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What matters the most in designing low-carbon buildings in Canada? Exploring the tradeoff between embodied and operational carbon in early stage design ☆

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ABSTRACT

Reducing global greenhouse gas emissions is a crucial sustainability objective around the world. The ambitious sustainability targets that have been defined for the building sector can only be achieved through carbon-sensitive design from the beginning. Multiple design parameters, their impacts on building performance, along with embodied and operational carbon tradeoffs makes it difficult for architects to compare design alternatives in the uncertain context of early-stage design. Tools and methods often focus more on either operating efficiency or material selection rather than assisting architects in making holistic carbon-sensitive design decisions.

In this research, a design-compatible methodology for low-carbon buildings was developed by using design exploration methods and parametric calculations of whole-life carbon emissions. The model was run for seven Canadian cities, resulting in over 20,000 design scenarios to capture a broad range of potential solutions. The study investigates the most influential design parameters in relation to the varying carbon intensity of local grid electricity. The results show that despite the significant impact of climate, local grid carbon emission intensity plays the most crucial role in defining building design priorities in order to optimize for total life carbon impacts. The results also indicate that mechanical and structural systems play a significant role in building carbon footprint. The results also show that in cities with high grid carbon factors, optimizing window-to-wall ratio, level of insulation and geometry can contribute the most to reducing carbon footprint. Conversely, in cities with low local grid carbon emission intensity, structural material and mechanical systems selection are highly impactful and all other factors play a marginal role.

1. Introduction

The urgency to mitigate climate change, emphasized by the IPCC, calls for substantial reductions in greenhouse gas (GHG) emissions to limit global warming to 1.5–2 °C [1]. Despite international pledges, a significant disparity persists between projected emissions and targets. Among major contributors to GHG emissions, the building sector stands out, accounting for 37 % of global emissions and 36 % of worldwide energy consumption in 2020 [2], as compared to other end use sectors. While this presents a formidable challenge, it also signifies a critical opportunity for transformative change.

With increasing importance of building sustainability, efforts to address this issue have led to the emergence of various codes and methodologies aiming to set ambitious goals to reduce emissions and promote sustainable building practices [3]. However, existing approaches often focused on optimizing material choices during the construction stage, overlooking the broader implications and fundamental impact of early-stage design decisions on the carbon footprint of the building [4,5]. Recent discussions highlight the need for a paradigm shift towards considering building carbon footprints at the early stages of design and planning. However, integrating carbon considerations into early-stage design poses significant challenges due to inherent uncertainties. This uncertainty refers to undecided building features in the early design stages, which make material take-off unfeasible. Examples of these uncertainties include the building's form, undefined structural

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Nomenclature

Acronym	Definition
GHG	Green House Gas
EC	Embodied Carbon
OC	Operational Carbon
TC	Total Carbon
GCI	Grid Carbon emission Intensity
LCA	Life Cycle Assessment
HVAC	Heating Ventilating Air-Conditioning
MOO	Multi-Objective Optimization
DSE	Design Space Exploration
EUI	Energy Use Intensity
PV	Photovoltaic
WWR	Window-To-Wall Ratio
IGU	Insulated Glass Unit
VAV	Variable Air Volume
AHU	Air Handling Units
PFP	Parallel Fan Powered Terminals
DOAS	Dedicated Outside Air Systems
VRF	Variable Refrigerant Flow
ERV	Energy Recovery Ventilators
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
GWP	Global Warming Potential
EPD	Environmental Product Declaration
IDF	Input Data File
OFAT	One Factor At a Time
HGC	High-Grid-Carbon
LGC	Low-Grid-Carbon
HDD	Heating Degree Days

and mechanical systems, uncertainties regarding fuel types, and the use of renewable energy technologies, etc.[5–9].

Table 1, summarizes some of the most related recent research that addressed the impact of design parameters on building carbon footprint. Previous researches have aimed to answer the question of design priorities for low-carbon building design during the conceptual design phase, however, the majority of them had adopted a simplistic approach to design by either defining a limited number of design variables or limiting range of accepted values. They also diminished the impact of Embodied Carbon (EC)-Operational (OC) trade-offs and their interwoven impact on building Total Carbon (TC) by focusing solely one of the two. Another simplification that is observed in previous research on early stage LCA, is estimating OC by per capita values instead of modeling and calculating energy consumption according to design features [10]. Another gap that limits the applicability of previous studies for Canadian built environments is that the impact of harsh cold climates, codes requirements, conventional building construction and energy sources has not been fully addressed in the literature in respect to the Canadian building sector. Therefore, there is a need to provide clear prioritization for low carbon built environment design in Canada.

As part of our research, we developed a design-compatible method for early-stage Life Cycle Assessment (LCA) to assist in fundamental decisions. Targeting architects and engineers who are becoming more conscientious regarding carbon emissions, our research aim to inform architects and engineers in building design process, and support them in reaching their low carbon goals. Through this study, we filled existing gaps in the literature and provided actionable insights for achieving low-carbon building designs in Canada.

2. Literature review

The literature review achieved three outcomes. Firstly, by identifying state-of-the-art research and their findings, gaps in the literature that impedes finding influential design parameters in building design were identified. Additionally, this review identified appropriate modeling methodologies to assess building environmental impacts in early stages of design.

Lastly, from the literature two sets of design parameters were selected; first the design parameters that were proven in the literature to have high influence on building total life carbon (TC) were selected, to be evaluated to see if they have the same level of importance for Canadian buildings. Secondly, the influential parameters that have received less attention in the literature due to difficulties in modeling have been identified to see the significance of varying the parameter on total building life carbon. These parameters were then used as inputs to the modeling framework developed for this study to evaluate their level of impact for low carbon building design in the Canadian context. We also use these findings to define a reasonable and practical range of values for each parameter.

2.1. Comparison of different approaches for building performance assessment during design

Given the growing awareness of the impact of design in impacting the carbon footprint of the buildings, researchers have employed diverse approaches to address EC in early stages of design in recent years. With a review of the literature, three main methods for this purpose have been identified which are summarized in the following sections.

2.1.1. Scenario-Based models

Some projects have approached the impact of design decisions on building carbon footprints by evaluating case studies and comparing them. These research works aim to identify the impact of either a specific material or technology or a limited set of design strategies on building sustainability performance. This is mainly conducted by describing a limited range of scenarios with similar parameters and quantifying the impact of changes on the building TC by varying one parameter. As an example, Tolia examined 5 scenarios defined based on the British Columbia's high performance operational energy code, the 'step code' and calculated the potential carbon reduction through changes in building insulation, Heating Ventilation Air-Conditioning (HVAC) systems, and fuel type [11]. In another study, Lukic et al investigated the embodied energy and GHG emissions of a residential multi-story timber building with an increase in height. To do so they performed whole-life carbon assessment for four scenarios with an integrated approach that considers structural behavior and includes connectors and fasteners. [12]. Similarly, Hawkins et al. explored the implications for structural design decisions by comparing three scenarios of concrete, steel, and timber options for a typical medium-rise building structure. They used dynamic life cycle assessment to convert greenhouse gas emission histories to key climate impacts using a simple dynamic model [13]. In a recent study, scenario-based models were utilized to compute and analyze the energy, carbon emissions, and embodied water in four university buildings [14].

2.1.2. Design optimization

The other methodology is the single or multi-objective optimization approach that aims at the lowest-carbon-intensive scenarios within the design space according to the goals of the study. This research has a wider range of parameters and objectives and better reflects the complexity of design decision-making and scope of the design space. In the research stream, energy use, carbon emissions, cost, and other

Table 1
Summary of the literature review on early stage low-carbon design, comparing scope, method and measures.

Reference	Design parameters													Methods	LCA stage	Building Scope	Building Type	Measures						Location
	Geometry	Orientation	Area	WWR	Window material	Envelope	Level of Insulation	HVAC	PV	Sharing	Structure	Occupancy	Infiltration					EC	OC	Cost	Energy Consumption	Embodied Energy	Solar Radiation	
[26]	X			X	X	X			X					MOO	A1–A5, B4, and B6	Envelope, Structure, HVAC	Single-family house	X	X				X	Oslo, Norway
[15]				X	X	X				X				MOO	A-C	Envelope, HVAC	Multi-story apartment building	X		X				Hungary
[27]		X			X	(X) Only Wall								MOO	unknown	Envelope	Medium officebuilding (ASHRAE benchmark model)	X				X		Texas, USA
[28]	X			X	X	X					X	X	X	DSE	A1-A5	Envelope, Structure	Midrise to high rise, residential or office	X		X	X			Singapore, Singapore Lagos, Nigeria Kiev, Ukraine Cairo,Egypt Shanghai, ChinaLondon, UK
[29]	X					(X) Only Wall	X	X						DSE	A-C (B6 excluded)	Envelope, HVAC	Apartment	X	X					Potsdam, Germany
[30]				X		X					X			Scenario-based modeling	A-D	Envelope, Structure	Mid-rise office	X			(X)Fuel Consumption	X		Charleston, South Carolina.
[31]	X			X	X	X	X							MOO	A1-A3	Envelope, HVAC,	Mid-rise exhibition hall	X	X	X	X			Tanjin (cold Climate), China
[32]	X	X		X		X		X					X	MOO	Not stated	envelope, PV design	Mid-rise residential building	X	X		X			Accra, Ghana
[33]		X	X	X	X	X	X				X			MOO	A1-A3	Envelope, Structure, Interior, renewables (PV), HVAC	Multifamily building	X	X	X	X			Bhubaneswar (hot and humid),New Delhi (composite), Jodhpur (hot and dry)

WWR = Window to wall Ratio.
LCA Stage= Stages of building life cycle which is materials manufacturing (A1-A3), construction (A4,A5), use and maintenance (B), and end of life (C), Beyond the scope emissions(D) [34].
Building element = Included elements and studies components of the building which can include; Structure, Envelope, HVAC, Interior, etc.
X Included (X) Partly Included.

environmental impact categories have attracted the most research interest [15,16].

While optimizing quantitative objectives have been widely addressed in the above referenced literature, interestingly recent advancements in computational modeling and performance assessment made optimizing even qualitative variables feasible. For example, carbon footprint and the view of the conceptual building form have been optimized to reach the lowest carbon and highest view score using multi-objective optimization implemented by parametric models [17]. In another study, Kaitouni et al. developed a parametric digital workflow in the Grasshopper environment to evaluate the energy performance and indoor thermal and visual comforts in a nearly Zero-Energy office building [18].

Decision-making during the building design and construction process is a complex issue with several influential parameters with different weights and impacts that can change simultaneously and dynamically. The goal of Multi-Objective Optimization (MOO) is to satisfy multiple design objectives in an optimum design solution. Therefore, while these methods are more generalizable than the scenario-based method, their scope is still limited to the number of objectives and default values/ranges for the parameters which may result in leaving a range of high performance scenarios unexplored [19].

2.1.3. Design exploration

The last approach is design exploration, which investigates the whole design space meticulously by calculating the objectives for each possible design solution within the design space. The advantage of this method is managing the uncertainty associated with the targeted variable (here, total life carbon) in early-stage design, as the whole design space has been explored [20]. The downfall, on the other hand, is the time and computation-heavy calculations; therefore, to make the modeling feasible using current computational power we summarize the parameter values to the representative discrete values, rather than continuous range. These values are selected with professional expertise and known or suspected to make difference in results. This method facilitates selecting the scenario that best satisfies design objectives by providing a clear and deterministic understanding of all possible scenarios within the design space. Unlike the other two methods, in design exploration, designers have full control over selecting the design strategies based on outputs and performance metrics and there are no possible solutions with unknown results. Therefore, this method provides better understanding of design options compared to two previous methods and also manages the uncertainty that exists in optimization [9].

These benefits overcome the gaps in previous methods and make Design Space Exploration (DSE) an appropriate method for integrating LCA into early-stage design. This method has been used to investigate the impact of structural design parameters on building carbon footprint of high-rise mass timber buildings [21]. In another study the DSE has been utilized in early stage design to quantify the impact of building subsystems on the carbon footprint of a commercial building [9,22]. In another study, a DSE-based model was developed to report the EC of building structures in early stage design by exploring all structural design parameters.

Due to the complexity of carbon assessment in conceptual structure design, this method has been of assistance to architects in design decision-making [23]. In this regard, previous studies deployed approaches to simplify calculations in order to overcome this challenge. For example, in a study DES has been applied to investigate the impact of building form on carbon emissions of a building with six potential geometries. The method evaluated the whole design space however, OC calculation was conducted on a per capita basis, which would neglect the impacted energy consumption by design modifications and therefore limit the ability of assessing the EC-OC interactions. [20]. To overcome the challenges associated with DSE, in another study, Li et al. reviewed and proposed different methods of guided DSE and compared them in terms of their performance [24]. They proposed that guided methods, such as near optimal DSE, Representative DSE and Local DSE, can overcome the time-intensity of the unguided DSE method by parting design space and excluding less efficient scenarios; however, this simplification would leave a part of design space unexplored. Therefore, while these methods can answer specific design questions, they are not design compatible as they leave a remarkable number of scenarios unexplored and they face some deficiency in addressing uncertainty.

Fig. 1 provides a diagram for comparing the main features of three mentioned methods in addressing building performance for design integration. With respect to all applied methods in the literature and the benefits, limitations and shortcomings associated with them, DSE shows the highest compatibility with the design process and can be integrated better in design. This is mainly due to both breadth of studied scenarios as well as the accuracy of modeling and deterministic results in each scenario. Due to these features the results of the DSE model are more generalizable and are useful for architects to steer the design progress to reach low TC. As this method assesses all scenarios, it is time intensive in application. On the other hand as the performance of all scenarios are available to the user, it is the best and most accurate method for decision making. On the other hand scenario-based modeling, May only evaluate a few scenarios for modeling and performance assessment which yield results faster but due to the uncertainty associated with unstudied scenarios cannot be a reliable decision making method. Optimization methods are between the two.

Fig. 1 shows our assessment of literature on the main characteristics of the four design-integrated performance assessment methods. In this diagram, the methods are compared based on the time and effort required computational capacity (indicated by color). The radius of the circles indicates the suitability of each method for decision-making in the early design stage, which is measured based on both determinism and comprehensiveness of the results within the design space. The methods that evaluate a greater segment of design space and provide deterministic results are the most suitable for early stage decision-making, while the methods looking on either a section of design space with low determinism or limited number scenarios are known to have limited application for early stage decision making. The vertical axis represents the extent of the studied sections of the design space, indicating the generalization of the results to the whole space. The horizontal axis reflects the expected determinism of the results within the study scope.

In scenario-based modeling, a limited number of scenarios are examined, leading to a specific and limited section of the overall design space being investigated. However, since the scenarios are modeled individually, the results are deterministic and reliable within the limited study scope. In other words, this method provides deterministic insights for a few scenarios, which cannot be helpful for design decision making beyond the studied scenarios. In contrast, optimization-based methods involve exploring multiple scenarios, scattered in the design space, which allows for a larger section of the design space to be investigated. While these methods claim to explore whole space approximately through scattered scenarios, due to unexplored segments of the space, there is always a risk of missing potentially better solutions. This makes the results less deterministic compared to DSE. DSE investigates all scenarios within the space, resulting in the highest level of comprehensiveness. Unlike optimization-based methods, DSE evaluates all scenarios and explores the whole design space, leading to deterministic results. This method shows the highest compatibility with decision making due to the extent of explored space along with determinism of results, however the method is time-intensive and demands computation resources.

In this study by deep understanding of advantages and limitations of design performance assessment methods, we aim to define the modeling process that provides the highest compatibility with early-stage decision making. Our goal is to develop a modeling framework that explores the whole design space efficiently and generates reliable results on building total carbon emissions of different designs.

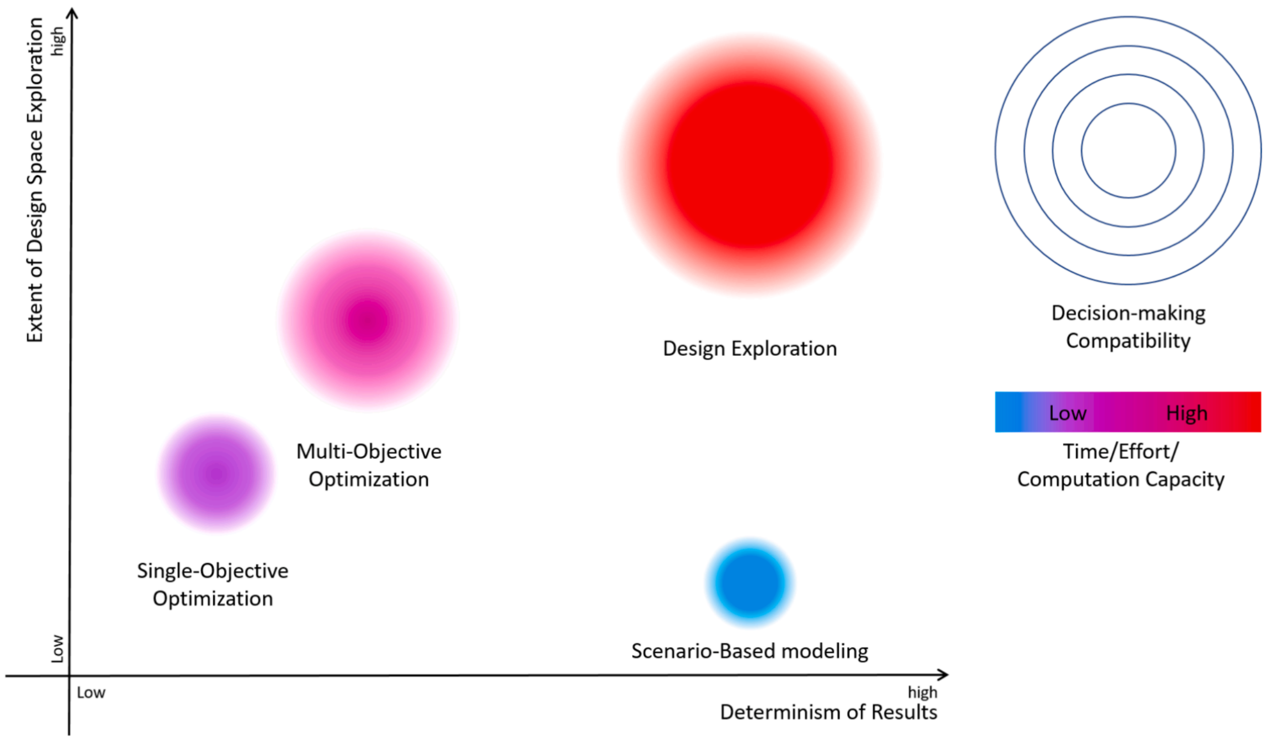

Fig. 1. Diagram comparing the main characteristics of methods for evaluating performance of design alternatives.

2.2. *Analysis of the different design parameters used in literature*

2.2.1. *Parameter selection*

In the next step, the literature was investigated to explore the most impactful early-stage design parameters on building TC. Review of the literature shows that a great portion of previous research on this topic focuses on the influence of design parameters on building energy consumption and therefore they targeted Energy Use Intensity (EUI) as their objective, leaving buildings' OC and EC impacts out of the scope of the study. In this literature review we focused on studies that aim to investigate the impact of design parameters on building total life carbon.

An exploratory search has been done to explore the recent research in this area and identify which parameters are frequently studied and find specific research on those that we identified as important design parameters for early stage design. Table 1 shares the results of the study. We aim to identify the design variables by the highest impact according to previous studies that have been proved impactful on building carbon. The results of a previous review identified the most influential design parameters on building LCA and revealed that twelve design variables had the most impact on building carbon. These parameters includes: building aspect ratio, window-to-wall ratio, shading area, building orientation, number of floors, building shape, floor area and floor-to-floor height, have an impact on a building's life-cycle environmental impacts, types of building components, sizes of building components, types of building materials, and thickness of building materials [25]. Therefore, in this study we selected a list of variables that are both associated with early stage design and are also playing an important role on building performance in cold climates.

2.2.2. *Range and value selection*

As the DSE generates and calculates the performance of each scenario, defining the realistic range for parameters is crucial. The literature review shows the commonly acceptable ranges for parameters. However as this amount is highly impacted by the area and design convention, The collected data on design parameters and their corresponding values were validated by consulting professionals in the construction industry for the studied cities. To ensure the defined ranges and values for design parameters were practical, realistic, and reflective of current construction practices in Canada, the expertise of the authors and their research teams was leveraged. Insights were also gathered through three sessions from nine engineering and architecture professionals to review and validate the proposed ranges and values based on common practices and preferences. This step was critical to ensure the assumptions were both viable and representative across various design contexts… All parameters along with their values and ranges are specified in Table 2 and has been used for developing the parametric model used in this research.

Table 2
Design parameters, ranges and discretization used in this model.

	Design parameter	Secondary Parameter	value/Range	Number of values
1	Geometry		Six different geometries per Section 3.1.1 (Sq, Sq+, SqH, Rec, Rec +, RecH)	6
2	Envelope	Level of Insulation	code-minimumHigh Insulation	2
		IGU	Double glaze-AluminumTriple glaze-Aluminum	2
		WWR	0.250.5	2
3	Structure Type		Concrete, Steel, and wood	3
4	HVAC system		Packaged rooftop heat pump VAV AHU w/PFP Terminals DOAS + VRFDOAS ERV (see section 3.1.4)	4
5	Orientation	Azimuth	−60, −30, 0, 30, 60	5
6	Cities		Vancouver, Edmonton, Winnipeg, Saskatoon, Toronto, Montreal, Halifax	7
	Total			**20,160**

2.3. Gaps identified in prior work and novelty of this paper

The majority of papers in the area of performance assessment in the early stage of design focused on consumption and building TC have received less attention. With a closer review on current literature of early-stage LCA for decision-making, several gaps are observed. One of the gaps is the approach to energy consumption and reducing the operational section of TC. A common approach is to simplify energy assessment, as mentioned in the previous section, which leaves the question of the real-time and accurate impact of building design features on OC.

Secondly, this paper incorporates the impact of climate in a more realistic way. Previous research shows building emissions can change depending on design features in different cities but the range of investigated climates mainly covered mild to warm and moist climates. Given the impact of climate on building performance and emissions [27], a gap is observed in addressing design priorities in the cold and very cold climate of Canada. Similar to climatic conditions, another factor that is dependent on the location, the Grid Carbon (emission) Intensity (GCI) can range significantly and thus can have a significant impact in defining low TC design priorities. The literature shows uneven attention to areas with low grid carbon when EC would likely have a higher influence on TC results.

Thirdly, the variety of design parameters and their range has received a simplified approach and in some of the studies, a limited number of design variables were considered or the ranges were very limited due to aforementioned computation constraints. Therefore, there is a need for a study that addresses a wide range of design parameters with realistic ranges that correctly reflect the diversity of design decisions faced by industry.

The main aspect of novelty of this paper lies in its applicability and design compatibility of the applied method to address total life carbon in the early stage of design. We aim to address this for major Canadian cities considering their contextual features such as GCI and climate. Moreover, we aim to answer the question using the DSE method that could be incorporated in the building design process and is flexible in terms of objectives providing flexibility in application. Specifically, we concentrated on fully electrified, high-performance buildings, aligning with guidelines and municipal recommendations for the future of Canadian built environments.

3. Methodology

In this study, we deployed a DSE tool to investigate a comprehensive set of design options and identify the most influential design parameters on building TC. To do so, a space of over twenty thousand scenarios in seven major Canadian cities was investigated. This study is focused on fully electrified mid-rise commercial buildings. Fig. 2 shows the methodology deployed in this study.

3.1. Design parameters

For this study, an eight-dimension design space was defined with eight design parameters and conventional ranges. This resulted in 2,880 design iterations per city. This analysis was done for seven major Canadian cities to find the most impactful design priority to reach the lowest building TC across different cities. In total 20,160 design solutions were generated using the modeling workflow. AlsoEC, OC, and TC for each scenario were calculated. Table 2 lists the design parameters and the ranges defined for each parameter.

3.1.1. Geometry

The base model is a typical standard five-story commercial building in the city of Vancouver with a square footprint and total floor area of 3075 sqm. To investigate the impact of early-stage form finding five variations of base model were included; elongated form which is the same area of a rectangle footprint. For each type, 2 other variations were also developed: protruded geometry with a protrusion in the façade (type plus) and a cavity geometry with negative protrusion in surfaces (type X). All types have the same total floor area footprint area and occupancy profile. See Fig. 3 that outlines the variation in geometry.

3.1.2. Envelope

To simulate the design options that impact envelope EC, different insulation levels and insulation materials were defined. Also due to the impact of the transparent envelope on TC, WWR and Insulating Glass Unit (IGU) number of glazing layers varied among studied scenarios.

To include the range of insulation levels, code-minimum insulation based on ASHRAE guidelines [35] was modeled for each city. In addition, to reflect scenarios with better thermal behavior, construction details for the colder climate were modeled to reflect user choice of higher insulation to mitigate energy loss through enclosure. For example, the City of Vancouver is located in a mixed climate zone (Zone 4) based on ASHRAE guidelines [34]. To study the environmental impact of conventional enclosure construction details for zone 4 were considered as scenarios with code-minimum insulation. Then, to model highly insulated enclosure construction details for cold climates (Zone 5) were also modeled which in this study is referred to as high-

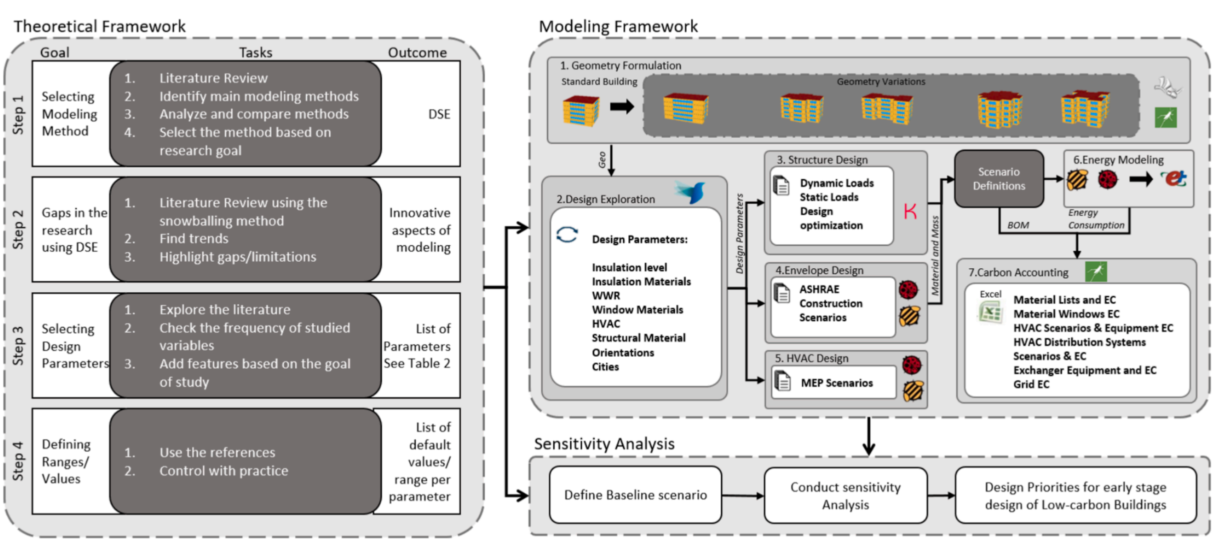

Fig. 2. Research and modeling framework.

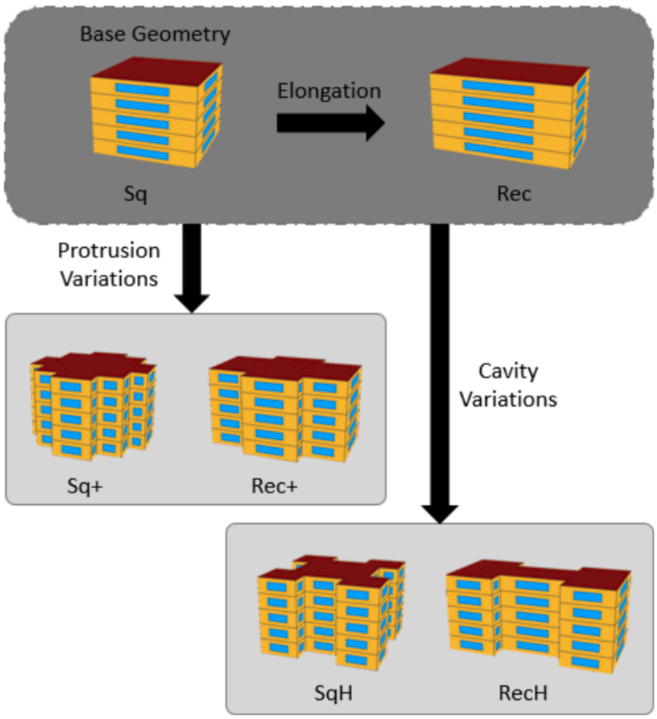

Fig. 3. The five variations in geometry.

performance scenarios (refer to Table 2). For windows, two high-performance common IGU were studied, double and triple paned. In addition, to model different variations of the transparent envelope, two WWRs were investigated: WWR of 0.25 was selected to represent stringent designs that minimize heat loss, while a WWR of 0.5 reflects a preference for more transparent envelopes, balancing daylighting and energy considerations.

3.1.3. Structure

For this study framing structure with three materials of concrete, steel, and mass timber was selected and the impact of structural material selection on building EC was calculated. It is noteworthy to mention that other design parameters such as bay length, floor-to-floor height, number of stories, etc. can affect structure design and its impact on building carbon footprint, however, due to the scope of this study, they are considered as control variables. Default values for structural design are as Table 3. The design loads are extracted from the British Columbia Building Code 2018 [35]. To model the building structure, Karamba was used to form the framing system based on the geometry. The internal component was used to optimize sizing cross-section and to control deformation and lateral displacement. The impact of structural parameters on the EC of the building was discussed in detail in another paper by authors [22].

Table 3
Design assumptions and input for structural automatic design.

	Design parameter	Value
1	Structural material	Reinforced Concrete, Steel and mass timber
2	Bay	6–8 m (Depending on the geometry)
3	Floor-to –floor height	3.5 m
4	Live load	4.8 kPa (First Floor) 2.4 kPa (Upper floors)
5	Dead load	3.1 kPa (Concrete Structure) 2.4 kPa (Steel Structure) 1.5 kPa (Mass Timber structure)
6	Snow load	3 kPa (Average for Canada)
7	Lateral forces	5 kPa (Average for low-risk areas)

3.1.4. HVAC systems

To correctly reflect the various available options for building an HVAC system, two conventional and two high-performance scenarios were selected. To select the HVAC scenarios, the results of a previous study by Rodrigues recommend a list of HVAC systems for a midrise commercial building. This study reveals per capita lifetime carbon values for listed HVAC scenarios that includes equipment, distribution systems as well as refrigerants [36].

- Packaged rooftop heat pump,
- Variable Air Volume Air Handling Units with Parallel Fan Powered Terminals (VAV AHU w/PFP)
- Dedicated Outside Air Systems with Variable Refrigerant Flow (DOAS + VRF)
- Dedicated Outside Air Systems with Energy Recovery Ventilators (DOAS ERV)

3.2. Life cycle analysis

The goal of this study is to evaluate, report and compare TC emissions across different building design scenarios for five-story commercial buildings. This study encompasses both EC and OC to identify the most impactful design parameters for reducing environmental impacts. The study covers life cycle stages A-C (product, construction, use, and end-of-life) as defined by EN 15978 [28], with a functional unit of 1 m^2 of total floor area over a 60-year lifespan. Design scenarios meet ASHRAE building code [29] requirements for thermal performance and British Columbia Building Code [30] for structural design.

The building scope evaluated included structure (excluding foundation), enclosure and HVAC systems. Significant aspects of building scope including electrical systems, piping, ducting and were excluded as they would not change based on the studied parameters. The environmental impact studied was global warming potential (GWP) which excludes biogenic carbon.

The carbon intensity of materials are extracted from Environmental Product Declaration (EPD)s. The EPDs are selected to be comparable in terms of life cycle stages (A1-A3), environmental impact indicator (GWP), and their method [37]. For GWP per material see Appendix 1. To estimate additional life cycle emissions (A4, A5, B1-B5 and C1-C4), City of Vancouver Embodied Carbon Guideline was utilized which recommends using following method in absence of carbon impact per life cycle stage [38]:

- Construction process stage – transportation to the construction site (module A4) impacts shall be assumed equal to 4 % of the A1-A3 impacts;
- Construction process stage – construction (module A5) impacts shall be assumed equal to 6 % of the A1-A3 impacts;
- Use stage (modules B1-B5) impacts shall be assumed equal to 10 % of the A1-A3 impacts; End-of-life stage (modules C1-C4) impacts shall be assumed equal to 5 % of the A1-A3 impacts.

To estimate OC, for each scenario energy consumption was calculated using an EnergyPlus model coupled with the parametric model (see Section 3.3). The grid carbon intensities (see Appendix 2) were extracted from Canada's National Inventory Report [39] and used to calculate OC for the life span of the building.

3.3. Modeling workflow

The modeling workflow of this study consists of a chain of software and tools to investigate design variations and related energy modeling as well as LCA calculations associated with scenarios within the design space. The parametric model developed in this study is capable of generating a physics based model for each scenario within the design space. In this space, the parameters are the dimensions of space and their values/ranges are the length of each dimension which is explored through DSE. To explore the complex and multidimensional design space, this parametric model first generates geometrical models in Rhinoceros and Grasshopper based on the six defined footprint geometries (module 1). To ensure all scenarios are generated and the whole design space is explored Colibri plugin was used in module 2. In module 3 which is the structure module, the building structural system is designed based on building form and analyzed using Karamba 3D for structural stability under static and dynamic forces and optimizing cross sections. After generating design scenarios, in module 4, they are translated into energy models using ladybug tools. This module will simulate weather conditions for each city and define envelope assemblies with respect to ASHRAE 2019 requirements and defines thermo-physical features of materials. In module 5 the HVAC scenario are assigned to models to prepare energy model for module 6, in which the model is translated into an Input Data File (IDF) file ready for energy modeling and predicting energy consumption using Energy Plus [24,40]. The energy consumption output in this module includes heating, cooling, equipment, lighting, fan and pump loads. In the last module of this modeling pipeline, bill-of-material is extracted from the model and further LCA calculations are conducted to quantify EC associated with structure, envelope, and HVAC systems. In addition, the energy consumption reported in form module 6 which is in the form of EUI, is first used to calculate energy demand annually and for building lifetime. Then, by using GCI (see Appendix 2) predicted energy consumption is used to calculate OC. Lastly all the input and outputs are exported for data preprocessing, analysis and visualization. The modeling framework in Fig. 2 depicts the modeling process.

3.4. Sensitivity analysis and benchmarks

The sensitivity analysis method used in this study is one-factor-at-a-time (OFAT) sensitivity analysis that was feasible through availability of data on EC and OC of all scenarios. This method has higher accuracy compared to other sensitivity methods such as Multi-Way or Global Sensitivity Analysis because it isolates the impact of a single variable, minimizing the complexity and potential interactions that could obscure the direct relationship between input and output, thus providing more precise insights into the effect of individual parameters [41]. This method evaluates the impact of varying one input parameter at a time on the output, while keeping all other parameters constant. The formula for calculating sensitivity in OFAT analysis is typically based on the percentage change or absolute change in the output due to a specified change in the input. To use the OFAT sensitivity analysis, a base model should be defined to measure the changes in TC against that. The benchmark developed for this analysis is the scenario with the first value for the design parameters in Table 2. Then the differences in TC was calculated and reported in the following sections. Lastly, to compare the effectiveness of parameters percentage of change was calculated for each parameter in each city.

$$Si = \Delta TC_i / TC_{BASE}$$

Where:

S_i = Sensitivity of the output TC to the input parameter i.
ΔTC_i = Change in the total carbon per changes in parameter i.
TC_{BASE} = Total Carbon of baseline scenario.

4. Results

4.1. Location, climate and grid carbon intensity

As a result, over 20 thousand scenarios were modeled and the OC, EC and TC were calculated. The Fig. 4 shows the distribution of EC, OC and TC across studied cases. As the whole design space exploration method was adopted, similar scenarios were studied in different cities and consequently the range of EC is similar in all cities. The only difference in the studied scenarios is the envelope insulation according to the ASHRAE requirements per region. On the other hand, the range of OC shows significant variation, which makes TC vary significantly across different cities. Fig. 4 shows the average while Fig. 5 shows the range of EC, OC and TC of studies scenarios along with carbon intensity of the grid. Grid carbon in Canada varies significantly across provinces due to their dependency to fossil fuels or hydro and renewable sources. As Fig. 4 Shows there is a strong correlation between GCI and average TC of studied scenarios per city. Cities such as Calgary, Halifax and Saskatoon with high GCI have significantly higher average TC, while scenarios studied in Toronto, Vancouver, Montreal and Winnipeg with almost decarbonized grid, have remarkably lower average TC. In this study, we call the former groups HGC (High Grid Carbon) and the Latter LGC (Low Grid Carbon). The results show that in LGC cities, despite cold climate and high Heating Degree Day (HDD), the OC is negligible due to carbon decarbonization leaving EC as the main contributor to building TC. Given the variation in expected TC across different cities and with

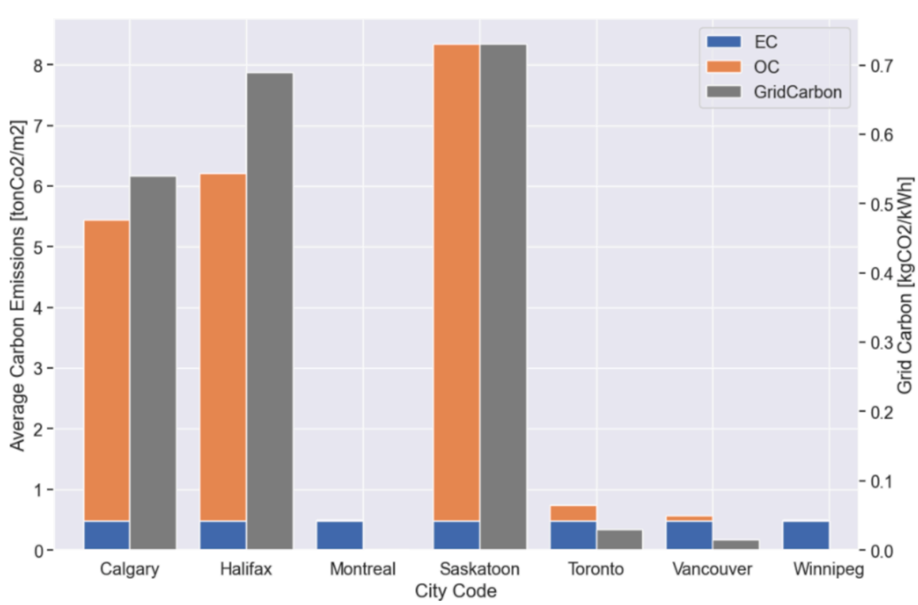

Fig. 4. Comparison of average EC, OC and TC as well as GCI per city.

respect to different roles of EC and OC in influencing building TC, It is expected that different design parameters will be impactful to reduce building TC and the level of their impact also be different per city (Fig. 5).

The results show that the impact of GCI is dominant on the climate and heating demand. For example, Winnipeg with an extremely colder climate (Zone 7) and coldest climate among studied cities, reports lowest bound of TC, due to the almost decarbonized grid carbon intensity. This is more meaningful when compared to TC of buildings in Toronto, which has a warmer climate (Zone 6), or even Vancouver with the warmest climate among studied cities (Zone 4). Both cities report higher bound of TC despite milder climate and lower energy consumption. This example shows that the impact of severe climate and high energy demand can be outweighed by low GCI, therefore, the first question for architects in defining design priorities and expected TC for low-carbon building, first refers to carbon intensity of source of energy. Although architects are not in control of GCI, by pinpointing the impact of GCI on building TC and by using the results of this study they will be able to identify the area of focus in design for cutting carbon by knowing the most influential design factors and the extent of impact.

4.2. Geometry

Building geometry is another important factor to consider when aiming to reduce a building's TC. As Fig. 6 shows, compact shapes, such as square floor plans, generally lead to lower EC, EUI and TC across all cities. Geometry has a greater impact on TC in HGC cities compared to LGC cities. This is because the shape of a building influences its EUI, and in HGC cities, changes in EUI have a big effect on TC due to the importance of OC. In LGC cities, however, EUI changes don't affect TC as much since EC plays a bigger role there.

Fig. 6 also highlights how TC varies with geometry. All the studied shapes have the same floor area, but their perimeters differ because of cavities or protrusions. Among these, the square, which is the most compact shape, consistently results in the lowest EC, EUI, and TC in all cities. On the flip side, Shapes with more protrusions, like SqrX, RecX, and RecH, tend to have the highest EC, EUI, and TC. This pattern holds true across different grid carbon factors HDD, and climates.

One thing to keep in mind, though, is the significant difference in TC levels between HGC and LGC cities. At first glance, the changes in TC from geometry adjustments might seem less significant in LGC cities because their overall TC is already much lower than in HGC cities. Appendix 3 provides detailed data on the minimum, maximum, and average TC for each geometry across all cities. It shows that altering building geometry can change TC by an average of 5 % in HGC cities and 7 % in LGC cities.

While geometry might not have as much potential for reducing carbon as some other design parameters, it's still an important consideration, especially in HGC cities. Making thoughtful choices about geometry can contribute to meaningful reductions in a building's TC.

4.3. Structural material

The results show significant impact of structural material on building TC in all cities. As the graphs in Fig. 7 show, in all cities mass timber structure has the lowest TC while steel structure has the highest TC. While the trend in both LGC and HGC is similar, the magnitude of TC fluctuations is significantly different.

In HGC cities due to dominance of OC and relatively limited impact of EC on building TC, the choice of structural material would not affect TC more than 13 %. On the contrary, as the Fig. 7 shows, in LGC cities the material choice affects TC remarkably and can increase TC to more than double. Therefore, architects should be cautious of selecting structural material when designing buildings in LGC regions. This underscores the critical role of structural material in managing building TC, particularly in regions with low grid carbon intensity.

4.4. Window design

In this study the window design has been classified under two design parameters, WWR and type of IGU. Since heating is a concern in Canadian buildings, a high WWR is less common. Therefore, a WWR of 0.25 was considered typical, while a WWR of 0.5 was used to represent more transparent designs. Also as the windows are typically a source of heat loss, IGUs with high thermal resistance (such as double and triple-pane windows) are used (see Appendix 1). For this purpose, two and three pane windows with Thermal break aluminum frame have been used.

The analysis shows that while lower WWR reduces EUI and OC, the choice of IGU has a limited impact on TC, suggesting that typical double-pane windows are adequate for carbon reduction in Canadian climates and using triple pane IGU will only increase the EC without noticeable benefits in reducing OC.

4.4.1. WWR

The results indicate that the trend in TC changes with WWR is consistent across all cities and climates. As the Fig. 8 shows the distribution of TC across the design space, lower WWR contributed to lower TC while higher WWR leads to higher TC. However, the extent of impact of WWR on changes in TC is different across studied cities. In HGC cities

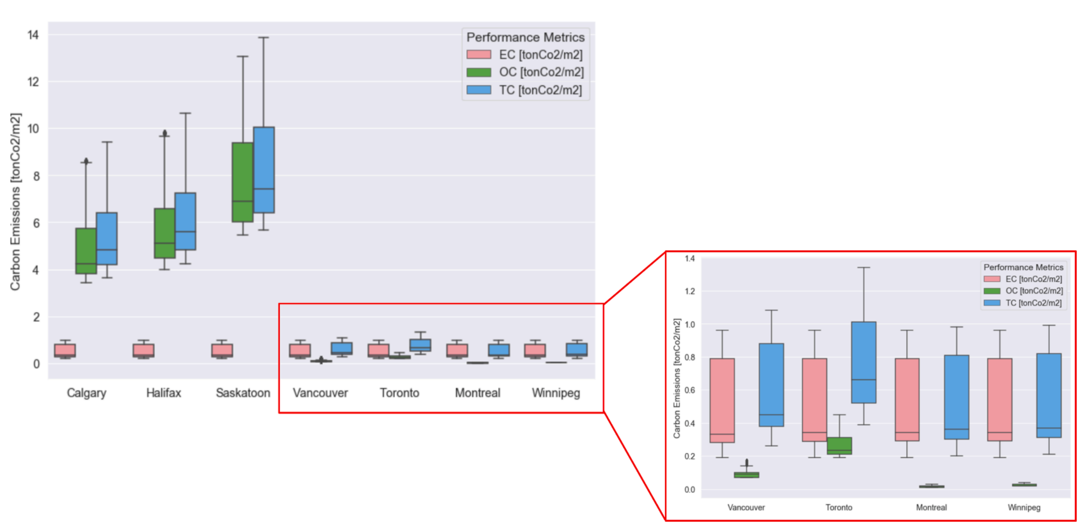

Fig. 5. Range of building EC, OC and TC by city.

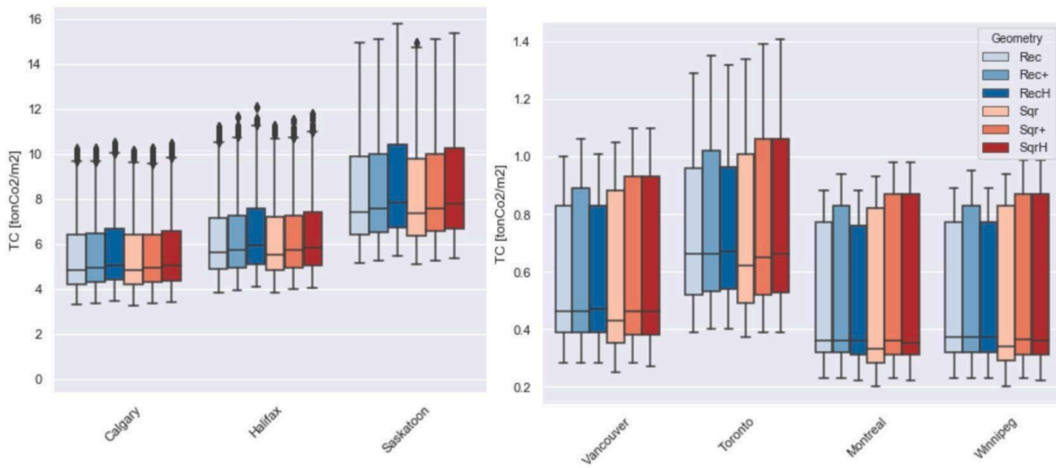

Fig. 6. The impact of geometry on TC in each city.

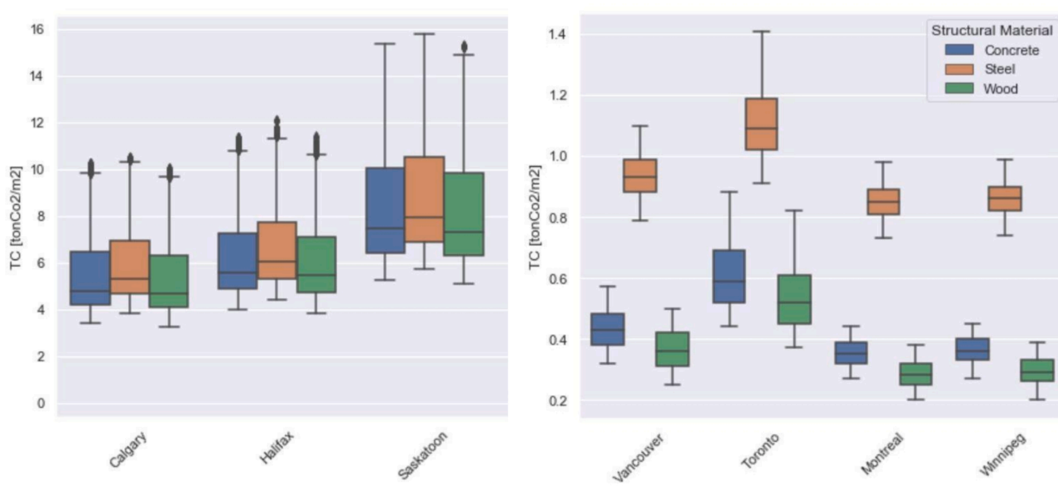

Fig. 7. TC range for each structural material.

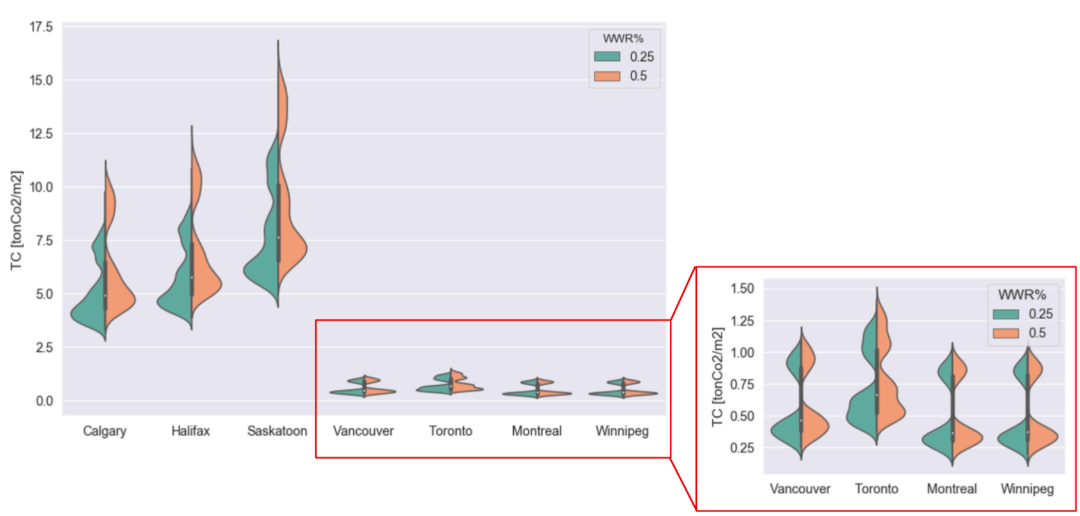

Fig. 8. EC, OC and TC range for each WWR.

using lower WWR has a remarkable positive impact on lowering TC due to the importance of OC and direct impact of WWR on EUI. Therefore, in cities with high GCI special attention should be placed on less transparent enclosure design to lower building carbon footprint. It is important to note that these results are based on highly efficient IGUs, which still do not justify high WWR in cold regions with high GCI from a carbon perspective. Therefore it is expected that by using typical GUI for higher WWR, will increases building TC.

Thus, in LGC cities, while lower WWR buildings still report lower TC, the difference is less significant and may be outweighed by other design considerations. Compared to HGC cities and it can be neglected in virtue of satisfying other design goals. In summary, optimizing WWR is particularly critical in HGC cities due to its substantial impact on TC.

4.4.2. Window material

On the contrary, as Fig. 9 shows, to the trend observed with WWR, the use of different IGUs shows limited impact on building TC across all cities. Notably, the results show that using three-pane IGU results in lower TC compared to using two-pane IGUs. This difference is more noticeable in HGC cities than LGC cities. However, use of more efficient IGUs compared to the impact of other design parameters, shows only a marginal difference in TC. To be more detailed, while three-pane windows can reduce EUI and cause reduction in OC, they are more carbon intensive and therefore these two impacts are overall balanced out. It is concluded that typical two-pane windows perform well in reducing building TC compared to triple-pane windows.

4.5. Insulation level

In this study, two levels of insulation were used: code-minimum insulation that satisfies the requirement of climate according to ASHRAE and a voluntary one-step higher level of insulation. For example, for Vancouver which is located in region 4, insulation levels for climate zone 4 (mix climate) and 5 (cool climate) were modeled.

The results show a consistent trend of TC reduction with higher levels of insulation (see Fig. 10). As higher insulation results in lower EUI and OC, this trend is more noticeable in HGC cities. In this study fiberglass was used as the insulating material (see Appendix 1). As fiberglass has relatively low carbon content, increased material usage does not contribute significantly to EC. However, it is impactful in reducing OC. Overall, a higher level of insulation is recommended in all cities, with a more pronounced impact expected in HGC cities. As different insulations have different EC impacts, this recommendation should not be generalized for all insulation types.

4.6. HVAC system

HVAC systems have a dual impact on building TC, influencing both EC through the carbon intensity of materials and OC through energy efficiency. The correct selection of HVAC systems is an important decision in all studied cities. In HGC cities, the impact of HVAC systems on EUI and therefore OC affects TC substantially. In LGC cities, while OC is negligible compared to EC, HVAC selection still shows a significant impact on TC due to the carbon intensity of equipment, distribution systems, and refrigerants. For instance, high-efficiency HVAC systems significantly reduce OC in HGC cities, whereas in LGC cities, selecting low-carbon HVAC components is crucial. Overall, the role of HVAC systems in both energy consumption and material carbon intensity makes them a critical factor in reducing TC across various climatic conditions.

4.7. Orientation

Orientation mainly affects solar gain and, to a lesser extent, conduction due to wind direction, both of which impact energy consumption, OC, and consequently TC. Given the high performance of building enclosures with efficient windows and opaque surfaces, the impact of orientation on thermal transmittance is minimal in the studied scenarios. This will diminish the influence of building orientation on building TC. The results indicate a negligible impact of changing orientation in LGC cities and a slightly higher, but still limited, impact in HGC cities. Therefore, the results shows that orientation of the building does not play a significant role in TC of thermally efficient buildings. Given the advanced thermal efficiency of modern building envelopes, orientation's role in TC reduction is secondary to other design considerations like HVAC systems and structural materials.

5. Discussion

Fig. 11 shows the range of changes in building TC in HGC and LGC cities. As the graph shows, in HGC cities higher ranges of TC is observed. The results show that design priorities change based on contextual conditions such as climate and GCI across Canadian cities. Our findings highlight the dominant role of GCI in both determining building TC range, and determining design parameters importance with the highest potential in reducing TC.

In HGC cities, due to the dominance of OC over EC, design parameters that directly impact EUI have the most potential for reducing TC. The results show HVAC scenarios play the most significant role in building TC. Secondly, the design process should focus on lowering TC by selecting less carbon-intensive structural materials, and opting for compact geometry, reducing WWR and increasing insulation levels.

In LGC cities, however, the studied parameters show different levels of influence on building TC. In these areas, due to dominance of EC in building TC, structural material is the most influential parameter and selecting bio-based material, efficient structural design through optimization can decrease TC significantly. In the next place, more efficient HVAC scenarios can play an important role in reducing building TC. Lastly, WWR, geometry and insulation level shows potential in reducing building TC which is by far of lower potential compared to structural material and HVAC scenarios. Other factors such as window material and orientation do not show significant impact on TC range for the studied cases in this study.

In Cities with LGC, very different weight of design parameters are observed for low-carbon building design in the cold climate of Canadian cities. In these cities, the share of OC is balanced by low impact of grid,

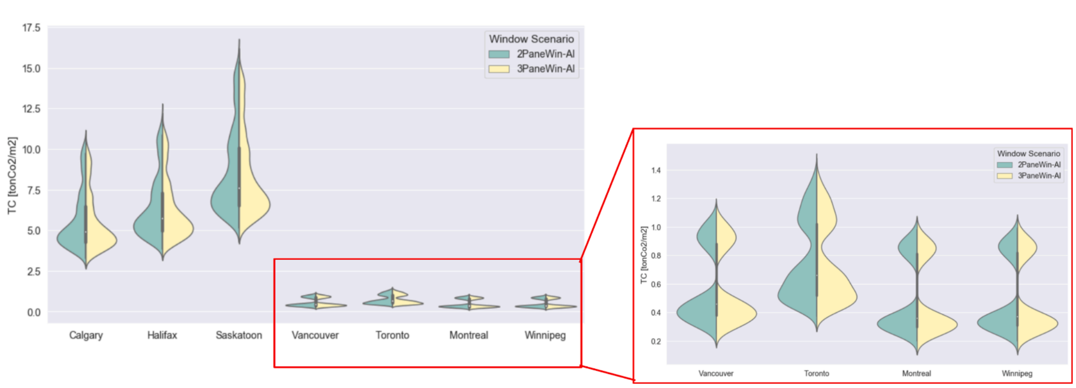

Fig. 9. IGU material and WWR by city.

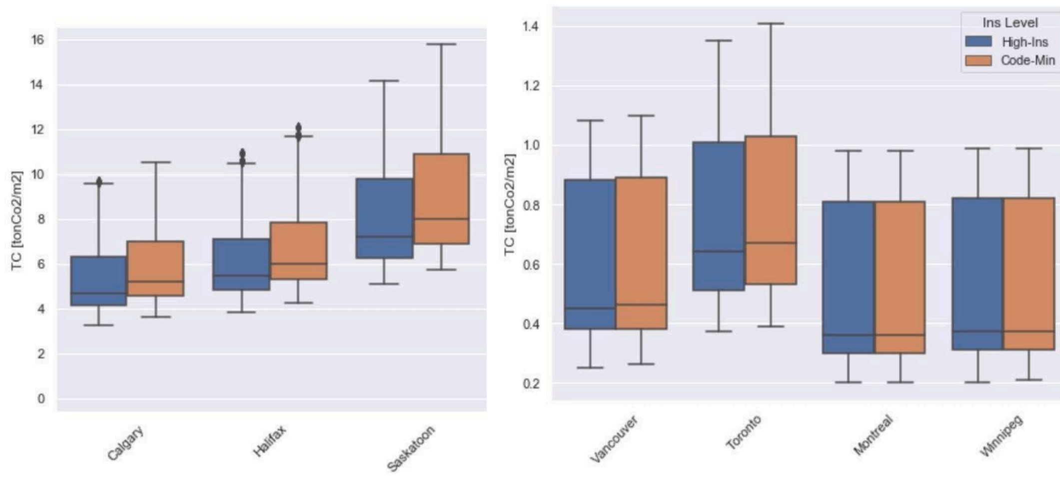

Fig. 10. Range of total carbon per area by insulation level per city.

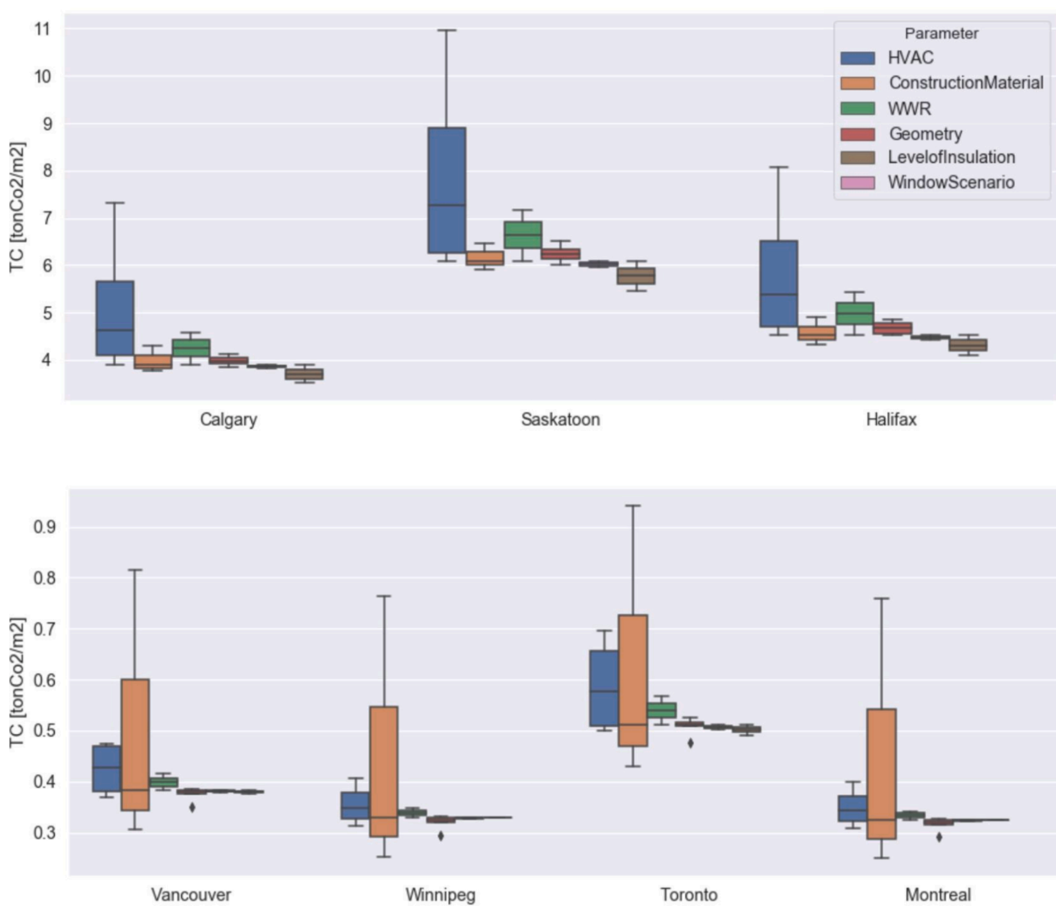

Fig. 11. Range of total carbon by design parameter.

therefore parameters related to EC, namely structural material, plays more important role. As it can be inferred from Fig. 11, in LGC cities due to low to near zero grid carbon emission, design priorities that affect EC are in higher priorities. Secondly, architects are advised to consider an optimized HVAC system. Next priorities includes WWR, geometry and insulation level, which have roughly similar impact in the range of TC.. Insulation level and window scenarios due to dual impact on TC (through EC and OC) show marginal impact on building TC in cities with LGC.

This analysis differentiates between the impact of each design parameter on TC, with percentage differences plotted relative to a baseline building model as explained in section 3.4 Sensitivity Analysis. Each bar represents the relative influence of a specific design parameter, and the error bars reflect the variability or uncertainty associated with each parameter's impact.

By comparing these parameters across multiple cities, distinct regional patterns emerge. For example:

- Error bar in LGC cities shows high deviation in structure, meaning that unoptimized structural design can roughly double the TC output to which is way more significant than any other parameters.
- In HGC cities in addition to structure, special attention should be placed on HVAC system design. The graph shows that in colder cities with HGC the ±20 % change of TC can be expected by different efficiency of HVAC systems.
- Mostly transparent envelope can also increase TC tremendously and that is by far more influential in HGC cities rather than LGC with corresponding change of ±17 % and 8 %.
- Orientation and U-Values, while important, generally result in smaller and more predictable TC changes, suggesting that while they influence performance, their relative impact is less compared to structural and mechanical system design. This is true for highly insulated and fully electrified buildings per this study and might have different potential impact on TC per fuel type, grid carbon and thermal behavior of building enclosure.

By consolidating these findings, the study highlights how holistic, context-responsive design approaches—addressing both operational and embodied carbon—can maximize carbon savings across diverse climate zones.

As highlighted in the literature review, no existing studies prioritize low-carbon design for cold climates while integrating current construction codes and national electrification goals. This lack of directly comparable studies underscores the novelty of our research. Moreover, HVAC systems are often excluded from existing literature, leaving no direct resource to compare findings in this critical area. However, our results align with prior studies, such as [29], which identify the structural system as a significant contributor to TC through impacting it's dominant impact on EC. At the same time, our findings reveal that factors like geometry, insulation, and window specifications exhibit varying impacts across Canadian Cities. As previously documented in the literature, this is not entirely aligned with other researches finding more prominent impact of envelope design factors on building TC in mild and hot climates, under less stringent building code [27,32,34]. The results also show that some parameters that previously were considered to have significant impact on building TC have lower impact in buildings with high-performance construction even in cold climates. For instance, in buildings with highly insulated enclosure, due to use of efficient components and subsystems, tolerance in TC is managed which allows freedom for creativity to satisfy other design objectives. On the contrary some design parameters have been neglected while they play a crucial role in the current low-carbon building design field. An example is the HVAC systems in buildings that play a significant role both in OC, especially in cities with HGC, and also in EC. This impact will be more significant in larger scale projects with more complex HVAC systems. This is while the literature shows that HVAC has been considered out of scope or left as a controlled variable to simplify LCA analysis in the design stage. The same is true for structural systems of the building.

The results also indicate the same features for the scenario with lowest TC in all cities. Buildings with mass timber structure which have compact form and lower WWR and are ventilated using efficient HVAC systems have the lowest TC reported. This trend can set an example for design preference in all locations to reach the lowest carbon footprint. In other words the results provide a possible prescriptive method for early stage TC prediction. For example, if the design objective requires using complex form with more protrusion or use of concrete construction and higher transparency for enclosure, higher TC from the building should be expected. The results summarized in Fig. 12 can help architect to estimate the difference roughly in concept design stage.

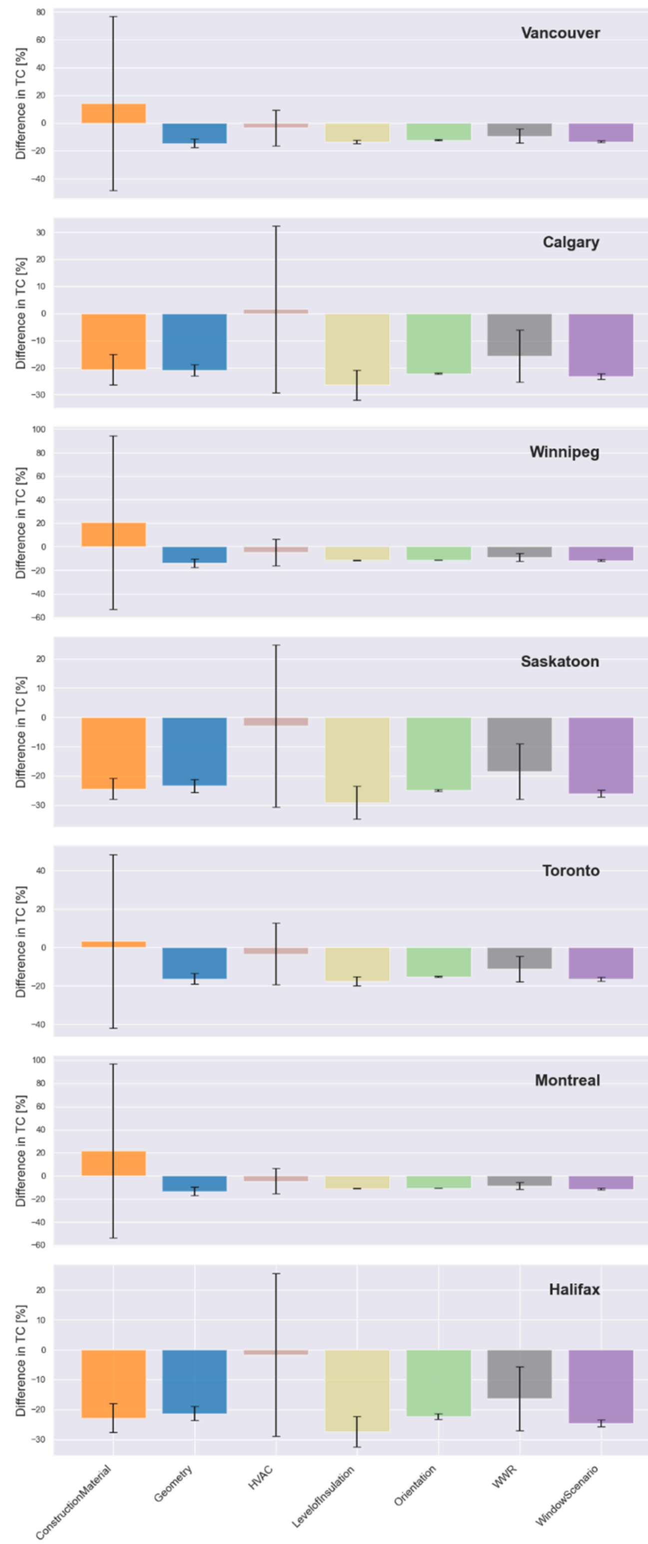

Fig. 12. TC sensitivity to design parameter in different cities.

6. Conclusions

In this research, we aim to answer the question of what matters the most regarding total life cycle carbon emissions when designing low carbon buildings across Canadian cities. This research evaluates more than 20,000 parametrically generated building designs across seven major Canadian cities with four different climates with substantially different GCI factors. Considering climate and GCI, the results show significant differences in expected range of TC for building across studied regions. The difference mainly stemmed from GCI,which showed an underlying impact on EC and OC tradeoff. The results also indicated that the similar design outputs can have substantially different TC depending on the design decisions and therefore architects should be aware of their design impact and potential of each design parameters in order to reach their sustainability targets.

The results of this study reveals clear distinction and influential impacts of design parameters on building TC across investigated cities. In summary architects are advised to be mindful of the high impact of HVAC choices as well as structural materials on the building carbon footprint. WWR is the third parameter with the highest potential for carbon reduction across all cities. The next priority for carbon reduction should be design decisions associated with geometry, level of insulation in HGC. Other factors such as window material and orientation of building however show lowest potential for reducing TC and should be regarded with more flexibility in favor of other design objectives.

The results of this study can assist architects in setting TC expectations more realistically and identify the hotspot area for carbon reduction through design. This study focuses on Canadian climate and uses local GCI for LCA calculations; however, the results can be applied to similar climates with comparable GCI, providing valuable guidance for architects worldwide in the pursuit of low-carbon building designs.

This study can be further expanded by including other factors and investigating their impact on building environmental impacts. Investigating the impact of window design by changing WWR, window material on TC under daylighting and comfort conditions are topics for potential future studies. Additionally, the significance of design parameters and their impact in lowering TC, considering dynamic LCA and grid decarbonization target can shed light on future of low-carbon buildings design. Another topic for future studies is deployment of a parametric LCA model to calculate impacts per life cycle stage.

CRediT authorship contribution statement

Mahsa Torabi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kate Simonen:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Ralph Evins:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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During the preparation of this work, the authors used OpenAI tool for language edit of some parts of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix 1. Material carbon intensity

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Table 1
List of materials and emissions per tonne.

Building element	Material name	A1-A3 Carbon [KgCo2/tonne]	Density [kg/m3]	Reference
Structure	Steel	2624	7870	cqd.io/e/ec3m4n2058
Structure	Rebar	813.1	7830	cqd.io/e/ec3ux61jxj

Table 2
List of materials and emissions per m3.

Building element	Material Name	A1-A3 Carbon [KgCo2/m3]	Thickness [m]	Density [kg/m3]	Reference
Structure	Reinforced Concrete(with %3 of weight rebar)	572.3	–	2400	cqd.io/e/ec3cwkf19z
Structure	Mass Timber	226.2	–	563	cqd.io/e/ec3yh6a1t4
Envelope	Normal weight Concrete Floor	237.5	0.1	2400	cqd.io/e/ec3t7c51b6
Envelope	CONCRETE HW RefBldg	376.9	19.6	2400	cqd.io/e/ec3yx2kaf9

Table 3
List of materials and emissions per m2.

Building element	Material name	A1-A3 carbon [KgCo2/m2]	Thickness [m]	Density [kg/m3]	Reference
Envelope	⅝" Gypsum Board	2.94	0.0158	640	cqd.io/e/ec3923010c
Envelope	½" Gypsum Board	1.83	0.0127	640	cqd.io/e/ec3nka35n3
Envelope	Metal Siding	2.71	0.025	7870	cqd.io/e/ec382nu1ux
Envelope	Roof Membrane	4.2	0.032	500	cqd.io/e/ec3b9xcfmp
Envelope	Typical Carpet Pad	3.87	0.03	400	cqd.io/e/ec3ape53st
Envelope	Typical Insulation-fiberglass	1.40	Per ISI	12	cqd.io/e/ec3tk883t4
Envelope	2PaneWin-Al	101	–	–	cqd.io/e/ec3ku1dd70
Envelope	3PaneWin-Al	116.7	–	–	cqd.io/e/ec3m65sdy5

Table 4
List of HVAC scenarios and emissions [42].

Building element	Material name	A-C Carbon [KgCo2/m2 floor area]	Efficiency [31]
HVAC	VAV chiller with central air source heat pump reheat	57.3	Standard
HVAC	PVAV_PFP	127.8	Standard
HVAC	DOAS_WSHP_FluidCooler_Boiler	39.8	High efficiency
HVAC	DOAS_FCU_Chiller_ASHP	82.3	High efficiency

Table 5
List of construction scenarios and pertaining U-Value and R-Value per building envelop element and climate region [34].

Construction type	Building element	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Concrete	Roof	R32	R32	R32	R36	R36
	Wall	R10	R12	R13	R15	R21
	Floor	R5	R5	R5	R5	R10
	Window	U 0.36	U0.36	U0.34	U0.29	U0.26
Steel	Roof	R32	R32	R32	R36	R36
	Wall	R16	R19	R21	R21	R28
	Floor	R5	R5	R5	R5	R10
	Window	U 0.36	U0.36	U0.34	U0.29	U0.26
Wood	Roof	R48	R48	R48	R59	R59
	Wall	R16	R20	R20	R20	R32
	Floor	R5	R5	R5	R5	R10
	Window	U0.36	U0.36	U0.34	U0.29	U0.26

Appendix 2. Grid carbon intensity

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Table 1
GCI and climatic region of studied cities.

	City	Province	Carbon intensity of grid [g Co2/KWh] [42]	ASHRAE climatic region
1	Montreal	Quebec	1.7	6A
2	Winnipeg	Manitoba	2	7
3	Vancouver	British Columbia	15	4C
4	Toronto	Ontario	30	5A
5	Calgary	Alberta	540	7
6	Halifax	Nova-Scotia	690	6A
7	Saskatoon	Saskatchewan	730	7

Appendix 3. Results summary

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Table 1
Average TC per structural material across cities.

City	Structural material	TC [tonCo2/m2]
Calgary	Concrete	4.80
	Steel	5.29
	Wood	4.69
Halifax	Concrete	5.59
	Steel	6.05
	Wood	5.45
Montreal	Concrete	0.35
	Steel	0.85
	Wood	0.28
Saskatoon	Concrete	7.46
	Steel	7.935
	Wood	7.30
Toronto	Concrete	0.59
	Steel	1.09
	Wood	0.52
Vancouver	Concrete	0.43
	Steel	0.93

(*continued on next page*)

Table 1 (*continued*)

City	Structural material	TC [tonCo2/m2]
	Wood	0.36
Winnipeg	Concrete	0.36
	Steel	0.86
	Wood	0.29

Table A2
TC per geometries across cities.

City	Geometry	TC [kgCo2/m2]			
		Min	Max	Mean	Median
Calgary	Rec	3.31	10.24	5.46	4.83
	Rec+	3.36	10.25	5.54	4.93
	RecH	3.46	10.51	5.73	5.07
	Sqr	3.28	10.17	5.42	4.825
	Sqr+	3.37	10.28	5.55	4.95
	SqrH	3.42	10.45	5.66	5.03
Halifax	Rec	3.84	11.22	6.24	5.61
	Rec+	3.92	11.66	6.33	5.72
	RecH	4.09	12.09	6.55	5.965
	Sqr	3.84	11.26	6.21	5.53
	Sqr+	3.97	11.53	6.35	5.71
	SqrH	4.07	11.78	6.47	5.845
Saskatoon	Rec	5.17	14.96	8.36	7.39
	Rec+	5.26	15.09	8.49	7.55
	RecH	5.45	15.8	8.8	7.86
	Sqr	5.12	14.95	8.31	7.34
	Sqr+	5.27	15.07	8.5	7.57
	SqrH	5.38	15.35	8.68	7.78
Toronto	Rec	0.39	1.29	0.73	0.66
	Rec+	0.4	1.35	0.76	0.66
	RecH	0.4	1.32	0.75	0.67
	Sqr	0.37	1.34	0.73	0.62
	Sqr+	0.39	1.39	0.77	0.65
	SqrH	0.39	1.41	0.77	0.66
Vancouver	Rec	0.28	1	0.56	0.46
	Rec+	0.28	1.06	0.59	0.46
	RecH	0.28	1.01	0.57	0.47
	Sqr	0.25	1.05	0.56	0.43
	Sqr+	0.28	1.1	0.6	0.46
	SqrH	0.27	1.1	0.6	0.46
Winnipeg	Rec	0.23	0.89	0.49	0.37
	Rec+	0.23	0.95	0.51	0.37
	RecH	0.23	0.89	0.49	0.37
	Sqr	0.2	0.94	0.49	0.34
	Sqr+	0.23	0.99	0.52	0.365
	SqrH	0.22	0.99	0.52	0.36
Montreal	Rec	0.23	0.88	0.48	0.36
	Rec+	0.23	0.94	0.51	0.36
	RecH	0.22	0.88	0.48	0.36
	Sqr	0.2	0.93	0.48	0.33
	Sqr+	0.23	0.98	0.52	0.36
	SqrH	0.22	0.98	0.51	0.35

Data availability

Data will be made available on request.

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