Research Square

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Evaluation of sustainable construction strategies for cold climate residential buildings in Canada using life cycle assessment and BIM energy analysis

Muhammad Muzamil
University of Northern British Columbia
Mohammad Kamali
mohammad.kamali@unbc.ca
University of Northern British Columbia
Ahmed Hassaan Zafar
University of Northern British Columbia
Zeerak Waryam Sajid
University of Northern British Columbia

Research Article

Keywords: Cold climate, sustainable construction, Building Information Modelling, life cycle assessment, energy simulation, embodied carbon, circular economy

Posted Date: October 8th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10935677/v1

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Additional Declarations: No competing interests reported.

Abstract

Construction in Canada's cold-climate regions is shaped by prolonged winters, severe freeze–thaw cycles and high heating demands, yet few studies evaluate sustainable strategies through a baseline-versus-optimized modelling framework, and the integration of Building Information Modelling (BIM), energy simulation and life cycle assessment (LCA) for comparative analysis remains rare. This study addresses that gap for a two-storey single-family dwelling in Winnipeg, Manitoba (ASHRAE Climate Zone 7A). Sustainable practices extracted from 40 peer-reviewed studies were consolidated into a binary-scored Sustainable Construction Practices Tool and complemented by a desk-based market survey of commercially available products. Three Autodesk Revit models were developed: a conventional Baseline, an Optimized model incorporating practices with evidence scores of 5–20%, and a Best Practice model integrating all identified practices. Operational energy and carbon were simulated with Revit Systems Analysis and Autodesk Insight (EnergyPlus), and a cradle-to-grave LCA (modules A1–A5, B2–B6 and C1–C4) was performed with the Athena Impact Estimator for Buildings using the TRACI 2.1 method over a 60-year reference study period. Relative to the Baseline, the Optimized and Best Practice models reduced global warming potential by 30.1% and 45.7%, fossil fuel consumption by 37.6% and 41.5%, and acidification, eutrophication, particulate, ozone depletion and smog impacts by 24–64%. Annual energy use intensity fell from 355.66 to 325.69 and 320.44 kWh/m², and total life-cycle carbon from 83,776 to 62,070 and 60,255 kgCO_2e. Envelope-first strategies, regionally sourced low-carbon materials and passive solar design substantially reduce both the operational and the embodied impacts of cold-climate housing.

1. Introduction

1.1 Background

Sustainable construction in Canada's cold-climate regions is shaped by prolonged winters, severe freeze–thaw cycles and high heating demands, requiring strategies that ensure thermal comfort, energy efficiency and resilience while meeting the national target of net-zero emissions by 2050 [1–4]. Research consistently identifies the building envelope as a critical determinant of performance, with airtightness, moisture management and thermal optimization as the primary drivers of energy efficiency [1, 5, 6]. High-performance systems such as climate-adaptive building envelopes, orientation-specific glazing, phase change materials and automated shading can significantly reduce heating loads in cold climates, as demonstrated in optimization studies of cold-region housing [7–9], in reviews of adaptive dynamic façades and bioclimatic passive strategies [10, 11] and in Canadian case studies from Montreal, Winnipeg and Quebec [1].

Material selection is equally important, with emphasis on locally sourced and renewable resources such as cross-laminated timber (CLT), reclaimed wood, recycled steel and low-carbon concrete blends to reduce embodied carbon and transportation emissions [12–15]. Prefabrication and modular construction methods, increasingly adopted in British Columbia and Quebec, have demonstrated benefits in minimizing waste, shortening construction schedules and enhancing quality control during winter builds [16–19]. These approaches also align with the principles of design for deconstruction, material reuse and recycling, as reflected in policy measures such as Vancouver's Green Demolition Bylaw [17, 20].

Technological advancements have further strengthened the integration of sustainable strategies in cold climates. Building Information Modelling (BIM) and digital twins enable detailed thermal simulation, real-time performance monitoring and life-cycle environmental assessment [21–23]. Integrating life cycle assessment (LCA) with energy simulation during the design phase supports balanced decision-making by avoiding trade-offs between operational and embodied carbon [21, 24–26]. Canadian research shows that combining parametric modelling with whole-building LCA yields optimized outcomes for both environmental impact and energy use, which directly informs the comparative Revit-based modelling, energy analysis and LCA undertaken in this study [6, 27].

1.2 Problem statement and research gap

Construction in Canada's cold-climate regions faces persistent sustainability challenges due to extreme winter conditions, high heating demands and material degradation from severe freeze–thaw cycles [1, 3, 28]. These environmental stressors, coupled with the limited availability of sustainable building materials and insufficient infrastructure for material reuse, hinder the integration of sustainable practices into mainstream construction [16, 17]. As a result, buildings in these regions often exhibit higher operational energy use, reduced life-cycle efficiency and increased waste generation, contributing to negative environmental impacts [24, 27, 29].

Despite growing awareness of sustainable strategies that emphasize resource efficiency, renewable and recyclable materials, design for disassembly and life-cycle optimization, their implementation in cold climates remains limited. Barriers such as technical feasibility concerns, lack of industry knowledge, financial constraints and policy gaps continue to impede adoption [2, 14, 30], and weather-related construction delays, which a changing climate is expected to amplify, add a further scheduling and cost dimension [31]. Without targeted frameworks and region-specific best practices, cold-climate construction risks falling short of national sustainability targets, including Canada's commitment to net-zero emissions by 2050 [6, 21].

This study addresses this gap by evaluating the adoption of circular economy (CE) principles in cold-climate construction, identifying key obstacles and demonstrating practical applications through a comparative case study. By developing and analysing Revit-based building models—a conventional baseline and alternatives optimized with CE-aligned materials and design strategies—integrated with energy analysis and LCA, the study quantifies the environmental benefits of these strategies [6, 24]. The outcomes provide evidence-based design guidance for enhancing life-cycle efficiency and sustainability in cold-climate Canadian construction.

1.3 Objectives, scope and contribution

The objectives of this study are to: (i) examine the obstacles that prevent cold-climate construction from adopting sustainable practices, such as material deterioration and insufficient infrastructure for material reuse; (ii) assess the environmental benefits of implementing such strategies in cold-region housing developments; and (iii) design cold-climate building models that incorporate sustainable construction strategies, with an emphasis on life-cycle efficiency and sustainability.

The research focuses on developing and evaluating sustainable construction strategies tailored to Canada's cold-climate regions, where prolonged winters, high heating loads and severe freeze–thaw cycles demand region-specific building solutions. The scope encompasses both operational and embodied environmental performance, integrating energy efficiency and life-cycle optimization. A comparative approach is adopted using three BIM models developed in Autodesk Revit: a conventional model, an optimized model and a best-practice model. For each model, an energy analysis was conducted to evaluate operational energy performance under cold-weather conditions, considering the building envelope design, thermal-bridging mitigation and passive solar strategies, while an LCA quantified embodied carbon and environmental impacts across the building life cycle, from material extraction and manufacturing to end-of-life disposal or reuse. The scope further includes evaluating the trade-offs between operational and embodied carbon to achieve balanced, low-carbon design solutions and developing design guidance for sustainable cold-climate construction that aligns with national net-zero targets and regional building codes.

The work aligns with Sustainable Development Goal (SDG) 11, Sustainable Cities and Communities, and SDG 12, Responsible Consumption and Production. By developing and evaluating construction strategies optimized for Canada's cold-climate regions, it promotes buildings that are environmentally responsible, resilient to harsh weather and supportive of comfortable, healthy living conditions, particularly in remote and northern communities where resource constraints and extreme climates demand innovative solutions. The findings are therefore relevant to architects, engineers, policymakers and construction professionals aiming to reduce carbon footprints, improve building resilience and advance sustainable development in northern and cold-climate regions.

2. Literature Review

2.1 Challenges and envelope strategies in cold climates

The review conducted for this study mapped the challenges, advancements and gaps in sustainable construction for cold-climate regions of Canada, with the aim of understanding how sustainable design strategies, materials and tools such as BIM and LCA are being utilized or underutilized in such environments. The reviewed studies were organized in a literature matrix recording the key area, project stage, building type, design aspect, method, materials and products, and relevance to the present work; the principal themes that emerged were material selection, simulation tools, climate-adaptive strategies and environmental impact analysis.

Extreme cold climates present significant challenges such as high heating loads, freeze–thaw degradation and moisture penetration, which compromise building durability and energy performance [3, 21, 33]. Bhuiyan et al. [3] document the effects of freezing on concrete, the safety of workers in low temperatures and the roles of modular building, BIM and thermal insulation strategies in cold-region construction, and Nilimaa and Zhaka [28] review the material-related challenges of cold-weather concreting—slow setting, reduced curing rates, early freezing and freeze–thaw actions—together with the admixtures, heated enclosures and curing technologies used to mitigate them. Multiple studies emphasize the need for climate-responsive envelope design, including high-performance insulation, air barriers and orientation strategies that reduce thermal bridging and maximize passive gains [1, 5, 12, 13]. Reviewing 59 studies on cold-climate envelopes, Al-Shatnawi et al. [1] identify hygrothermal and energy performance, building-integrated photovoltaics, double-skin façades, phase change materials, CLT and green roofs as the principal research fronts, and highlight remaining gaps in the climate-specific optimization of these systems. Passive design strategies adapted to site-specific weather conditions can lead to significant reductions in operational energy use and heating demand [11], envelope-optimization studies confirm large savings from insulation, glazing and window-to-wall-ratio choices in cold, heating-dominated climates [9, 10], and optimization frameworks developed for the cold regions of China, which couple LCA, life cycle costing and multi-objective algorithms to balance energy, cost and thermal comfort in envelope design, are transferable to climates with similar characteristics [7, 8]. Long-standing benchmark work also frames these efforts: Zimmermann et al. [32] proposed energy and pollutant benchmarks for sustainable construction, and recent benchmarking of social and affordable housing in British Columbia provides Canadian reference values for residential energy performance [34].

2.2 Low-carbon materials, prefabrication and circularity

Embodied carbon is gaining increasing attention in the Canadian sustainable construction discourse. Materials such as wood-based products, cellulose, hempcrete and recycled insulation offer strong environmental profiles, yet their adoption remains limited in practice [13–15, 17]. Abera [13] provides technical and environmental data on recycled concrete, bamboo, hempcrete, geopolymers, fly ash and engineered wood, while Patel and Patel [14] report that green buildings cost approximately 12–15% more initially but have lower life-cycle costs. Timber is the only major structural material that is grown, and reviews of its use in construction conclude that, under sustainable forestry, engineered wood products such as CLT and glulam can substitute for more carbon-intensive materials [15]; at scale, such substitution could turn mid-rise buildings into a long-term carbon store [37], while recycled building materials and recycled-aggregate concrete offer parallel reductions in embodied impacts [38, 39]. Kwan [12] examines the feasibility, benefits and technical challenges of CLT, light wood-frame and hybrid systems for mid-rise construction in British Columbia, and Cabral and Blanchet [35] prioritize material-selection criteria for prefabricated wooden construction in the Canadian and United States context, identifying watertightness, fire resistance, local availability and occupant health as the most important. Comparative research on modular construction explains why prefabrication features so strongly in cold-climate best practice: Kamali and Hewage [18] critically review the life-cycle performance of modular buildings and report, on average, better environmental performance than their conventional counterparts; a cradle-to-gate LCA of single-family homes in British

Columbia benchmarks the environmental trade-offs between the two delivery methods [19]; and subsequent case studies in the same region assess the environmental sustainability of modular homes against conventional performance benchmarks [40]. At the end of life, Earle et al. [16] identify country-specific barriers and strategies for the deconstruction, reuse and recycling of steel, wood, concrete and drywall in Canada, and Lynch [17] documents Vancouver's evolving deconstruction sector, advocating deconstruction hubs, education and policy support. Circular economy research in the building and construction sector has expanded rapidly, with recycling, reuse, energy efficiency and Industry 4.0 identified as research hotspots [41], and dedicated frameworks now define the governmental, economic, environmental, behavioural, societal and technological dimensions of a circular built environment [20]. Methodological reviews of the LCA of construction materials [42] and of the data-quality challenges in developing environmental product declarations [43] support life-cycle thinking in circular procurement; Meneghelli [36] further shows how recycled content, transportation, waste and replacement assumptions materially change whole-building embodied carbon, underlining the sensitivity of such assessments to inventory choices. The financial incentives available for green residential buildings differ markedly among Canadian provinces [30].

2.3 BIM, energy simulation and LCA integration

BIM-based modelling paired with LCA is emerging as a critical strategy for optimizing building designs early in the project life cycle [6, 21, 23, 27]. Reviews of building LCA and life-cycle energy analysis show that although operational energy has historically dominated life-cycle impacts, embodied impacts become decisive as operational efficiency improves, which strengthens the case for whole-life evaluation at the design stage [25, 26, 29]. Zhu and Feng [6] integrated BIM with whole-building LCA, life cycle costing and HOT2000 energy simulation for a detached house under the British Columbia Energy Step Code, tracking XPS and EPS insulation, triple-pane windows, heat pumps and heat recovery ventilation, and revealed rebound impacts such as ozone depletion despite energy savings. Kathiravel et al. [44] combined BIM, LCA, life cycle costing and fuzzy multi-criteria decision-making to identify the optimal HVAC system for net-zero energy houses in each Canadian climate zone—complementing United States studies that rank heat-pump HVAC and photovoltaic combinations for residential net-zero energy buildings across climate zones [50, 51]—and Li and Feng [45] extended BIM-based LCA to the urban scale using GIS, EnergyPlus and openLCA to identify emission hotspots for municipal planning. Feng et al. [46] compared the whole-building LCA results of a single-family residential building obtained with the Revit add-in Tally and with the Athena database over a 60-year building lifespan. Torabi and Evins [21] devised a parametric LCA framework covering the envelope, structure and heating system of a mid-rise residential building in British Columbia, and Torabi et al. [24] explored 20,160 design alternatives to show how form, HVAC, insulation, window-to-wall ratio and material choices govern the trade-off between embodied and operational carbon in early-stage design across Canadian cities, while Torabi and Evins [47] quantify how early-stage structural choices govern embodied carbon across more than 8,200 design solutions. Zhou et al. [27] combined BIM–LCA integration with Morris sensitivity analysis to identify the most influential design variables at each design stage. Digital twins, which link BIM with IoT sensors and data analytics, are increasingly applied to energy management, logistics and facilities management across the building life cycle [22, 52]. Post-occupancy evidence reinforces the importance of monitoring: Salehi et al. [48] found that the Centre for Interactive Research on Sustainability at the University of British Columbia used about 60% more energy than modelled because of occupancy, heat export and lighting, highlighting the value of sub-metering and model calibration, and Masoso and Grobler [49] showed that more than half of building energy can be consumed outside working hours through occupant behaviour, reinforcing the case for monitoring and digital-twin-based operation.

2.4 Research gaps

Despite these advances, the review found a gap in studies that evaluate construction methods using a baseline-versus-optimized model framework. Most research either remains theoretical or lacks region-specific detail on Canadian climate zones such as Yukon, Nunavut and northern Manitoba. Furthermore, many papers emphasize energy modelling using Revit, DesignBuilder or similar tools, yet integration with LCA for comparative analysis is rare. The reviewed literature also suggests that although net-zero goals are shaping national policies, implementation at the building level—especially for

small- to medium-scale projects in remote areas—remains inconsistent [2, 21]. While several researchers acknowledge the benefits of low-carbon materials, few studies integrate them with BIM tools for comparative simulation; the comparative evaluation of green materials reported by Patel and Patel [14] offers a useful precedent for the multi-model approach adopted in this study.

3. Materials and Methods

3.1 Research framework

The study followed a sequential workflow (Fig. 1): (1) a literature review to identify the challenges, advancements and gaps in sustainable cold-climate construction; (2) data collection comprising a literature-derived evidence base and a desk-based market survey of sustainable products; (3) development of three-dimensional BIM models of a residential building in Autodesk Revit; (4) energy and carbon analysis and whole-building LCA of each model; and (5) formulation of design guidelines and recommendations from the comparative results.

3.2 Literature-based evidence base and decision-support tool

To systematically identify sustainable strategies, an Excel-based decision-support tool was first developed. The tool compiled stage-wise practices and materials across the full building life cycle: design, material procurement, construction, maintenance and operation, renovation, and end of life. Each practice was extracted from 40 peer-reviewed studies focused on sustainable construction in cold climates. The tool was structured with rows representing sustainable practices or materials and columns representing the research papers. A binary scoring approach was applied: a score of 1 was assigned where a practice was explicitly validated or recommended in a paper, and 0 where the practice was absent. A total-score column then summed the scores across all papers, enabling the comparison and ranking of practices; the total score expressed as a percentage of the 40 papers is reported in the Sustainable Construction Practices Tool presented in Section 3.4. This evidence base underpinned the subsequent development of the Sustainable Construction Practices Tool.

3.3 Desk-based market survey

Cold-climate construction poses distinctive challenges that often require context-specific material choices and design solutions. While extensive academic research exists on energy-efficient construction, there is frequently a disconnect between theoretical frameworks and the products actually available in the marketplace, particularly in Canada's diverse and extreme climate zones. To address this, a market survey was undertaken to complement the literature review by directly examining the current industry offerings, certifications and sustainability claims of real-world building materials and systems, so that the proposals and models are not only rooted in best practice but also technically and commercially viable.

The survey followed a desk-based methodology, relying entirely on web-based tools and digital platforms to gather data on sustainable building materials and systems applicable to cold-climate construction, without field visits or supplier interviews. An Excel-based matrix was developed to systematically record and organize the information, capturing the product name and vendor, the intended functional use (e.g., insulation, envelope, HVAC), climate-specific suitability and the relevant certifications, including LEED contributions, Cradle-to-Cradle ratings, Declare labels and environmental product declarations (EPDs). The matrix also recorded the circularity claim associated with each product, expressed in terms of the reduce, reuse and recycle principles, together with approximate cost ranges and potential barriers to adoption such as regional availability, cost implications or installation complexity. This structured approach provided a

robust basis for comparing products and served as the evidence base for material selection in the Optimized model. Table 1 summarizes representative products identified for the principal material categories.

Table 1. Representative sustainable products and systems identified in the desk-based market survey.

Material	Vendor and product	Application	Circularity attribute claimed	Certifications / labels
Aluminium	Kawneer Canada – 1600 Wall System	Curtain wall / façade	Recycle: 50% or more recycled aluminium; Reduce: low embodied carbon, high thermal performance	LEED, WELL, Cradle to Cradle
Aluminium	Alumicor – 2600 Series window; 5000 Series thermal door	Windows and doors	Reduce: thermally broken frames with double or triple glazing; Recycle: recyclable aluminium	LEED, EPD
Wood	Maibec – siding and shingles; TexelWood – decking and cladding	Exterior siding and cladding	Reduce: durable, thermally modified or treated certified wood extends service life	FSC/SFI, Red List Free, Declare, EPD
Wood	Holz100 Canada – solid wood flooring	Interior flooring	Reuse: glue-free, fully dismantlable and reusable; Recycle: biodegradable	Cradle to Cradle, Red List Free
Wood	West Fraser – SPF lumber and particleboard; Forest Forward – glulam and mass timber	Structural lumber, panels and mass timber	Recycle: full-log and residual-chip utilization; Reuse: long lifespan and disassembly potential	SFI/PEFC/FSC, EPD, LEED, Passive House supportive
Composite	NewTechWood Canada – composite beams and decking	Decorative beams and decking	Recycle: 95% recycled plastics and wood fibre; Reduce: no painting or staining required	LEED contributing, ISO 14001
Steel	Vulcraft Canada – deck and open-web joists; AltaSteel, ArcelorMittal and AGF Group – rebar	Structural steel and reinforcement	Recycle: 77–100% scrap steel via electric arc furnace; Reduce: prefabricated rebar cuts site waste	EPD, ISO 14001, CSA, LEED credits
Glass	Vitro – Solarban; Guardian – ClimaGuard and SunGuard	Exterior and interior glazing	Reduce: low-e coatings cut HVAC loads; Solarban 13% lower embodied carbon than industry average	Cradle to Cradle, EPD, LEED, ENERGY STAR
Glass	Columbia Skylights – triple-glazed skylights; JELD-WEN – JWC8500 windows	Rooflights and residential windows	Reduce: triple glazing and durable frames cut energy use and replacements; production waste recycled	ENERGY STAR, LEED

3.4 Sustainable Construction Practices Tool and selection of practices

Building on the Excel tool, a Sustainable Construction Practices Tool was created to translate the research evidence into practical decision-making. The tool is structured as a matrix that records, for each practice, the stage of the life cycle (design, procurement, construction, etc.), the category (e.g., wall assembly, glazing, HVAC), the conventional practice (baseline approach), the optimized practice (sustainable alternative), the justification for its selection and the total evidence score (Table 2). Unlike the underlying scoring tool, which contains the raw scores across the 40 papers, the

Sustainable Construction Practices Tool consolidates and communicates the practices most relevant to cold-climate sustainable design and provides direct visibility of the highest-priority practices.

Table 2. Sustainable Construction Practices Tool: conventional and optimized practices and materials with their evidence scores.

Stage	Category	Conventional practice / material	Optimized practice / material	Justification (why selected)	Evidence score (%)
Design	Glazing	Single or standard double-glazing without low-E or argon fill	Low-E argon-filled glazing in PVC/aluminium-clad frames, solar-oriented	Improves insulation, reduces heat loss, enhances daylighting.	5
Design	Shading & envelope	Standard envelope without airtight detailing	Moisture-managed CLT envelopes (vapour-tight detailing)	Prevents heat loss; improves durability.	5
Design	General	Conventional construction practice (unspecified)	Green roofs and vegetative façades	Improves cold-climate sustainability performance.	12.5
Design	Façade systems	Conventional brick/stone façade without PV or ventilation	Double-skin façades with PV/PCM	Integrates renewable energy and passive cooling.	7.5
Design	Shading & envelope	No external shading; reliance only on curtains/blinds	Dynamic shading systems (automated/smart shades)	Controls summer gain; admits winter sun.	12.5
Design	Glazing	Single or standard double-glazing without low-E or argon fill	Thermochromic/spectrally selective glazing (VO_2 coatings)	Improves insulation and daylighting control.	12.5
Design	Wall assembly	Conventional concrete/masonry walls with low insulation	High-performance envelope (VIPs, multi-layer CLT walls)	Improves thermal resistance; cuts heating demand.	2.5
Design	Building form	Non-optimized geometry (complex shapes with higher heat loss)	Compact building geometry and south orientation	Reduces envelope exposure and energy use.	7.5
Design	Wall assembly	Conventional concrete/masonry walls with low insulation	Window-to-wall ratio optimization (0.25–0.40)	Improves thermal resistance; cuts heating demand.	2.5
Design	General	Conventional construction practice (unspecified)	Parametric carbon-sensitive design (SCID, BIM-integrated LCA)	Improves cold-climate sustainability performance.	2.5
Design	General	Conventional construction practice (unspecified)	Electrification strategy aligned with provincial grid carbon intensity	Improves cold-climate sustainability performance.	2.5
Design	Building form	Irregular or large building footprint without optimization	Compact footprint and shape optimization	Minimizes surface area and heat loss.	5
Design	Wall assembly	Conventional concrete/masonry	High-R wall: glue-laminated timber substrate +	Improves thermal	5

		walls with low insulation	fibreglass batt + vapour retarder + gypsum	resistance; cuts heating demand.	
Design	General	Conventional construction practice (unspecified)	Solar PV, thermal collectors, battery integration	Improves cold-climate sustainability performance.	20
Design	General	Conventional construction practice (unspecified)	Occupancy sensors, automated HVAC/lighting	Improves cold-climate sustainability performance.	35
Design	Concrete	Ordinary Portland cement (OPC)-based concrete	FSC wood, recycled concrete/steel, low-carbon panels	SCMs reduce life-cycle CO_2 emissions.	20
Design	General	Conventional construction practice (unspecified)	Rainwater harvesting, freeze-proof plumbing	Improves cold-climate sustainability performance.	35
Design	Shading & envelope	No external shading; reliance only on curtains/blinds	Passive solar shading + airtight envelope detailing	Controls summer gain; admits winter sun.	5
Material procurement	General	Conventional construction practice (unspecified)	HRVs/ERVs with frost protection, zoned systems, heat pumps	Improves cold-climate sustainability performance.	50
Material procurement	Glazing	Conventional windows without energy-efficient coatings	Triple-pane windows, low-e coatings, thermal breaks	Reduces infiltration; improves comfort.	27.5
Material procurement	Sourcing	Imported materials without life-cycle tracking	Regionally sourced, EPD-tracked, BIM-monitored	Cuts transport emissions; supports local economy.	5
Material procurement	Structural systems	Conventional steel or reinforced concrete structures	FSC-certified timber / CLT panels	Timber/CLT lowers embodied carbon.	5
Material procurement	Concrete	Ordinary Portland cement (OPC)-based concrete	Fly ash / recycled concrete with industrial by-products	Replaces high-carbon Portland cement.	5
Material procurement	Insulation	Basic fibreglass insulation only	Hybrid: fibreglass + rock wool + limited bio-based (hempcrete/flax wool)	Outperforms fibreglass-only assemblies.	5
Construction	General	Conventional construction practice (unspecified)	Insulated slab-on-grade, frost-protected shallow foundations	Improves cold-climate sustainability performance.	40
Construction	Insulation	Minimal fibreglass batt insulation only	High R-value cellulose/wood-fibre insulation, continuous exterior layers	Lowers U-values; improves efficiency.	30
Construction	Site logistics	On-site construction with	Prefabricated CLT panels, lean site layout	Minimizes waste; speeds	5

		high waste generation		winter construction.	
Construction	Wall assembly	Conventional concrete/masonry walls with low insulation	Double-stud or ICF walls, air barriers, thermal-bridging control	Improves thermal resistance; cuts heating demand.	32.5
Construction	Winter work	Unprotected curing of concrete in cold conditions	Thermal blankets + curing shelters	Protects winter concrete curing.	2.5
Construction	Insulation	Basic fibreglass insulation only	Rock wool + fibreglass insulated laminated timber/metal doors	Outperforms fibreglass-only assemblies.	5
Construction	Structural systems	Conventional steel or reinforced concrete structures	Glue-laminated timber + aluminium frame + low-E glass inserts	Timber/CLT lowers embodied carbon.	0
Construction	Insulation	Minimal fibreglass batt insulation only	Cool/reflective roofing, vented roofs, high-performance insulation	Lowers U-values; improves efficiency.	22.5
Construction	General	Conventional construction practice (unspecified)	Preserve terrain, orient for solar gain, minimize site disturbance	Improves cold-climate sustainability performance.	25
Construction	General	Conventional construction practice (unspecified)	Low-VOC finishes, exposed thermal mass, demountable partitions	Improves cold-climate sustainability performance.	37.5
Maintenance and operation	Shading & envelope	No external shading; reliance only on curtains/blinds	Adaptive HVAC (HRVs, geothermal, shading-integrated)	Controls summer gain; admits winter sun.	5
Maintenance and operation	Monitoring	No sub-metering, only total building energy data	Sub-metering + digital-twin maintenance scheduling	Identifies inefficiencies; optimizes energy use.	5
Maintenance and operation	General	Conventional construction practice (unspecified)	Seasonal commissioning, user engagement for passive systems	Improves cold-climate sustainability performance.	37.5
Maintenance and operation	Glazing	Conventional windows without energy-efficient coatings	Operable windows with cross ventilation	Reduces infiltration; improves comfort.	5
Renovation	Façade systems	Conventional brick/stone façade without PV or ventilation	Snap-on ventilated façades, PV skins	Integrates renewable energy and passive cooling.	5
Renovation	Glazing	Single or standard double-glazing without low-E or argon fill	Low-E argon glazing retrofit	Improves insulation, reduces heat loss, enhances daylighting.	2.5

Renovation	General	Conventional construction practice (unspecified)	Modular hempcrete/CLT over-cladding panels	Improves cold-climate sustainability performance.	2.5
End of life	Waste handling	Mixed disposal of waste without material separation	On-site sorting, material banks	Maximizes recycling; reduces landfill.	5
End of life	Deconstruction	No tracking of material flows for reuse	Modular connections, material passports, traceable QR-coded elements	Enables traceability and reuse planning.	5
End of life	Deconstruction	Demolition without reuse of materials	Material reuse, deconstruction, waste separation	Enables reuse; supports circular economy.	40

Note: the evidence score is the number of papers, out of the 40 reviewed, that explicitly validated or recommended the practice, expressed as a percentage.

Using the tool, the highest-scoring practices were prioritized for Canada's climate. These included:

- Design stage: high-R wall assemblies with airtight detailing, compact building geometry, optimized window-to-wall ratios, passive solar orientation and triple-glazed low-E argon windows.
- Material procurement: FSC-certified CLT/timber, fly ash or recycled concrete, and hybrid insulation (rock wool + cellulose).
- Construction: prefabricated CLT panels, insulated slab-on-grade foundations and winter concrete-curing methods (thermal blankets).
- Operation and maintenance: adaptive HVAC with HRVs, digital-twin-based monitoring and operable windows for cross ventilation.
- Renovation: low-E glazing retrofits and snap-on ventilated façades with PV skins.
- End of life: modular connections with material passports and on-site sorting for material reuse.

Two improved design scenarios were derived from the tool: the Optimized model, which was developed using the practices scoring between 5% and 20% in the evidence base, and the Best Practice model, which integrates all of the identified practices. Both reflect the highest-scoring sustainable practices identified in the Sustainable Construction Practices Tool for Winnipeg.

3.5 BIM model development

To quantify and visualize the differences between conventional and sustainable construction practices in cold-climate regions, BIM tools were employed with Autodesk Revit as the primary modelling platform. The model development simulated comparative design scenarios: a baseline conventional building and optimized sustainable designs integrating best practices and energy-efficient materials. These models served as the foundation for the subsequent energy analysis and environmental performance assessment, in line with the overarching objective of evaluating sustainable solutions for Canada's cold regions.

3.5.1 Baseline (conventional) model

The Baseline model represents a conventional two-storey (ground plus one) residential building designed using standard construction methods typical of the cold-climate regions of Canada. Developed in Autodesk Revit, the model reflects code-compliant practices but excludes advanced sustainability strategies. Exterior walls were modelled using wood framing with batt insulation, covered externally with vinyl siding and internally with gypsum board. Wall sections varied in dimension, with heights of 8 ft and areas between 70 and 372 ft². These walls were constructed using a regular framed stud assembly with plywood or OSB sheathing and no thermal-break detailing, consistent with common practice in colder provinces such as Alberta and Manitoba.

The windows in the model are sliding vinyl-framed units, such as double-glazed Windsor white and Pella 250 series products, with dimensions ranging from 5 ft × 4 ft to larger 8 ft-wide units. These offer moderate thermal performance but do not include advanced coatings or triple glazing, resulting in higher U-values and heat loss during the winter months. The doors include insulated steel garage doors (Garage SSG) and aluminium sliding patio doors, both chosen for their widespread use and affordability, with widths between 6 and 17 ft and without additional thermal insulation enhancements. The building envelope lacks advanced sealing or airtight detailing, and roof insulation levels are assumed to meet, but not exceed, minimum local code requirements.

3.5.2 Geometry and functional spaces

The model comprises two floors: a ground floor area of 1,068 ft² and a first floor of 1,292 ft². Internal zoning follows a typical residential layout including utility areas, washrooms, food-service spaces and open zones (Fig. 2). Room areas range from small 37 ft² utility rooms to large 386 ft² living spaces. The volumes of individual spaces extend up to 2,894 ft³, with ceiling heights standardized at 8 ft. The space types also include parking, storage and circulation areas, representing the full spectrum of functional requirements in a conventional dwelling.

3.5.3 Mechanical and electrical systems

The Baseline model incorporates a natural-gas forced-air heating system and a standard gas-fired water heater. Mechanical zoning is not optimized; distribution is uniform, without temperature zoning or demand-based control. Lighting is represented by compact fluorescent fixtures, and no renewable energy systems, heat recovery ventilators (HRVs) or demand-controlled ventilation are included. This baseline version serves as the comparative reference for assessing the improvements introduced in the Optimized and Best Practice models, particularly with respect to energy efficiency, thermal performance and environmental impact.

3.5.4 Optimized and Best Practice models

The selected practices were integrated into the BIM workflow in Autodesk Revit through four activities: (i) customizing assemblies, whereby wall, roof and floor layers were defined with sustainable materials (e.g., CLT with hybrid insulation and triple-glazed windows); (ii) applying design parameters, whereby building form, orientation and window-to-wall ratios were optimized using Revit's parametric environment; (iii) embedding material data, whereby the material libraries were enriched with sustainable product information (FSC-certified timber, fly ash concrete and hybrid insulation); and (iv) providing renovation and end-of-life readiness, whereby modular elements and deconstruction-ready connections were modelled for adaptability and reuse. The Optimized model modified the structural and envelope assemblies through the use of glue-laminated timber (glulam), CLT, laminated veneer lumber, softwood lumber, cellulose insulation, PVC window frames and double-glazed hard-coated argon glazing, whereas the Best Practice model further refined the assemblies through greater use of softwood lumber, softwood plywood, OSB, gypsum products, cellulose insulation, high-performance glazing and water-based latex paint. By embedding research-backed practices directly into a BIM workflow, the models demonstrate how evidence from the literature can be systematically translated into architectural design.

3.6 Energy and carbon analysis

The Baseline, Optimized and Best Practice models were analysed using the energy-analysis facilities of Autodesk Revit in three steps: location setup, creation of the energy analytical model, and definition of the energy settings and simulation.

3.6.1 Location setup

The project location was set to Winnipeg, Manitoba, Canada, representing a cold-climate region classified as ASHRAE Climate Zone 7A. In Revit, the project address was defined as Winnipeg, MB using the Internet Mapping Service under the Location and Site settings; the specified project location corresponds to approximately 49.900497° N latitude and 97.139313° W longitude. Based on this location, weather station 29324, located approximately 7.40 miles from the project site, was selected as the weather station for the subsequent energy analysis and provided the climatic data used for the building energy performance assessment. For the carbon analysis, Autodesk Insight Carbon Analysis using EnergyPlus was employed to evaluate the operational and embodied carbon performance of the building. The electricity emissions rate was set to 0.37 $kgCO_2e/kWh$ in the Carbon Analysis settings; this factor was applied to the building's electricity consumption to estimate the associated operational carbon emissions.

3.6.2 Energy analytical model

An energy analytical model was created by dividing the building into thermal zones. Perimeter zoning was applied with a perimeter zone depth of 15 ft so as to capture the thermal loads at the façades, and the analytical space resolution and analytical surface resolution were both set to 1.0 ft. The analytical spaces, which constitute the thermal volumes used in the energy calculation, are depicted in Fig. 3.

3.6.3 Energy settings and simulation

The New Construction phase was defined as the project phase, the energy analytical model mode was set to use building elements, and the building assemblies (walls, roofs, floors, windows, doors and foundations) were mapped to the analytical model. With these inputs, Carbon Analysis and Systems Analysis were performed to determine the approximate annual energy use, the end-use applications and the associated carbon generation for each model. The Insight scope comprised the envelope and interior subset of the architectural elements included in the energy analytical model, and its total carbon analysis covered the manufacturing stage (A1–A3) and the operational energy stage (B6); the outputs included the annual energy use intensity (EUI), the embodied carbon, the annual operational carbon and the load distributions for heating and cooling.

3.7 Life cycle assessment

3.7.1 Goal and scope

An LCA was performed for the three building models—Baseline, Optimized and Best Practice—using the Athena Impact Estimator for Buildings. The purpose of the LCA was twofold. First, to quantify the environmental impacts: to systematically measure and compare the environmental burdens associated with the major building assemblies, such as walls, roofs, windows, doors, flooring, beams and columns, foundations and finishes, which is useful in determining which components contribute the most to global warming potential, energy demand and other impact categories. Second, to evaluate the improvements in design: to assess the effectiveness of the design strategies incorporated in the Optimized

and Best Practice models by comparing them with the Baseline and thereby to identify the environmental benefits of introducing sustainable construction practices and circular economy principles into building design.

The whole-building LCA was conducted using the Athena Impact Estimator for Buildings, version 5.5.0113.04, with the assessment based on the TRACI v2.1 life-cycle impact assessment method [53]. The assessment follows the general LCA framework of ISO 14040 and ISO 14044 [54, 55] and the modular building-level structure of EN 15978 [56]. The assessment considered a single-family residential building located in Winnipeg, with a gross floor area (GFA) of 254 m² and a 60-year reference study period. The analysis location was set to Winnipeg because this was the most suitable option available in Athena for representing cold-climate conditions in the Canadian context. The same building size, type, location and reference study period were applied to all three buildings, allowing the comparison to focus on the differences in material quantities and building assemblies. Previous research has also identified the importance of maintaining consistent material take-offs when comparing LCA alternatives [46].

3.7.2 Life cycle inventory

The life cycle inventory stage involved collecting and organizing all of the input and output data required for the environmental assessment. Data were obtained from three main sources: (i) the Athena database, which provides region-specific life-cycle inventory data for construction materials, manufacturing processes and transportation scenarios relevant to North American conditions; (ii) the literature, with published academic studies and technical reports reviewed to validate the assumptions on service life, material performance and maintenance practices; and (iii) the project specifications, with the material quantities and design details derived from the Revit building models, ensuring that the inputs reflect realistic construction scenarios.

3.7.3 Material assemblies included

The following major assemblies were modelled in Athena for all three building scenarios: walls (exterior and interior walls, including insulation and cladding); windows (glazing type and frame material); doors (exterior and interior door systems); roofs (structural layers, insulation and finishing); flooring (structural flooring and finishing layers); beams and columns (the structural elements of the building frame); the foundation (footings, slabs and related sub-structural components); and paint and finishes (coatings and surface treatments applied to walls and other assemblies).

3.7.4 Functional unit, system boundary and reference study period

The functional unit for the assessment is defined as 1 m² of gross floor area providing the required function of a single-family residential building over a 60-year reference study period; the total building assessment corresponds to 254 m² of GFA over the 60-year study period. The assessment adopts a cradle-to-grave system boundary, as illustrated in Fig. 4, covering the product, construction, use and end-of-life stages. The included modules are A1–A3 (raw material supply, transportation and manufacturing), A4–A5 (transport to site and construction/installation), B2–B5 (maintenance, repair, replacement and refurbishment), B6 (operational energy use) and C1–C4 (deconstruction/demolition, transport, waste processing and disposal). Module B1 is not included because it is not applicable within the Athena assessment framework used for this study, and Module D, representing benefits and loads beyond the system boundary, is excluded from the reported results. Within the use stage, the material-related contributions quantified by Athena are reported under modules B2 and B4 (maintenance and replacement), which is how the use-stage columns are labelled in Table 3, alongside the separately reported operational energy use (B6).

A 60-year reference study period is used for the Baseline and the proposed buildings. This choice is supported by Feng et al. [46], who used a 60-year building lifespan for their whole-building Athena LCA of a single-family residential building in

British Columbia. The 60-year period is therefore adopted consistently for all alternatives in the present assessment; maintaining the same reference period is particularly important because differences in replacement, maintenance and other use-stage processes can influence the comparative LCA results.

4. Results and Discussion

4.1 Life cycle assessment results by impact category

This section presents the LCA results of the Baseline, Optimized and Best Practice models for the seven TRACI 2.1 impact indicators calculated with the Athena Impact Estimator. The stage-wise contributions for each indicator are reported in Table 3 and illustrated in Fig. 5, and the percentage changes relative to the Baseline are summarized in Table 4.

Table 3. Life-cycle impact results of the three models by life-cycle stage (Athena Impact Estimator for Buildings, TRACI 2.1, 60-year reference study period).

Impact category	Unit	Model	Product (A1–A3)	Constr. (A4–A5)	Use (B2 & B4)	Operational energy (B6)	End of life (C1–C4)	Total
Global warming potential	kg CO_2 eq	Baseline	−5.91E+04	3.53E+03	2.68E+03	2.56E+04	4.11E+04	1.38E+04
		Optimized	−4.30E+04	1.71E+03	3.11E+02	1.83E+04	3.22E+04	9.64E+03
		Best Practice	−3.66E+04	1.87E+03	5.59E+02	1.54E+04	2.63E+04	7.49E+03
Acidification potential	kg SO_2 eq	Baseline	2.54E+02	6.26E+01	8.10E+00	1.37E+01	3.67E+01	3.75E+02
		Optimized	1.72E+02	4.79E+01	2.46E+00	9.79E+00	3.87E+01	2.70E+02
		Best Practice	1.04E+02	4.72E+01	4.75E+00	8.24E+00	3.77E+01	2.02E+02
Eutrophication potential	kg N eq	Baseline	6.81E+01	5.93E+00	5.43E−01	3.62E+01	2.53E+00	1.13E+02
		Optimized	5.24E+01	4.20E+00	7.61E−02	2.59E+01	3.14E+00	8.58E+01
		Best Practice	2.43E+01	4.30E+00	2.93E−01	2.18E+01	3.22E+00	5.39E+01
Fossil fuel consumption	MJ	Baseline	5.86E+05	7.68E+04	5.70E+04	4.07E+04	4.29E+04	8.03E+05
		Optimized	3.76E+05	4.81E+04	2.75E+03	2.91E+04	4.56E+04	5.01E+05
		Best Practice	3.25E+05	5.08E+04	2.50E+04	2.45E+04	4.52E+04	4.70E+05
Human health particulate	kg $PM_{2.5}$ eq	Baseline	4.65E+01	4.95E+00	3.16E+01	1.52E+01	1.69E+01	1.15E+02
		Optimized	1.79E+01	2.66E+00	5.31E−01	1.09E+01	1.17E+01	4.37E+01
		Best Practice	1.96E+01	3.26E+00	1.54E+01	9.15E+00	1.19E+01	5.92E+01
Ozone depletion potential	kg CFC-11 eq	Baseline	2.45E−03	1.29E−04	3.89E−06	1.96E−04	9.24E−05	2.87E−03
		Optimized	1.79E−03	8.93E−05	6.68E−06	1.40E−04	1.33E−04	2.16E−03
		Best Practice	7.06E−04	6.62E−05	2.24E−06	1.18E−04	1.50E−04	1.04E−03
Smog formation potential	kg O_3 eq	Baseline	3.99E+03	1.79E+03	1.64E+02	1.30E+02	1.19E+03	7.26E+03
		Optimized	2.44E+03	1.37E+03	1.49E+01	9.34E+01	1.21E+03	5.12E+03
		Best Practice	1.64E+03	1.36E+03	1.04E+02	7.85E+01	1.16E+03	4.34E+03

Note: stage columns follow the Athena reporting format; negative product-stage values for global warming potential reflect the net biogenic carbon storage accounted for by Athena.

4.1.1 Global warming potential

The Baseline model recorded a net global warming potential (GWP) of 1.38×10^4 kg CO_2 eq, while the Optimized model recorded 9.64×10^3 kg CO_2 eq, representing a reduction of approximately 30.1% compared with the Baseline. The Best Practice model achieved the lowest total GWP at 7.49×10^3 kg CO_2 eq, corresponding to a reduction of approximately 45.7% compared with the Baseline and a further 22.3% reduction compared with the Optimized model (Table 3; Fig. 5a).

The reduction in total GWP is associated with the progressive changes in material selection and building design. The Optimized model modified the structural and envelope assemblies through changes in glulam, CLT, laminated veneer lumber, softwood lumber and cellulose insulation. These material substitutions altered the embodied impacts and the amount of biogenic carbon accounted for at the product stage, while the improved envelope performance contributed to lower operational impacts. The Best Practice model further refined the assemblies through greater use of softwood lumber, softwood plywood, OSB, gypsum products and cellulose insulation, and these changes, together with the improved building performance, contributed to the further reduction in whole-life GWP.

Although the product stage (A1–A3) became less negative from the Baseline to the Best Practice model, this does not indicate poorer overall carbon performance. The negative A1–A3 values reflect the net biogenic-carbon storage under the accounting approach used by Athena, consistent with the carbon-storage role of wood-based construction materials [15, 37]. The reduction in this storage benefit is outweighed by the improvements in the other life-cycle stages: in particular, the reductions in operational energy (B6), maintenance and replacement (B2–B4), construction (A4–A5) and end-of-life impacts (C1–C4) resulted in a substantial decrease in total GWP.

4.1.2 Acidification potential

The Baseline model generated 3.75×10^2 kg SO_2 eq, the Optimized model reduced this to 2.70×10^2 kg SO_2 eq and the Best Practice model further reduced it to 2.02×10^2 kg SO_2 eq (Fig. 5b). Compared with the Baseline, the Optimized model achieved a 28% reduction and the Best Practice model a 46% reduction in acidification potential (AP).

The reduction in AP is primarily associated with the improved material selection and envelope strategies across the three models. The product stage (A1–A3) decreased from 2.54×10^2 kg SO_2 eq in the Baseline model to 1.72×10^2 kg SO_2 eq in the Optimized model and 1.04×10^2 kg SO_2 eq in the Best Practice model. The use of cellulose-based insulation, fibreglass insulation and high-performance glazing in the optimized material strategy supports improved building performance and contributes to the observed reduction in AP. In addition, the Optimized model uses PVC window frames and double-glazed hard-coated argon glazing, which are consistent with the emphasis of the evidence base on high-performance glazing using low-E/argon glazing and PVC/aluminium-clad frames to improve thermal performance and reduce heat loss.

4.1.3 Eutrophication potential

The Baseline model generated 1.13×10^2 kg N eq, while the Optimized model reduced this to 8.58×10^1 kg N eq and the Best Practice model further reduced it to 5.39×10^1 kg N eq (Fig. 5c). Compared with the Baseline, the Optimized model achieved a 24% reduction and the Best Practice model a 52% reduction in eutrophication potential (EP).

The Optimized model incorporates glulam, which is supported by the evidence base as an alternative structural material. Mass-timber structural systems can reduce eutrophication impacts compared with conventional structural systems in

some whole-building LCAs, although the actual impact depends on the production process and supply chain. Cellulose insulation is also included in the Optimized and Best Practice models and is supported by the evidence base as a high-R-value insulation strategy; its improved thermal performance can reduce heating requirements and the associated emissions. In addition, the operational energy contribution decreased from 3.62×10^{1} kg N eq in the Baseline model to 2.59×10^{1} kg N eq in the Optimized model and 2.18×10^{1} kg N eq in the Best Practice model. Since nitrogen oxides from energy generation and fuel combustion can contribute to eutrophication, the reduction in operational energy demand supports the overall decreasing trend.

4.1.4 Fossil fuel consumption

The Baseline model consumed 8.03×10^{5} MJ of fossil fuel, the Optimized model 5.01×10^{5} MJ and the Best Practice model 4.70×10^{5} MJ (Fig. 5d). The Optimized design therefore reduced fossil fuel consumption (FFC) by 37.6% and the Best Practice model by 41.5% compared with the Baseline. According to the results, design strategies that target efficient building assemblies and operational energy savings substantially reduce the reliance on fossil fuels: the product-stage contribution decreased from 5.86×10^{5} MJ to 3.76×10^{5} and 3.25×10^{5} MJ, and the operational-energy contribution from 4.07×10^{4} MJ to 2.91×10^{4} and 2.45×10^{4} MJ. The decreased use of fossil energy by the Best Practice model is a strong indicator of the attainment of sustainable building objectives.

4.1.5 Human health particulate

The Baseline model generated 1.15×10^{2} kg $PM_{2.5}$ eq, while the Optimized model reduced this to 4.37×10^{1} kg $PM_{2.5}$ eq and the Best Practice model to 5.92×10^{1} kg $PM_{2.5}$ eq (Fig. 5e). Compared with the Baseline, the Optimized model achieved a 62.0% reduction and the Best Practice model a 48.5% reduction in the human health particulate (HH particulate) impact.

The decreases are attributed to the reduced burning of fossil fuels in the manufacture of materials as well as during the operational processes. A material-specific change that is particularly relevant to this indicator is the use of water-based latex paint in the Best Practice model: the selection framework specifies low-VOC finishes as a preferred construction practice, and the Best Practice model accordingly contains water-based latex paint. Reducing solvent-intensive finishing products can lower the associated atmospheric precursor emissions; however, this should be considered a supporting factor rather than the primary cause of the $PM_{2.5}$ reduction. The higher use-stage (B2 & B4) contribution of the Best Practice model relative to the Optimized model (1.54×10^{1} versus 5.31×10^{-1} kg $PM_{2.5}$ eq) accounts for most of the difference between the two improved models.

4.1.6 Ozone depletion potential

The Baseline model generated 2.87×10^{-3} kg CFC-11 eq, while the Optimized model reduced this to 2.16×10^{-3} kg CFC-11 eq and the Best Practice model further reduced it to 1.04×10^{-3} kg CFC-11 eq (Fig. 5f). Compared with the Baseline, the Optimized model achieved a 24.7% reduction and the Best Practice model a 63.8% reduction in ozone depletion potential (ODP).

A particularly relevant change is the reduced use of fluorinated foam insulation between the models. The Baseline model contains substantial expanded and extruded polystyrene insulation, while the Optimized model contains much less of these foam products and relies more on alternative envelope strategies. This is technically relevant because the historical CFC/HCFC blowing agents used in foam insulation can have ozone-depletion impacts; the formulation and blowing-agent inventory of foam products can therefore materially affect ODP. The Best Practice model shows the superior management

of refrigerant-related impacts and material choice, with the product-stage contribution falling from 2.45 × 10^{-3} kg CFC-11 eq in the Baseline to 7.06 × 10^{-4} kg CFC-11 eq.

4.1.7 Smog formation potential

The Baseline model generated 7.26 × 10^3 kg O_3 eq, while the Optimized model reduced this to 5.12 × 10^3 kg O_3 eq and the Best Practice model further reduced it to 4.34 × 10^3 kg O_3 eq (Fig. 5g). Compared with the Baseline, the Optimized model achieved a 29% reduction and the Best Practice model a 40% reduction in smog formation potential (SFP).

The reduction in SFP is associated with the changes in material selection and the improved building performance. The product stage (A1–A3) decreased from 3.99 × 10^3 kg O_3 eq in the Baseline model to 2.44 × 10^3 kg O_3 eq in the Optimized model and further to 1.64 × 10^3 kg O_3 eq in the Best Practice model. The Optimized model incorporates cellulose insulation, fibreglass and glulam, which are consistent with the material strategies identified in the evidence base. The Best Practice model continues the use of cellulose insulation and high-performance glazing, supporting improved envelope performance. These material strategies, together with the optimized building design, contribute to the lower life-cycle smog potential observed in the Optimized and Best Practice models.

4.2 Summary of the LCA results

The comparative LCA tells a subtler tale: although both the Optimized and the Best Practice models cut a number of environmental burdens to well below the Baseline, the extent and allocation of the improvements differ across categories (Table 4). The percentage changes emphasize the areas where the gains were most significant. The Best Practice model achieved the largest reductions in ozone depletion potential (63.8%), eutrophication potential (52.3%), acidification potential (46.1%) and global warming potential (45.7%), whereas the Optimized model achieved the largest reduction in human health particulate impact (62.0%), the only category in which the Optimized model outperformed the Best Practice model.

Table 4. Summary of the life-cycle impact results and percentage change relative to the Baseline model.

No.	Impact category (unit)	Baseline	Optimized	Best Practice	Change, Optimized vs Baseline (%)	Change, Best Practice vs Baseline (%)
1	Global warming potential (kg CO_2 eq)	13,800	9,640	7,490	−30.14	−45.72
2	Acidification potential (kg SO_2 eq)	375.0	270.0	202.0	−28.00	−46.13
3	Eutrophication potential (kg N eq)	113.0	85.8	53.9	−24.07	−52.30
4	Fossil fuel consumption (MJ)	8.03E+05	5.01E+05	4.70E+05	−37.61	−41.47
5	Human health particulate (kg $PM_{2.5}$ eq)	115.0	43.7	59.2	−62.00	−48.52
6	Ozone depletion potential (kg CFC-11 eq)	2.87E−03	2.16E−03	1.04E−03	−24.74	−63.76
7	Smog formation potential (kg O_3 eq)	7,260	5,120	4,340	−29.48	−40.22

4.3 Energy and carbon analysis

The energy analysis evaluated the three single-family residential building models in Winnipeg, each representing a different level of design improvement. The purpose of this assessment was to compare how the changes in the building envelope and the passive strategies influence operational energy demand, embodied carbon and total life-cycle emissions. The simulations were performed with the Autodesk Insight plug-in and Revit Systems Analysis, with outputs including the annual EUI, the embodied carbon, the annual operational carbon and the load distributions for heating and cooling. The results are summarized in Table 5 and Fig. 6.

Table 5. Energy and carbon analysis results of the three models (Autodesk Insight Carbon Analysis, Winnipeg).

Parameter	Baseline	Optimized	Best Practice
Building area (m^2)	256.16	254.73	254.72
Annual energy use intensity (kWh/m^2)	355.66	325.69	320.44
Operational carbon ($kgCO_2e$)	23,533.17	21,605.47	21,314.58
Embodied carbon ($kgCO_2e$)	60,243.24	40,464.85	38,939.98
Total carbon ($kgCO_2e$)	83,776.41	62,070.32	60,254.57

4.3.1 Baseline model

The Baseline model represents a conventional single-family dwelling situated in Winnipeg. The results highlight the limitations of standard construction in cold climates, where poor insulation and infiltration contribute to excessive energy use. The annual EUI was calculated at 355.66 kWh/m^2, a value that underscores the significant reliance on mechanical heating and cooling systems to achieve acceptable indoor comfort levels. The carbon analysis further illustrates the high-impact nature of the baseline design: operational carbon emissions amounted to 23,533 $kgCO_2e$, while embodied carbon was substantially greater at 60,243 $kgCO_2e$. Together, these produced a total life-cycle carbon footprint of 83,776 $kgCO_2e$, making the Baseline the least sustainable of the three scenarios. The imbalance between operational and embodied emissions is consistent with recent research findings, which emphasize that, without targeted strategies, embodied carbon can dominate the life-cycle emissions of conventional housing [6, 25].

4.3.2 Optimized model

The Optimized model introduces significant envelope improvements, including enhanced insulation, reduced infiltration and tighter airtightness, while retaining the same building typology and location. These interventions led to a marked improvement in energy performance, with the annual EUI reduced to 325.69 kWh/m^2, an 8.43% reduction compared with the Baseline. This result demonstrates the effectiveness of envelope-first strategies in mitigating energy demand in severe Canadian climates. The carbon analysis further supports the benefits of optimization: operational carbon emissions were reduced to 21,605 $kgCO_2e$, while embodied carbon dropped sharply to 40,465 $kgCO_2e$ owing to efficient material substitution and more sustainable construction practices. The total life-cycle carbon footprint of the Optimized model was 62,070 $kgCO_2e$, representing a 25.91% reduction compared with the Baseline. These results align with the findings of Al-Shatnawi et al. [1], which emphasize the dual benefits of envelope performance improvements and material efficiency in reducing both operational and embodied emissions.

4.3.3 Best Practice model

The best-performing model was developed by applying advanced passive design strategies alongside the optimized envelope improvements. This configuration yielded the highest efficiency among the three models: the annual EUI was reduced further to 320.44 kWh/m², the lowest value achieved in this study, reflecting the successful integration of passive solar utilization, optimized glazing ratios and insulation enhancements into the building design. The carbon assessment confirmed the advantages of this approach. Operational carbon emissions were 21,315 $kgCO_2e$, while embodied carbon was 38,940 $kgCO_2e$. The total life-cycle carbon footprint of the Best Practice model was 60,255 $kgCO_2e$, representing a 28.08% reduction compared with the Baseline. This demonstrates the potential of combining envelope-first design with passive strategies to achieve deep carbon reductions in residential housing.

4.4 Limitations

The findings should be interpreted in light of several limitations. First, the study is based on a single two-storey single-family dwelling, and the analysis location was set to Winnipeg because it was the most suitable option available in Athena for representing Canadian cold-climate conditions; the results are therefore not directly generalizable to other typologies or climate zones without further modelling. Second, the operational results were generated by two tools with different scopes: the Autodesk Insight carbon analysis covers the manufacturing stage (A1–A3) and operational energy (B6) of the envelope and interior elements with a fixed electricity emissions factor of 0.37 $kgCO_2e/kWh$, whereas the Athena assessment is cradle-to-grave; the absolute values from the two workflows are therefore not directly comparable and are used here for the relative comparison of the three models. Third, Modules B1 and D are excluded, biogenic carbon is accounted for according to the Athena approach, and future changes in grid carbon intensity are not modelled. Fourth, the evaluation is environmental only; construction cost and life-cycle cost were outside the scope, although the literature indicates that green materials can carry an initial cost premium that is recovered over the life cycle [14, 30]. Finally, the market survey was desk-based and did not include supplier interviews or field verification of product claims, and the simulated performance has not been validated against measured data, a gap that is well documented in the post-occupancy literature [48, 49]. Future work should extend the comparison to additional Canadian climate zones and building typologies, couple the assessment with life-cycle costing, and validate the models against monitored performance.

5. Conclusions and Recommendations

5.1 Summary of the research

This study examined sustainable building methods for cold-climate areas of Canada, where severe winter temperatures, freeze–thaw cycles and large heating loads pose considerable design and material challenges. The analysis was motivated by the Canadian pledge to reach net-zero emissions by 2050 and by the existing inefficiencies of traditional construction technology in delivering low-carbon performance in these areas. Three BIM scenarios—Baseline, Optimized and Best Practice—were used to demonstrate a comparative approach, reflecting respectively standard practice, the integration of selected sustainable strategies, and the demonstration of advanced passive design and sustainable construction principles. The models were tested by energy simulation and LCA using Autodesk Revit and the Athena Impact Estimator.

The study found major obstacles to sustainable construction, such as inadequate local infrastructure to support the reuse of materials, inappropriate policy frameworks and the low use of life-cycle design tools. Nevertheless, it also showed that envelope-first strategies, regionally sourced low-carbon materials and passive solar design can contribute to a substantial decrease in the operational energy and embodied emissions of residential construction. The LCA findings indicated that the Optimized and Best Practice models achieved significant reductions in global warming potential (up to 46%), fossil

fuel consumption (up to 41%) and the other environmental impact categories. The energy analysis also confirmed that the EUI was reduced from 355 kWh/m² in the Baseline to 320 kWh/m² in the Best Practice model.

5.2 Conclusions

The results make it clear that making cold-climate building design more sustainable is not only possible but also highly effective. The substantial reduction of carbon emissions and environmental impacts achieved through the judicious choice of materials, careful attention to building geometry and the integration of life-cycle analysis tools does not necessitate a reduction in building performance. The Optimized and Best Practice models show that envelope-related improvements—such as upgraded insulation, passive strategies and airtight construction—all lead to performance improvements. Such measures not only favour climate objectives but also help to create healthier indoor spaces and long-term cost savings.

Furthermore, BIM and LCA as integrated design tools are critical to making data-driven decisions at the early design stage. This approach allows stakeholders to manage the trade-offs between embodied and operational carbon and to create buildings that are resilient, efficient and future-ready. In conclusion, this research shows that sustainable construction in low-temperature Canadian climates is a realistic goal grounded in evidence, technology and sound design.

5.3 Recommendations

In light of the findings of this study, the following recommendations are made to practitioners, policymakers and researchers:

- Give preference to high-performance building envelopes with airtight detailing, advanced insulation and climate-adaptive glazing; these strategies are the most rewarding in lowering energy consumption in cold climates.
- Use BIM tools and LCA from the beginning of the project to allow comprehensive evaluations of both operational and embodied carbon, and explore and optimize design alternatives using parametric design tools.
- Favour local, low-carbon materials, including FSC-certified timber, recycled concrete and hybrid insulation; local sourcing reduces transportation emissions and supports the circular economy.
- Governments and municipalities should encourage prefabrication approaches through funding and the revision of building codes; these techniques reduce construction waste and can achieve higher quality control even in extreme winter climates.
- Implement uniform systems for measuring and reporting life-cycle environmental performance in codes and procurement processes; the metrics should consider global warming potential, fossil fuel use and effects on human health.
- Regional governments should publish best-practice manuals and case studies that translate research into actionable design strategies for the various climate zones of Canada.
- Implement economic incentives, rebates and policy measures that promote the adoption of sustainable building practices, particularly in remote and under-resourced communities.
- Increase awareness of sustainable design, BIM modelling and life-cycle assessment tools among architects, engineers and construction workers.

Declarations

Ethics approval and consent to participate

Not applicable. This study did not involve human participants, human data or animals.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Funding

This work was supported by Mitacs through Mitacs Globalink Research Award.

Author Contribution

Muhammad Muzamil: conceptualization, investigation, methodology, formal analysis, writing- original draft preparation; Mohammad Kamali: conceptualization, supervision, funding acquisition, project administration, writing-review and editing; Ahmed Hassan Zafar: validation, writing- original draft preparation; Zeerak Waryam Sajid: validation, writing- original draft preparation. All authors read and approved the final manuscript.

Acknowledgement

Authors acknowledge Mitacs for providing Mitacs Globalink Reserach Award to support this research.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

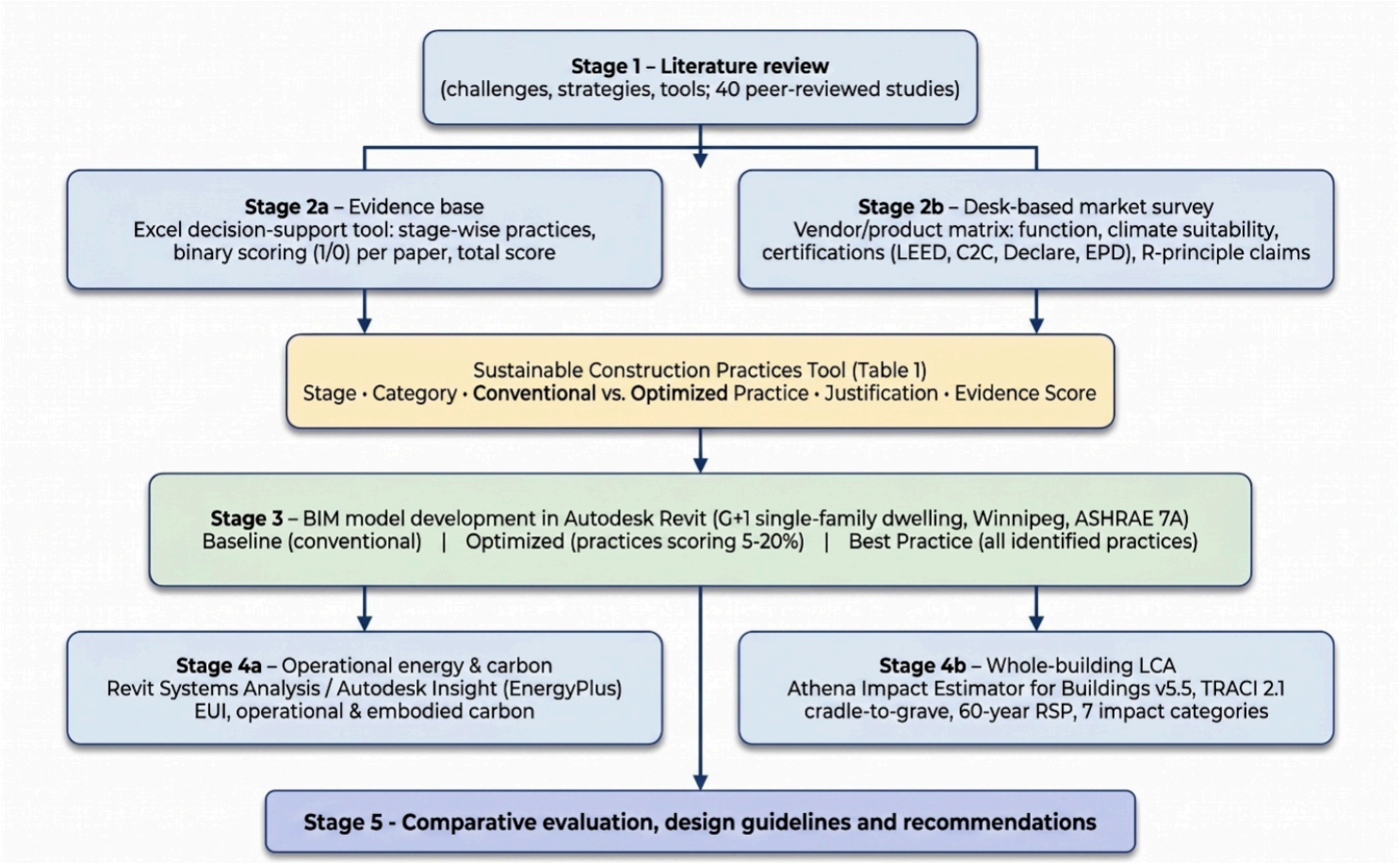


Figure 1

Research workflow adopted in the study

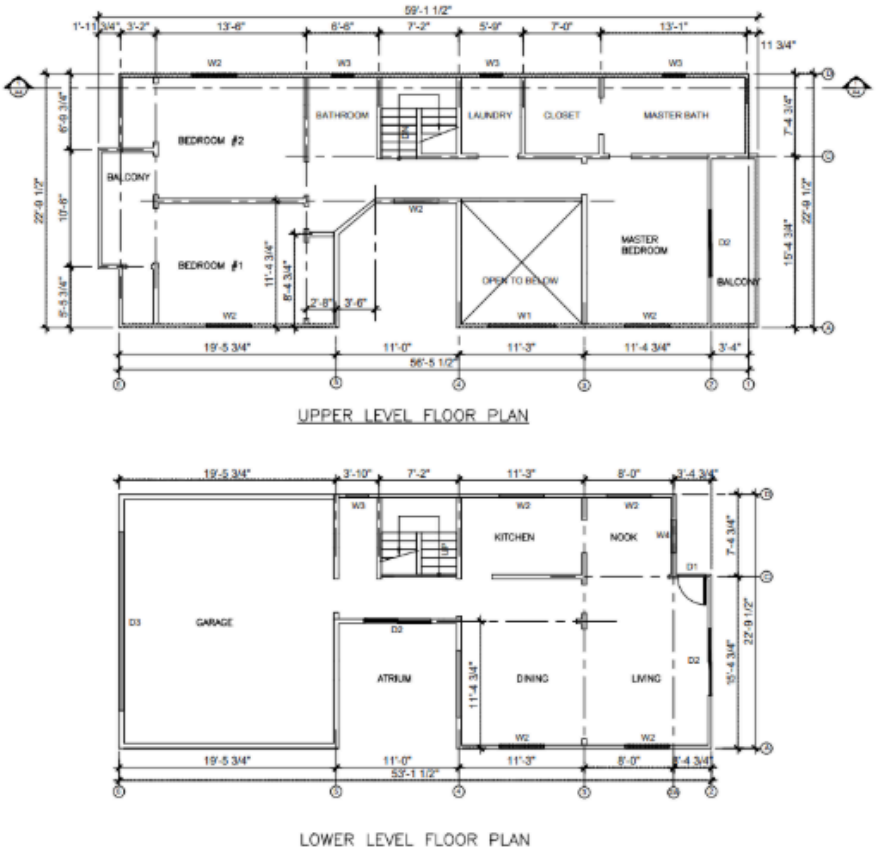


Figure 2

Upper- and lower-level floor plans of the residential building modelled in Revit

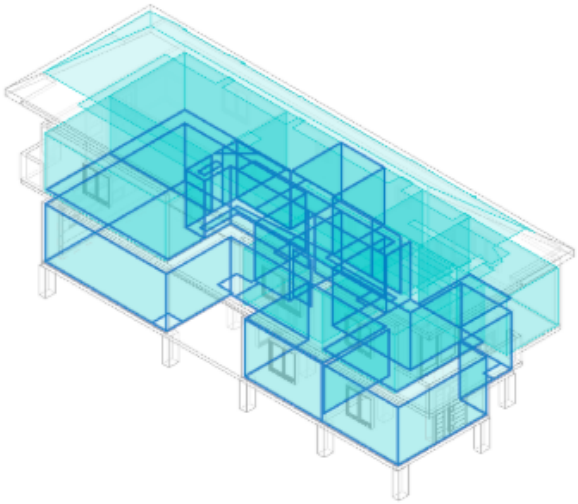


Figure 3

Energy analytical model of the residential building showing the analytical spaces (thermal zones)

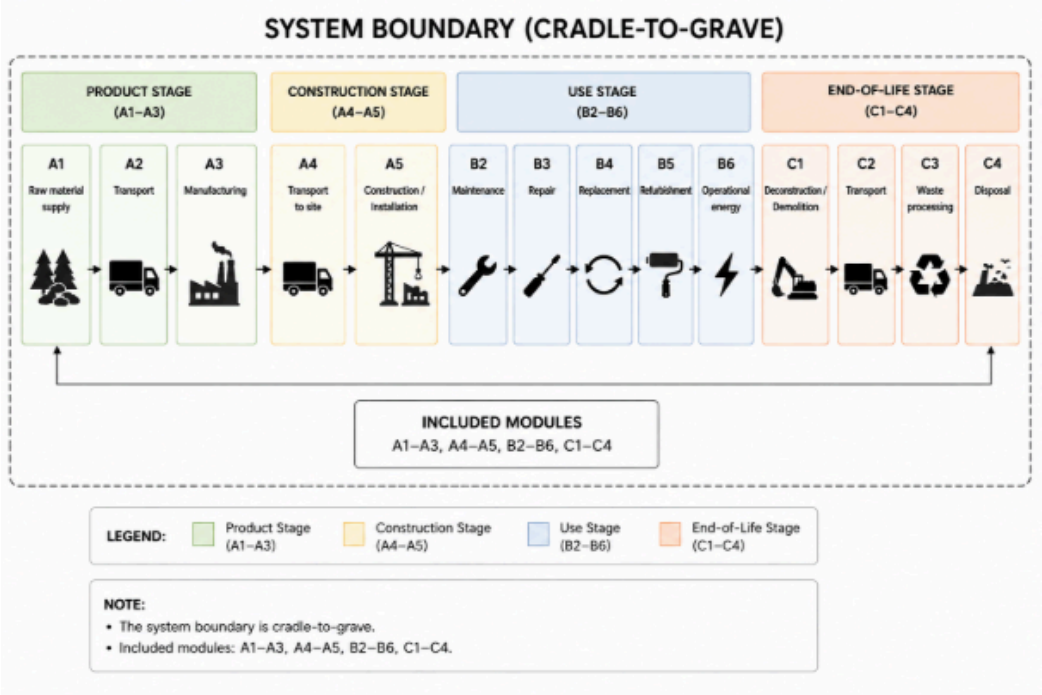


Figure 4

Cradle-to-grave system boundary and life-cycle modules included in the assessment

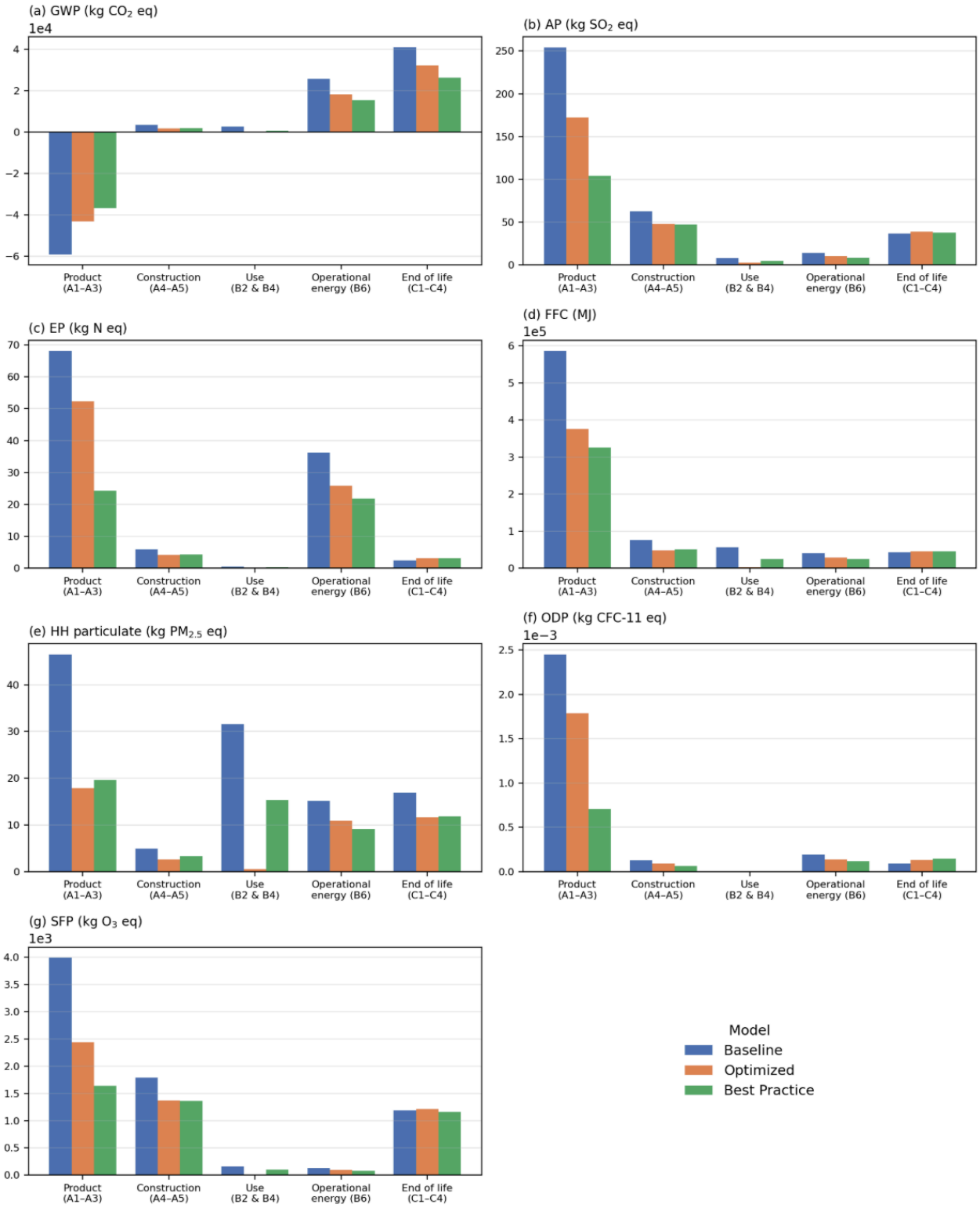


Figure 5

Stage-wise comparison of the three models for (a) global warming potential, (b) acidification potential, (c) eutrophication potential, (d) fossil fuel consumption, (e) human health particulate, (f) ozone depletion potential and (g) smog formation potential

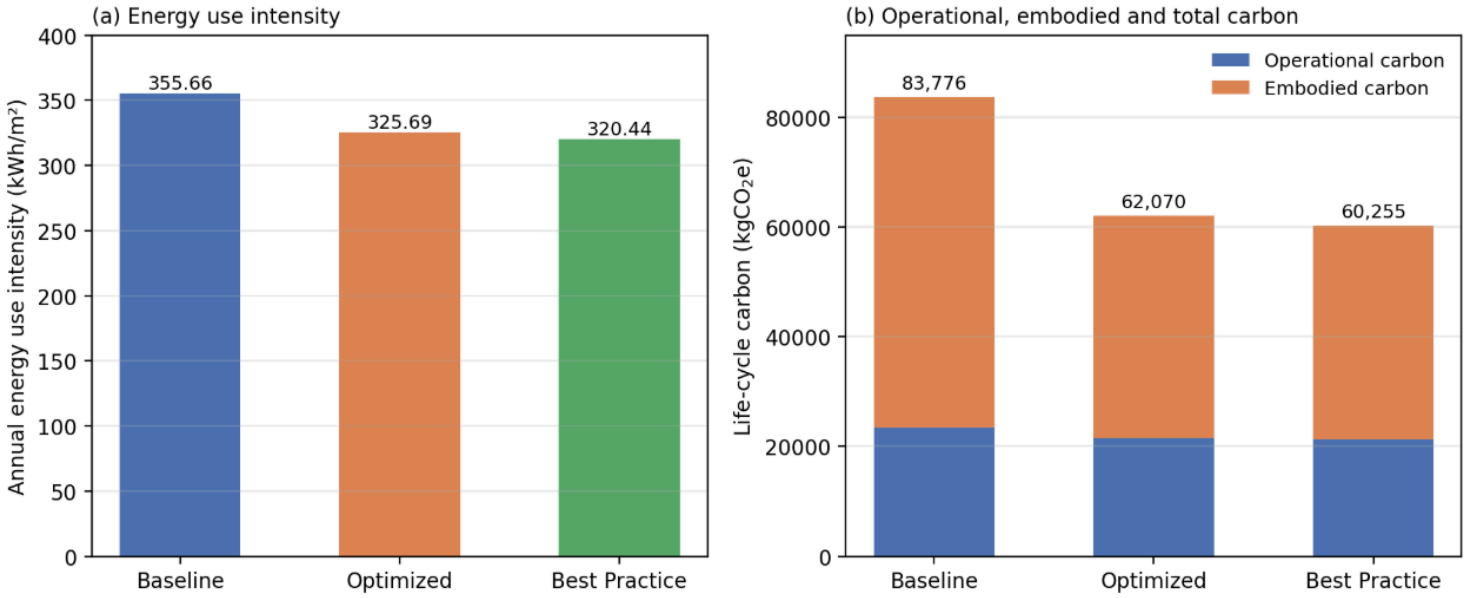


Figure 6

(a) Annual energy use intensity and (b) operational, embodied and total life-cycle carbon of the three models

Supplementary Files

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