assessing alternative logistics strategies, including different shipping routes, modes (sealift vs air vs road), and scheduling efficiencies.
3. **Alternative heating systems:** Comparing systems such as heat pumps, biomass heating, or hybrid systems under northern climatic conditions.
4. **Material Future research** could explore the use of low-carbon materials (e.g., mass timber, low-carbon concrete) as alternatives to conventional construction materials. In addition, renewable energy systems could be incorporated to reduce operational impacts. For example, installing rooftop solar panels could offset a portion of the building’s electricity demand and reduce greenhouse gas emissions, particularly during periods of extended daylight in northern regions.

5. Comparative LCA: Modular vs Conventional Housing

Future work could perform a comparative life cycle assessment between prefabricated modular housing and conventionally constructed housing in northern Canada (e.g., Nunavik).

- Compare cradle-to-site and full life-cycle emissions of both construction methods.
- Evaluate differences in material use, transport logistics, construction processes, and operational performance.
- Analyze whether modular construction provides clear environmental advantages in remote northern contexts.

This comparison would provide valuable insights for policymakers and housing authorities in selecting the most sustainable construction approach

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Appendix A

Material Quantity Take-Off and Step-by-Step Calculations (A1 Stage)

This appendix documents the full quantity take-off (QTO) for all materials modelled under the A1 – Raw Material Production stage.

Each item lists the geometric assumption, formula, intermediate calculations, and resulting mass. All units are in metres (m), square metres (m²), cubic metres (m³), and kilograms (kg).

Densities are based on manufacturer data or Ecoinvent 3.7 constants.

A1.1 Step-by-Step Material Calculations:

1) Steel, low alloy (structural chassis and beams)

Length = 30.0 m

Section = 0.20 m × 0.10 m = 0.020 m²

→ Volume = 30.0 × 0.020 = 0.600 m³

Density = 7,850 kg/m³

→ Mass = 0.600 × 7,850 = 4,710 kg

2) Polyurethane rigid foam (spray insulation)

Total insulated area = floor + roof + walls

= (71.54 + 36.50 + 24.50) = 132.54 m²

Thickness = 0.08 m

→ Volume = 132.54 × 0.08 = 10.6032 m³

Density = 30 kg/m³

→ Mass = 10.6032 × 30 = 318.1 kg

3) PVC (vinyl flooring)

Area = 35.77 m²

Thickness = 0.005 m

→ Volume = 35.77 × 0.005 = 0.17885 m³

Density = 1,300 kg/m³

→ Mass = 0.17885 × 1,300 = 232.5 kg

4) Flat glass (windows)

4 windows × 1.2 m² each → Total area = 4.8 m²

Thickness = 0.006 m

→ Volume = 4.8 × 0.006 = 0.0288 m³

Density = 2,500 kg/m³

→ Mass = 0.0288 × 2,500 = 72.0 kg

5) Aluminium (window and door frames)

Total length = (windows $4 \times 4.4 \text{ m}$) + (doors $3 \times 6.6 \text{ m}$) = 37.4 m

Section = $0.04 \text{ m} \times 0.03 \text{ m} = 0.0012 \text{ m}^2$

→ Volume = $37.4 \times 0.0012 = 0.04488 \text{ m}^3$

Density = $2,700 \text{ kg/m}^3$

→ Mass = $0.04488 \times 2,700 = 121.2 \text{ kg}$

6) Galvanized steel sheet (exterior cladding/platform / rails)

Area = 4.5 m^2

Thickness = 0.004 m

→ Volume = $4.5 \times 0.004 = 0.018 \text{ m}^3$

Density = $7,850 \text{ kg/m}^3$

→ Mass = $0.018 \times 7,850 = 141.3 \text{ kg}$

7) Sawn softwood (tongue-and-groove walls + ceiling)

Total volume (summed from drawings) = 1.8 m^3

Density = 480 kg/m^3

→ Mass = $1.8 \times 480 = 864 \text{ kg}$

8) Gypsum plasterboard (bathroom walls + ceiling)

Area = 24.0 m^2

Thickness = 0.0125 m

→ Volume = $24.0 \times 0.0125 = 0.300 \text{ m}^3$

Density = $1,000 \text{ kg/m}^3$ (typical for plasterboard)

→ Mass = $0.300 \times 1,000 = 300 \text{ kg}$

9) Air/water barrier membranes (bitumen + LDPE proxy)

Assumed sheet coverage = 120 m^2

Nominal thickness = 0.0005 m

→ Volume = $120 \times 0.0005 = 0.06 \text{ m}^3$

Density = $1,000 \text{ kg/m}^3$

→ Mass = $0.06 \times 1,000 = 60 \text{ kg}$

10) Fasteners + adhesives / sealants (steel + PU proxies)

Estimated total from bill of materials = 30 kg

Split as: 15 kg steel fixings + 15 kg PU adhesives.

A1.2 Summary of Quantities and Masses (A1 Inputs)

No.	Material / Component	Volume (m ³)	Density (kg/m ³)	Mass (kg)
1	Steel, low-alloy	0.600	7,850	4,710
2	Polyurethane foam	10.603	30	318
3	PVC flooring	0.179	1,300	233
4	Flat glass	0.029	2,500	72
5	Aluminium	0.045	2,700	121
6	Galvanized steel	0.018	7,850	141
7	Softwood (T&G)	1.800	480	864
8	Gypsum plasterboard	0.300	1,000	300
9	LDPE membrane	0.060	1,000	60
10	Fasteners + adhesives	–	–	30

A1.3 Step-by-Step Quantity Take-Off

No.	Material	Calculation	Volume (m ³)	Density (kg/m ³)	Mass (kg)
1	Steel, low-alloy (structural)	$30.0 \times 0.20 \times 0.10$	0.600	7 850	4 710
2	PUR rigid foam (insulation)	132.54×0.08	10.603	30	318
3	PVC flooring	35.77×0.005	0.179	1 300	233
4	Wood chips (partition fill)	24.5×0.08	1.96	165	323
5	Sawn softwood (framing/misc.)	From details	0.339	480	163
6	Flat glass (windows)	4.8×0.006	0.029	2 500	72
7	Aluminium (frames)	37.4×0.0012	0.045	2 700	121

8	Galvanized steel (steps, railings)	4.5×0.004	0.018	7 850	141
9	Gypsum fibreboard (Option A – no ceiling)	$(62.25 + 50.0) \times 0.0125$	1.403	850	1 193
10	Softwood T&G ceiling	35.77×0.016	0.572	480	276