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ORIGINAL PAPER

Sustainability assessment framework for low rise commercial buildings: life cycle impact index-based approach

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Abstract The building industry has regularly been criticized for resource exploitation, energy use, waste production, greenhouse gas emissions, and impacts on the landscape. The growing population demands more built environment to accommodate the socioeconomic wellbeing. Adopting conventional construction practices would continue the aforementioned issues. Therefore, it is important to integrate life cycle thinking into building construction to minimize its social, environmental, and economic impacts. The objective of this study is to assess the life cycle impact of commonly used wall–roof systems for low rise commercial building construction in Canada. A framework is developed to assess different building alternatives using the triple bottom line of sustainability. Identified environmental and socioeconomic impact indicators are eventually aggregated to develop a life cycle impact index. Material quantities of six wall–roof combinations for a single-storey commercial building were obtained from industrial partners. State-of-the-art life cycle assessment software is used to assess the life cycle impacts of different wall–roof systems. To accommodate decision makers' preferences of sustainability, wall–roof combinations are assessed for three potential scenarios namely, eco-centric, neutral, and economy-centric using multi-criteria decision analysis. The framework has also been implemented on a case study of low rise building in Calgary (Alberta, Canada) to evaluate its practicality. The study results revealed that the concrete–steel building is the most sustainable alternative in neutral and economy-centric scenario while steel–wood building is the most sustainable building in eco-centric scenario.

Keywords Life cycle assessment · Life cycle costing · Multi-criteria decision methods · Canada · Low rise commercial buildings

Introduction

The construction industry is considered to be one of the largest exploiters of natural resources which has a momentous effect on landscape and natural environment through energy use, waste production, and generation of greenhouse gas (GHG) emissions (Jones et al. 2006; Spence and Mulligan 1995). According to Industry Canada (2011), buildings consume 50 % of extracted natural resources and 33 % of a country's energy use. In addition buildings produce 25 % of the landfill waste, 10 % of airborne particles, and 35 % of GHG emissions. GHG emissions from the building sector are expected to reach 91

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Mt CO_2e[1] in 2020[2] (Environment Canada 2012a, b). In 2010, total energy consumption of the construction industry was 72,812 PJ, exceeding 1990 levels for the first time (Nyboer and Kamiya 2012). Above-mentioned effects call for immediate attention to improve the sustainability performance of Canadian building construction industry.

Sustainable construction has been a topic of limelight in the construction research. Kibert (2012) and Kashyap et al. (2003) defined sustainable construction as "creating and operating a healthy built environment which is based on resource efficiency and ecological design". Sustainable construction aims to: (i) improve quality of life and customer satisfaction, (ii) provide flexibility and satisfy future user demands, (iii) offer and support desirable ecological and social environments, and (iv) make best use of resources (Kashyap et al. 2003). Sustainable construction aims at an economic growth with an emphasis on social and environmental integrity involving a large number of processes associated with the whole life cycle of a project (Kibert 2012). Important considerations for sustainable construction, include resource management, life cycle design, human and environmentally friendly designs, site planning, material selection and use, recycling waste, and energy minimization (Adetunji et al. 2003; Sev 2009). Early consideration of sustainability initiatives appear key to realizing a sustainable building (Demaid and Quintas 2006).

Several hurdles for sustainable construction have been highlighted in the literature. Knowledge of sustainable development in the construction industry is fragmented, dissimilar, disseminated, and not integrated across all macro and micro stakeholders (Rezgui et al. 2010). Some of the main issues to achieve sustainable development, include unavailability of structured sustainability information and know-how, lack of awareness among project stakeholders, non-coordinated construction practices, and variations in principles developed through practice across the industry (Carter and Fortune 2007; Rezgui et al. 2010; Liu and Fellows 2008).

This research aims to focus on sustainability performance of low rise commercial buildings. Canadian statistics for 2012 shows that commercial buildings account for 12 % of the secondary energy use and emits 11 % of the total GHG emission (Natural Resources Canada 2014). Moreover, total expenditure for operational energy of commercial and institutional buildings totalled to CAD 24 billion, which is equal to 3 % of the GDP (Natural Resources Canada 2012). Commercial and institution buildings imposes higher environmental impact compared to residential buildings (Sharma et al. 2011). Statistics show that energy intensity of commercial buildings are significantly higher than that of residential buildings (Van Ooteghem and Xu 2012). Since low rise storey buildings account for the large majority of commercial buildings in North America, more scrutiny is needed to improve the environmental and economic performance throughout their life cycle (Van Ooteghem and Xu 2012).

Minimizing the life cycle impacts of built environment has been a popular approach to reinforce sustainable construction. Several authors highlighted the importance of material selection for construction projects, for example it can reduce embodied energy of the building by 14 % (Thormark 2006). Decisions made during the design stage of the building can certainly enhance the environmental benefits (Goggins et al. 2010). Moreover, a systematic project evaluation process that looks at the triple bottom line (TBL) of sustainability would assist construction managers in identifying the optimal alternative for construction (Akadiri and Olomolaiye 2012). Many of the life cycle assessment (LCA) tools available for built environment are complex and have not been customized for practical use in the construction industry. Therefore, there is a need to develop a life cycle-based tool to support decision making in the project initiation stage.

Built environment consumes large amounts of material, energy, and water, and release variety of pollutants and waste throughout its life cycle (Crawford 2011). Therefore in order to successfully address environmental issues related to build environment, it is important to consider all the phases of a built asset over its entire life cycle (i.e. from raw material extraction and conversion; to manufacture and distribution; through use, reuse, and recycling; to ultimate disposal). Life cycle thinking allows improvements across the industrial systems and through the built assets of life cycle stages. Review of reported literature revealed that the life cycle of a building encompasses the following seven main stages (Cabeza et al. 2014): (i) preliminary design, (ii) detailed design, (iii) procurement and contracting, (iv) construction, (v) commissioning, (vi) Operation, i.e. energy use for electricity use, heating, ventilating, and air conditioning (HVAC), manufacturing and maintenance, water use, waste generation, natural resource consumption, and (vii) demolition, i.e. energy for building demolition, transportation of construction and demolition (C & D) waste, land filling, and recycling.

Several studies have been done on sustainability of built environment. Chen et al. (2010) developed a framework to compare construction method selection in concrete buildings. Medineckiene et al. (2010) proposed an analytic hierarchy process (AHP)-based framework for comparing construction materials to evaluate environmental and human health effects of buildings. Though wall–roof material selection has an insignificant effect in the

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[1] Carbon dioxide equivalents.

[2] From 79 Mt CO_2e in 2010.

operational energy consumption, there is a significant impact on the embodied environmental foot print of the building (Cabeza et al. 2014; Takano et al. 2015). A previous study identified that 80–90 % of energy use was on operation and 10–20 % of energy use was on embodied effect (Ramesh et al. 2010). Akadiri and Olomolaiye (2012) found that construction material selection, maintainability and energy, saving and thermal insulation are the main sustainability evaluation criteria. Fard (2012) developed the emergy-based "Em-Green sustainability rating system" as a decision support tool for construction projects. Reza et al. (2013) developed emergy-based life cycle assessment (Em-LCA) as an evaluation technique that can estimate not only environmental burdens but also economic and social flows.

Typically construction projects are evaluated on the basis of initial costs ignoring operational and maintenance costs (Wübbenhorst 1986; Bull 1993). This approach ignores the most significant bottom line costs. Life cycle costing (LCC) including all possible costs (i.e. including initial cost, maintenance cost, finance cost, renewal cost, and disposal cost) is a recommended solution to overcome this concern (Bull 1993; Hampton 1994; Assaf et al. 2002; National Audit Office 2005; European Commission 2014).

Life cycle index-based decision support systems can commonly be found in the sustainable construction research (Gu et al. 2008; Kahhat et al. 2009; Pizzol et al. 2015; Ji and Hong 2016). A majority of existing life cycle impact-based decision support systems focused only on the environmental impacts. It is important to develop an integrated framework to assess the environmental and socioeconomic impact form buildings (Industry Canada 2011). Life cycle sustainability assessment (LCSA) is the evaluation of all environmental, social, and economic negative impacts and benefits throughout a product's life cycle (Kloepffer 2008; United Nations Environment Program (UNEP) 2011). LCSA enables effective decision making with regards to the built environment by combining LCA, LCC, and social impacts.

Hence, the objective of this paper is to develop a sustainability assessment framework based on LCSA and life cycle impact index (LCII) for low rise commercial building construction. The framework will assist project teams for informed decision making to select the most sustainable building construction alternative. The proposed framework has also been demonstrated through a case study to investigate the sustainability of construction alternatives for single-storey commercial building in Calgary, Alberta, Canada.

Methodology

Life cycle assessment

In this research the term 'alternatives' is used for 'building material combinations'. Figure 1 illustrates the system boundary for LCA of different low rise commercial building alternatives. Every alternative goes through the same life cycle stages but consume varying amount of energy, water, and other resources and causes associated environmental and socioeconomic impacts through different processes.

During the last few decades, LCA has become one of the most commonly applied instruments to evaluate environmental performance of products or processes over the life span of a facility. This can be achieved by compiling an inventory of relevant inputs and outputs of a system, evaluating the potential impacts of these inputs and outputs, and interpreting the results in relation to the objectives of the study. The International Standards Organization (ISO) outlined the following basic steps for LCA (ISO 2006):

a. *Goal and scope definition* which includes the preliminary assumptions about the aim of the study, the functional unit, and the boundaries of the system.
b. *Life cycle inventory* (*LCI*) which focuses on the quantification of mass and energy flows.
c. *Life cycle impact assessment* (*LCIA*) where the environmental impact of the activity is assessed by means of impact indicators.
d. *Life cycle interpretation* which aims at evaluating the possible changes or modifications of the system that can reduce its environmental impact.

In general, LCA covers the use of material and energy as well as all emissions contributed by the product system holistically. Nordic Guidelines on Life Cycle Assessment (Lindfors 1995) stated that in an LCA the product system is followed from the processing of raw material to the manufacturing, distribution, use, reuse, maintenance, and recycling stages, and then to final disposal, including all transports involved. Quantitative or qualitative information on emissions, material, and energy used in all phases should be gathered and processed so that an assessment can be made on the overall impact on the environment and on the resource base. General categories of environmental impacts include resource use, human health, and ecological considerations (ISO 2006).

Fig. 1 System boundary for LCA of building alternatives

Sustainability performance indicators for material selection

Sustainability impacts associated with construction material selection can be categorized into various categories. Table 1 presents different impact categories identified in reported literature for each component of TBL of sustainability.

To assess the impacts of the building design on TBL of sustainability, suitable indicators have been identified in Table 1 through a comprehensive review of literature. Life cycle impact indicators are used to develop sustainability indices for each TBL dimensions (i.e. social, economic, and environmental) and used to compare commonly available wall–roof systems in Canada for low rise

Table 1 Life cycle sustainability indicators for material selection

TBL dimension/ Impact category	Impact indicators	References
Environmental	Global warming potential	Windapo and Ogunsanmi (2014), Reza et al. (2011), Hossaini et al. (2015), Chen et al. (2010), Medineckiene et al. (2010), Scheuer et al. (2003)
	Acidification potential	Hossaini et al. (2015), Medineckiene et al. (2010), Scheuer et al. (2003)
	Eutrophication potential	(Medineckiene et al. 2010)
	Ozone depletion potential	Windapo and Ogunsanmi (2014), Akadiri and Olomolaiye (2012), Hossaini et al. (2015), Anderson et al. (2009), Scheuer et al. (2003), Medineckiene et al. (2010)
	Embodied energy	(Takano et al. 2014), Windapo and Ogunsanmi (2014), Akadiri and Olomolaiye (2012), Reza et al. (2011), Goggins et al. (2010), Monahan and Powell (2011)
	Water footprint	Bank et al. (2011), Hoekstra et al. (2011)
	Resource depletion	Windapo and Ogunsanmi (2014), Akadiri and Olomolaiye (2012), Reza et al. (2011), Bank et al. (2011), Takano et al. (2014), Hossaini et al. (2015)
	Potential for recycling	Akadiri and Olomolaiye (2012), Thormark (2006), Osmani et al. (2008), Asokan et al. (2009), Reza et al. (2011), Hossaini et al. (2015), Chen et al. (2010), Thormark (2006)
Social	Impact on air quality	Akadiri and Olomolaiye (2012), Reza et al. (2011)
	Human health	Windapo and Ogunsanmi (2014), Akadiri and Olomolaiye (2012), Hossaini et al. (2015), Anderson et al. (2009), Bank et al. (2011), Medineckiene et al. (2010), Akadiri and Olomolaiye (2012), Hossaini et al. (2015), Medineckiene et al. (2010)
Economic	Material cost	Takano et al. (2014), Windapo and Ogunsanmi (2014), Akadiri and Olomolaiye (2012), Reza et al. (2011), Hossaini et al. (2015), Chen et al. (2010), Wong and Li (2008)
	O & M cost	Akadiri and Olomolaiye (2012), Reza et al. (2011), Hossaini et al. (2015), Chen et al. (2010), Wong and Li (2008)
	Disposal cost	(Chen et al. 2010)

commercial building construction. Table 1 illustrates the hierarchical framework for sustainability assessment of these building alternatives.

The total primary energy, global warming potential, water footprint, smog potential, and human health (HH) impacts by particulate matter have been estimated with the help of Athena Impact Estimator software and were used to estimate the embodied energy, air quality impacts, and human health impacts (particulate), respectively. Athena Impact indicator reports environmental impact measures consistent with the latest US EPA TRACI methodology (Athena Sustainable Materials Institute 2016). Water footprint refers to the amount of freshwater consumed by a building in its life cycle processes (Hoekstra et al. 2011). More specifically, the water consumption value provided by Athena Impact Estimator is mainly the blue water footprint meaning surface and groundwater. The mineral resource depletion calculated by SimaPro software was used as the indicator for resource depletion. The mineral resource depletion is expressed as the additional costs ($) society has to pay as a result of a resource extraction (Goedkoop et al. 2012). Moreover, among the C & D wastes, steel is the most commonly recycled material due to economic reason (Jeffrey 2011; Recycling council of Alberta 2012; CCME 2014). Therefore, only steel is included as an indicator of potential for recycling using the material's scrap values ($). The quantities of recycled material were estimated assuming scrap structural steel with the recycling efficiency of 95 % and reinforcement bar with a recycling efficiency of 45 % (Nisbet et al. 2002; Scrap Monster 2015). Furthermore, building performance for each impact indicator is assessed to obtain the life cycle impact for each category. Performance related to each category would be aggregated to arrive at life cycle impact index for each building.

Development of construction alternatives

The framework developed in "Results" section was used to compare various alternatives for low rise commercial building construction. Details for a building were obtained from a leading architectural, engineering, and construction company in BC. The building is intended to be constructed in Calgary, Alberta and will be used as a warehouse. Six alternatives based on different material for building construction suggested by the industry partner are presented in Table 2.

Table 2 Details of construction alternatives

Building alternative	Wall–roof system details
B1	Steel–steel system
B2	Concrete–steel system
B3	Steel–wood system
B4	Wood–wood system
B5	Wood–steel system
B6	Concrete–wood system

Building energy simulations and life cycle impact assessment

A building model was built and simulated in the Design Builder software to estimate the annual energy demand for each construction alternatives presented in Table 2. The software is capable of calculating energy consumption, internal comfort data, and HVAC load. A life span of 75 years was considered for the building (Toronto and Barrie Commercial Building Inspector 2016). The 3-D model of the building with a floor area of 30,000 square feet is shown in Fig. 2.

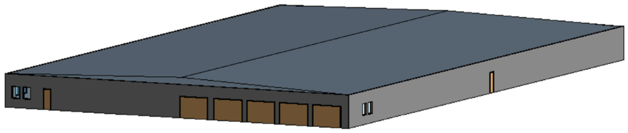

Fig. 2 3-D model of the low rise commercial building developed using Design Builder software

Athena Impact Estimator for buildings (version 4.1) was used to conduct LCA. Material and assembly database available in Athena software is specifically developed for North American context. The software has been effectively used by several researchers in the past to assess the sustainability performance of built environment (Meil et al. 2006; Frenette et al. 2010; Srinivasan et al. 2014; Ajayi et al. 2015). Material quantities and annual operational energy simulation values estimated for each construction alternative were used in Athena Impact Estimator to assess the life cycle impacts. Since, the software doesn't provide an aggregate value for the resource depletion category, the mineral resources consumed by each building construction were used as an input to the SimaPro 8.0.5 software to obtain an aggregate value (Risch et al. 2014). Furthermore, the end of life was considered as the default scenario for Canada inbuilt in Athena Impact Estimator, which mainly includes landfilling.

The life cycle cost includes construction cost, annual operation cost, and disposal cost. Construction cost information for building alternatives were obtained from RSMeans[3] square foot costs 2015 (Phelan 2015). Annual operational costs were calculated based on the building energy demand. In addition, disposal cost, particularly the landfilling cost of demolition waste, except the recyclable

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[3] RSMeans provides updated building construction cost data for estimation.

steel, was obtained from the City of Calgary website (City of Calgary 2015).

Multi-criteria decision analysis

Multi-criteria decision methods (MCDM) have been commonly used in construction research for comparing alternatives to select most sustainable option (Chen et al. 2010) (Wong and Li 2008). The estimated value of an individual indicator obtained from analysis might not be desirable by the top-level decision makers. At large, the senior management is more interested in composite indices to save their time and efforts which are required to evaluate the individual indicator. An index combines the information obtained by assessing several indicators into one final sustainability score; it consists of a weighting process and an aggregation process. The weighting process determines the important weights of all the indicators under each impact category; and the aggregation process finally combines the impact values with their respective weights (Haider et al. 2015). In this research, all the indicators except "potential for recycling" are cost attributable (lower the better). The benefit attribute criteria "potential for recycling" was transformed to cost attribute by taking inverse rating ($1/x_{ij}$) (Yoon and Hwang 1995).

The weighted sum method is used to aggregate the life cycle impacts of building construction alternatives using the following Eq. 1 (Yoon and Hwang 1995).

$$f_i = \sum_{j=1}^{n} W_j r_{ij} \tag{1}$$

and

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad \mathrm{i} = 1, 2, \ldots \mathrm{m}, \tag{2}$$

where r_{ij} is a normalized value of variable x_i in criterion j, W is the weight of criterion j, and f_i is the weighted sum factor of variable x_i.

Development of criteria weighting scheme is an important step for aggregation of indicators in MCDM. Goedkoop and Spriensma (2001) developed the Eco-indicator 99 system for life cycle impact assessment and used 40, 20, and 40 % as default weights of damage categories for ecosystem quality, resources, and human health, respectively. This weighting scheme seems rational and has been adopted in this study. These weights were equally distributed to their constituent impact indicators. The indicators of the ecosystem quality and resource impact categories were used under the environmental dimension, whereas the indicators of the human health impact category were used in the social dimension in this framework. Based on Eco-indicator 99, each indicator EN1 to EN4 belonged to the ecosystem quality impact category and received 10 % weight individually. Similarly, the indicators EN5 to EN8 were constituents of the resource impact category and each indicator received 5 % weight in Eco-indicator 99 system. These indicators were further normalized to obtain a sum of 100 % in the environmental dimension as given in Table 3. In the social dimension, the human health impact indicators SO1 and SO2 received 50 % weight (Table 3). Similarly, the three indicators EC1 to EC3 received equal weights under the economic category.

The environmental life cycle impact score can be obtained by aggregating the values of environmental life cycle impact indicators. Same procedure is applied to estimate the economic and social life cycle impact scores. Finally, an overall LCII can be estimated by aggregating the life cycle impact scores of each TBL dimension using pre-determined weights. Weights for the TBL were determined considering priorities of an organization and government policies. This variability on the weighting of the TBL dimensions has been analysed by considering three scenarios: eco-centric, neutral, and economy-centric with varying weights in different dimensions.

Eco-centric: This scenario provides higher emphasis to environmental performance.
Neutral: This scenario provides equal weights to TBL of sustainability.
Economy-centric: This scenario provides higher emphasis to economic performance (i.e. LCC).

These scenarios with their respective weights are given in Table 4. The LCII for each building construction will be estimated and the building with the least LCII value will be considered as the most sustainable alternative.

Results

Energy simulations

Energy simulation results for various wall–roof combinations are presented in Table 5.

Life cycle impact indicators

The LCA of the building shown in Fig. 2 were carried out with the help of Athena Impact Estimator. The results of life cycle impact indicators of the environmental and social dimensions are given in Tables 6 and 7 respectively. The results for economic dimension of the life cycle impact indicators are presented in Table 8. Different impact indicators presented in Tables 6 and 7 have varying units and therefore are aggregated into life cycle impact scores using the weighting scheme given in Table 3.

Table 3 Weights of environmental and social life cycle impact indicators

Code	Impact indicators	Weights (%)
Environmental (EN)		
EN1	Global warming potential	16.7
EN2	Acidification potential	16.7
EN3	Eutrophication potential	16.7
EN4	Ozone depletion potential	16.7
EN5	Total primary energy	8.3
EN6	Water footprint	8.3
EN7	Mineral resource depletion	8.3
EN8	Recycling materials	8.3
	Total	100.0
Social (SO)		
SO1	Human health (particulate)	50.0
SO2	Smog potential	50.0
	Total	100.0
Economic (EC)		
EC1	Construction cost	33.33
EC2	Operational cost	33.33
EC3	Disposal cost	33.33
	Total	100.0

Table 4 Weights of TBL dimensions considered in different scenarios

Dimensions	Weight (%) in scenarios		
	Eco-centric	Neutral	Economy-centric
Environmental	80.0	33.33	10.0
Economic	10.0	33.33	80.0
Social	10.0	33.33	10.0
Total	100.0	100.0	100.0

Table 5 Energy simulation results

Alternatives	Annual energy demand (operational)	
	Electricity (KWh)	Natural gas (GJ)
Steel–steel system	1,997,236.546	2937.014096
Concrete–steel system	1,942,507.119	2702.161222
Steel–wood system	1,997,236.546	2937.014096
Wood–wood system	1,962,181.884	2762.012138
Concrete–wood system	1,946,655.334	2705.247167

Life cycle impact indices

The aggregated life cycle impact scores of various buildings for three TBL dimensions were estimated and illustrated in Fig. 3. Figure 3 shows that the building B3, i.e. steel–wood system obtained the lowest environmental and social life cycle impact scores of 0.102 and 0.062, respectively. These results indicates that B3 is the most sustainable alternative based on the environmental and social dimensions. However, building B2, i.e. concrete–steel system was found to be the most economical alternative with lowest economic life cycle impact score of 0.388. Similar conflicting results can be observed for all the alternatives in Fig. 3.

Establishing preferences of sustainable buildings based on the life cycle impact scores of any single TBL dimension is not a rational approach. Therefore, these scores are further aggregated using equations (1) and (2) to develope an overall LCII under different scenarios with the corresponding weights for TBL dimensions listed in Table 4. The results for six building alternatives shown in Fig. 4 depict that the building B2, i.e. concrete–steel system is the most sustainable alternative with lowest LCII under neutral and economy-centric scenarios with values 0.1983 and 0.3309 respectively. In case of eco-centric scenario, the building B3 (steel–wood system) was found to be the most sustainable alternative with minimum LCII; however the difference with B2 is virtually negligible.

Discussions

Even though, Canadians highly value sustainable development and environmental quality, recent trends show a contradictory picture of existing trends (Natural Resources Canada 2013). Canada lacks in overall environmental performance and ranked 24th on an environmental performance index developed by the Yale University when compared to many developed countries (Boyd, 2001; David Suzuki Foundation, 2010; Yale University, 2014). David Suzuki Foundation (2010) stated that Canada has the room to improve the current environmental performance and can become a world leader in sustainability. Focusing on built environment is one of the most feasible routes to assist sustainable development in Canada.

This study developed a comprehensive framework to assess the life cycle sustainability performance of low rise commercial building alternatives. Six design alternatives are compared for a proposed warehouse building in Calgary, Alberta. Most sustainable design alternatives are ranked based on the three different scenarios considering varying priorities of the client and decision makers. This research contributes to the growing literature on sustainable construction by comparing life cycle impacts of common wall–roof systems used for low rise commercial building construction in Canada.

The life cycle impact scores are estimated for six alternative buildings of Calgary, Alberta. Based on the

Table 6 Environmental impact indicators

Alternatives	Global warming Potential (kg CO2 eq)	Acidification potential (kg SO2 eq)	Eutrophication potential (kg N eq)	Ozone depletion Potential (kg CFC-11 eq)	Total primary energy (MJ)	Water footprint (L)	Mineral resource depletion ($)	Recycling materials ($)
B1	1.44E+08	8.03E+05	7.53E+03	1.51E−03	1.88E+09	2.10E+07	13,367	304,689
B2	5.48E+06	3.65E+04	1.57E+03	4.10E−05	6.04E+07	2.20E+07	13,431	307,125
B3	4.61E+06	3.02E+04	1.28E+03	3.39E−05	5.31E+07	2.10E+07	13,252	304,272
B4	9.64E+07	7.58E+05	7.47E+03	3.35E−02	1.60E+09	6.54E+07	13,838	298,897
B5	9.64E+07	7.58E+05	7.47E+03	3.35E−02	1.60E+09	6.56E+07	13,871	299,312
B6	1.88E+08	1.04E+06	1.05E+04	2.01E−03	2.41E+09	2.50E+07	17,346	310,511

Table 7 Social impact indicators

Alternatives	HH particulate (kg PM2.5 eq)	Smog potential (kg O3 eq)
B1	1.09E+05	2.52E+06
B2	1.46E+04	7.95E+05
B3	1.25E+04	6.40E+05
B4	8.91E+04	3.04E+06
B5	8.91E+04	3.04E+06
B6	1.46E+05	3.72E+06

Table 8 Economic impact indicators

Alternatives	Construction cost ($)	Operational cost ($)	Disposal cost ($)
B1	41,427,000	150,268	2,904,232
B2	37,824,000	145,380	3,685,677
B3	42,012,000	150,268	2,904,316
B4	39,168,000	147,015	2,903,964
B5	38,850,000	147,015	2,912,439
B6	40,833,000	145,677	6,537,708

environmental and social dimensions, steel–wood system (i.e. building B3) is found to be the most sustainable option with minimum global warming potential, acidification potential, eutrophication potential, ozone depletion potential, total primary energy, water footprint, mineral resource depletion, human health (particulate) impacts, smog potential, and higher recycling materials. The lower life cycle impacts are caused due to lesser resource consumption compared to concrete and steel (Goedkoop 2001). However, concrete–steel system (i.e. Building B2) has the lowest life cycle cost, making B2 the best alternative from an economic point of view. In this research, these conflicting preferences have been solved using an overall LCII.

TBL-based decision making is becoming popular in the construction industry. Decision making within an organization can be defined as eco-centric (decisions are made considering environmental sustainability as the priority) and economy-centric (decisions are made considering economy as the priority). Most often organizations may be neutral by assigning equal importance to all three TBL dimensions. All these possibilities have been considered for evaluating different construction alternatives. Building B2, i.e. concrete–steel system is found be the most sustainable alternative with lowest LCII under the neutral and economy-centric scenarios. Under eco-centric scenario, building B3 (steel–wood system) is found to be the most sustainable alternative and ranked first with the least LCII; however it can be seen in Fig. 4 that the difference between B2 and B3 is almost negligible. Therefore, alternative ‘B2’ overall can be considered as the most sustainable alternative. This analysis reflects the importance of weighting TBL that is affected by organizational priorities and government’s eco-stewardship policies.

Green/sustainable procurement is a viable approach to improve the sustainability performance of built environment (Ruparathna and Hewage 2015). Sustainable procurement sets procedures to purchase material and services that are environmentally, socially, and economically

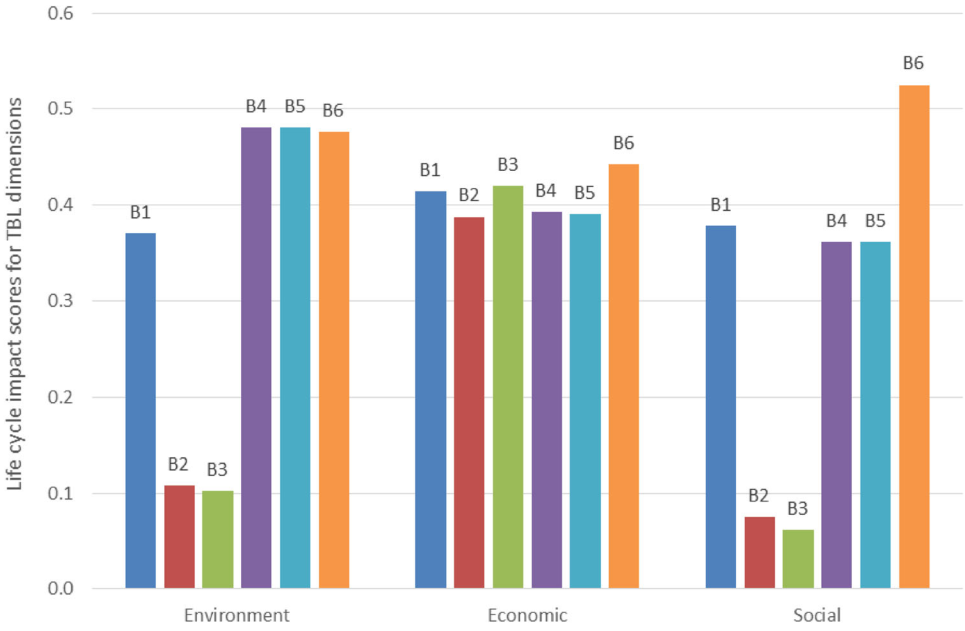

Fig. 3 Life cycle impact scores of various buildings for TBL dimensions

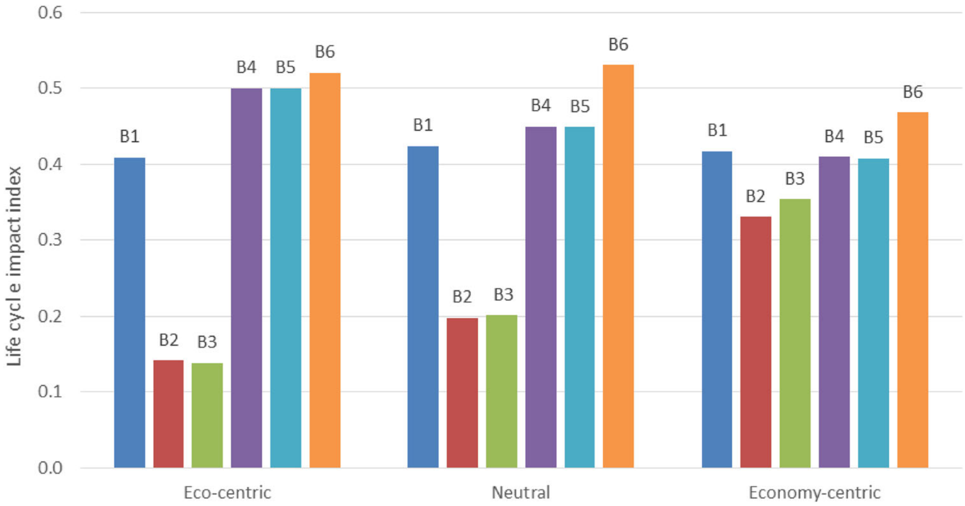

Fig. 4 Life cycle impact index of buildings under various scenarios

sustainable through life cycle thinking. Identifying the most sustainable project alternative has always been a challenging task for construction project managers. Proposed life cycle impact index would support the managers in identifying the sustainable alternative during the project procurement process. Currently Canada lacks resources for sustainable procurement (Ruparathna and Hewage 2015), and this approach would support procuring the most sustainable design alternative for construction.

Certification of sustainable construction materials is an important initiative. Though life cycle impact assessment provides general details about the material, it is important to determine the specific manufacturing process, i.e. whether the material manufacturer obeys labour laws or the raw material source is in an environmentally sensitive area. Environmental and social labels are useful tools for identifying sustainable goods. They help procurers to ensure that a product or service is incorporated with specific sustainability considerations, which cannot be measured using objective methods during the procurement process. Environmental and social label certification sets out specific environmental or social requirements that must be met by products or services for them to carry the label. This allows procurers to draft technical specifications, verify compliance through labels or their equivalent, and benchmark offers at the award stage (Ruparathna 2013).

Importantly building energy consumption accounts for the highest environmental impact of the building (Scheuer et al. 2003; Hossaini et al. 2015). Therefore, reduction of the operational energy demand is of pivotal importance. It is important to concentrate on the additions to the building code to enhance the building performance. Furthermore, state-of-the-art initiatives such as net zero energy buildings (NZEB) and net positive energy buildings should be taken into account in the building construction (Takano et al. 2015).

The life cycle impact index proposed in this study incorporates a wider spectrum of aspects into sustainability evaluation of material selection. It is important to assess the environmental impacts of building material quantitatively (Windapo and Ogunsanmi 2014). Several socioeconomic indicators affect the material selection criteria including climate, culture, site, labour skill requirements, labour amount requirement, contribution to the local economic development, etc. (Windapo and Ogunsanmi 2014). More relevant indicators could be identified from performance standards, building guidelines, requirements, and practices for sustainable construction material selection.

Several additional indicators could have been included in the analysis such as local availability of the material, and innovative features of the material (Windapo and Ogunsanmi 2014). Moreover durability, constructability, service life, impact on building environmental system, maintainability, and serviceability are several other technical performance criteria that should be considered in the analysis. This deficiency can be a potential limitation of this analysis. Performance related to aforementioned indicators requires qualitative assessment and cannot be used in this deterministic analysis.

Limitations of LCA studies include data uncertainty, model uncertainty, and scenario uncertainty (Zamagni et al. 2008). One model uncertainty is the inclusion of global warming potential and ozone layer depletion only in environmental dimension. Global warming and ozone layer depletion both have impacts on human health, i.e. social dimension in addition to ecosystem impacts. Moreover, LCA studies are compelled to use several assumptions that does not totally represent the actual system. Similarly, this study adopted several assumptions in data collection, performance categories, and the weight schemes. Additionally, cost data considered in this study (i.e. construction cost, operational cost, and disposal costs) could vary with macro-economic changes.

Conclusions

This research proposed a life cycle impact index for comparing alternatives for building construction. As a proof of concept a case study was conducted for a proposed low rise commercial building in Calgary. Various design alternatives were compared using MCDM to select the most sustainable wall–roof combination for a low rise commercial building construction. Among the six buildings considered in the case study, Building B2 (concrete–steel system) was ranked first with the lowest LCII under the neutral and economy-centric scenarios, whereas Building B3 (steel–wood system) was ranked first under the eco-centric scenario. These results reflect the importance of the changing weights of TBL dimensions based on the organizational priorities and government policies in decision making. Moreover, it is important to focus on the building design details to enhance the reusability and reduction of embodied energy of the building.

This research unfolded several potential future research areas. Firstly, proposed life cycle impact index-based framework can be generalized for a wider spectrum of building types. Further research should be conducted in determining the weights of sustainability performance indicators for site-specific conditions, such as type of the building, geographic location, etc. Secondly, there is a considerable level of uncertainty associated with performance values associated with life cycle impact indicators. Using techniques like fuzzy logic, the issues related to uncertainties can be efficiently addressed as well as the linguistic performance values can be integrated into the index to accommodate qualitative indicators. It is important to identify other relevant indicators for LCII framework; a comprehensive literature review with expert consultation is required to overcome this barrier. Thirdly, this study opens a door for developing a computer-aided tool similar to Athena with an option of defining weights which will facilitate the decision makers to include the interaction among the environment people and industry in the decision making process.

The computer-aided tool, based on this research, will be helpful for practical implementation of this framework during the procurement process for low rise commercial buildings in Canada. Ideally, a cloud-based software with an extensive database would ease the design selection process for project managers.

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