



Integrated LCA–LEED sustainability assessment model for structure and envelope systems of school buildings



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ARTICLE INFO

Article history:

Received 10 January 2014

Received in revised form

20 May 2014

Accepted 22 May 2014

Available online 2 June 2014

Keywords:

Sustainability assessment

Structure and envelope

Integrated LCA–LEED model

LEED score

Energy consumption

Global warming potential

ABSTRACT

In Canada and USA, nearly 80 million students and teachers spend at least eight hours daily in schools that could be unhealthy and restrict their ability to learn. Despite this fact there is lack of adopting sustainability principles in school buildings. Even though life cycle assessment (LCA) and LEED® could serve as sustainability measurement tools, studies show that the integration of sustainability principles to LCA has not become standard practice yet. This paper presents an integrated LCA–LEED model that incorporates LCA into LEED and assigns corresponding LEED scores to achieve a high level of sustainability assessment, for the structure and envelope systems of Canadian school buildings. In this model, the selection of the most sustainable structure and envelope type for school buildings is done through the evaluation of three categories of the LEED rating system: energy and atmosphere, materials and resources, and LCA (incorporated under the innovation and design process category of LEED). Various options are tested by considering structures such as concrete, steel, masonry and wood, and envelope types such as precast panels, steel stud, wood stud and cavity wall. Energy simulation is performed by eQUEST® (version 3.64) program and LCA is performed by ATHENA® impact estimator. The results show that concrete and masonry buildings have high energy consumption and global warming potential during certain life cycle stages such as manufacturing, construction and demolition. However they have lower annual energy consumption and environmental impact during the operating stage, as well as for the overall life span. Concrete building with minimum insulation has obtained the highest total LEED score (19) followed by masonry (17), while steel and steel-masonry buildings have the least score (14).

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1. Introduction

Quality in the design and construction of buildings has a crucial role in energy conservation, minimizing the greenhouse gas emissions and ensuring proper comfort conditions. Integrated environmental assessment methods and global sustainability indicators are imperative to evaluate the performance of buildings, as housing is greatly concerned with global environmental problems such as the use of non-renewable energy, the overexploitation of materials, the exhaustion of resources and the wasting of energy [1]. School buildings must ensure adequate technical and

morphological standards to all spaces used by the students, while fulfilling the criteria of sustainable design. Unfortunately, most of the existing school buildings suffer from a low level of architectural quality and of performance leading to a high consumption of energy and to an indoor microclimate below comfort level [2]. It is estimated [3] that approximately 73 million U.S. citizens (out of which 68.5 million are children) attend 117,007 private and public primary and secondary schools, while the Government of Canada [4] states that approximately 7 million students and teachers spend at least eight hours in the school, during working days. These schools are too often unhealthy and somewhat polluted, which affects students' productivity and their ability to learn [5]. Sustainability and environmental assessment tools for buildings vary to a great extent; a detailed review of 16 such tools was provided by Haapio and Viitaniemi [6]. The reviews by Ortiz et al. [7] and Sharma et al. [8] focused on life cycle assessment (LCA) based studies, and Cabeza et al. [9] outlined the studies on LCA, life cycle

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energy Analysis (LCEA) and life cycle cost analysis (LCCA) carried out for the environmental evaluation of buildings. However few recent works that form a background of the current study are reviewed here.

Zhang et al. [10] developed a building environmental performance analysis system (BEPAS) based on the LCA framework, which investigated three main aspects of a building such as facilities, materials and location. Application of the LCA approach in the strategic design of a Flagship Store in Shanghai was reported by Wang et al. [11]. Mora et al. [12] presented an integration framework based on an iterative methodology, which incorporated life-cycle considerations in the design process to enable selection of materials and systems not only from environmentally friendly resources but also to match service life performance expectations. Ali and Al Nsairat [13] attempted to develop an effective green building assessment tool for residential units in Jordan. The international green building assessment tools such as LEED, CASBEE, BREEAM, GBTool and others were studied, and new assessment items were defined with respect to the local conditions of Jordan and were weighted using the Analytical hierarchy process (AHP) method. Eventually, a green building assessment tool namely SABA Green Building Rating System was suggested. Use of AHP was also reported by Reza et al. [14] who focused on the selection of a sustainable flooring system in Iran, and Chandratilake and Dias [15] who addressed the issue of subjectivity in assigning weights for the domains and aspects in sustainability rating systems, for the Sri-lankan scenario. LCA study of a low-energy consumption building in Italy was presented by Proietti et al. [16] who performed the modeling by using the SimaPro software application, by considering a life span of 70 years.

In a study at Colombia, Castro-Lacouture et al. [17] proposed a mixed integer optimization model that incorporated design and budget constraints while maximizing the number of credits reached under LEED rating system. Pons and Aguado [18] presented the Integrated Value Model for Sustainable Assessment (MIVES) for searching the architectural technology which had the least economic, environmental and social impact, for the construction of educational centers in Spain. Mateus and Bragança [19] developed a methodology based on SBTool^{PT}-H, to assess the sustainability of existing, new and renovated urban residential buildings in Portugal. Alyami and co-workers [20,21] critically analyzed the applicability of BREEAM, LEED, SBTool and CASBEE for the sustainability assessment of Saudi Arabia's built environment and a comprehensive framework was developed through a consensus based approach (Delphi consultation approach). The proposed framework incorporated certain categories common to SBTool and CASBEE, such as Economic aspects and quality of service, in addition to the most important environmental categories evaluated by BREEAM and LEED. El-Shenawy and Zmeureanu [22] proposed an exergy-based definition of a sustainable building, calculation method of the corresponding sustainability index, and the rating scale.

Boeri and Longo [2] conducted case study projects, highlighting criteria and strategies adopted in the design of school buildings. An assessment technique namely, Sustainable Building Assessment Tool (SBAT) suitable for developing countries and South Africa in particular, was developed by Gibberd [23]. Vatalis et al. [24] investigated the sustainability components affecting decisions for green building projects in Greece. Energy efficiency and renewable energy were identified as the most crucial, followed by the reduction of toxic materials, indoor pollution and water saving. Iwaro [25] presented a criteria weighting framework incorporated into an integrated performance model for sustainable building envelope design. The 'emergy' analysis proposed by Pulselli et al. [1] was another breakthrough, in building sustainability assessment,

which accounted for the energy and material inflows during manufacturing, maintenance and use. Few more related works worth mentioning include those reported by Wedding [26], Attalla and Yousefi [27], Basbagill et al. [28], Guggemos and Horvath [29] and Glover et al. [30].

It is obvious from the literature that many researchers worked with LCA based tools, AHP, and other criteria scoring systems such as LEED, CASBEE, BREEAM and GBTool. Moreover, depending on the type of building, location and assessment objectives, development of novel models and techniques have also been reported. However, effective incorporation of LCA into the aforementioned criteria scoring systems is at the exploratory stage. The United States' green building council (USGBC) is in the process of incorporating LCA into LEED [31]. The USGBC Life Cycle Assessment working group has been established at the end of 2004 to develop recommendations to USGBC on how best to integrate LCA into LEED, and the report of this group was released at the end of 2006 [31]. One of the recommendations was to undertake LCA of the assemblies that constitute a building's structure and envelope [31]. The assemblies would be ranked according to their environmental impact, with LEED credits awarded accordingly [31].

Wayne and Trusty [32] have pointed out the weaknesses in LCA and LEED systems with examples, and discussed the importance of integrating LCA into green building rating systems, to achieve more realistic assessment. Mer'eb [31] provided a detailed account of the limitations of scoring systems and LCA-based tools, and made a successful attempt to integrate LCA into LEED. He developed a tool named GREENOMETER-7 to measure and to enhance sustainability performance of a building over its entire life cycle, at the conceptual design stage itself. The performance of this tool was demonstrated on a single-story residential building in Columbus, Ohio. Motivated by the recommendation of USGBC LCA working group, this study has developed an integrated LCA–LEED model for the enhanced sustainability assessment of structure and envelope types of Canadian School Buildings. Various structure–envelope options are tested by using concrete, masonry, steel and wood as structural materials, precast panels, steel stud, wood stud and cavity wall as envelope systems, and their different combinations, by taking into account all the life cycle phases for a life span of 75 years.

2. The proposed LCA–LEED model

The proposed LCA–LEED model is developed to enable school boards in Canada to select the structure and envelope types of new school buildings. In this model, as shown in Fig. 1, LCA is incorporated into LEED® ratings under the 'innovation and design process' category, with maximum 5 LEED scores. It should be noted that, from the various LEED criteria [33], only those criteria that are significantly influenced by the structure and envelope (e.g. energy and atmosphere, and materials and resources) are taken into account in the model. Thus, selection of the sustainable structure and envelope for school buildings is done through the LEED scores obtained from three categories such as (a) Energy and Atmosphere (EA), (b) Materials and Resources (MR) and (c) LCA. Under the EA category, only the 'Optimize Energy Performance' criterion which requires a minimum of 2 LEED points and has scope of achieving up to 19 [33], is incorporated. The MR category has 13 points [33], so a total of 37 LEED scores are achievable from the proposed model. The seven structure–envelope alternatives are concrete (CC), Masonry (CM), Steel (SS), Wood (WW), Wood + Masonry (WM), Steel + Wood (SW) and Steel + Masonry (SM). The types of frame, exterior wall, floor and roof for these options are summarized in Table 1, and their constructional details are shown in Fig. 2. These

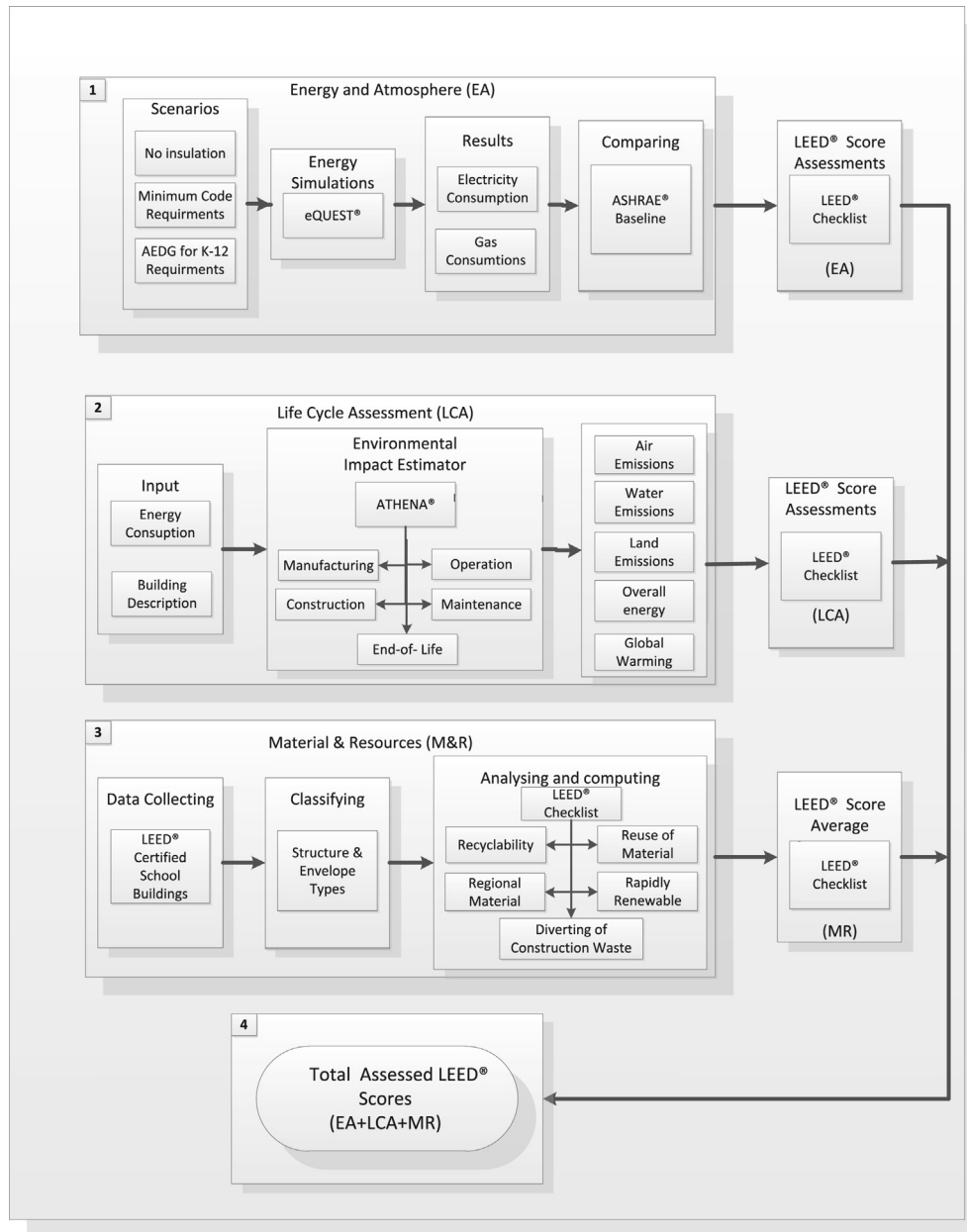


Fig. 1. The proposed LCA-LEED model.

are the most commonly used structure-envelope options in North America, as identified through a survey of 109 LEED certified schools of the region. The following subsections describe how the assessments are performed in the EA, LCA and MR categories, respectively.

2.1. Energy and atmosphere

This assessment is done through energy simulation as required by the US green building council (USGBC 2010) [34], by using energy simulation software (eQUEST® version 3.64) [35]. Fig. 3 shows

Table 1
Details of tested structure and envelope options.

Options	Frame type	Exterior wall	Floor type	Roof type
CC	Precast concrete	Precast concrete panels	Hollow core slab	Hollow core slab
CM	Reinforced Concrete	Face brick with concrete block	Solid concrete slab	Solid concrete slab
SS	Steel frame	Steel siding on steel studs	Concrete/metal deck/open joists	Metal deck on open web joists
WW	Wooden frame	Wood siding with wood studs	Wooden floor	Wood roof on wood trusses
WM	Wooden frame	Face brick with GYP BD	Wooden floor	Wood roof on wood trusses
SW	Steel frame	Wood siding with wood studs	Concrete/metal deck/open joists	Metal deck on open web joists
SM	Steel frame	Face brick with steel studs	Concrete/metal deck/open joists	Metal deck on open web joists

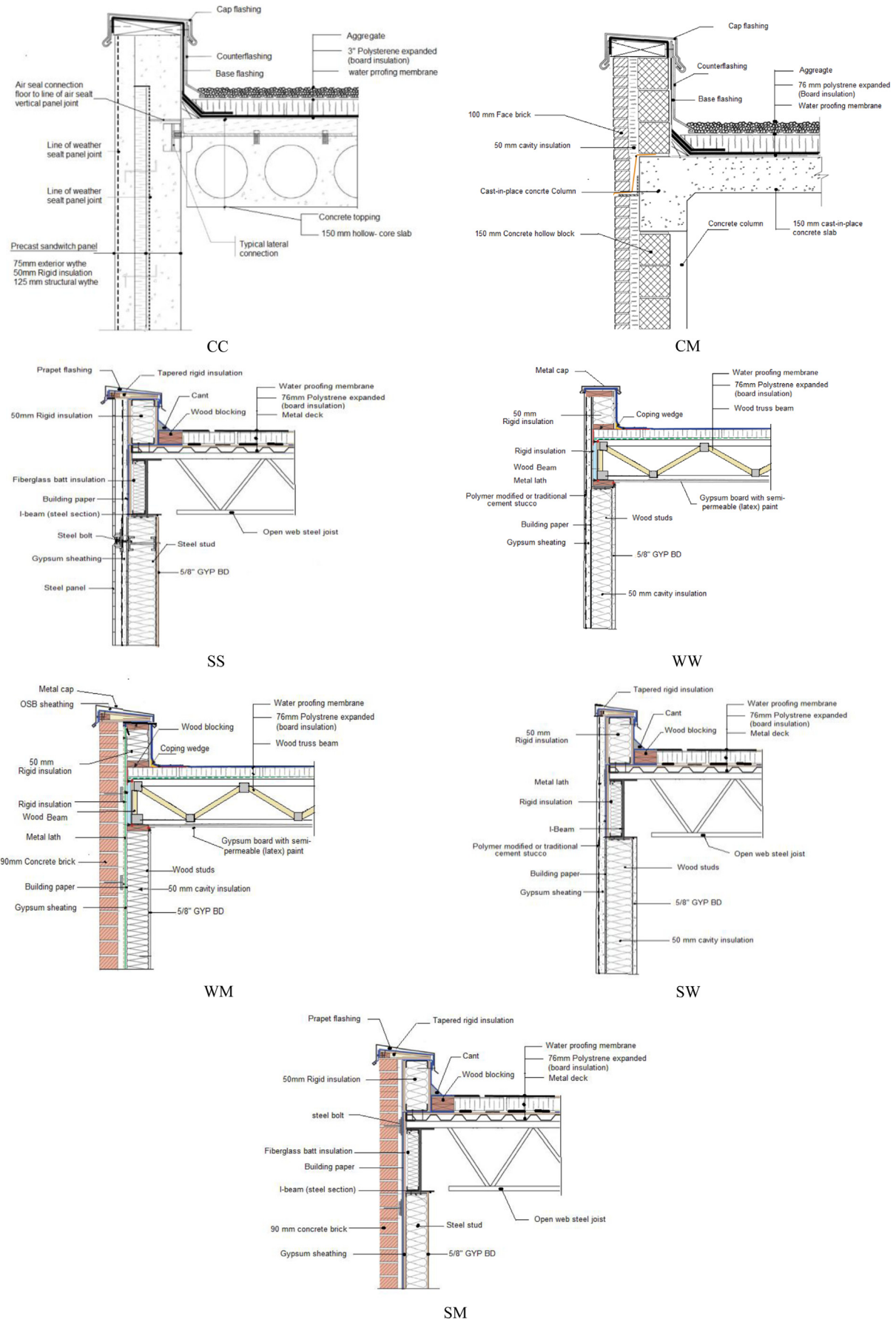


Fig. 2. Constructional details of various structure-envelope alternatives.

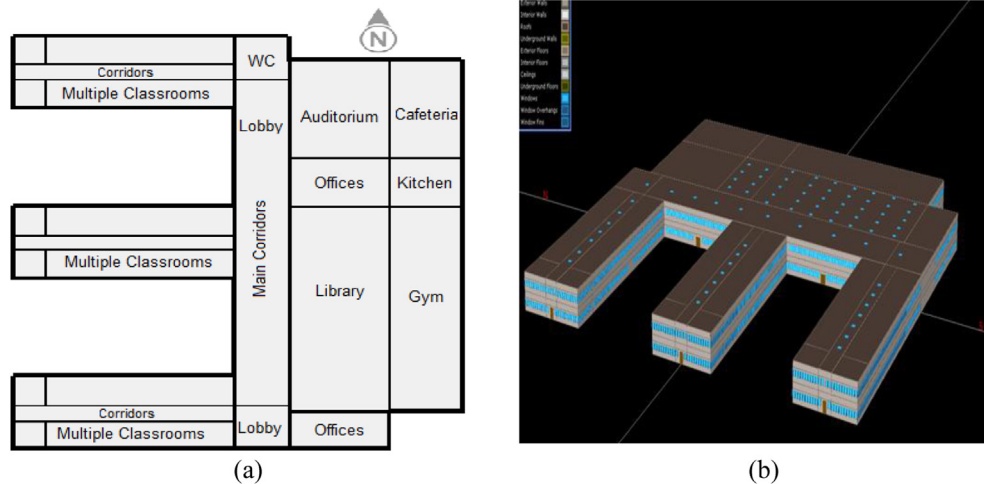


Fig. 3. Energy simulation model: (a) floor plan with zones and (b) 3D Model.

the floor plan and the 3D model of the high school building used for this simulation. The design of the fenestration, lighting systems (including electrical lights and daytime lighting), HVAC (heating, ventilation, and air conditioning) systems, building automation and controls, outside air treatment, and service water heating are defined based on the recommendations of ASHRAE 90.1 in the Advanced Energy Design Guide (AEDG) for K-12 school buildings [36], as summarized in Table 2. The school operational schedule according to Montreal school boards and other simulation inputs are provided in Table 3. The heating and cooling degree days (for estimating the heating and cooling loads) are calculated with respect to the base temperature of 65 °F.

The annual energy consumption is estimated for the 7 structure–envelope options by considering 3 cases: 1) No insulation, 2) Minimum insulation (as per local municipality code of Montreal) and 3) Recommended insulation (as per K-12 AEDG for school buildings, by ASHRAE). The 'no insulation' case is considered here to study the envelope performance based on its material properties and resistance without insulation. Moreover, there are zones (such as 1 and 2) where insulation is not mandatory for concrete and masonry walls [37]. Energy performances of the various envelope systems are estimated for the above 3 cases by performing hourly energy simulations to calculate the monthly electricity and natural gas consumptions. This simulation is performed based on identifying some normalized and variable parameters that affect the

energy consumption of school buildings and the overall energy costs. The normalized energy parameters include the building form and floor plan, building orientation, internal loads and operating schedules. Since this study is to measure the performance of the various facade and roof systems, these alternatives are defined as variable parameters, as detailed in Table 4.

The EA category is assigned 1 to 19 LEED® points (by considering 'Optimize Energy Performance' criterion alone), which ranges from an estimated 12%–48% reduction of energy consumption compared to the ASHRAE 90.1 baseline. The minimum acceptable energy reduction to be certified by LEED is 14% compared to the ASHRAE baseline, which is worth 2 LEED point. Each 2% of energy reduction beyond 14% will earn additional 1 LEED point, up to 19 LEED points for a 48% reduction from the baseline. This test yields a sustainability score for the EA category, which enables selecting the structure–envelope type that contributes to the highest reduction in energy consumption (and hence obtains the highest LEED® score).

2.2. Life cycle assessment

Life cycle assessment (LCA) components such as global warming potential (GWP), overall energy consumption, and air, water and land emissions are estimated in this study, and 1 LEED point is assigned for the maximum reduction in each component, making a

Table 2
Prototype description applying K-12 AEDG recommendations.

Items	Prototype characteristic
School type	Secondary school
Total gross area	250,000 ft ²
No. of floor	2 floors
Climate zone	6a (Cold- Dry)
Building orientation	Long Axis oriented (North-South)
Windows area	33% fenestration to gross wall area
Occupancy	Fully occupied during school hours, partially year round
Peak plug loads	1.0 W/ft ² for middle and high
Percent conditioned	Fully heated and cooled
Floor height	13.1 ft
Thermal transmittance of window	$U = 0.42 \text{ Btu/h/ft}^2\text{/}^\circ\text{F}$
Solar heat gain coefficient	(SHGC)-0.40
Number of students	1200
Plan shape	H- shape
Location (City)	Montreal, Canada

Table 3
Energy simulation inputs.

School operating schedule for the year 2011 ^a		
Opening	Ending	Occupied time
January 07, Friday	February 27, Sunday	8 a.m. to 4 p.m.
March 08, Tuesday	June 30, Thursday	
August 25, Thursday	December 22, Thursday	
Other inputs		
Thermostat set points	• 76 °F for cooling and 70 °F for heating (occupied) • 82 °F for cooling and 64 °F for heating (unoccupied)	
Air change rate	• 0.25 ACH (air changes per hour) when the HVAC system is enabled and the building is pressurized. • 0.5 ACH when the HVAC system is disabled at night and on weekends.	
Internal heat gain per person	Sensible: 245 Btu/h; Latent: 155 Btu/h	

^a Data from Montreal school boards.

Table 4
Wall and roof system specifications for different alternatives.

No.	Wall type	Case-1 No insulation		Case-2 Minimum insulation		Case-3 Recommended insulation	
		Thickness	Insulation U-value Btu/h/ft ² /°F	Thickness	Insulation U-value Btu/h/ft ² /°F	Thickness	Insulation U-value Btu/h/ft ² /°F
1	Pre cast wall	200 mm	N/A U (0.25)	257 mm	R-7 U (0.073)	290 mm	R-13 U (0.026)
2	Masonry (Cavity wall)	250 mm	N/A U (0.37)	307 mm	R-7 U (0.098)	330 mm	R-13 U (0.055)
3	Steel stud	107 mm	N/A U (0.92)	107 mm	R-7 U (0.142)	157 mm	R-13 + R7.5 U (0.050)
4	Wood stud	107 mm	N/A U (0.74)	107 mm	R-7 U (0.120)	157 mm	R-13 + R7.5 U (0.043)
5	Steel + Masonry brick	150 mm	N/A U (0.61)	157 mm	R-7 U (0.115)	207 mm	R-13 + R7.5 U (0.046)
6	Wood + Masonry brick	150 mm	N/A U (0.51)	157 mm	R-7 U (0.109)	207 mm	R-13 + R7.5 U (0.045)
7	Steel + Wood stud	107 mm	N/A U (0.74)	107 mm	R-7 U (0.120)	157 mm	R-13 + R7.5 U (0.043)
Roof type							
1	Solid concrete slab	150 mm	N/A U (0.35)	240 mm	R-13 U (0.055)	330 mm	R-25 U (0.026)
2	Hollow core slab	150 mm	N/A U (0.30)	240 mm	R-13 U (0.050)	330 mm	R-25 U (0.020)
3	Wood roof-wood truss	75 mm	N/A U (0.57)	150 mm	R-13 U (0.069)	250 mm	R-13 + R19 U (0.031)
4	Built up – Metal Deck	75 mm	N/A U (0.50)	150 mm	R-13 U (0.076)	250 mm	R-13 + R19 U (0.035)

total of 5 LEED points. The LCA test is performed by using ATHENA[®] [38] impact estimator which is the authorized software tool in North America that evaluates whole buildings and assemblies based on LCA methodology. In the present LCA–LEED model, the annual energy consumption estimated by the energy simulation software is inputted to ATHENA[®] which provides the overall energy consumption by considering the whole life span. The feedstock energy is accounted in the LCA, which represents the energy of the fuel-bearing materials that are not used as fuels. The input parameters and assemblies defined into the software include footings, slabs on grade, columns and beams, floors, roofs, interior walls, exterior walls, windows, other material such as insulation, fire proofing and water proofing membranes. The environmental impact is assessed based on the type and bill of materials; the summary of bill of materials for steel school buildings is provided in Table 5. ATHENA has been developed for projects with plain (square and rectangular) configurations. Hence the original plan (Fig. 4a) is adjusted to a rectangular plan of equivalent size (Fig. 4b). Parameters such as the floor area, roof area, number of columns and number of beams, bay and span sizes, and column and beam dimensions are defined according to the adjusted structural framing plan.

The seven structure–envelope options are assigned LEED[®] scores according to their impacts in reducing GWP, overall energy use, and air, water and land emissions, over a life span of 75 years.

Table 5
Bill of materials report for conventional steel school buildings.

Material	Quantity	Unit
3 mil Polyethylene	127,500	sf
5/8" Fire-Rated Type X Gypsum Board	275,000	sf
Aluminum	0.34	Tons
Batt. fiberglass	525,000	sf (1")
Batt. rockwool	50,115.45	sf (1")
Concrete 20 MPa (fly ash av)	1,805.3792	yd ³
Concrete 30 MPa (fly ash av)	1,589.864	yd ³
Foam Polyisocyanurate	1050,000	sf (1")
Galvanized decking	126.7311	Tons
Galvanized studs	347.8137	Tons
Glazing panel	0.6708	Tons
Low E tin glazing	22,885.5898	Sf
Nails	0.0259	Tons
Open web joists	115.6855	Tons
Rebar, rod, light sections	14.0214	Tons
Roofing asphalt	2,363.6364	lbs
Screws nuts & bolts	39.2489	Tons
Softwood plywood	633.4416	msf (3/8 basis)
Welded wire mesh/Ladder wire	11.5343	Tons
Wide flange sections	684.474	Tons

Material and transportation are accounted in the life cycle stages such as manufacturing, construction, maintenance and end-of-life, while electricity and gas consumptions are considered in the operation stage. The biogenic carbon in wood is accounted as 'global warming neutral' in accordance with the Norwegian Product Category Rules (NPCR 015 September 2009, The Norwegian EPD Foundation) [39]. In this approach, the CO₂ emission from the combustion of wood is considered equal to the CO₂ uptake in the forest during the tree growth. Thus the biogenic carbon emission is not considered as contributing to GWP impact category; however the emissions from wood burning in the form of methane or nitrous oxides are accounted.

2.3. Materials and resources

The materials and resources category is significantly affected by structure and envelope types. This category requires applying a prerequisite point rating, storage and collection of recyclables. The material and resources category is assigned 13 LEED scores and contains the reuse of major structural components, recyclability of content, the diversion of the disposal of construction waste, and the use of regional materials and of rapidly renewable material. 109 LEED-certified school buildings in the United States and Canada, North America are analyzed in this study to determine the average LEED[®] scores that can be achieved in this category by applying each structure and envelope type. Each certified building is studied separately and classified according to its structure and envelope system. After classifying each school, each LEED credit is investigated to compute the total obtained scores. The total LEED score is reached by adding up the scores obtained in each category, as indicated in Fig. 1.

3. Results and discussion

3.1. Energy simulation results

The results of the energy simulation (annual energy consumption, Case 2) is shown in Fig. 5 which demonstrates that the peak electricity consumption occurs in June due to high temperatures that cause high energy consumption due to space cooling, miscellaneous equipment, and lighting systems. Even though July and August record the highest temperatures of the year, they correspond to the lowest energy consumption because of the school vacation. January, February, December and March have the highest gas consumption due to winter that causes high energy

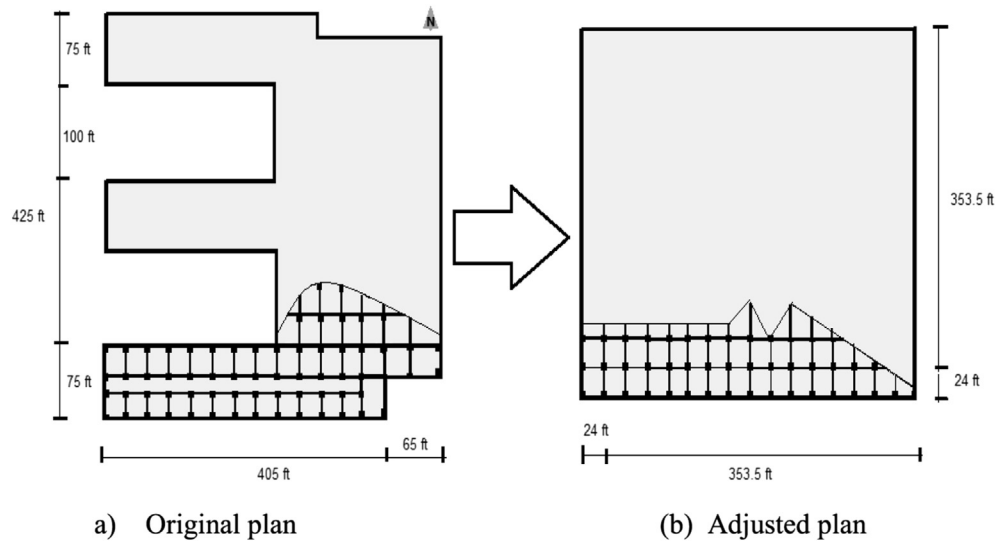


Fig. 4. The original and adjusted structural framing plans.

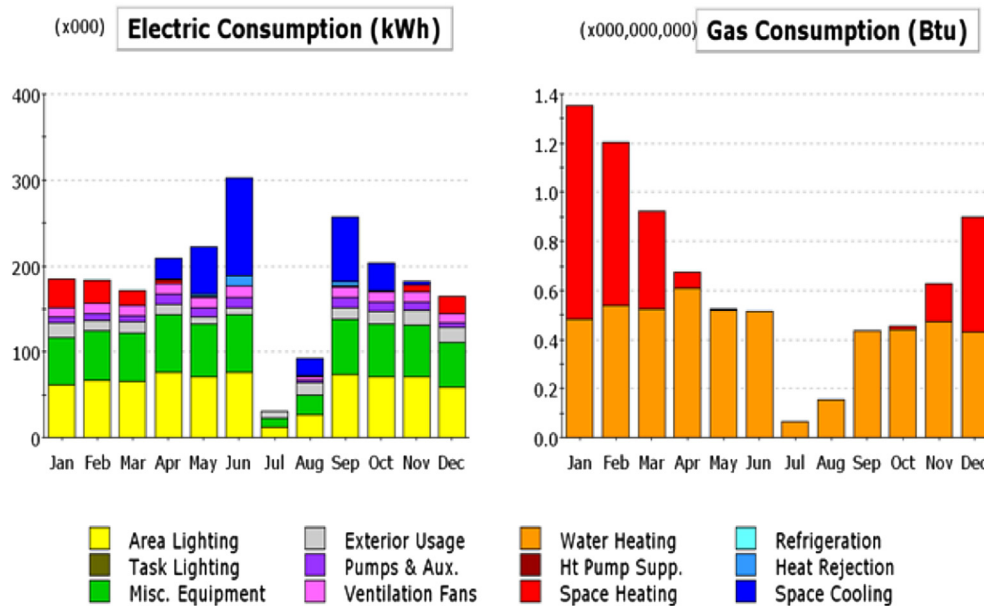


Fig. 5. Annual energy consumption for high school in Case 2.

consumption for space and water heating. Moderate energy consumption is recorded in April, May, September, and October due to the moderate weather.

Table 6 summarizes the annual energy consumptions of various options, the reductions achieved and the resulting LEED scores (EA category), for Case 1, Case 2 and Case 3. The percentage reduction is calculated with respect to the baseline value of 25.8 kWh/ft² according to the ASHRAE 90.1 standard for high school buildings in climate zone 6a. In all the above cases, the entire building is assumed to comply with the K-12 AEDG recommendations, except the envelope which is varied to study its impact on energy consumption. It can be observed that with no insulation (Case 1), the concrete envelope is the best alternative, with energy consumption of 20.07 kWh/ft², which yields a saving of 22.17% compared to the baseline, while the worst is steel. A LEED® score of 6 is achieved by the concrete envelope while the steel envelope yields only 2. When

Table 6
Annual energy consumption and LEED scores in EA category.

Options	CC	CM	SS	WW	WM	SW	SM
Case-1: Without insulation							
Energy consumption (kWh/ft ²)	20.07	20.39	22.03	21.64	21.28	21.64	21.48
Reduction (%)	22.17	20.91	14.59	16.07	17.46	16.07	16.72
LEED score	6	5	2	3	3	3	3
Case-2: With minimum insulation							
Energy consumption (kWh/ft ²)	17.89	17.99	18.43	18.33	18.29	18.33	18.35
Reduction (%)	30.62	30.24	28.55	28.91	29.04	28.91	28.90
LEED score	10	10	9	9	9	9	9
Case-3: With recommended insulation							
Energy consumption (kWh/ft ²)	17.43	17.47	17.41	17.39	17.41	17.39	17.42
Reduction (%)	32.40	32.25	32.48	32.54	32.48	32.54	32.46
LEED score	11	11	11	11	11	11	11

Table 7
Summary of LCA results for energy consumption (Case 2).

Options	Energy consumption (kWh $\times 10^6$)					Overall
	Life cycle stages					
	Manufacture	Construction	Maintenance	End-of-life	Operating	
CC	9.43	0.61	0.14	0.59	242.85	253.62
CM	10.84	1.00	0.14	1.60	249.17	262.75
SS	11.48	0.31	0.11	0.34	280.10	292.34
WW	5.52	0.36	0.11	0.38	273.03	279.40
WM	5.46	0.39	0.34	0.40	266.21	272.78
SW	8.15	0.36	0.11	0.36	273.03	282.00
SM	11.59	0.33	0.11	0.35	269.86	282.24

minimum insulation is provided (Case 2) CC records the highest energy saving (30.6%) while steel has the least (28.55%). Concrete and Masonry have the highest LEED scores (10) and all others achieved a score of 9. When the insulation is provided as per the K-12 AEDG recommendations (Case 3), it is interesting to note that, the energy savings by all the options fall within a narrow range of 32.25%–32.54%. This indicates that the building shows almost the same energy performance regardless of the type of envelope, which leads to a common LEED score of 11.

3.2. Life cycle assessment results

3.2.1. Energy consumption

Table 7 summarizes the energy consumptions for various structure–envelope options during each life cycle stage and the respective overall energy consumptions, by considering minimum insulation (Case 2). In general, the operating stage consumes maximum energy, followed by the manufacturing stage. SS has the highest score, and WW and SM share the second highest position, while CC and CM have the lowest scores. During the manufacturing stage, WM and WW have the lowest energy consumption while SS and SM represent the highest, followed by CM. Conversely, SS and SM record the lowest energy consumption during the construction and end-of-life stages, while during maintenance stage, SS, WW, SM and SW have the lowest energy consumption. However during construction, maintenance and end-of-life stages, CC and CM record the highest energy consumption. It is worth noting that while considering the life span of 75 years, CC and CM record the lowest energy consumption (253.62 million kW and 262.75 million kW respectively), thereby earning 1 additional LEED® score. This is due to the fact that buildings with concrete and masonry envelopes consume lower energy during their operating stages.

3.2.2. Global warming potential (GWP)

Table 8 shows the global warming potential (GWP) of various options for various life cycle stages, for Case 2. In estimating GWP,

Table 8
Summary of LCA results for global warming potential (Case 2).

Structure-envelope type	Global warming potential (kg Co ₂ eq. × 10 ⁶)					Overall
	Life cycle stages					
	Manufacture	Construction	Maintenance	End-of-life	Operating	
CC	3.52	0.052	0.123	0.071	47.24	51.00
CM	4.03	0.117	0.123	0.030	48.50	53.07
SS	2.77	0.032	0.094	0.064	54.67	57.63
WW	1.43	0.030	0.094	0.078	53.26	54.89
WM	1.46	0.030	0.181	0.078	51.90	53.65
SW	1.83	0.030	0.094	0.073	53.26	55.28
SM	2.81	0.032	0.094	0.064	52.63	55.63

Table 9
Summary of air, land and water emissions (Case 2).

Options	Emission index ($\times 10^8$)		
	Air	Land	Water
CC	7.73	0.01200	70,800
CM	7.98	0.01840	73,100
SS	8.61	0.01090	82,000
WW	8.28	0.00972	79,000
WM	8.11	0.00970	77,100
SW	8.32	0.01020	79,300
SM	8.31	0.01070	7,9000

ATHENA quantifies the environmental impacts of emissions such as oxides of carbon and nitrogen, ammonia, ethane and organic acids, etc., and converts them into CO₂ equivalent in kg. The highest global warming emission is generated during the operating stage (90% of the overall) followed by the manufacturing stage. This corroborates the findings of Sharma et al. [8] who reported that the operational phase alone contributed more than 50% to GHG emissions and was the highest energy consumer (80–85%). It is also worth noting that except for CC and CM, the GWP during the end-of-life stage (demolishing) is almost double (or more), compared to the construction stage. This indicates that demolishing a building can have serious impact on GWP. Over the 75-year lifespan CC has the lowest GWP, while SS contributes the highest. Thus concrete buildings achieve 1 additional LEED score with respect to GWP.

4. Air, land and water emissions

Table 9 summarizes the air, land and water emission indices of the various 'structure–envelope' options, by considering Case 2. In general, water emission is incomparably higher, and air and land emissions are relatively low. However, for the purpose of assigning the LEED score, each category is separately analyzed. Concrete buildings contribute the least to overall air emissions while steel buildings show the highest. Thus concrete buildings achieve 1 LEED score with respect to air emission. Regarding land emission, WM has the lowest index while CM is at the top, qualifying wood and brick buildings for 1 LEED score. CM produces the lowest overall water emissions while SS is at the highest level. Therefore masonry buildings achieve 1 LEED score in the water emissions factor.

4.1. Results of material and resources

Most LEED® certified school buildings in the US and Canada are built of concrete with masonry walls, and built of steel structure with exterior brick. The 109 green schools tested in this study are typical, since the total number of certified schools does not exceed 250. Table 10 presents the average LEED® scores earned by various options in the materials and resources (MR) category. The highest

Table 10
Average LEED score for material and resources.

Options	CC	CM	SS	WW	WM	SW	SM
No of schools tested	12	27	14	14	10	8	24
Average LEED score	5.83	5.7	4.85	6.35	5.4	5.87	5.29

score is recorded for wood buildings (6.35 scores), while steel buildings have the lowest (4.85). It should be noted that, the materials and resource category could not achieve an average LEED score of more than 6 (out of 13), for the overall tested cases. This low score is attributed to the possible obstacles and challenges in the construction industry in terms of recycling and reuse of building materials.

4.2. Overall results of LCA–LEED model

Table 11 summarizes the individual and overall LEED scores for various options with minimum insulation, based on the analysis by the present LCA–LEED model. The highest overall LEED score is for CC, followed by CM and the least is for SS. This indicates that concrete building with minimum insulation is the most favorable choice (LEED score 19), the second option being masonry (LEED score 17) and the least favorable are steel and steel-masonry (LEED score 14). It is worth noting that had the LCA not been accounted in the model, CC and CM would get the same score (16), indicating equal status; however the LEED scores contributed by LCA enable the decision makers identify the merit of CC over CM. LEED only assigns scores for various sustainability criteria that are evaluated by software tools and other techniques, while LCA performs assessment of its components without assigning scores. In this model, the LEED scoring is noticeably influenced by LCA. However, as LCA is accommodated under the innovation and design category which offers only fewer scores compared with the other LEED categories, the LEED system needs careful re-structuring to include LCA as an independent category with appropriate scores. The choice of minimum insulation case in this study is due to the fact most of the buildings satisfy this condition. Nevertheless, it is obvious that the LEED score of the building could be increased by adopting recommended insulation, but its economic viability should be analyzed before implementation.

5. Conclusion

A model that incorporates LCA into LEED for enhanced sustainability assessment of structure and envelope types of school buildings is developed, and its performance is verified successfully by applying it on 109 sustainable (LEED – certified) school buildings in North America. The evaluation was based on the LEED categories such as energy and atmosphere, materials and resources, and innovation and design process under which the LCA technique has been included. Various options are studied by considering

Table 11
LEED scores by LCA–LEED model (for Case 2).

Options	Individual LEED scores			Total LEED score
	EA	MR	LCA	
CC	10	6	3	19
CM	10	6	1	17
SS	9	5	0	14
WW	9	6	0	15
WM	9	5	1	15
SW	9	6	0	15
SM	9	5	0	14

concrete, steel, masonry, and wood structures incorporated with envelope systems such precast panels, steel stud, wood stud, and cavity wall. This work is a preliminary step towards integrating LCA into LEED for sustainability assessment of building's structure–envelope, as recommended by the USGBC LCA study group. Incorporating LCA into LEED has enhanced the sustainability assessment and enabled to decide the most favorable structure–envelope option for the building, by considering a life span of 75 years. The following remarks and suggestions for future work are worth noting:

- The concrete and masonry buildings have high energy consumption and global warming potential during manufacturing, construction and demolition stages. However they have lower energy consumption and environmental impact during the operating stage, as well as for the overall life cycle span.
- Concrete building with minimum insulation has obtained the highest total LEED score (19) followed by masonry (17), while steel and steel-masonry got the least (14).
- Applying the K-12 AEDG recommendations resulted in maximum energy saving, showing almost the same energy performance irrespective of the envelope type. Though the LEED score could be enhanced by adopting recommended insulation, its economic viability should be analyzed before implementation.
- The average LEED score in the material and resources category has not exceeded 6, which indicates the level of the obstacles in the construction industry in the recycling and reuse of materials. If this is the case for a developed country like Canada, the situation would be more alarming for underdeveloped and developing countries.
- Selecting an alternative should be based on its performance in all the life cycle stages over its entire life span.
- In this model, LCA is included under the 'Innovation and Design Process' category of LEED which has scores far fewer than LCA deserves. Therefore, the entire LEED structure needs revision to accommodate LCA into it with LEED scores assigned according to its decisive role in the sustainability scoring.
- This model can be improved by including the indoor air quality, and with appropriate modifications, this can be applied for other type of buildings and for different climatic regions. The cost analysis for selecting an alternative would also be interesting.

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