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Advancing urban resilience with modular construction: An integrated sustainability assessment framework

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ABSTRACT

Given the rapid growth of sustainable construction strategies globally and the importance of resiliency in civil infrastructure, it is crucial to adopt best practices. Modular construction is one such practice and is considered a better alternative to conventional construction in terms of resilience, construction times, resource efficiency, and sustainability. However, the continued expansion of modular construction relies on quantifying and evaluating its sustainability and the purported benefits. This paper develops and checks feasibility through an integrated multi-level decision support framework to empirically evaluate the sustainability performances of single-family residential modular homes. Criteria and indicator development and calculation, benchmark scale establishment, quantitative and qualitative data collection from literature and surveys, and multi-criteria decision analysis are unique aspects of this framework. The results of the two case studies located in the Okanagan region, Canada showed that modular homes perform at a higher level of sustainability than their conventional counterparts across multiple metrics and levels related to environmental and economic factors. The modular homes scored eco-efficiency values of 62.5 and 56.0, respectively and fell into higher performance range. The proposed framework offers flexibility in examining different dimensions of sustainability, providing valuable insights into the key parameters that need to be addressed to enhance overall sustainability. This research, which integrates life cycle thinking and decision-making, helps the construction industry and, municipalities, governments, and policymakers in making informed decisions on the selection of suitable construction methods in city developments and move towards a more resilient and sustainable sector.

1. Introduction

The adverse impacts of climate change, such as decreased agricultural productivity, infrastructure damage, human health, and other domains, are well documented [1–4]. Likewise, Canada's infrastructure is exposed to multiple natural disasters and extreme weather events related to climate change [5]. These climate impacts cause economic ramifications that are felt across sectors. Floods wreak havoc among natural disasters and have documented over 1 billion inductance damages yearly [6]. Wildfires, such as those in Fort McMurray, caused \$8.9 million in damage in water treatment expenditure alone [7]. A storm system in November 2021 stuck in southern British Columbia, damaging multiple infrastructures and required a rebuilding cost of \$10 billion (in Canadian dollars) [8]. Concomitantly, these disasters continue to increase in duration, frequency, and intensity.

The building sector plays a crucial role in infrastructure, accounting for over 40 % of Canada's infrastructure monetary value [9]. Under climate change, buildings in Canada are vulnerable to a range of hazards such as changing precipitation patterns, storm surges, high winds, permafrost degradation, heat waves, and cold snaps [5]. On the other hand, there is an urgent need to upgrade and increase the construction of buildings and supporting infrastructure to accommodate the demands of the rising population [10]. For example, Canada requires 5.8 million new homes by 2030 to accommodate the housing needs [11]. In addition, the construction and operation of buildings involve significant carbon emissions and other environmental impacts that contribute to climate change [12]. Hence, to address the problems of climate change and reduce environmental impacts from construction and operation, new buildings must be both resilient (*capable of resisting or adapting to adverse events*) and sustainable (*capable of meeting present needs without compro-*

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missing the ability of future generations) [13,14]. In this regard, modular construction has emerged as a promising solution.

Modular construction is constructing building components or modules under controlled conditions, ensuring better quality control, less wastage of materials, and lower construction time [15,16]. In addition, modular construction is associated with increased on-site safety [17], and cost savings associated with labor and materials [18,19]. In fact, modular construction and other off-site construction practices are considered to be logical solutions under current market conditions, practices and driving forces, such as the need to improved living conditions, better environmental awareness, among others [14,20]. In the same vein, the ability of modular buildings to be disassembled, reused, and repurposed helps increase the longevity of buildings and components. Though design of a building plays a crucial role in defining its vulnerability, various factors such as strength, flexibility, quality control, and ability to be customized to requirements make modular buildings less vulnerable than conventional construction [21–26]. Although Canadian construction is predominantly on-site, in the next 10 to 15 years, a significant shift towards off-site construction practices (such as modular construction) is predicted [27].

Despite the numerous advantages of modular construction two key challenges persist: (a) the need to prove better performance of modular construction over its conventional counterpart in terms of environmental, economic, and social sustainability and (b) the increased adoption rate [14]. Addressing these challenges will ensure a more sustainable and resilient building sector. A growing body of literature recognizes the importance of empirical measurement of sustainability and the dearth of knowledge on how sustainability can be holistically measured. Building standards and green building rating systems such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Methodology (BREEAM) deal with multiple sustainability metrics. However, these rating systems and standards are designed to mainly address the environmental aspects of buildings and often cannot address the two other dimensions of sustainability (i.e., economic and social) [28]. The importance assigned to different metrics also varies, and the rating systems are often not regionally representative [30]. Therefore, moving beyond relying solely on a single rating system and evaluating the significance of various metrics in collaboration with local construction practitioners is essential.

The majority of the published literature on sustainability aims to address one or more aspects of sustainability. Hong et al. [31] compared the costs of conventional construction with off-site construction and found the material costs to be a significant component; Hong et al. [32] assessed the energy performance of two types of construction and found precast components to be most energy intensive; Lawson et al. [17] work determined that waste reduction could be reduced up to one third with modular construction, Nahmens and Ikuma [33] investigated modular homes and found a reduction of 64 % and 31 % in waste and construction time, respectively. Three dimensions of sustainability (i.e., environmental, economic, and social) can be addressed separately but some form of aggregation is needed to represent the overall sustainability performance. The most common method to integrate the three dimensions of sustainability is by aggregating results of life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA) [34]. Moreover, it is essential to assess the holistic sustainability of modular homes' performance against their conventional counterparts. In this regard, the approach of performance benchmarks becomes relevant. This approach has been used extensively in both engineering and non-engineering disciplines [35–38,77,86]. Elmuti and Kathawala [39] defined performance benchmarking as a process of comparing the performance of entities against other entities.

While benchmarking has been extensively applied for energy performance and, in recent years, to the embodied carbon evaluation, benchmarking assessments using other sustainability indices and indicators, in particular on economic and social fronts, are largely absent [40–43]. Likewise, the developments in policies at local levels, such as City of

Toronto's Green Standard and Vancouver Building By-law (VBBL), and national levels, such as material procurement policy Standard of Embodied Carbon in Construction are making the data on sustainability performance of materials, components, and processes more widely accessible [44–47]. However, the scope of such developments is limited to a few aspects of sustainability. Therefore, there is an urgent need to develop a region-specific sustainability assessment framework.

This research introduces a holistic approach incorporating multiple phases of data collection and analysis with the aim of comparing the performance of single-family residential modular buildings with conventional buildings in the area. The novelty of the work is the introduction of regionally specific indices and benchmarks representing the sustainability performance at different levels which enables sustainability assessments at different levels. The first phase involves the identification of sustainability indicators and criteria and the creation of sets of indices at three assessment levels including criteria level, sustainability dimension level (economic and environmental), and eco-efficiency sustainability level. The second phase involves generating benchmarks of the performances of conventional homes in the local region and establishing the corresponding benchmark scales at the three assessment levels. In the third phase, two real case study modular buildings are used to demonstrate the framework and compare it against conventional homes. In this regard, modular homes in the Okanagan region, British Columbia (BC), Canada, were selected. This region has been hit by multiple disasters in the last decade, exposing local housing and infrastructure vulnerability. Some of these disasters include the wildfires of August 2023 that destroyed several homes, the heat dome of 2021 resulting in an estimated 619 fatalities, and an alarming rise in the water table level in 2017 [47–49]. Hence, assessing the sustainability of modular homes in the region would help direct the local construction industry towards planning houses for pre- and post-disasters.

2. Methodology

In this research, the concepts of index generation, performance benchmarking, and comparison have been integrated to assess holistic sustainability of modular homes in Canada and provide a decision support framework (DSF) for construction policy makers, builders, and homeowners. Different stages of this research and the corresponding methodologies are presented in Fig. 1.

2.1. Index development

2.1.1. Sustainability criteria and indicators

To compare the sustainability performances of modular homes with the corresponding benchmark performances of conventional homes, first, these sustainability performances should be quantified using suitable criteria and indicators. Data collection related to criteria, indicators, and sub-indicators was performed through conducting literature review, content analysis, and surveys. The main sources of data included green building rating systems, peer reviewed publications, and construction expert input. Green building rating systems most widely used around the world such as Green Globes, Leadership in Energy and Environmental Design (LEED) and Building Research Establishment's Environmental Assessment Method (BREEAM) were used while those not relevant to the region under study (i.e. Okanagan Region, Canada), such as Green Mark (GM) of Singapore or Comprehensive Assessment System for Built Environment Efficiency (CASBEE) of Japan were excluded [50–53]. The literature review revealed several criteria related to sustainability dimensions of buildings. The criteria were shortlisted by following an iterative process. In the first round, the most relevant criteria were identified and selected and in the second round, the selected criteria were placed under the related sustainability dimension categories (i.e., environmental, economic and social). In the third round, the criteria with similar yet unique meanings were merged under one criterion. In order not to ensure double counting errors did not occur,

Phases	Data Collection	Data Analysis, Method and Tools	Outputs
Sustainability Indices	Survey 1 & 2: Expert Interview -Literature Review -Green Building Rating Systems LEED BREAM DGNB -Living Building Challenge -Utilities-BC Hydro -ISO Standards -Others	Delphi Method, Linkert Scale Ranking of Sustainability Criteria -Reliability Analysis -Ranking Analysis Weighting Scores Survey 1 & 2 Aggregation Method : TOPSIS	Environmental SPCs Economic SPCs Social SPCs Environmental Sustainability Index Environmental Sustainability Index Eco-Efficiency Index
Performance Benchmarks	-Literature Review -Survey 2 & 3 <i>Estimate historical performance of buildings with respect to each indicator, criteria and overall environmental sustainability</i>	Monte Carlo Simulation (@ Risk Tool) Delphi Method Simple Weighted Average method	Probability distribution for other sub-SPIs/ SPIs Performance Level Functions Sustainability Performance Benchmarks
Case Studies	-Literature Review -Survey 4 & 5 <i>Collect data of case study homes</i>	Life Cycle Analysis (Athena) TOPSIS MCDM	Embodied Carbon Sustainability Performance of Modular Homes for indices
Outcome	Overall sustainability of two case study Modular homes in Okanagan Region, British Columbia (Canada) and compared with conventional homes benchmarks		

Where: SPC stands for sustainability performance criteria

Fig. 1. Research phases and corresponding methodologies.

each criterion was cross reference with existing before merging and any repetitions were removed. In the last round, a frequency analysis was performed to identify the list of criteria that would be suitable for assessing sustainability of modular residential buildings. In this paper, these criteria are named sustainability performance criteria (SPCs). Eqs. (1) and (2) describes the rules followed to select the final list of environmental and economic SPCs, respectively. In contrast to environmental criteria with frequency greater than 50 % was considered a smaller frequency was considered appropriate for economic SPCs because there is relatively less literature available on the economic criteria of green buildings. This limited availability of research makes it challenging to establish a broader basis for analysis, making a smaller frequency both practical and feasible from an economic standpoint.

$$SPC_{Environmental} = \begin{cases} 1, & \text{if } F > 50\% \\ 1, & \text{if } G > 50\% \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

$$SPC_{Economic} = \begin{cases} 1, & \text{if } G > 20\% \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

Where:

SPC= Sustainability Performance Criterion

F = Frequency of SPC presence in reviewed green building rating systems

G = Frequency of SPC presence in reviewed literature plus green building rating systems

Based on the selection criteria in Eqs. (1) and (2), feedback from five academic researchers and survey a set of 7 environmental and 8 economic SPCs were selected. To determine the relative importance of the selected SPCs and rank them, a survey involving 51 construction industry experts was conducted using a five-point scale. In considering this five-point scale it was assumed that the numbers are at equal intervals on this scale, there is uniform interpretation from participants for instance “good” does not mean “very good” or “excellent”, the participants have no contextual bias while using this scale. The results of the survey were incorporated into the ranking analysis and severity index methods to rank the selected SPCs. These methods are extensively used for determining the applicability of sustainability criteria for comparing two or more products or processes [55]. The Severity Index (SI) of each SPC was calculated as:

$$Severity\ Index\ (SI) = \left(\sum_{i=1}^5 w_i \frac{f_i}{n} \right) / a \quad (3)$$

Where, i is each ranking score assigned by the questionnaire respondents; w_i is the weight of the assigned; f_i is the total frequency of the score i ; n is the total number of the completed questionnaires; and a

Table 1
Economic and environmental criteria level of importance and weights.

Dimension	Sustainability Performance Criteria	Level of Importance	Weight
Economic	Integrated management (IM)	H	0.120
	Durability of building (DB)	H	0.123
	Adaptability of building (AB)	M	0.109
	Design and construction time (DCT)	VH	0.157
	Design and construction costs (DCC)	VH	0.152
	Operational costs (OC)	H	0.114
	Maintenance costs (MC)	M	0.108
	Investment and related risks (IRR)	H	0.117
Environmental	Energy performance and efficiency strategies (EP)	H	0.210
	Regional materials (RM)	M	0.130
	Construction waste management (CWM)	H	0.214
	Renewable and environmentally preferable products (REP)	M	0.150
	Site disruption and appropriate strategies (SD)	M	0.168
	Renewable energy use (RE)	M	0.128

Source: Kamali and Hewage [54].

is the highest weight. Subsequently, all the selected SPCs were ranked from “Very High” to “Very Low” according to their SI values [56,57]. Specific details on this survey can be found in Kamali and Hewage [58]. The summary of the selected SPCs and their ranking is presented in Table 1.

The selected and ranked SPCs cannot be quantified unless suitable measurable indicators (called sustainability performance indicators, SPIs, in this paper) and sub-indicators (sub-SPIs) are identified. The SPIs and sub-SPIs related to each selected SPC were identified using similar selection rules of frequency defined in Eqs. (1) and (2) for environmental and economic sustainability dimensions, respectively. Efforts were made to ensure the selected set of indicators under sustainability dimensions were not overlapping, sensitive towards spatial-temporal dimensions and capable of capturing long term sustainability [59]. Based on the analysis, a total of thirty-seven (37) SPIs and forty-four (44) sub-SPIs were selected under the environmental SPCs and seventeen (17) SPIs and twenty (20) sub-SPIs were selected under the economic SPCs. Tables 2 and 3 list the selected indicators and sub-indicators for the economic and environmental criteria, respectively.

2.1.2. Normalization

In the next step of the research, to assess the empirical values for modular house under the selected criteria, a performance level function (PLF) was developed for each indicator and sub-indicators. In index development, the SPIs and sub-SPIs identified under each SPC have different measurement units and dimensions. Hence, to create an integrated index, the data related with these indicators and sub-indicators needs to be normalized [60]. Several methods are available for normalization of indicators and indicators in the construction sector. These include ranking, standardization, Min-Max, Distance to reference, Categorical scale, among others [59]. However, in this study the PLF for each indicator and sub-indicator was developed in a way that the calculated output of the function, i.e., performance level (PL), ranges from 0 to 100 ($0 \leq PL \leq 100$) and no normalization is required [57]. The PLFs were developed based on threshold set by green building best practices (reflected in green building rating systems) and expert opinions through surveys. The type of PLFs varies and could be discrete or continuous [61]. Detailed descriptions of the developed PLFs and the required data variables are provided in Appendix A.

2.1.3. Weighting and aggregation

Weighting and aggregation are essential components of index development [62]. Once PLFs are formed, the weights are assigned to rank the criteria, indicators and sub-indicators according to their relative importance. Out of three possible methods to assign weights [63], two surveys were conducted with construction experts. Aggregation of sub-

SPIs into their parent SPI and aggregation of SPIs into their parent SPC was performed using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [64,65]. This multi-criterion decision-making method has been extensively used in literature to assess competing criteria/attributes and select the best alternative [66,67]. Specific steps performed to carry out aggregation are provided in Appendix B. TOPSIS was employed to perform the aggregation process to generate sustainability indices in three assessment levels, i.e., SPC level, sustainability dimension level, and combined sustainability level. First, the calculated PLFs of the sub-SPIs and SPIs were aggregated to generate sets of indices for the corresponding economic and environmental SPCs. The 7 environmental indices and 8 economic indices were then aggregated to yield into a single environmental sustainability Index and economic sustainability Index, respectively. Finally, to aggregate sustainability indices, the economic and environmental sustainability indices were aggregated into an eco-efficiency Index (Eq. (4)). It should be noted that inclusion of social criteria into this index would provide a more robust index. However, the current work was only limited to detailed investigation of environmental and economic index and inclusion of social criteria could follow similar method of indicator and criteria identification and aggregation.

$$\text{Eco - Efficiency Index (SI)} = \text{Environmental Sustainability Index} + \text{Economic Sustainability Index} \quad (4)$$

2.1.4. Sensitivity analysis

Sensitivity analysis was the last stage of index development and has been extensively applied in construction sustainability index developed [68]. The aim of this stage is to assess how change in input impacts the final index score. This work involved determining the weights of different sub-indicators and indicators based on expert surveys. However, though the Delphi technique is adopted, and multiple rounds of surveys were conducted there is need to assess how the change in weights of these factors can impact ultimate sustainability of the modular homes. This stage is essential to study the propagation of uncertainty into the Eco-efficiency index. This analysis can also yield the most important sub-indicator, indicator and criteria (i.e., hot spots) the building industry involved in modular construction should focus on increasing the overall sustainability of this sector. Hence, sensitivity analysis serves as an additional benefit in helping in improving index by gathering data most relevant and testing robustness of the indices developed [90]. Sensitivity analysis can be conducted through local or global sensitivity analysis methods. In this work local sensitivity analysis is performed with respect to the weighting criteria by employing the @Risk tool.

Table 2
Economic sustainability performance criteria and corresponding indicators.

SPC	SPIs	sub-SPIs	Sources
Integrated management (IM)	IM1 Integrated design processes	IM1–1 Pre-design meetings	RS, EO
		IM1–2 Performance goals	
		IM1–3 Progress meetings	
	IM2 Life cycle cost	IM2–1 Elemental life cycle cost	
		IM2–2 Component level life cycle cost	
	IM3 Commissioning	IM3–1 Commissioning schedule and responsibilities	
		IM3–2 Whole building commissioning	
		IM3–3 Training and handover	
	Durability of building (DB)	DB1 Roofing and openings	
DB1–2 Envelope flashings			
DB1–3 Roof and wall openings			
DB2 Foundation waterproofing			
DB4 Barriers		DB4–1 Air barriers	
		DB4–2 Vapor retarders	
DB3 Cladding		DB3–1 Exterior wall cladding systems	
		DB3–2 Rain screen wall cladding	
Adaptability of building (AB)		AB1 Expandability	AB1–1 Lateral expandability
	AB1–2 Vertical expandability		
	AB2 Dismantlability		
AB3 Record keeping			
Design and construction time (DCT)	DCT1 Design time		
	DCT2 Construction time		
Design and construction costs (DCC)	DCC1 Design cost		
	DCC2 Construction cost		
Operational costs (OC)	OC1 Running costs		
Maintenance costs (MC)	MC1 Repair and replacement costs		
Investment and related risks (IRR)	IRR1–1 Sale price		
	IRR1–2 Design cost		
	IRR1–3 Construction cost		

Where L-Literature; RS-Rating systems (One or more of international rating systems that included LEED = Leadership in Energy and Environmental Design; LBC = Living Building Challenge; BREEAM= Building Research Establishment Environmental Assessment Method; NRC = National Research Council Canada; NAHB =National Association of Homebuilders Research Center); and EO-Expert Opinion (Collected through surveys).

At the end of this stage, a set of sustainability indices are developed at different assessment levels (i.e., SPC level, sustainability dimension level, and Eco-efficiency level).

2.2. Benchmark development

The set indices developed at the three assessment levels provide a method to compare the sustainability performance of two or more modular homes with each other. However, it is essential that the sustainability of modular buildings is assessed with respect to the historical performance of conventional residential houses. To compare the life cycle performance of a modular building with similar conventional buildings, the developed sustainability indices should be benchmarked at the corresponding assessment levels. To this end, suitable performance benchmark scales (PBSs) for each assessment level should be established based on the historical performances of conventional buildings as described below.

Benchmarks can be used to represent the best and the worst performing sustainability indicators [69]. Green building rating systems, such

as LEED and BREEM can help represent the performance of buildings; however, the related benchmarks are criticized to be non-scientific and are not representative of regional requirements [29,30]. Furthermore, these standards are not comprehensive and represent substantivity on a limited set of indicators and criteria. To overcome the limitations of benchmarks associated with green building rating systems and represent regional performance of modular houses, a set of performance benchmark scales (PBSs) was developed for all indicators and criteria (Level 1) through another survey questionnaire participated by local industry practitioners. The survey design was based on the Delphi Technique [70], to ensure robust data collection and consensus on the threshold limits [71,72]. Multiple rounds of questionnaires were rotated and revisited until a consensus on threshold limits was achieved. The minimum and maximum thresholds were developed for conventional housing and a comparison was made with the modular houses built in the locality. The details of this third survey can be viewed in Kamali et al. [56]. The PBSs ranged from zero (0) meaning the “least desirable” to the value of hundred (100) meaning the “most desirable” performance of conventional homes with respect to the subject indicator or criterion. To make

Table 3
Environmental sustainability performance criteria and corresponding indicators.

Criteria	Indicators	Sub-Indicators	Sources	
Energy performance and efficiency strategies (EP)	EP1 Envelope insulation	EP1-1 R-value	L,RS	
		EP1-2 Quality of insulation installation	L,RS	
	EP2 Air infiltration		L,RS	
	EP3 Windows and glass doors		RS	
	EP4 Space heating and cooling equipment	EP4-1 Heating equipment		
		EP4-2 Cooling equipment		
	EP5 Heating & cooling distribution system		RS, EO	
	EP6 Efficient hot water equipment	EP6-1 Hot water distribution system		RS
		EP6-2 Pipe insulation		
		EP6-3 Hot water equipment		
EP7 Efficient lighting				
EP8 Efficient appliances				
EP9 Residential refrigerant management				
Regional materials (RM)	RM1 Local materials in exterior walls	RM1-1 Framing/wall structure	RS, EO	
		RM1-2 Siding or masonry	RS	
	RM2 Local materials in floor	RM2-1 Floor framing		
		RM2-2 Floor flooring		
	RM3 Local materials in foundation			
	RM4 Local materials in interior walls/ceiling	RM4-1 Framing of interior walls		
		RM4-2 Gypsum board		
	RM5 Local materials in landscape			
	RM6 Local materials in roof	RM6-1 Roof framing		
		RM6-2 Roof roofing		
	RM7 Local materials in roof, floor, and wall	RM7-1 Cavity insulation		
		RM7-2 Sheathing		
	RM8 Local materials in other components	RM8-1 Adhesives and sealant		
RM8-2 Counters				
RM8-3 Doors				
Construction waste management (CWM)	CWM1 Efficient material consumption plans	CWM1-1 Detailed framing plans	L,RS,EO	
		CWM1-2 Efficient framing		
	CWM2 Construction waste diversion			
	CWM3 Construction waste reuse	CWM3-1 Reuse of façades		
		CWM3-2 Reuse of structural systems		
CWM3-3 Reuse of non-structural elements				
Renewable and environmentally preferable products (REP)	REP1 Exterior wall content	REP1-1 Framing/wall structure	RS, EO	
		REP1-2 Siding or masonry		
	REP2 Floor content	REP2-1 Floor framing		
		REP2-2 Floor flooring		
	REP3 Foundation content			
	REP4 Interior wall and ceiling content	REP4-1 Framing of interior walls		
		REP4-2 Paints and coatings		
	REP5 Landscape content			
	REP6 Roof content	REP6-1 Roof framing	RS, EO	
REP6-2 Roof roofing				
REP7 Roof, floor, and wall content	REP7-1 Cavity insulation			
	REP7-2 Sheathing			
REP8 Other components' content	REP8-1 Cabinets			
	REP8-2 Counters			
	REP8-3 Doors			
Site disruption and appropriate strategies (SD)	SD1 Construction activity pollution		RS,EO	
	SD2 Efficient landscaping	SD2-1 Landscape design	L,RS,EO	
		SD2-2 Conventional turf	RS,EO	
		SD2-3 Drought-tolerant plants		
	SD3 Heat Island effect		L,RS,EO	
	SD4 Rainwater management	SD4-1 Permeable site	RS,EO	
		SD4-2 Erosion management		
		SD4-3 Roof runoff management		
	SD5 Efficient pest control			
	Renewable energy use (RE)	RE1 Renewable electricity		L, RS, U
RE2 Renewable space heating			L, RS	
RE3 Renewable water heating				
Greenhouse gas emissions (GE)	GE1 Global warming potential and other impact measures		L, LCA	

Where L-Literature; RS-Rating systems (One or more of international rating systems that included LEED = Leadership in Energy and Environmental Design; LBC = Living Building Challenge; BREEAM= Building Research Establishment Environmental Assessment Method; NRC = National Research Council Canada; NAHB =National Association of Homebuilders Research Center); EO-Expert Opinion (Collected through surveys); LCA-Life Cycle Assessment (ISO standards and TRACI Method of global warming potential assessment); and U-local utility (BC Hydro).

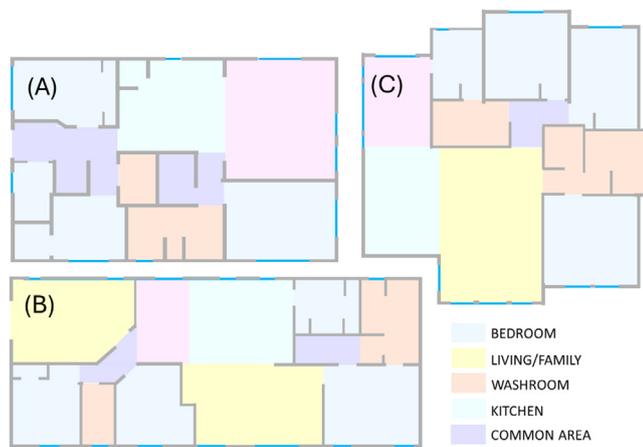


Fig. 2. Case study homes (A) Mod 1, (B) Mod 2 and (C) Conventional home.

the developed PBSs more robust by converting them into probability curves using Monte Carlo Analysis on @Risk Software, inputs for each indicator and criterion was iterated 100,000 times to yield set of performance benchmark scales (PBSs). Monte Carlo Analysis is a common technique used to assess the effect of random change in input parameters to the output [73,74]. The probability curves were assigned four categories, Low, Fair, medium, and Excellent. The probability curves for indicators were combined to yield probability curves for related criteria (assessment Level1). Likewise, the probability curves for the criteria were combined to generate the probability curves for related environmental or economic sustainability dimensions (Level 2), which were combined to give the probability curve for Eco-efficiency index at the top assessment level (Level 3).

By establishing the PBSs for different assessment levels, the sustainability performance of a modular home can be benchmarked at each level which highlights the low-performing areas and the potential for improvement compared to conventional buildings.

2.3. Framework demonstration

The feasibility of the proposed framework was demonstrated by applying on two modular houses located in Okanagan Region, BC, Canada. In recent years, the region has been hit by multiple natural disasters including floods, wildfires, heat waves and cold snaps. Among these, the wildfires of 2023 alone caused \$710 million in insured damages while 2017 saw highest rise in water table levels for the local lakes that caused damage to properties and residences [47,75]. Hence, increasing resilience and sustainability of local infrastructure and housing is a priority for the associated municipalities and first nation communities. Data and design info for the two modular homes was collected from two local modular houses construction firms. Both houses are single story with areas of 1480 ft² (138 m²) and 1782 ft² (165 m²), respectively. The smaller house was composed of two modules and consisted of three bedrooms, two bathrooms, living, dining kitchen and a den; while the larger house was composed of three modules and contained three bedrooms, two bathrooms, living, family, dining, and den. Using the proposed integrated framework, the life cycle performances of the two modular homes are benchmarked at different assessment levels. More details on the sustainability benchmarks at different levels can be found in Kamali et al. [56,57]. In addition, the findings of this work are compared with a study previously published by the authors [76]. Here, the results related to the most common sustainability measurement criteria i.e., global warming potential is compared for the two modular homes against a typical conventional detached home in Okanagan Region was also collected (Fig. 2). Readers can find details on life cycle analysis methods and materials in Kamali et al. [76].

3. Results and discussion

The main purpose of this work is to assess the sustainability of modular detached homes against regional best practices. In this regard a multi-level decision support framework is developed that is capable of assessing different levels of sustainability from the individual contributing indicators to Eco-efficiency of modular homes. In this regard, indicators and sub-indicators needed to assess economic or environmental sustainability criteria were first identified and evaluated. These indicators were aggregated through TOPSIS to form criteria indices (Level 3). The criteria were likewise aggregated to represent economic level or environmental level sustainability (Level 2) which collectively aggregated to represent Eco-efficiency sustainability (Level 1). Performance benchmark scales (PBSs) are developed for each of the assessment levels based on the survey studies to compare performance of modular homes against worst and best performing conventional homes in the region.

3.1. Performance benchmark scales

Benchmarking is common practice in energy modelling of buildings, though recent years have seen a rise in the generation of embodied carbon benchmarks. Despite the relevance of benchmarks and the huge economic and environmental footprints of residential buildings, the research on benchmark generations in this field is limited. Additionally, regional benchmarks need to consider comprehensive sustainability criteria that extend beyond typical benchmarks such as operational energy [78], costs [69], and embodied carbon [79]. However, benchmarks related to other criteria of sustainability are rare.

3.1.1. Performance benchmark scales for economic criteria

In this work benchmarks for different criteria were established by assessing the associated key performance indicators. Delphi method-based surveys were performed to assess the indicators and sub-indicators. Two main types of indicators were identified: discrete and continuous. Discrete indicators were converted to discrete triangular distribution while the continuous indicators were converted to triangular probability distributions. Multiple rounds of survey with the participating experts were used to finalize the estimated probabilities. Fig. 3 shows sub-indicators' performance for the Integrated management (IM) criterion. In this case, all the sub-indicators were discrete functions. To evaluate a benchmark scale for IM, the results for sub-indicators were input into @Risk tool and 100,000 Monte Carlo Simulations were performed on it. The data generated was aggregated considering the importance of weightage of each sub-indicator collected through survey to generate the historical performance of the IM criterion for conventional residential buildings in the region. Normal and centralized distribution is observed for this criterion with mean at 45.8.

Using the predefined performance levels of “Low”, “Fair”, “Good”, “Excellent” a PBS was generated from this probability distribution curve. Similarly, PBSs for other corresponding economic criteria were generated (Fig. 4). It should be noted that for some criteria there were no sub-indicators, for instance in the cases of Durability of Building (DB) criterion and Adaptability of building (AB). In these cases, the probability distributions for the criteria were generated directly from the indicators. In Fig. 4 it can be observed that the “Low” and “Excellent” performance evaluation categories were assigned a significant portion of the performance range. This implies that for economic criteria conventional homes are more likely to fall under low or excellent performance category. However, the performance threshold values for vary across the criteria. For example, the excellent threshold can be achieved by Design and Construction time at 64.1 value while it is easier to achieve excellence in Integrated Management at lower value of 51.2. Most criteria benchmarks show normal and centralized distribution (around 50) except Integrated Management (40.4) and Adaptability of Building (32.5) which show lower number to obtain a “Fair” level of economic performance.

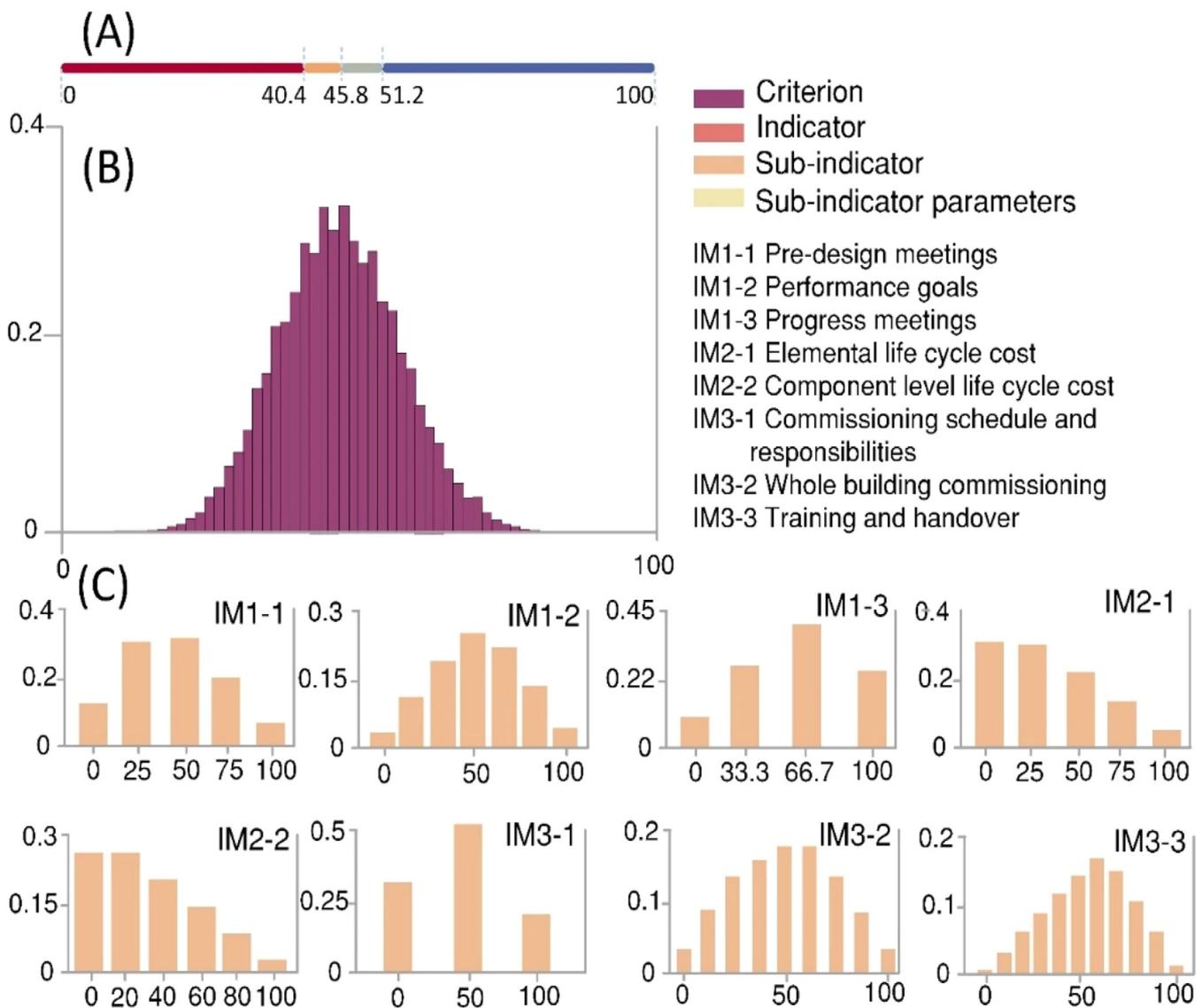


Fig. 3. Generation of benchmark scale of Integrated management (IM) criterion: (A) Corresponding performance benchmark scale of IM; (B) Historical performance of single-family conventional buildings for IM and (C) Corresponding probability distributions of indicators and sub-indicators of IM.

3.1.2. Performance benchmark scales for environmental criteria

Establishing the PBSs for the environmental criteria followed similar methodologies explained above. Fig. 5 illustrates the three steps for PBS generation for Energy Performance and Efficiency Strategies (EP). Compared to the IM criterion (Fig. 3), the EP criterion also contains sub- sub-indicators parameters. In contrast to IM, some indicators are continuous in nature and some are discrete. The historical performance of conventional residential construction is more directed towards right with higher threshold values to achieve “Fair”, “Good”, and “Excellent” performance. This is likely due to higher emphasis on energy performance and efficiency of residential buildings over the past few decades [80]. Furthermore, detached homes fall under the category of low-rise buildings that are constructed of wood with a greater capacity of better insulation and better window systems. Likewise, a number of financial incentives, in the form rebates and subsidies, exist in the region to use more energy efficient heating, ventilation and air conditioning systems, water heaters, and insulation that encourage construction of more energy efficient housing [81].

Fig. 6 illustrates the PBSs for six criteria related to environmental sustainability. Most PBSs show that a modular building can achieve a fair to good performance around threshold values of PL = 50. However,

Renewable and Environmentally Preferable Products (REP) and Renewable Energy Use (RE) indicate even an excellent performance is possible around the threshold value of PL = 40. These low thresholds are likely influenced by the adoption of renewable energy sources, such as solar photovoltaic systems and heat pumps driven by their economic and environmental benefits. The rebates offered for these systems by CleanBC Better Homes Energy

Saving Programs and local utilities are increasing the adaptation of renewable energy systems in BC, Canada [80]. In the coming year, these thresholds are going to decrease further as building codes start adapting the embodied carbon evaluation as a requirement. The environmental impacts of buildings is an evolving landscape and new policies and standards are currently being developed and implemented. For example, RESNET Standard 1550 and ASHRAE 240P currently under development and review are significant for buildings in North America [82,83].

3.1.3. Performance benchmark scales for sustainability dimensions and eco-efficiency

Similar methodologies were employed to establish PBSs at the assessment Level 2 and Level 1. The probability distributions for the criteria at Level 1 were aggregated into the corresponding sustainability dimen-

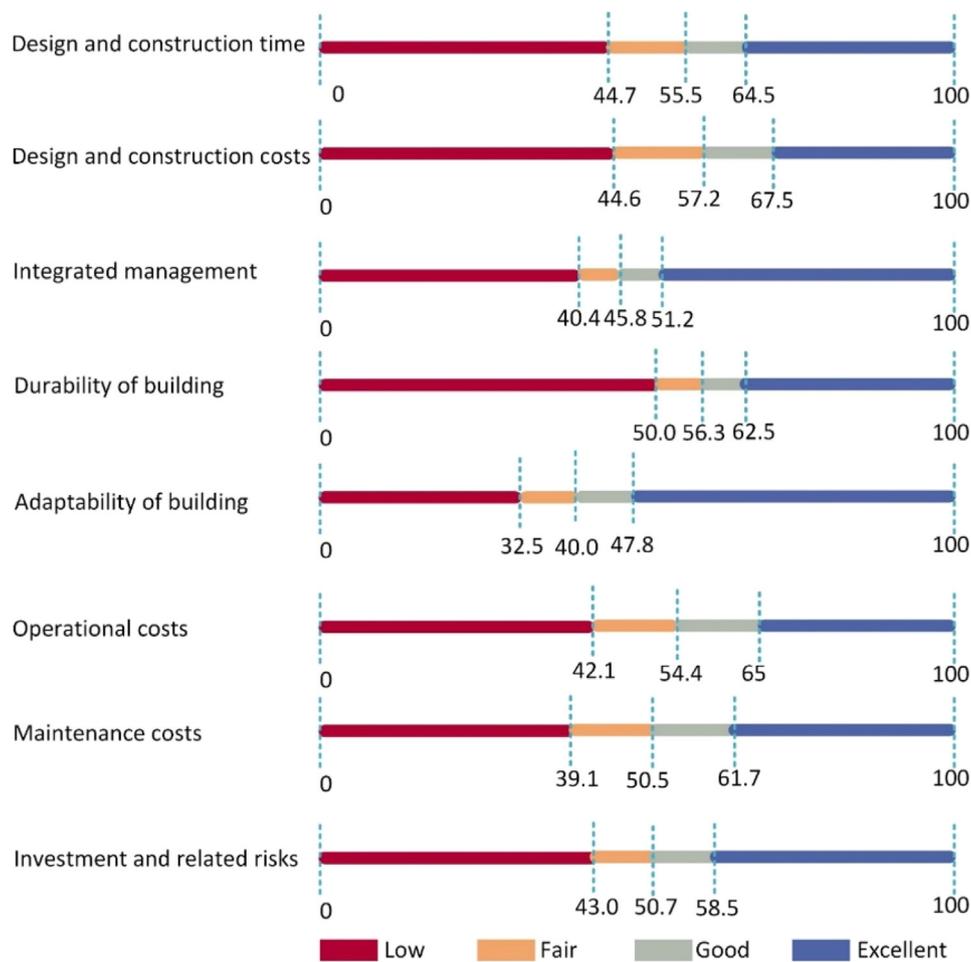


Fig. 4. Performance benchmarks scale for economic criteria.

sions (i.e., economic and environmental) by running a second round of Monte Carlo Simulations via @Risk and incorporating the associated weights collected through the literature and surveys. The probability distributions and associated PBSs for the economic and environmental dimensions are shown in Fig. 7. For environmental benchmarks a symmetric distribution is observed with mean performance for achieving “Good” performance at $PL = 48.6$ and a standard deviation of $\sigma = 4.8$ that indicates most single-family conventional houses perform either “Fair” or “Good” and a smaller number fall in “Low” and “Excellent” limits. The PBS for the economic dimension shows a similar trend with a mean threshold value achievable at $PL = 51.1$ and a standard deviation of $\sigma = 6.7$. Compared to the environmental sustainability benchmark, the Economic sustainability benchmark has slightly higher threshold values to achieve “Excellent” performance. To establish the PBS for eco-efficiency, the distributions of economic and environmental sustainability were combined by performing Monte Carlo Simulation for the third round. The resulting historical performance curve is symmetric with a mean distribution at $PL = 49.9$ and standard deviation of $\sigma = 4.1$. Following the trends of economic and environmental sustainability, majority of the buildings fall in the “Fair” and “Good” limits while smaller number fall under “Low” and “Excellent”.

It should be noted that although suitable social criteria for sustainability assessment of modular homes were initially identified in another work by the authors [58], the development of the PLFs for the social indicators and the establishment of the PBSs for the social criteria and the social sustainability dimension was outside the scope of this research. Therefore, the impact of this dimension in the eco-efficiency benchmark was not included. However, the development of PLFs for social indica-

tors and establishment of PBSs for the social criteria (Level 3) and social sustainability dimension (Level 2) follow similar methods used for economic and environmental cases. Once these benchmarks are generated the eco-efficiency benchmarks need to be updated.

3.2. Modular homes sustainability performance

Benchmarks developed in the previous section help identify the performance of the two-case study modular homes (hereafter Mod1 and Mod2). The performance of the two homes is calculated by the performance level functions (PLFs) developed for the indicators and sub-indicators (see Appendix A). The calculated values for all indicators are presented between the performance level limits ($0 \leq PL \leq 100$). These indicators are combined into higher level criteria using TOPSIS method and weights are obtained through the surveys completed by the construction experts. The criteria performance indices for the economic and environmental criteria are shown in Fig. 8.

It is observed that for most cases Mod 1 performs better than Mod 2 except for the Integrated Management (IM) and Adaptability of Building (AB) criteria. Interestingly these are the same two criteria which do not follow a symmetric and centralized distribution for conventional homes as well. This may be possible as Mod 2 is more similar to conventional homes in design compared to Mod 1. As for the environmental criteria, Mod 1 again performs better than Mod 2 with respect to all criteria except Construction Waste Management (CWM) and Renewable Energy Use (RE). Comparing the values of the economic criteria indices with benchmarks in Fig. 4 indicates that Mod 1 and Mod 2 both fall under the “Excellent” category in five out of

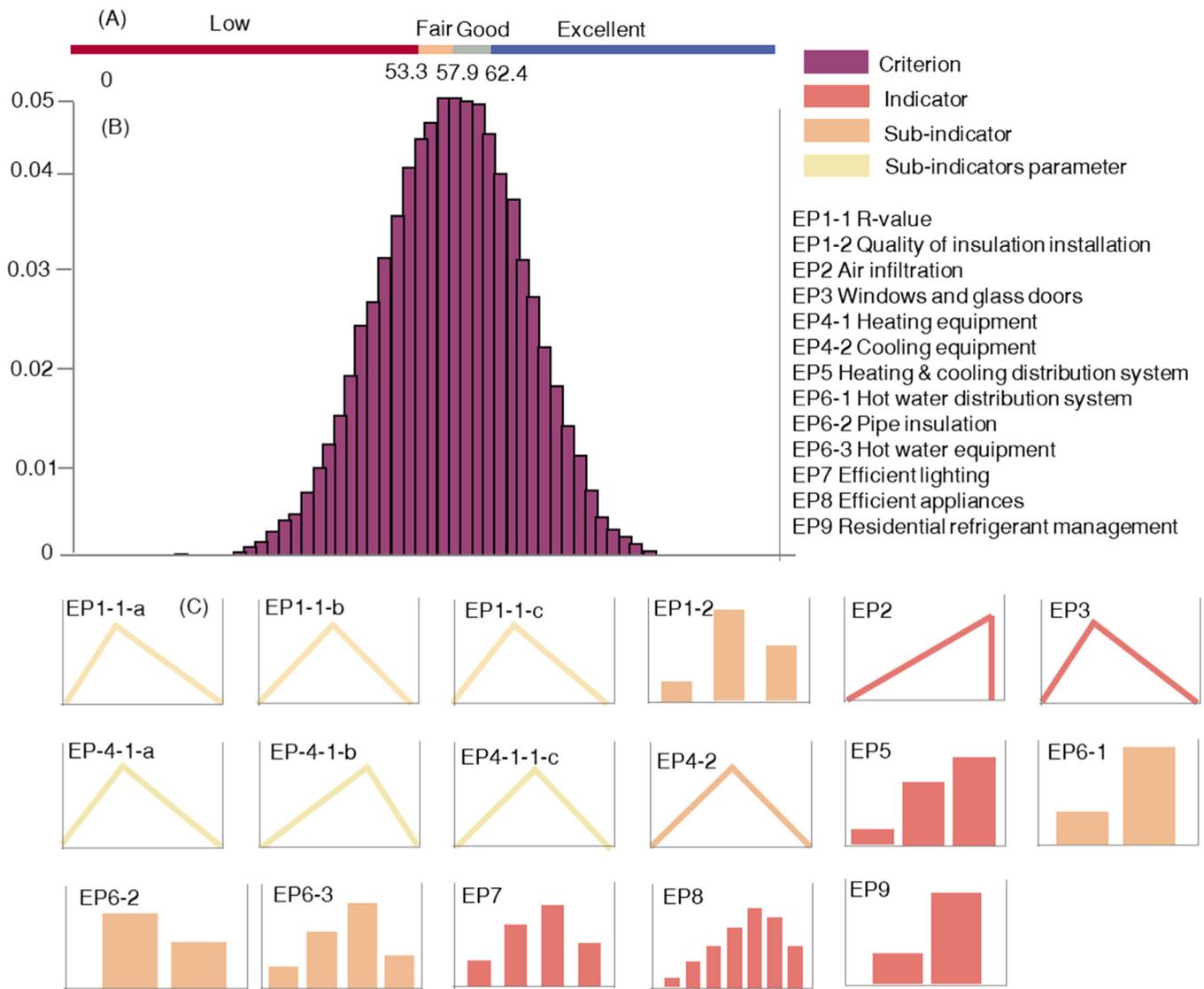


Fig. 5. Generation of benchmark scale of Energy performance and efficiency strategies (EP) criterion: (A) Corresponding performance benchmark scale of EP; (B) Historical performance of single-family conventional buildings for EP and (C) Corresponding probability distributions of indicators and sub-indicators of EP.

the eight economic criteria. The two homes perform poorly in Maintenance Costs (MC) and Operating Costs (OC) compared to conventional homes. Particularly, Mod 2 is needing more attention as it falls under the “Low” category of performance. When the environmental criteria indices are compared against benchmarks in Fig. 6, it is observed that the two homes only perform “Excellent” under Regional Materials (RM) and Construction Waste Management (CWM). In contrast to the economic performance, both homes fall under “Low” for three categories of performance. This implies the design and construction of modular homes need more attention in these specific criteria to ensure sustainable construction. Similar methodology used to aggregate the criteria indices to obtain the indices for economic and environmental sustainability dimensions (ECONi and ENVRi) Fig. 9. The results showed that in the case of economic sustainability, Mod 1 (ECONi-Mod1 = 71.8) performs better than Mod 2 (ECONi-Mod2 = 56.0) though both fall in the “Excellent” category of performance. In case of environmental sustainability, the Mod 1 outperforms Mod 2; however, the Mod 1 (ENVRi-Mod1 = 51.6) just falls into “Excellent” level while Mod 2 (ENVRi-Mod2 = 50.4) falls under the “Good” category. Hence there is much more potential for these homes to improve their environmental sustainability.

The eco-efficiency of the two homes is shown in Fig. 10(A). The final results highlight that eco-efficiency, both homes are able to attain “Excellent” performance; with Mod 1 performing better than Mod 2. However, the results also indicate that there is a large potential of these homes to attain the threshold of the most sustainable residential buildings in the region. The main weakness of failing to achieve best or near the best performer is mainly low environmental sustainability. To further investigate the eco-efficiency of modular homes vs conventional homes in the same region, an LCA analysis was performed for the two case study modular homes and also a similar conventional home in the region [35]. The LCA result for the most commonly used parameter in research and policies, i.e., global warming potential, is shown in Fig. 10(B). The normalized values indicate that, compared to the conventional home, Mod 1 and Mod 2 have higher emissions.

It should be noted that the scope of this LCA study was limited to material stages A1–A4. The emissions associated with operational energy (Stage B) are not included. Despite this limitation the findings are in line with the criteria of sustainability where Mod 1 and Mod 2 fall mostly under the “Low” category of performance. This finding also exposes the limitation of using a single parameter of assessment such as embodied carbon to evaluate sustainability. Single parameters often provide

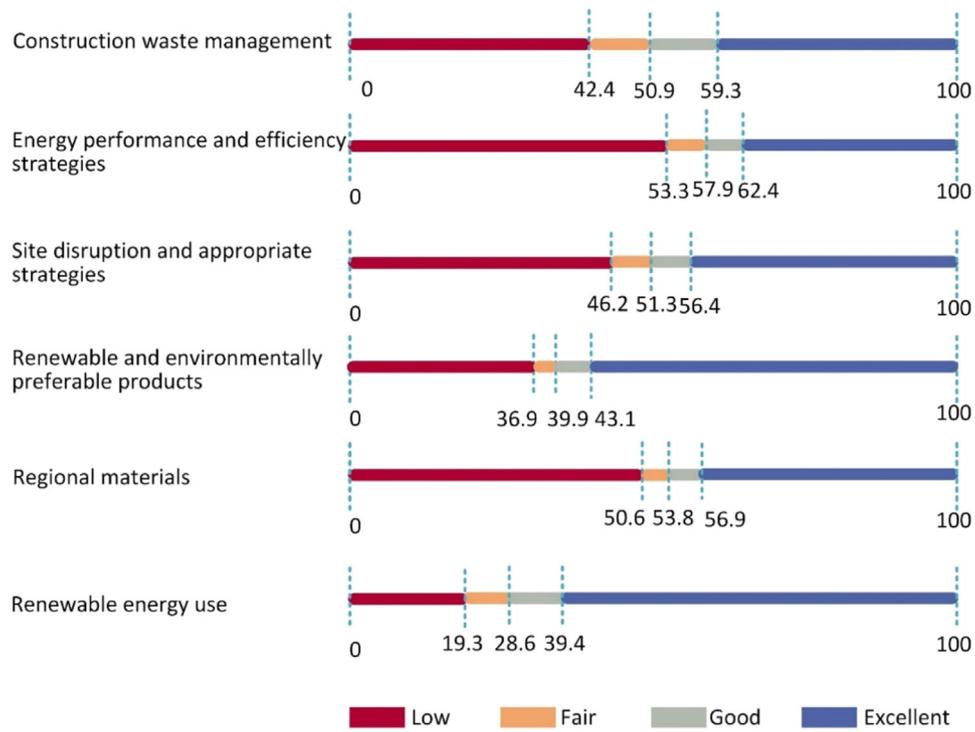


Fig. 6. Performance benchmarks scale for environmental criteria.

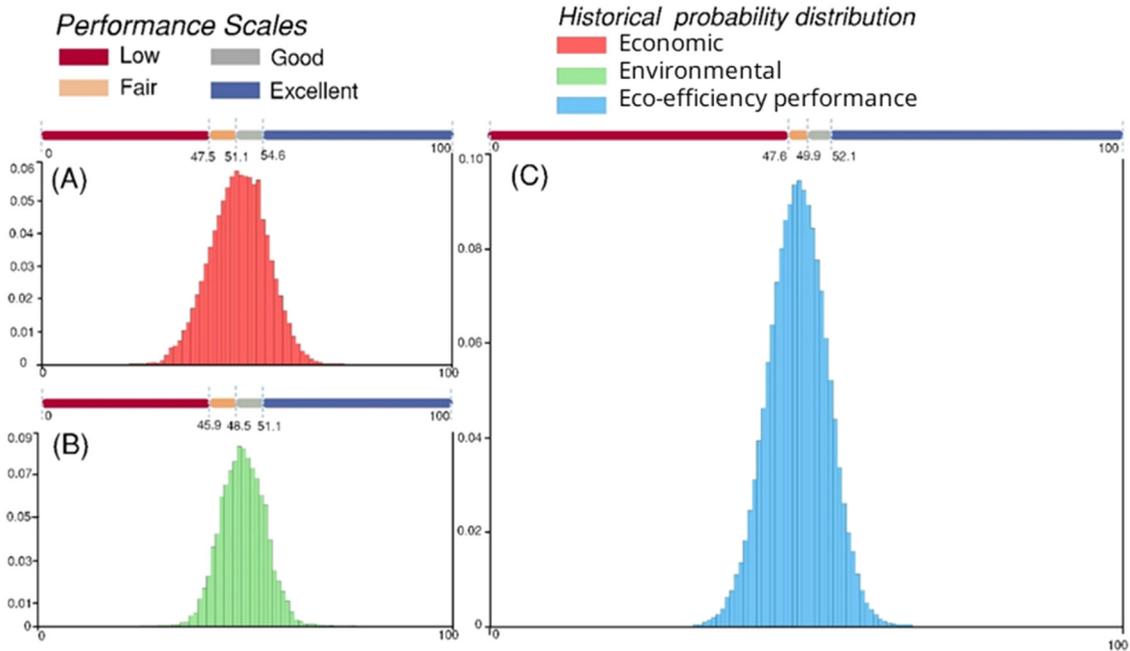


Fig. 7. Probability distribution and performance scales for (A): Economic Sustainability; (B) Environmental Sustainability and; (C) Eco-efficiency.

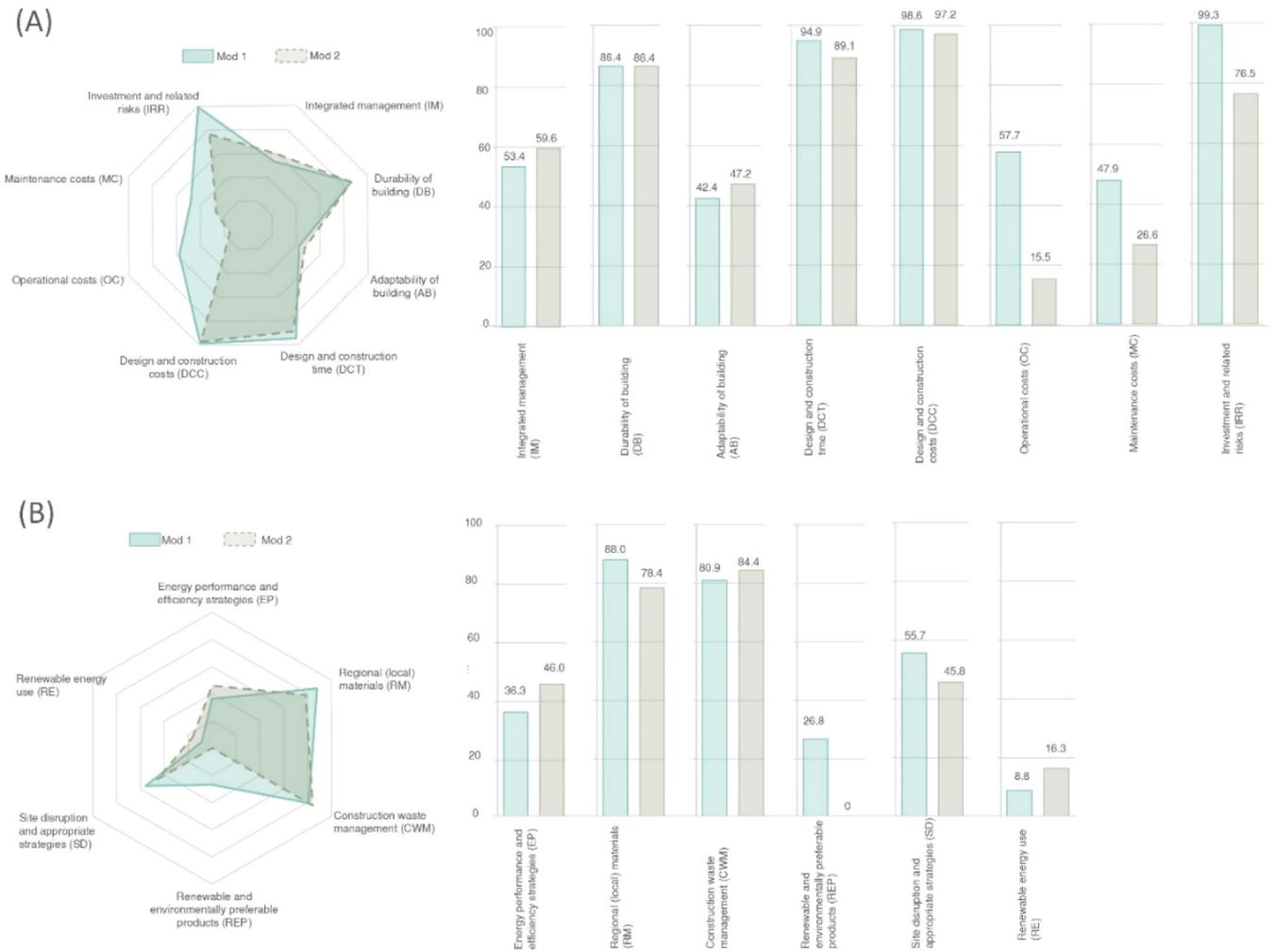


Fig. 8. Sustainability indices for modular homes (A) Economic and (B) Environmental.

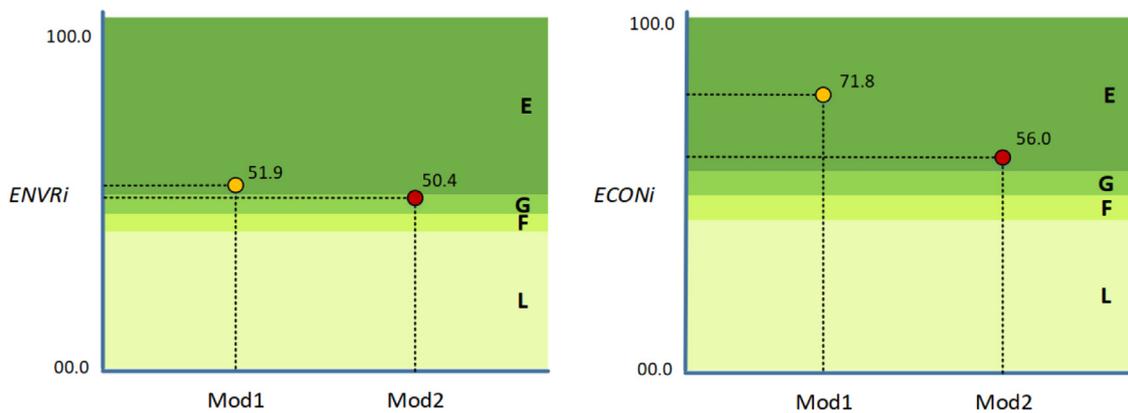


Fig. 9. Environmental (Left) and economic (Right) performance benchmarking.

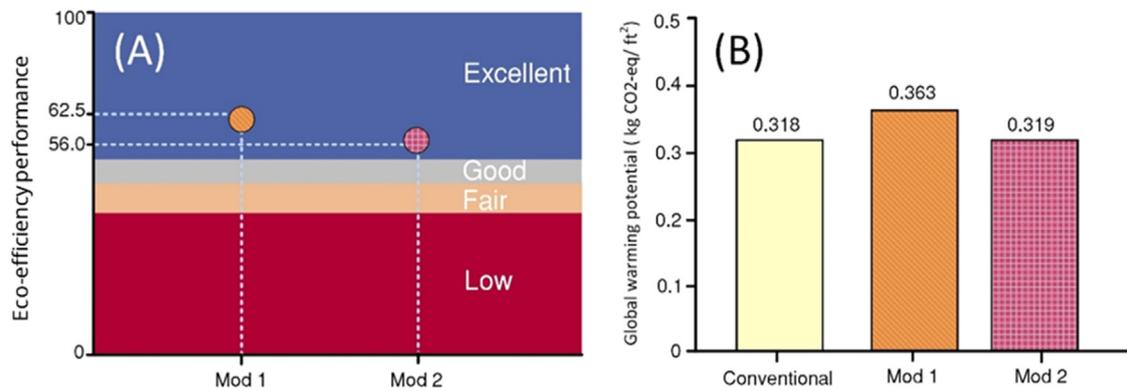


Fig. 10. Comparison of sustainability (A) Eco-efficiency of two Modular Homes against performance benchmark developed; (B) Normalized global warming potential of modular homes against a conventional residential building.

only a narrow view of sustainability performance of modular and other construction. For instance, a building with lower embodied carbon can have very economic impacts or result in burden shifting towards social dimension. Likewise, performing a sustainability assessment study without including feedback from local construction stakeholders may result in a skewed picture and not represent actual realities on site.

The last stage of this research was conducting a sensitivity analysis by assuming that the desired performance target of the framework user for both homes with respect to all criteria has been set at ‘Good’. To this end, the @Risk software was used to perform the sensitivity analysis on all the criteria whose sustainability indices fell into ‘Low’ or ‘Fair’ performance evaluation categories. Fig. 11 shows results of sensitivity analysis for the environmental criteria: Energy Performance and Efficiency Strategies, Renewable and Environmentally Preferable Products, and Renewable Energy Use. The contributions have been arranged in descending order. Longer bars indicate that a change input parameter (indicator or sub-indicator) has higher impact on environmental sustainability performance of that criterion. It is observed that the degree of contribution varies with the type of criterion. The highest contributors range from 20 % to 80 % while lowest contribution can vary from less than 1 % to about 5 % for the four criteria considered. It should be stressed that the sensitivity analysis can be performed for each of the “Good” and “Excellent” performing environmental criteria if the framework user wants to investigate the top priority indicators for further improvement of environmental sustainability performance of the home under study.

4. Conclusions, limitations and future work

Modular construction is claimed to offer several benefits including sustainability and resiliency; however, the empirical data on their performance is still infancy. This research aimed to fill the gap in existing literature about assessing regionally specific performance of modular construction. In this regard, a multi-level decision support framework was introduced that was based on principles of life cycle thinking and integrated sustainability assessment methods. This research employed green building rating systems and standards, and construction expert surveys to develop a set of indices at three different assessment levels and to establish the corresponding sustainability benchmark scales. Therefore, the proposed framework enables benchmarking the sustainability performance of modular homes with respect to the historical performances of

Lastly, a sensitivity analysis was performed to check robustness of the developed indices and to identify relevant indicators needed for improving different levels of sustainability. The findings are relevant to local construction industry of Okanagan region in particular and construction industry of Canada in general. The work has potential to be adopted for other non-conventional constructions such as 3-D printed

homes, earthbag construction and others. However, it is crucial to take precautions to ensure that local best practices are incorporated, and local experts are involved in the updating of the proposed framework.

The present work focused on current state of modular and conventional construction in BC, Canada. It is essential to perform more research by considering future projections spatially in the context of changing climate. A bottom-up approach was used to develop the decision support framework in this research. Although bottom-up approaches are more robust and context specific [59,99,100], a comparison with existing top-down approaches would help identify the weakness in this area. It would also be helpful to generate a second set of sustainability benchmarks, that is using a database of the historical performance of single-family conventional buildings for different indicators and sub-indicators. However, though a database exists for energy use of buildings extensively [87], no such database is present for many of the indicators and sub-indicators identified. Therefore, the first step to generate these benchmarks is compilation of actual buildings datasets.

As stated earlier in this paper, the social criteria were not considered in this work. Compared to the economic and environmental criteria where empirical values can be attained, the generation of social criteria would be subjective and a larger set of experts from different socio-economic dimensions and minority groups need to be involved to create a robust and acceptable social criteria benchmark of single detached homes. Social sustainability assessment is an evolving research area and new databases are being introduced. Though authors have started exploring social sustainability of residential buildings such as recent work by Sultana et al. [85] and Tomlinson [84], more work is needed in this direction to generate benchmarks of conventional homes. To attain a more holistic sustainability assessment results, the inclusion of all sustainability dimensions including environmental, economic, and social (i.e., triple bottom line approach) is essential. Bottom-up index development such as this present work where an index is developed starting from indicators at lowest possible level upward and region-specific inclusion of social dimensions is essential and can effectively represent advantages for construction industry and building users. According to Coelho et al. [88], in regional level sustainability assessment studies, the ratio of social indicators is higher compared to economic and environmental indicators. Hence, when the scope of sustainability index is for a community rather than individual home consideration of social index will become more important. In the same vein, more work is needed to assess the resilience of modular homes in pre- and post-disasters since the resiliency of the modular home is also dependent on a number of factors including the production capacity of the construction industry, and supply chain, local regulations and policies, among others. Hence, the next step of this work will involve development of resilience index, such as those developed for model villages post floods in Pakistan [89]. The next natural step will be combining the sustainability indices developed in the current work with planned resilience index into a unified

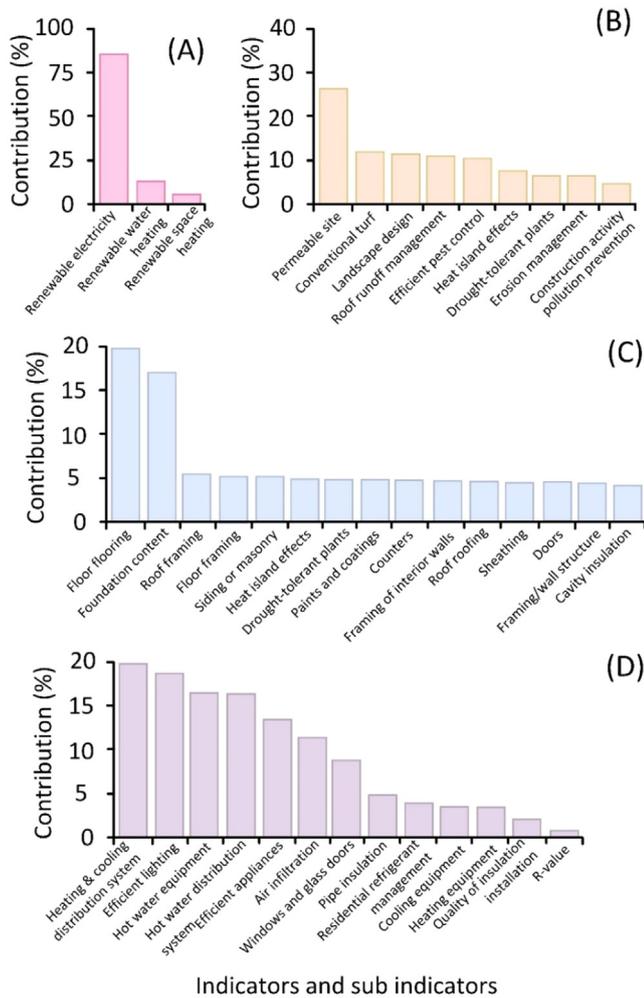


Fig. 11. Sensitivity analysis results for the low performing SPCs (A) Renewable energy use; (B) Site disruption and appropriate strategies; (C) Renewable and environmentally preferable products and (D) Energy performance and efficiency strategies conventional homes at different levels. The framework was demonstrated using two case study modular homes present in Okanagan region, BC, Canada. The region is exposed to multiple natural hazards induced by climate change and has seen increased rainfall, risks of floods, wildfires, and heatwaves in recent years. The assessment of homes showed that a comparison is possible between modular and conventional homes and some areas of modular construction are still lagging best performers in conventional residential buildings. Surprisingly, the modular homes performed well in economic dimensions ranking among the best performers in conventional homes. This suggests that modular homes are a viable solution and can help provide evidence to remove cited concern of higher costs, often seen as a barrier to adoption within the construction industry. On the other hand, the modular homes performed poorly in categories related to environmental performance, particularly energy performance and renewable energy. Hence, there is a potential to improve the environmental performance and make this construction method feasible for a larger set of users. The work also compared the life cycle assessment of modular homes with a conventional building located in the same region; hence exposed to similar climate and geographical parameters. The results show that just considering embodied carbon from initial material stages (Stage A1-A4), the modular homes performed poorly compared to conventional homes. However, the results could vary if all life cycle stages were considered in performing life cycle assessment. These results on embodied carbon can also vary with the building energy efficiency level. Further studies, such as those by Satola et al. [97] and Dara and Hachem-Vermette [98], which compare the performance of modular homes across different energy efficiency levels, are needed to provide a more comprehensive understanding of their environmental impacts.

Sustainability-Resilience Index (SRI) similar in other science domains, such as agrifood [90]. Such indices will facilitate comparative studies with other structures designed for disaster resilience.

Another potential research direction to improve existing framework by performing multivariate analysis between various indicators, criteria, and indices. Studies related to construction sustainability index development have used multivariate analyses to study the correlations between variables and ensure various dimensions of sustainability are well balanced in composite indicators [55]. Common multivariate analysis approaches used include Principal Component Analysis, Factor Analysis and Cluster Analysis.

The developed decision support framework can be used for determining sustainability of modular homes in other regions and climates. However, caution needs to be applied when using benchmarks and weights as they are very specific for the construction industry in Okanagan Region. In addition, there is continuous development of Green Building Rating Systems and building energy standards that are moving the residential sector towards a more sustainable direction. Although the analysis was limited to the most common rating systems, it is recommended to consider the incorporation of a local rating system, if available, for updating the list of indicators. For instance, if the eco-efficiency needs to measure for buildings in Singapore, the Green Mark Certification Scheme becomes relevant [91]. Similarly, in order to generate sustainability benchmarks for a modular home constructed in Germany consideration of Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) standard and EU Level (s) framework becomes relevant [92,93]. Hence, future benchmarks should consider the current and emerging trends in green residential buildings.

The data collection, indices, PLFs, and performance assessments were based on input from industry experts. As a result, the findings reflect current practices and the state of modular home construction in the region. However, market conditions may introduce some bias into the results if only the perspective of industry experts is involved [94,95]. To enhance the reliability of future research, it is recommended to also involve academic experts and regulators [96]. This would help ensure that comparisons between modular and conventional homes account for the latest advancements and integrate relevant policy perspectives.

Relevance to resilience

Modular construction is increasingly recognized as construction suitable for both pre- and post-disaster events and has a potential to increase resilience of buildings in urban settings. This work directly addresses two focus areas of building resiliency. Firstly, it is a recognized resilient technology that offers flexibility, adaptability, and scalability. The reduced construction time and wastage of materials, quick assembly and construction has seen its application in numerous post disasters recovery efforts. Secondly, it deals with and goes beyond life cycle assessment and provides more comprehensive sustainably benchmarks. Resilience based design is ensured as suitable parameters such as energy efficiency, adaptability, and economic criteria where they are prioritized and investigated individually as well as collectively.

This research, which integrates life cycle thinking and decision-making, helps the construction industry and, municipalities, governments, and policymakers in making informed decisions on the selection of suitable construction methods in city settings and move towards a more resilient and sustainable sector. In addition, the novel framework presented in this paper can be adapted for assessing sustainability of other civil infrastructure that contributes to resilient cities.

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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.

CRedit authorship contribution statement

Mohammad Kamali: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kasun Hewage:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Anber Rana:** Writing – review & editing, Writing – original draft, Visualization. **Shahria Alam:** Writing – review & editing, Supervision. **Rehan Sadiq:** Writing – review & editing, Supervision.

Appendix A. Descriptions of the PLFs development

In this appendix, the indicators and sub-indicators determined under the environmental and economic criteria, corresponding performance level functions (PLFs), and the data variable required to calculate the PLFs are presented (Tables A1 and A2).

Appendix B. TOPSIS MCDA method

In this appendix, different steps of the TOPSIS MCDA method to develop sustainability indices for the sustainability criteria were described (adapted from Yoon and Hwang, [131]). A similar procedure is used to develop the overall environmental sustainability index.

Step 1. Weights of Indicators

The relative importance weights of all ESIs under each ESC should be determined.

Step 2. Normalized Indicators

Once the *Indicators* are calculated (performance score or x_{ij}), if the x_{ij} values are not already normalized, they need to be normalized (r_{ij}). To this end, the vector normalization can be used:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad i = 1, \dots, m \quad j = 1, \dots, n \tag{A.1}$$

Step 3. Weighted normalized matrix

The weighted normalized matrix should be developed. The weighted normalized performance score of each *Indicators* is calculated as:

$$v_{ij} = w_j r_{ij} \tag{A.2}$$

where w_j = corresponding weight of that *Indicators*

Step 4. Positive-Ideal and Negative-Ideal Solutions

In this step, the positive-ideal solution (PIS) and negative-ideal solution (NIS) are identified. X^+ and X^- are defined as the PIS and NIS, respectively, in terms of weighted performance scores as follows:

$$X^+ = \left\{ v_1^+, v_2^+, \dots, v_j^+, \dots, v_n^+ \right\} \\ = \left\{ (max_i v_{ij} | j \in J_1), (min_i v_{ij} | j \in J_2), i = 1, 2, \dots, m \right\} \tag{A.3}$$

$$X^- = \left\{ v_1^-, v_2^-, \dots, v_j^-, \dots, v_n^- \right\} \\ = \left\{ (min_i v_{ij} | j \in J_1), (max_i v_{ij} | j \in J_2), i = 1, 2, \dots, m \right\} \tag{A.4}$$

where J_1 = set of benefit attributes; and J_2 = set of cost attributes.

Step 5. Separation measures

In this step, the distance of the subject building from PIS and NIS values (i.e., separation measures) is calculated. The distances of all the performance levels of *Indicators* associated with an *Criteria* are measured using the n-dimensional Euclidean distance. The separation measure of each ESC from the PIS can be calculated as:

$$S_i^+ = \sqrt{\sum_{i=1}^n (v_{ij} - v_j^+)^2}, \quad i = 1, 2, \dots, m \tag{A.5}$$

and separation measure of each ESC from the NIS can be calculated as

$$S_i^- = \sqrt{\sum_{i=1}^n (v_{ij} - v_j^-)^2}, \quad i = 1, 2, \dots, m \tag{A.6}$$

Step 6. Aggregated indices

An aggregated sustainability index for each criterion (e.g., Renewable Energy) is developed by calculating similarities to PIS as:

$$SPCi = \frac{S_i^-}{S_i^- + S_i^+} \tag{A.7}$$

Table A1

Developed PLFs for calculation of indicators and sub-indicators (SPIs and sub-SPIs) under environmental SPCs.

Indicators/Sub-indicators	Performance Level Functions	Variables or Measures	Sources
CWM1 Efficient material consumption plans	$PL_{CWM1} = 0.4 \times PL_{CWM1-1} + 0.6 \times PL_{CWM1-2}$		Wang et al. [101], GBI [102,103], BRE [104], CaGBC [105], Bakshan et al. [106], Merlino [107]; and expert opinions.
CWM1-1 Detailed framing plans	$PL_{CWM1-1} = \begin{cases} 0 & \text{none} \\ 50 & \text{a} \\ 100 & \text{both a and b} \end{cases}$	a- Detailed framing documents including plans and work scope is available. b- If 'a' is available, then the existence of a detailed cut list and also the lumber order documents associated with framing plans and/or the work scopes is checked.	
CWM1-2 Efficient framing	$PL_{CWM1-2} = Min\{33.3i + 16.7j, 100\}$ $i = 1, \dots, 6 \ \& \ j = 0, \dots, 5$ i and j are the number of items under G1 and G2, respectively, which have been met in the design	G1: Precut framing packages, Open-web floor trusses, Structural insulated panel (SIP) walls, Structural insulated panel (SIP) roof, Structural insulated panel (SIP) floors, Stud spacing $\geq 16"$ (40 cm) oc. G2: Joist spacing in ceiling $\geq 16"$ (40 cm) oc., Finger-jointed framing materials, Joist spacing in floors $\geq 16"$ oc., Joist spacing in roof $\geq 16"$ oc., Implement any two of the following: size headers for actual loads, ladder blocking/drywall clips, two-stud corners	
CWM2 Construction waste diversion	$PL_{CWM2} = \begin{cases} -16.7 (WGR) + 66.7 & 3.0 \leq WGR \leq 4.0 \\ -33.3 (WGR) + 116.7 & 0.5 \leq WGR \leq 3.0 \end{cases}$	WGR: Waste generation rate (total weight of construction waste/ total floor area of building, lb/ft ²)	

(continued on next page)

Table A1 (continued)

Indicators/Sub-indicators	Performance Level Functions	Variables or Measures	Sources
EP1 Envelope insulation EP1-1 R-value	$PL_{EP1} = 0.5 \times PL_{EP1-1} + 0.5 \times PL_{EP1-2}$ $PL_{EP1-1} = 0.33PL_{EP1-ceiling}$ $+ 0.33PL_{EP1-wall} + 0.33PL_{EP1-floor}$ $PL_{EP1-ceiling} = 8.01(Rvalue) - 374.23$ $49.2 \leq Rvalue \leq 59.2$ $PL_{EP1-wall} = 18.31(Rvalue) - 300.18$ $17.5 \leq Rvalue \leq 21.9$ $PL_{EP1-floor} = 40.40(Rvalue) - 1051.5$ $26.5 \leq Rvalue \leq 28.5$	R-values: Measure of thermal resistance for ceilings, walls, and floor	NAIMA Canada [108], BCBC [109], RESNET [110], CaGBC [105], Straube [111], GBI [102], NRC [112,113,115,116]; and expert opinions.
EP1-2 Quality of insulation installation	$PL_{EP1-2} = 10 + 30i$ $i = 1(\text{Grade III}), 2(\text{Grade II}), 3(\text{Grade I})$	Grade I- Almost no gaps or compression. Grade II- Up to 2 % insulation gaps and up to 10 % compression over insulation surface. Grade III- Insulation gaps exceed 2 % and compression exceeds 10 %.	
EP2 Air infiltration	$PL_{EP2} = \begin{cases} -133.34(AL) + 466.69 & 3.0 \leq AL \leq 3.5 \\ -66.66(AL) + 266.65 & 2.5 \leq AL \leq 3.0 \end{cases}$	AL: Air leakage of building (in ACH@50PA)	
EP3 Windows and glass doors	$PL_{EP3} = \begin{cases} 16.67(ER) - 416.75 & 25 \leq ER \leq 29 \\ 6.67(ER) - 126.75 & 29 \leq ER \leq 34 \end{cases}$	ER: Energy rating	
EP4 Space heating and cooling equipment EP4-1 Heating equipment	$PL_{EP4-1} = 125(HSPF) - 1025 \quad 8.2 \leq HSPF \leq 9.0$ (Heat pumps) $PL_{EP4-1} = \begin{cases} 25(AFUE) - 2250 & 90 \leq AFUE \leq 92 \\ 16.7(AFUE) - 1483.3 & 92 \leq AFUE \leq 95 \end{cases}$ (Furnaces) $PL_{EP4-1} = \begin{cases} 25(AFUE) - 2125 & 85 \leq AFUE \leq 87 \\ 16.7(AFUE) - 1400 & 87 \leq AFUE \leq 90 \end{cases}$ (Boilers)	HSPF: Heat seasonal performance factor AFUE: Annual fuel utilization efficiency	
EP4-2 Cooling equipment	$PL_{EP4-2} = 50(SEER) - 700 \quad 14 \leq SEER \leq 16$	SEER: Seasonal energy efficiency ratio	
EP5 Heating & cooling distribution system	$PL_{EP5} = \begin{cases} 0 & \text{none} \\ 67 & a \\ 100 & \text{either } b, c, \text{ or } d \end{cases}$	a- If the tested duct leakage rate ≤ 0.08 cmm (3.0 cfm) at 25 Pascals per 9.2 m ² (100 ft ²) of conditioned floor area; b- If the tested duct leakage rate is ≤ 0.03 cmm (1.0 cfm) at 25 Pascals per 9.2 m ² (100 ft ²) of conditioned floor area; c- If all ductwork such as the air-handler unit is installed within the conditioned envelope and envelope leakage is minimized; d- If all ductwork such as the air-handler is visible within conditioned spaces	
EP6 Efficient hot water equipment EP6-1 Hot water distribution system	$PL_{EP6-1} = \begin{cases} 0 & \text{none} \\ 100 & \text{any of Systems 1, 2, 3} \end{cases}$	1. Structured plumbing system 2. Central manifold distribution system 3. Compact design of conventional system	
EP6-2 Pipe insulation	$PL_{EP6-2} = \begin{cases} 0 & a \\ 100 & b \end{cases}$	a- No insulation of domestic hot water piping b- Insulation of all domestic hot water piping	
EP6-3 Hot water equipment	$PL_{EP6-3} = \begin{cases} 0 & \text{none} \\ 33 & a \text{ (Gas water heaters)} \\ 67 & \text{either } b \text{ or } c \end{cases}$ $PL_{EP6-3} = \begin{cases} 0 & \text{none} \\ 33 & a \text{ (Electric water heaters)} \\ 67 & b \\ 100 & c \end{cases}$ $PL_{EP6-3} = \begin{cases} 0 & \text{none} \text{ (Drain water heat recovery)} \\ 33 & a \end{cases}$	a- High-efficiency storage water heater: EF ≥ 0.53 b- Storage or tank-less water heater: EF ≥ 0.8 c- Combination of water and space heaters: CAE ≥ 0.8 EF is energy factor and CAE is combined annual efficiency a- High-efficiency storage water heater: EF ≥ 0.89 b- Tank-less water heater: EF ≥ 0.99 c- Heat pump water heater (ground- or air-sourced): EF ≥ 2.0 a- Heat exchanger that captures waste heat from drain water and pre-heats domestic hot water.	
EP7 Efficient lighting	$PL_{EP7} = \begin{cases} 0 & \text{none} \\ 17 & \text{Interior lighting} \\ 33 & \text{Exterior lighting} \\ 50 & \text{both interior and exterior lighting} \\ 100 & \text{any of advanced lighting packages} \end{cases}$	Interior lighting. 5–7 ENERGY STAR labeled light fixtures or compact fluorescent light bulbs in high use rooms. Exterior lighting. All exterior lighting must have either motion sensor controls or integrated solar electric cells. Advanced Lighting Package 1. The package consists of at least 60 % ENERGY STAR qualified hard-wired fixtures and 100 % ENERGY STAR qualified ceiling fans (if any). Advanced Lighting Package 2. Install ENERGY STAR labeled lamps in 80 % of the fixtures throughout the home.	
EP8 Efficient appliances	$PL_{EP8} = \begin{cases} 0 & \text{none} \\ 17 & \text{either } b, c \\ 33 & \text{either } a, d, bc \\ 50 & \text{either } ab, ac, bd \\ 67 & \text{either } ab, abc \\ 84 & abd \\ 100 & a, b, c, d \end{cases}$	a. ENERGY STAR labeled refrigerator(s). b. ENERGY STAR labeled dishwasher(s) that use 6.0 gallons or less per cycle. c. ENERGY STAR labeled clothes washer(s). d- Clothes washer(s) with modified energy factor (MEF) ≥ 2.0 and water factor (WF) < 5.5 .	
EP9 Residential refrigerant management	$PL_{EP9} = \begin{cases} 0 & \text{none} \\ 100 & \text{either of conditions } a, b \end{cases}$	a. Refrigerants are not needed because of passive cooling design. b. An HVAC system with a non-HCFC refrigerant is installed.	

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Table A1 (continued)

Indicators/Sub-indicators	Performance Level Functions	Variables or Measures	Sources
SD1 Construction activity pollution prevention	$PL_{SD1} = 50n + 100m$ $n = 0, 1, 2; m = 0, 1$ if site is not previously developed: n is the number of implemented actions a and b. if site is previously developed: m is 1 if either c or d was implemented.	a) Develop a tree/plant preservation plan with “no-disturbance” zones. b) Leave minimum 40 % of buildable lot area (excl. under roof area) as undisturbed c) Develop a tree/plant preservation plan with “no-disturbance” zones outlined on both drawings and site. Restore the undisturbed portion of the lot by undoing any previous soil compaction. Remove existing invasive plants. Use drought-tolerant turf in the landscape design. Also, use mulch or soil amendments as appropriate. d) Build on site with a lot area of lesser than 0.06 hectares (600 m2), or with a housing density of one unit per 0.06 hectares.	REAP [118], BRE [104], CaGBC [105], USGBC [119], GBI [102,103], EPA [120], and expert opinions.
SD2 Efficient landscaping SD2-1 Landscape design	$PL_{SD2} = 0.29 \times PL_{SD2-1} + 0.42 \times PL_{SD2-2} + 0.29 \times PL_{SD2-3}$ $PL_{SD2-1} = 25n$ $n = 0, 1, \dots, 4$ n is the number of items ‘a’ to ‘e’ that were included in the design.	a- Any turf must be drought-tolerant. b- Do not use turf in densely shaded areas. c- Do not use turf in areas with a slope of 4:1. d- Add mulch or soil amendments as appropriate. e- Till all compacted soil to at least 6 inches. CT%: Percentage of conventional (chemical) turf in the softscape DTP%: Percentage of drought-tolerant plants	
SD2-2 Conventional turf SD2-3 Drought-tolerant plants	$PL_{SD2-2} = -1.67(CT\%) + 133.34$ $20 \leq CT\% \leq 80$ $PL_{SD2-3} = 1.11(DTP\%)$ $0 \leq DTP\% \leq 90$	Option 1- Use trees or other plantings by which shading is provided for over half of the patios, sidewalks, and driveways within 50 ft of the building. Option 2- Install non-absorptive materials such as light-colored, high-albedo materials, or vegetation-covered hardscapes for over half of the patios, sidewalks, and driveways within 50 ft of building.	
SD3 Heat island effects	$PL_{SD3} = \begin{cases} 0 & \text{none} \\ 100 & \text{either of Options implemented} \end{cases}$		
SD4 Rainwater management SD4-1 Permeable site SD4-2 Erosion management	$PL_{SD4} = 0.57 \times PL_{SD4-1} + 0.14 \times PL_{SD4-2} + 0.29 \times PL_{SD4-3}$ $PL_{SD4-1} = 2.5(PeL\%) - 150$ $60 \leq PeL\% \leq 100$ $PL_{SD4-2} = 100k$ $k = 0, 1$ k is 1 if either Option 1 or 2 for permanent erosion controls was implemented.	PeL%: Percentage of permeable land Option 1- In case the site is located on a steep slope, install terracing and retaining walls to decrease the long-term runoff effects. Option 2- Plant one tree, four 19-litre (5-gallon) shrubs, or 4.6 square meters of native groundcover per 46 m2 of disturbed lot area (including area under roof).	
SD4-3 Roof runoff management	$PL_{SD4-3} = Min\{100, 25i + 50j + 100k\}$ $i = 0, 1; j = 0, 1, 2; k = 0, 1$ i is 1 if measure a was met, j is the number of measures b and c that were met, and k is 1 if measure d was met.	a. Installation of vegetated roof with roof coverage $\geq 50\%$. b. Installation of vegetated roof with roof coverage $\geq 100\%$. c. Installation of permanent stormwater controls such as vegetated swales, on-site rain garden, dry well, or rainwater cistern. d. Site design by licensed landscape designer or engineering professional such that all water runoff from the building is managed through an on-site design element.	
SD5 Efficient pest control	$PL_{SD5} = 25n$ $n = 0, 1, 2, 3, 4$ n is the number of implemented measures a to d	a- All wood (e.g., siding, structure) should be more than 1 ft above soil. b- All external cracks, joints, penetrations, edges, and entry points should be sealed with caulking. c- Use no wood-to-concrete connections or separate any exterior wood-to-concrete connections with metal or plastic fasteners or dividers. d- Install landscaping so all parts of mature plants are min 2 ft from the building.	
REP1 Exterior wall content REP1-1 Framing/wall structure	$PL_{REP1} = 0.5 \times PL_{REP1-1} + 0.5 \times PL_{REP1-2}$ $PL_{REP1-1} = 125(WFr)$ $0 \leq WFr \leq 80\%$	WFr: Percentage of FSC-certified or reclaimed materials, or finger joint studs in exterior wall framing/structure	BRE [104], CaGBC [105], USGBC [119], and expert opinions
REP1-2 Siding or masonry	$PL_{REP1-2} = 142.85(WSi)$ $0 \leq WSi \leq 70\%$	WSi: Percentage of recycled, reclaimed, or FSC-certified materials in siding or masonry component of exterior walls	
REP2 Floor content REP2-1 Floor framing REP2-2 Floor flooring	$PL_{REP2} = 0.333 \times PL_{REP2-1} + 0.667 \times PL_{REP2-2}$ $PL_{REP2-1} = 142.86(FFr)$ $0 \leq FFr \leq 70\%$ $PL_{REP2-2} = 142.86(FFl)$ $0 \leq FFl \leq 70\%$	FFr: Percentage of FSC-certified or reclaimed materials in floor framing FFL: Percentage of floor’s flooring that contains environmentally responsible materials such as cork, FSC-certified, reclaimed wood, bamboo, sealed concrete, recycled materials	
REP3 Foundation content	$PL_{REP3} = \begin{cases} 166.67(Fo) & 0 \leq Fo \leq 30\% \\ 250(Fo) - 25 & 30\% \leq Fo \leq 50\% \end{cases}$	Fo: Percentage of foundation content of supplemental cementitious materials	
REP4 Interior wall and ceiling content REP4-1 Framing of interior walls	$PL_{REP4} = 0.5 \times PL_{REP4-1} + 0.5 \times PL_{REP4-2}$ $PL_{REP4-1} = 125(IWFr)$ $0 \leq IWFr \leq 80\%$	IWFr: Percentage of FSC-certified or reclaimed materials in framing component of interior walls	
REP4-2 Paints and coatings	$PL_{REP4-2} = 111.11(IWPa)$ $0 \leq IWPa \leq 90\%$	IWPa: Recycled paint in painting and coating of interior walls and ceiling that satisfies valid standards	
REP5 Landscape content	$PL_{REP5} = 142.86(La)$ $0 \leq La \leq 70\%$	La: Percentage of recycled, FSC-certified or reclaimed content in landscape including deck or patio	
REP6 Roof content REP6-1 Roof framing REP6-2 Roof roofing	$PL_{REP6} = 0.5 \times PL_{REP6-1} + 0.5 \times PL_{REP6-2}$ $PL_{REP6-1} = 250(RFr)$ $0 \leq RFr \leq 40\%$ $PL_{REP6-2} = 133.33(RRo)$ $0 \leq RRo \leq 75\%$	RFr: FSC-certified content of roof framing RRo: Recycled content of roof roofing	
REP7 Roof, floor, and wall content REP7-1 Cavity insulation REP7-2 Sheathing	$PL_{REP7} = 0.5 \times PL_{REP7-1} + 0.5 \times PL_{REP7-2}$ $PL_{REP7-1} = 500(CIn)$ $0 \leq CIn \leq 20\%$ $PL_{REP7-2} = 166.67(Sh)$ $0 \leq Sh \leq 60\%$	CIn: Percentage of recycled materials used for cavity insulation Sh: Percentage of recycled, FSC-certified or reclaimed materials used for sheathing of roof, floor, and wall assemblies	
REP8 Other components’ content REP8-1 Cabinets	$PL_{REP8} = 0.333 \times PL_{REP8-1} + 0.333 \times PL_{REP8-2} + 0.333 \times PL_{REP8-3}$ $PL_{REP8-1} = 133.33(Ca)$ $0 \leq Ca \leq 75\%$	Ca: Percentage of recycled, FSC-certified or reclaimed, and composite materials in cabinets	
REP8-2 Counters	$PL_{REP8-2} = 142.86(Co)$ $0 \leq Co \leq 70\%$	Co: Percentage of recycled, FSC-certified or reclaimed, and composite materials in counters including kitchens and bathrooms	
REP8-3 Doors	$PL_{REP8-3} = 125(Do)$ $0 \leq Do \leq 80\%$	Do: Percentage of environmentally friendly materials in doors and trims	

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Table A1 (continued)

Indicators/Sub-indicators	Performance Level Functions	Variables or Measures	Sources
RM1 Local materials in exterior walls	$PL_{RM1} = 0.5 \times PL_{RM1-1} + 0.5 \times PL_{RM1-2}$		ILFI [121], CaGBC [105], USGBC [119]; and expert opinions. ¹ In this research, the local (regional) distance was defined as 800 km and 2400 km from the project site if materials and products are transported by truck and train, respectively ILFI [121], CaGBC [105].
RM1-1 Framing/wall structure	$PL_{RM1-1} = 111.11(LWFr) \quad 0 \leq LWFr \leq 90\%$	LWFr: Local content of exterior wall framing/structure	
RM1-2 Siding or masonry	$PL_{RM1-2} = 111.11(LWSi) \quad 0 \leq LWSi \leq 90\%$	LWSi: Local content of siding or masonry component of exterior walls	
RM2 Local materials in floor	$PL_{RM2} = 0.333 \times PL_{RM2-1} + 0.667 \times PL_{RM2-2}$		
RM2-1 Floor framing	$PL_{RM2-1} = 111.11(LFFr) \quad 0 \leq LFFr \leq 90\%$	LFFr: Local material content of floor framing	
RM2-2 Floor flooring	$PL_{RM2-2} = 125(LFFI) \quad 0 \leq LFFI \leq 80\%$	LFFI: Local content of flooring component of building floors	
RM3 Local materials in foundation	$PL_{RM3} = \begin{cases} 166.67(LFo) & 0 \leq LFo \leq 30\% \\ 250(LFo) - 25 & 30\% \leq LFo \leq 50\% \end{cases}$	LFO: Local content of foundation	
RM4 Local materials in interior walls/ceiling	$PL_{RM4} = 0.5 \times PL_{RM4-1} + 0.5 \times PL_{RM4-2}$		
RM4-1 Framing of interior walls	$PL_{RM4-1} = 111.11(LIWFr) \quad 0 \leq LIWFr \leq 90\%$	LIWFr: Local materials used in framing components of interior walls	
RM4-2 Gypsum board	$PL_{RM4-2} = 117.65(LIWGy) \quad 0 \leq LIWGy \leq 85\%$	LIWGy: Local gypsum board content of interior walls	
RM5 Local materials in landscape	$PL_{RM5} = 105.26(LLa) \quad 0 \leq LLa \leq 95\%$	LLa: Local material content of landscape including deck or patio	
RM6 Local materials in roof	$PL_{RM6} = 0.5 \times PL_{RM6-1} + 0.5 \times PL_{RM6-2}$		
RM6-1 Roof framing	$PL_{RM6-1} = 111.11(LRFR) \quad 0 \leq LRFR \leq 90\%$	LRFR: Local content percentage in roof framing	
RM6-2 Roof roofing	$PL_{RM6-2} = 142.86(LRRo) \quad 0 \leq LRRo \leq 70\%$	LRRo: Local content of roof roofing	
RM7 Local materials in roof, floor, and wall	$PL_{RM7} = 0.5 \times PL_{RM7-1} + 0.5 \times PL_{RM7-2}$		
RM7-1 Cavity insulation	$PL_{RM7-1} = 500(LCIn) \quad 0 \leq LCIn \leq 20\%$	LCIn: Local content of cavity insulation of roof, floor, and walls.	
RM7-2 Sheathing	$PL_{RM7-2} = 153.85(LSh) \quad 0 \leq LSh \leq 65\%$	LSh: Local content of floor, roof, and walls' sheathing	
RM8 Local materials in other components	$PL_{RM8} = 0.33 \times PL_{RM8-1} + 0.33PL_{RM8-2} + 0.33 \times PL_{RM8-3}$		
RM8-1 Adhesives and sealant	$PL_{RM8-1} = 250(LAd) \quad 0 \leq LAd \leq 40\%$	Lad: Local content of adhesives and sealant in a building.	
RM8-2 Counters	$PL_{RM8-2} = 125(LCo) \quad 0 \leq LCo \leq 80\%$	LCo: Local material content of counters including kitchens and bathrooms	
RM8-3 Doors	$PL_{RM8-3} = 111.11(LDo) \quad 0 \leq LDo \leq 90\%$	LDo: Local content of doors and trims	
RE1 Renewable electricity	$PL_{RE1} = 3.33(REL\%) \quad 0 \leq REL\% \leq 30$	REL%: Renewable electric load ratio = (Annual electricity supplied by renewable energy sources)/ (Annual electricity consumption in reference home)	EIA [122], Peterson et al. [123], NRC [114,117], CER [124], BCSEA [125], BC Hydro [126], Hayter and Kandt [127], Energyhub [128], Terratek Energy [129], CaGBC [105], Environment Canada [130]; BCSEA [125]; and expert opinions.
RE2 Renewable space heating	$PL_{SD3} = \begin{cases} 0 & \text{none} \\ 100 & a \end{cases}$	a- A solar thermal system is installed in the building	
RE3 Renewable water heating	$PL_{RE3} = \begin{cases} 0 & \text{none} \\ 33.3 & \text{one of G1} \\ 66.7 & \text{one of G2} \\ 100 & \text{one of G3} \end{cases}$	G1. High-efficiency storage electric water heater with EF (energy efficiency) ≥ 0.89 G1. Solar heat exchanger that absorbs waste heat from drain water to pre-heat domestic hot water G2. Tankless electric water heater with EF ≥ 0.99 G2. Solar water heater with preheat tank that supplies 40% \leq annual domestic hot water load $\leq 60\%$ G3. Electric heat pump water heater (ground- or air-sourced) with EF ≥ 2.0 G3. Solar water heater with preheat tank that supplies annual domestic hot water load $\geq 60\%$	

Table A2

Developed PLFs for calculation of indicators and sub-indicators (SPIs and sub-SPIs) under economic SPCs.

EPIs and sub-EPIs	PLFs	Variables or Measures
Design and construction time (DCT)		
DCT1 Design time	$PLF_{DCT1} = -6250DT + 200 \quad 0.016 \leq DT \leq 0.032$	DT: Time of designing 1 ft ² of the building in day/ft ²
DCT2 Construction time	$PLF_{DCT2} = -2777.8CT + 380.6 \quad 0.101 \leq CT \leq 0.137$	CT: Time of constructing 1 ft ² of the building in day/ft ²
Design and construction costs (DCC)		
DCC1 Design cost	$PLF_{DCC1} = -19.38DC + 200.19 \quad 5.17 \leq DC \leq 10.33$	DC: Design cost of 1 ft ² of the building in \$/ft ²
DCC2 Construction cost	$PLF_{DCC2} = -1.18CC + 339.77 \quad 202.68 \leq CC \leq 287.21$	CC: Construction cost of 1 ft ² of the building in \$/ft ²
Integrated management (IM)		
IM1 Integrated design processes	$PLF_{IM1} = 0.25PL_{IM1-1} + 0.5PL_{IM1-2} + 0.25PL_{IM1-3}$	
IM1-1 Pre-design meetings	$PLF_{IM1-1} = 25n \quad n = 0,1,\dots,4$ n:is number of key disciplines involved in “all hands” meetings, design charrettes, or workshops.	Key disciplines: Owner's representative, Architect, Green building expert or sustainable design coordinator, Civil engineer, Electrical engineer, Mechanical engineer (HVAC), Structural engineer
IM1-2 Performance goals	$PLF_{IM1-2} = 16.67n \quad n = 0,1,\dots,6$ n is the number of items whose qualitative green design goals and quantitative performance metrics have been established at the pre-design stage.	Site design, Envelope, Materials efficiency, Indoor environment, Energy efficiency, Renewable energy (percentage of total energy), Greenhouse gas emissions and life cycle impact, Water conservation, efficiency, and reuse, Construction waste management
IM1-3 Progress meetings	$PLF_{IM1-3} = 33.33n \quad n = 0,1,2,3$ n is the number of the project design stages listed above for which progress meetings have been held prior to their completion.	a- Concept design stage where the general scope, initial design, and the relationships between various components are defined and the cost and timeline are also established. b- Design development stage where detailed plans and drawings that show the main elements such as electrical, mechanical, structural, plumbing systems, etc., are produced. c- Construction documents stage where the finalized drawings that show detailed specifications of all systems and components are generated.

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Table A2 (continued)

EPIs and sub-EPIs	PLFs	Variables or Measures
IM2 Life cycle cost	$PLF_{IM2} = 0.67PL_{IM2-1} + 0.33PL_{IM2-2}$	
IM2-1 Elemental life cycle cost	$PLF_{IM2-1} = 25n + 25nm$ $n = 0,1$; $m = 0,1,2,3$ n is 1 if 'a' was met and m is the number of conditions 'b', 'c', and 'd' that were met.	<p>a- Conducting an elemental LCC (such as construction costs, maintenance costs, operational costs) at the concept design stage together with any design option appraisals.</p> <p>b- If elemental LCC was performed, does it predict the future replacement costs at particular time from the start of the use phase required by the client such as 20, 40, or 50 years?</p> <p>c- If elemental LCC plan was performed, does it provide maintenance and operational cost estimates?</p> <p>d- Was it demonstrated, using appropriate examples provided by the analysis team that how the results of the performed elemental LCC was utilized to modify the design of systems and specification to minimize the life cycle costs?</p> <p>The main component types to perform LCC: Envelope, such as roofing, windows, and cladding.</p> <ul style="list-style-type: none"> - Services such as heating, cooling, and controls. - Finishes such as floors, walls, and ceilings. - External spaces such as alternative hard landscaping and boundary protection
IM2-2 Component level life cycle cost	$PLF_{IM2-2} = 20n + 20m$ $n = 0,1,...,4$; $m = 0,1$ n is the number of component types that LCC were performed for, and m is 1 if the design team demonstrated, using appropriate examples, that how the results used to modify the designed systems and specification to minimize the life cycle costs.	
IM3 Commissioning	$PLF_{IM3} = 0.25PL_{IM3-1} + 0.5PL_{IM3-2} + 0.25PL_{IM3-3}$	
IM3-1 Commissioning schedule	$PLF_{IM3-1} = 50n$ $n = 0,1,2$ n is the number of conditions 'a' and 'b' if met.	<p>a- Is there a schedule of commissioning and testing that specifies all the activities required by suitable standards such as national best practice commissioning codes?</p> <p>b- Is an individual from the project team chosen to monitor and program the pre-commissioning, commissioning, and testing activities?</p>
IM3-2 Whole building commissioning	$PLF_{IM3-2} = \{Max(25n + 12.5m), 100\}$ $n = 0,1,2$; $m = 0,1,...,5$ n is the number of the building envelope and systems 'C1' and 'C2', and m is the number of 'C3' to 'C7' that were commissioned.	<p>C1- HVAC and refrigeration systems and their controls;</p> <p>C2- Building envelope (roofing assemblies, windows and doors, waterproofing assemblies, and cladding/skin);</p> <p>C3- Structural systems;</p> <p>C4- Fire protection system;</p> <p>C5- Plumbing system;</p> <p>C6- Electrical system; and</p> <p>C7- Lighting system and their controls.</p>
IM3-3 Training and handover	$PLF_{IM3-3} = 50n + 10m$ $n = 0,1$; $m = 1,2,...,5$ n is 1 if condition 'a' was met and m is the number of items under condition 'b' that were met.	<p>a- Before handover of the building, a building or home user guide is developed and delivered to the end user(s).</p> <p>b- Around handover of the building, a training session is schedule that includes: building's design objectives;</p> <ul style="list-style-type: none"> - aftercare activities by the builder/contractor such as any scheduled seasonal commissioning and post occupancy testing; - explanation and description of installed systems and key features, controls and their interface, to end user(s); - explanation of the developed user guide and other relevant building documentation; - maintenance information and requirements of the building.
Durability of building (DB)		
DB1 Roofing and openings	$PLF_{DB1} = 0.3PL_{DB1-1} + 0.3PL_{DB1-2} + 0.4PL_{DB1-3}$	
DB1-1 Roofing membrane	$PLF_{DB1-1} = 50n$ $n = 0,1,2$ n is the number of implemented items 'a' and 'b' while constructing and commissioning roof assemblies.	<p>a- Roofing membrane assemblies and systems should be installed in accordance with the instructions by the corresponding manufacturers.</p> <p>b- The installed roofing membrane assemblies and systems should be inspected by professionals by the manufacturers or a third-party roofing expert</p>
DB1-2 Envelope flashings	$PLF_{DB1-2} = 50m$ $m = 0,1,2$ m is the number of implemented items 'a' and 'b'.	<p>a- Envelope flashings and sheet metal assemblies should be installed in accordance with the instructions by the industry best practices.</p> <p>b- The installed envelope flashings and sheet metal assemblies should be inspected as per prescribed industry protocol or by a third-party expert.</p>
DB1-3 Roof and wall openings	$PLF_{DB1-3} = 50k$ $k = 0,1,2$ k is the number of conditions 'a' and 'b' that were met.	<p>a- All products associated with wall and roof openings such as windows and doors, should include moisture management designs.</p> <p>b- These products should be inspected against water penetration in accordance with industry best practices.</p>
DB2 Foundation waterproofing	$PLF_{DB2} = 25m + 50n$ $m = 0,1,2$; $n = 0,1$ m is the number of measures 'a' and 'b' that were met and n is 1 if measure 'c' was met.	<p>a- Newly installed foundation systems for conditioned spaces are constructed with slab-on-ground vapor retarders in accordance with industry best practices.</p> <p>b- Newly installed foundation systems for conditioned spaces are constructed such that all slabs on grade will be positioned directly over vapor retarders and capillary-break base courses.</p> <p>c- The installed foundations should be field-inspected conforming to industry protocol.</p>

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Table A2 (continued)

EPIs and sub-EPIs	PLFs	Variables or Measures
DB3 Cladding DB3–1 Exterior wall cladding	$PLF_{DB3} = 0.6PL_{DB3-1} + 0.4PL_{DB3-2}$ $PLF_{DB3-1} = 33.3n \quad n = 0,1,2,3$ n is the number of implemented measures 'a' to 'c'.	a- Has one of the following cladding systems been installed as per industry best practices? - Install Exterior Insulation Finishing Systems (EIFS) as water-managed systems conforming to the instructions by the corresponding manufacturers. - Install masonry veneer cladding conforming to industry technical instructions. - Install aluminum framed glazing systems conforming to the instructions by the manufacturers. The systems should be warranted by the corresponding manufacturers. b- If the answer to measure 'a' is YES, has the installed cladding system been inspected as per the appropriate prescribed industry protocols? c- Have joint sealers been installed and field-inspected in accordance with industry best practice?
DB3–2 Rain screen wall cladding	$PLF_{DB3-2} = 25k + 25l \quad k = 0,1,2,3; l = 0,1$ k is the number of implemented items listed under measure 'a' and 1 is l if measure 'b' has been met.	a- Do the construction documents indicate that exterior rain screen wall cladding systems specified over framed walls are to be installed with the following items? - Primary and secondary line of defense. - An air barrier. - A means for incidental bulk water intrusion to escape the cladding system assembly. b- Are the rain screen cladding assemblies installed in accordance with AAMA 508–07 laboratory testing requirements or any other accepted standard?
DB4 Barriers DB4–1 Air barriers	$PLF_{DB4} = 0.57PL_{DB4-1} + 0.43PL_{DB4-2}$ $PLF_{DB4-1} = 12.5i + 50j \quad i = 0,1,\dots,4; j = 0,1$ i is the number of practices listed under measure 'a' that were implemented and j is 1 if any of the standards mentioned under measure 'b' was followed.	a- If installation of a continuous air barrier has been incorporated in the design stage, indicate if any of the following practices have been considered: An airtight and flexible joint between the air barrier material and adjacent assemblies. - The designed air barrier is able to withstand combined design winds (negative and positive), stack and fan pressures without displacement or damage. - The designed air barrier is able to withstand structural movement and also no displacement due to full load. - Connection details of the air barrier between different assemblies and components, such as foundation and walls, wall and roof, walls and windows, and so forth, are available in the construction documents. b- Is the designed continuous air barrier for the opaque building envelope in accordance with the relevant local building code or either of the following standards? - ASTM E2178–11 Standard Test Method for material testing; - ASTM E2357–11 Standard Test Method for assembly testing; - ASTM E779–03 or equivalent method for building testing
DB4–2 Vapor retarders	$PLF_{DB4-2} = 33.3n \quad m = 0,1,2,3$ n is the number of vapor retarder measures 'a', 'b', and 'c' that were implemented.	a- Install the interior side of framed walls with a Class I or II vapor retarder conforming to the relevant local building code or (in absence) and an accepted international code such as Energy Conservation Code 2012. b- Install on the walls of unvented crawl spaces insulation that is permanently fastened to the walls and extends downward from the floor to the finished grade level, and then vertically and/or horizontally for at least an additional 60 cm. c- Use a continuous Class I vapor retarder to cover exposed earth in unvented crawl space foundations and implement the items below: all joints of the vapor retarder are overlapped by 15 cm and are sealed or taped; and - the edges of the vapor retarder extend at least 15 cm up the stem wall and are attached to the stem wall.
Adaptability of building (AB)	$PLF_{AB1} = 0.6PL_{AB1-1} + 0.4PL_{AB1-2}$ $PLF_{AB1-1} = 25i + 12.5j \quad i \text{ and } j = 0,1,\dots,4$ i and j are the number of the above lateral expandability measures that were highly and moderately incorporated in the design of the building, respectively.	- The building is located and oriented in a way that there is sufficient space around all or part of it for horizontal extensions. - There are means of access and exit regarding the site and building during the lateral extension activities in order to make less interruption to the surroundings people (e.g., noise, dust). - Lateral expansions do not disturb the neighborhood access to light, view, and so forth. - The connections between materials and components facilitate disassembly required for extensions or re-configurations of the space (e.g., prefabricated components, bolted connections). - Substructure (foundation) has been adequately over-designed to accommodate additional loads due to lateral expansion.

(continued on next page)

Table A2 (continued)

EPIs and sub-EPIs	PLFs	Variables or Measures
AB1–2 Vertical expandability	$PLF_{AB1-2} = 25i + 12.5j$ and $j = 0, 1, \dots, 4$ i and j are the number of the vertical expandability measures that were highly and moderately considered at the design stage of the given building, respectively.	<ul style="list-style-type: none"> - There are means of access and exit regarding the site and the building during the vertical expansion activities to make less interruption to the surroundings people (e.g., noise, dust) - Vertical expansions do not disturb the neighborhood access to light, view, and so forth. - The flat-roof construction and detailing facilitate disassembles required for extensions or re-configurations of the space (e.g., prefabricated components, bolted connections). - Substructure (foundation) has been adequately over-designed. - Soil conditions can accommodate the extra loading associated with expansion (new basement or additional story).
AB2 Dismantlability	$PLF_{AB2} = 20k + 10l$ and $l = 0, 1, \dots, 5$ k and l are the number of the measures that were highly and moderately incorporated in the design of the building, respectively.	<ul style="list-style-type: none"> - Use of mechanical connections such as bolt and nut fasteners should be preferred to fewer mechanical connections such as screws or nails and chemical connections such as adhesives and glues, where possible. - Use of standard sized materials and products should be maximized to promote reuse. - Use of recyclable materials and products should be maximized. - Use of modular and prefabricated components and systems should be maximized, where possible. - Use systems and components that are capable of accommodating potential increased performance requirements (e.g., anticipating future advanced HVAC systems). - Strong interconnections between different layers including structure, services (heating, plumbing, etc.), and scenery (partitioning, ceiling, finishes) should be avoided. - Number of different types of components should be minimized.
AB3 Record keeping	$PLF_{AB3} = 33.3n + 33.3m$ $n = 0, 1, 2$; $m = 0, 1$ n is 1 and 2 if at the end of design phase, the information category 'a' is moderately and fully available, respectively, and m is 1 if the information category 'b' is available	<ul style="list-style-type: none"> - Information regarding the degree of connections (i.e., levels of intervention) between the building layers such as site (geographic setting, urban location), main structure (foundation and load bearing elements), services (heating, plumbing, pipes, ducts, cables), scenery (fittings, partitioning, ceiling, finishes), and set (e.g. furniture). - Information regarding the adaptability options that have been designed for the building's future changes.
Operational costs (OC)		
OC1 Running costs	$PLF_{OC1} = -140.9RC + 212.7$ $0.80 \leq RC \leq 1.51$	RC: Annual running costs per 1 ft ² of the subject building in \$/ft ² /year
Maintenance costs (MC)		
MC1 Repair & replacement costs	$PLF_{MC1} = -106.4RCC + 154.3$ $0.51 \leq RCC \leq 1.45$	RCC: Annual repair and replacement costs per 1 ft ² of the subject building in \$/ft ² /year
Investment and related risks (IRR)		
IRR1 Profitability of investment	$PLF_{IRR1} = 0.5PL_{IRR1-1} + 0.016PL_{IRR1-2} + 0.484PL_{IRR1-3}$	
IRR1–1 Sale price	$PL_{IRR1-1} = 1.91SP - 540.45$ $283.63 \leq SP \leq 336.11$	SP: Sale price per 1 ft ² of a building in \$/ft ²
IRR1–2 Design cost	$PLF_{IRR1-2} = -19.38DC + 200.19$ $5.17 \leq DC \leq 10.33$	DC: Design cost of 1 ft ² of the building in \$/ft ²
IRR1–3 Construction cost	$PLF_{IRR1-3} = -1.18CC + 339.77$ $202.68 \leq CC \leq 287.21$	CC: Construction cost of 1 ft ² of the building in \$/ft ²

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