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Emergy-based life cycle assessment (Em-LCA) of multi-unit and single-family residential buildings in Canada

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Abstract

The construction and building process depends on substantial consumption of natural resources with far-reaching impacts beyond their development area. In general, a significant portion of annual resource consumption by the building and construction industry is a result of applying traditional building strategies and practices such as designing and selecting types of development (e.g. multi-unit condo and single-family house, etc.), building materials and structure, heating/cooling systems, and planning renovation and maintenance practices. On the other hand, apart from structural suitability, building developers mostly consider the basic requirements of public owners or private occupants of the buildings, where the main criteria for selecting building strategies are costs, and long-term environmental and socio-economic impacts are generally ignored. The main purpose of this paper is to develop an improved building sustainability assessment framework to measure and integrate different sustainability factors, i.e. long-term environmental upstream and downstream impacts and associated socio-economic costs, in a unified and quantitative basis. The application of the proposed framework has been explained through a case study of single-family houses and multi-unit residential buildings in Canada. A comprehensive framework based on the integration of emergy synthesis and life cycle assessment (LCA) has been developed and applied. The results of this research prove that the proposed *emergy-based life cycle assessment* (Em-LCA) framework offers a practical sustainability assessment tool by providing quantitative and transparent results for informed decision-making.

Keywords: Sustainability assessment; Emergy synthesis; Life cycle assessment (LCA); Multi-unit residential building; Single-family house

1. Introduction

Buildings as systems metabolize matter and energy and produce waste and emissions that substantially affect the natural environment and human health. On a global scale, the construction and building industry is responsible for ~70–80% of all resources entering the world economy (Baccini, 1997). The building industry, including housing, accounts for ~44% of all extracted materials from the earth's biological or mineral resources (Roodman and Lenssen, 1994), one-third of the total landfill waste stream (Kibert et al., 2001), 25–40% of society's energy consumption (Perez-Lombard et al., 2008), and around 30% of greenhouse gas emissions (UNEP SBCI, 2009).

It has been globally accepted that the potential impacts of buildings and their related activities need to be determined in order to implement necessary controls and

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optimum management strategies to make policy decisions (e.g., see Balta, 2012; Balta et al., 2010; Kim and Todorovic, 2013; Ortiz et al., 2009). An integrated sustainability assessment framework for built environments may assist in finding a plausible compromise between socio-economic growth of modern societies and environmental protection for building industry stakeholders. In general, a sustainability assessment framework implies *Triple Bottom Line* (TBL) evaluation criteria that include environmental protection, economic prosperity, and social acceptability and equity of an activity as a result of short- and long-term policy decisions.

Rebitzer et al. [6] stated that, achieving sustainable development requires methods and tools to help quantify and compare the environmental impacts of providing goods and services ("products") to our societies. In general, every product – including a building – encompasses a life cycle that begins with designing of the product, followed by resource extraction, manufacturing and production, use/consumption, and finally an end-of-life process that includes activities such as collection/sorting, reuse, recycling, and waste disposal (Rebitzer et al., 2004). All building life cycle stages and their related activities and processes can bring about environmental impacts due to consumption of resources, emissions of substances into the natural environment, and other environmental exchanges such as radiation (Balta, 2012).

A comprehensive literature review shows that although several innovative environmental assessment tools and techniques have been developed, there are still very few comprehensive, practical frameworks to address all sustainability aspects of building and infrastructure systems (Horvath and Hendrickson, 1998; Keoleian et al., 2005; H. Zhang et al., 2010; Reza, 2013). Some of the most recently used environmental assessment tools include, but are not limited to:

- Life Cycle Assessment (LCA), e.g. (Azari, 2014; Hossaini et al., 2014; Reza et al., 2011).
- Ecological Footprint (EF), e.g. (Teng and Wu, 2014).
- Cost-Benefit Analysis (CBA), e.g. (Issa et al., 2010; Mahlia and Iqbal, 2010).
- Environmental Risk Assessment (ERA), e.g. (Hauschild et al., 2008).
- Material Flow Accounting (MFA), e.g. (Hu, 2010; Cochran and Townsend, 2010).
- Embodied Energy (or Emission) Analysis (EEA), e.g. (Acquaye et al., 2011; Haynes, 2010).
- Emergy Synthesis, e.g. (Reza et al., 2014).

Reza (2013) discussed the promise and problems of the above environmental assessment tools (Reza, 2013). Among these tools, LCA-based tools were found to be more practical than other methods as they can be applied for various built environment systems with different levels of complexity, in different regions, and based on different scenarios (Reza, 2013). Dealing with non-commensurate units of varying environmental impacts (e.g., grams of CO_2 emissions, kcals of energy consumption) and socio-economic costs is a major shortcoming of using LCA for the building sector (Brown and Buranakarn, 2003). Currently, there are three main approaches in the literature to characterize and compare the sustainability of a product or process based on the LCA technique:

1. Comparative sustainability assessment and selecting the most sustainable option based on initial results of standard LCA (and/or life cycle costing, i.e. LCC). This approach is only possible when the value of all (or most) life cycle impact categories (including upstream, downstream, and socio-economic impacts) in one alternative are less than the other alternatives (e.g. see this paper Reza et al., 2013b). However, the LCA result for a building alternative is often a combination of pros and cons; a building material 'X' might have a large global warming potential effect while having excellent durability and recyclability potential as compared to a building material 'Y'.

2. Applying a multi-criteria decision analysis (MCDA) tool, e.g. AHP, PROMETHEE, ELECTRE, TOPSIS, etc. This method is very popular, and some recent application can be seen in Reza et al. (2011), Mattiussi et al. (2013), Hahn (2014), Iwaro et al. (2014), Kucukvar et al. (2014a,b), Myllyviita et al. (2014), Prado-Lopez et al. (2014), Scannapieco et al. (2014), Yadollahi and Ansari (2014), Hossaini et al. (2014). However, weighting scoring systems are often based on expert judgment and can sometimes be extremely biased. Moreover, weighting aggregation techniques usually ignore the fundamental essence and usefulness of various energy and resources related to ecosystem services (e.g. services needed to dilute a particular emission), biodiversity, carbon sequestration, and hydrological functions. Consequently, weighting is not being allowed when following ISO14044 in comparative assertions disclosed to the public (Klöpffer and Grah, 2014).
3. Decision making based on a single indicator, e.g. embodied energy, ecological footprint, and embodied carbon, and cost-benefit. While all these methods are scientifically sound, they fail to portray a comprehensive picture of sustainability aspects of building products.

Motivation for this research stems from the recognition that applying a holistic and accurate sustainability assessment framework over the life cycle of building systems is critical for developing effective management plans that will ensure adequate safety, serviceability, functionality, and optimized allocation of limited funds over their life span. The aim of this paper is to propose a sustainability assessment framework based on emergy synthesis, to obtain a *unified performance metric* to assess the TBL impacts over the life cycle of building systems.

The proposed emergy-based life cycle assessment (Em-LCA) framework is applied for two types of residential buildings (i.e. multi-unit condo and single-family house) to evaluate the environmental impacts (upstream impacts or resource use, and downstream impacts including natural and human loss, and ecological services to remove waste and emission) and the associated socio-economic costs over their life cycle (cradle to grave). This research ultimately aims to quantitatively investigate the metabolism (inflow–outflow) of each building system and compare the total environmental and socio-economic burdens of each building system in terms of emergy per unit area and emergy per capita.

2. Background

2.1. Life cycle assessment (LCA)

In recent years, the LCA has successfully been applied to integrate environmental issues like climate change and resource depletion (Khan et al., 2004). The LCA "cradle-to-grave" approach makes it unique among other sustainability appraisal tools (Finnveden et al., 2009). LCA methodology is based on the axiom that all phases in the life of a product cause environmental impacts and must therefore be analysed, including raw material acquisition, product manufacture, transportation, installation, operation and maintenance, and ultimately recycling and waste management (Lippiatt, 2000).

LCA has become a globally recognized approach to assess the comparative environmental performance of products or processes including buildings. In addition, the LCA approach has widely been employed to carry out life cycle sustainability assessment (LCSA). A comprehensive effort has been made to standardize LCA by the International Organization for Standardization (ISO 14040, 2006). However, final results of LCA are still based on subjective evaluations as LCA leaves the choice of the impact assessment method to the analyst (Ulgiati et al., 2006).

On the other hand, LCA is based on utilitarian *user-side* perspective that only focuses on environmental impacts due to resource consumption and emissions and ignores the work of ecosystems to provide 'freely available' services and products (e.g. land restoration, rainfall, soil organic matter, etc.) (Raugei et al., 2014). A critical review by (Y. Zhang et al., 2010) indicates that, in order to apply life cycle oriented methods to address sustainable development, the role of ecosystem goods and services must be accounted for, as they form the basis of planetary activities and human well-being. Accordingly, the system boundary should be large enough to account for all the ecosystem goods and services that support technological activities in the life cycle (Y. Zhang et al., 2010).

2.2. Emergy synthesis: a valuable complementary tool to LCA

In the early 1980s, H.T. Odum and co-workers at the University of Florida proposed and developed the groundbreaking idea of *emergy* as a way of understanding the behaviour of self-organized systems, valuing ecological products and services, and analysing ecological and economic systems together (Hau and Bakshi, 2004). *Emergy synthesis* is the process of determining the sorts of energies and resources used up directly or indirectly in the biosphere in order to produce a specific product or service. Emergy is expressed with the unit of solar emjoule (SeJ), a unit referring to the available energy of "one kind" consumed in transformations. Later emergy synthesis was extended in the time to evaluate the environmental works and services needed for resource formation. This method is based on a holistic and donor-side perspective which estimates the value of non-moneyed and free environmental resources and inputs (such as sunlight, wind, and rain) and moneyed resources (such as fossil fuel and minerals), and indirect environmental support embodied in human labour, services, and commodities in a *unified unit* (solar energy) that was previously used to generate a resource, service or product (Brown and Herendeen, 1996).

The most important characteristic of the emergy approach is that it can develop a link between economic and ecological systems (Hau and Bakshi, 2004). By applying the emergy analysis method, it is possible to tangibly evaluate the contribution of environmental, economic, and social impacts in an energy-based unit, and to determine an overall unbiased value for different TBL sustainability objectives. This will help to directly compare socio-economic and environmental concerns with the same measurement unit (Odum, 2007).

Emergy synthesis is based on basic thermodynamic laws, general system theories (Von Bertalanffy, 1973), energetics[1] (Lotka, 1945), and system ecology (Odum., 1988). To develop emergy synthesis, a system is converted into a network of energy streams and a measure of solar emergy assigned to energy flows (Hau and Bakshi, 2004). Solar emergy represents the total amount of available solar energy that was directly or indirectly used in order to generate or support a given product or service, and it is calculated in solar equivalent joules (seJ) Pulselli et al., 2009.

A key concept in the emergy evaluation process is *solar transformity* or *unit emergy value (UEV)*. The amount of emergy required to produce one joule of an input will be determined by its solar transformity from (1). For example, if 12E+04 solar emjoule (seJ) of coal and 4E+04 seJ of service are required to generate 1 J electricity, the solar transformity of electricity is 16E+04 (seJ/J).

$$\text{Solar transformity} = \frac{\text{Solar emergy flow (SeJ)}}{\text{Available energy flow (exergy) (J)}} \quad (1)$$

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[1] Maximum power principal.

Solar transformity can therefore be considered a *quality factor* or a major of *intensity of the biosphere support* to the product under study (Ulgiati et al., 2006), (Sciubba and Ulgiati, 2005). Moreover, the total solar emergy, U, can be derived from Eq. (2).

$$U = \sum_{i=1}^{n} E_i \times Tr_i \tag{2}$$

where U is the total emergy calculated over all independent input flows, E_i is the available energy or exergy, and Tr_i is the solar transformity of the ith input flow of a product or service. The emergy accounting method and its step-by-step procedure are discussed in detail in Odum (2007, 1988, Campbell et al, 2005, Odum (2000, 1995, 1996).

Emergy synthesis has been used in different areas, and more frequently by urban planners and ecologists to evaluate urban metabolism and sustainability of built environment on a regional/national scale (macro level studies) (Su et al., 2011; Y. Zhang et al., 2011 Duan et al., 2011). Review of the literature shows that emergy synthesis is rarely used for micro-scale and project-specific case studies related to the built environment and as a complement to the conventional LCA (Reza et al., 2014).

Recently, some research has been initiated by emergy and LCA practitioners in the direction of integrating and combining emergy synthesis with LCA to meet the challenges of sustainability (e.g., Raugei et al., 2014; Y. Zhang et al., 2010; Ingwesen, 2011; Brown et al., 2012; Rugani et al., 2012. For example, Raugei et al. (2014) argued the added value of LCA by linking it with emergy synthesis. They primarily discussed the basic theories and conceptual models of emergy synthesis and LCA and concluded that emergy can be adopted as a valuable complement to conventional LCA. Brown et al. (2012) discussed the LCA technique's capability to provide emergy with accurate datasets, precise assessment of data quality, source, uncertainty, and age. Furthermore, Reza et al. (2013a) noted that to accurately estimate emergy values of a system, and to precisely propagate the data uncertainty in emergy analysis, the analyser needs to trace back far enough to determine all basic pathways (or background data) using environmental accounting techniques such as LCA.

3. Methodology

In this research, to meet the challenges of measuring long-term sustainability of buildings, an emergy-based life cycle sustainability assessment (Em-LCA) was proposed. Em-LCA aims to offer a more quantitative and comprehensive technique than existing LCA tools. It should be stressed that the emergy concept has been applied as a valuable complement, rather than an alternative to existing LCA, as standard LCA is an important part of this method.

Fig. 1 shows a schematic of the Em-LCA framework for a general building system. As shown in Fig. 1, by applying Em-LCA it will be possible to transform all life cycle inflows and outflows throughout the life cycle of a building to an emergy equivalent. Em-LCA methodology and its application for two different residential buildings (i.e. multi-unit residential and single-family house) are presented in the following sections.

3.1. Step 1: identifying Em-LCA scope and system diagram boundary

A *top-down* system analysis approach was applied for this study. The first step of Em-LCA is goal definition and scoping. In this step the process is described as an energy system diagram and the boundaries of analysis are established. The primary objective of Em-LCA is to evaluate environmental and associated socio-economic impacts of a built environment system over its life cycle (cradle to grave). The secondary objective of conducting Em-LCA can be identified according to the information that decision makers need, selected impact categories (e.g. upstream and/or downstream environmental impacts), and different characteristics of the system under study and design scenarios. In this study, the Em-LCA framework considers three main impact categories:

(1) Resource inputs or upstream impacts including renewable and non-renewable resources.
(2) Waste and emission or downstream impacts.
(3) Associated socio-economic impacts including monetary costs and purchased labour and services.

After identifying the scope of analysis, a system diagram as a means of organizing thinking and interactions between constituents and pathways of exchange, resource flows, and downstream outflows need to be established. A system diagram is an overview of the scope and boundaries of analysis. The building system under study can be perceived as a thermodynamic engine that ingests resources to produce specific amenities; produces emissions to air, water, and land; and sustains its performance with regard to variable situations, such as demand changes, over its life cycle. All driving energies and interactions (system inflows) as well as outflows and feedbacks from the system are simulated as energy pathways. In addition, the system diagram of a building must be included in the economy and environment interactions of the system.

In this study, a typical 200 square metre single-family house was designed based on BC building code (under part 9) and Vancouver seismic load. A 2-level wood-frame structural system has been selected based on common practices for single family houses in BC and Canada.

In addition a typical 4000 square metre, multi-unit condominium residential was designed based on BC building code (under part 4) and Vancouver seismic load. A 7-storey plus one underground parking concrete-frame structural system has been chosen according to the common practices for multi-unit residential buildings in BC and Canada. The

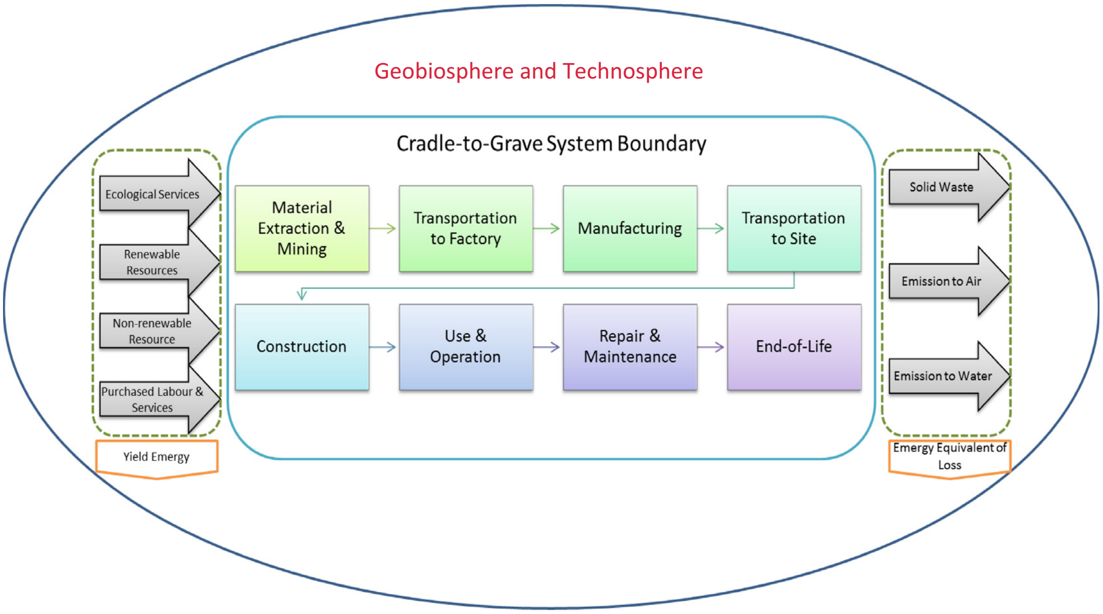

Fig. 1. Em-LCA methodology for a general building system.

building has been designed to serve as a rental multi-unit residential encompassing six, two-bedroom suites at each level. Both buildings have then been redesigned based on design requirements and seismic load for the cities of Toronto, Calgary, and Montreal. Full level of occupancy and an average of 3 and 4 residents were assumed per each unit of multi-unit residential and single-family houses respectively.

The operational energy of a single-family house has been assigned based on nationally and/or regionally averaged data for household energy use reported by Statistics Canada (Statistics Canada, 2007). In that document the 'heated area' of a building excludes basements and garages. Accordingly, the annual energy consumption per household has been estimated for the understudied buildings based on the heated area of each unit. Table 1 indicates average household energy use considered for each building type in different provinces of Canada. It was assumed that the water consumption per capita, per household is not variable for different types of dwelling, and therefore annual water consumption was neglected.

A 60-year service design life for the general Canadian building has been considered for all building assemblies. The system diagram of the examined buildings and the boundary of analysis have been shown in Fig. 2 to visualize the mass and energy flows and their interaction. Later, the differences between building types and locations will be analysed by quantifying the pathways through the system diagram.

3.2. Step 2: inventory analysis and developing emergy evaluation table

In the previous Em-LCA step, the system boundaries were established, while in this step the quantity of system inflows and outflows (pathways that crossed the system boundary) is accounted for. Inventory analysis requires collecting data for all process units and life cycle phases, and their associated energy and mass flows, as well as data on emissions and discharges into the receiving waters, soil, and air (Reza et al., 2011).

The first step to compile the life cycle inventory data of a building is to identify the bill of material (refer to Table 4 and Table 5) and average annual service/operation energy, and associated life cycle cost of that building. Next, a standard local life cycle inventory database was applied to facilitate inventory analysis and avoid duplication in data compilation. For that reason, Athena libraries were used as a Canadian database to obtain background data for different building assemblies and different building life cycle processes and activities (such as transportation and site activities, service energy and operation process, and end-of-life disposal) (Athena Sustainable Materials Institute, 2014). In this study, building assemblies (floors,

Table 1
Average annual operating energy use (gigajoules per household).

Building type	Size of heated area (m^2)	Energy type	BC	ON	AB	QC
Single-family house	186–232	Natural gas (NG)	122	147	166	139
Multi-unit residential	93–139	Electricity & NG	97	101	128	118

BC: British Columbia, ON: Ontario, AB: Alberta, QC: Quebec.

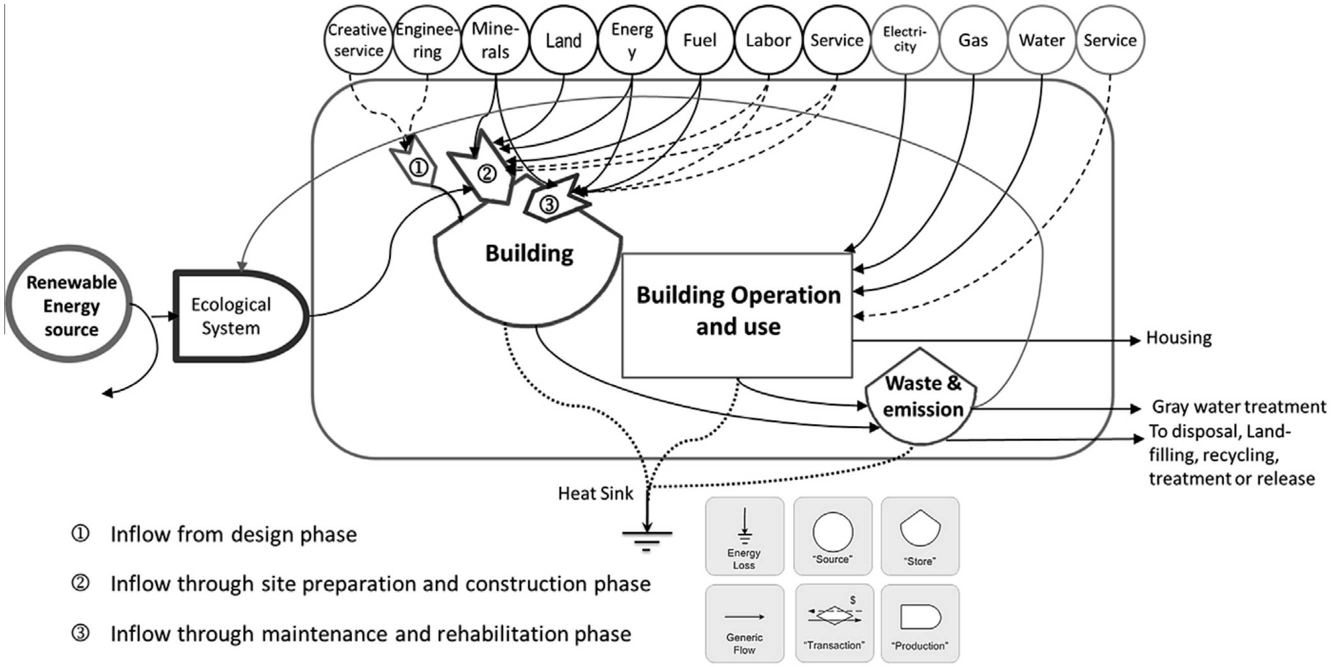

Fig. 2. To understand energy system language symbols and their inherent mathematics see (Odum, 1996, 1994).

roof, foundation, walls, and extra materials) were modelled in Athena Impact Estimator for Buildings. The Athena LCA software is not able to model building operating energy. However, operating energy can be included in the building LCA if the user inputs an estimate for annual operating fuel consumption. (Athena Sustainable Materials Institute, 2013). In this study, the average annual operation energy values (Table 1) were entered in the Athena Impact Estimator software. The software then calculated total energy, including pre-combustion energy (the energy used to extract, refine, and deliver energy), and the related emissions to air, water, and land over the life cycle of the building (Athena Sustainable Materials Institute, 2013).

The functional unit considered in the Athena software is the whole building operated over a given duration (i.e. 60 years in this study). However, as the built area and heated area for a single-family house and a multi-unit residential are not equal[2], the final Em-LCA results can be reported as emergy per unit area of buildings (a built m^2) and emergy per capita (of building residents). Bill of material tables (Table 2 and Table 4) and energy consumption (MJ/m^2) of multi-unit residential and single-family house in different life cycle stages (Fig. 9) are indicated in the Appendix.

3.3. Step 3: data analysis and impact assessment

In step 3, the inflows and outflows of the buildings life cycle have been converted into the emergy values. Data analysis and impact assessment for three classes of impacts (i.e. upstream, downstream, and socio-economic impacts) are described in the following sections. The impact categories are expressed as measures of environmental contribution (Ingwersen, 2011) and/or socio-economic contribution to make a product, process, or service available and are estimated based on their corresponding emergy equivalent.

3.3.1. Quantifying resource use or upstream impacts

In this step, the impact of resource inputs to a building's life cycle (upstream impacts) was evaluated as energy resources for geo-biosphere work and services needed for resource formation. Resource inputs to a typical building system can be classified into 5 different categories[3]:

i. Non-renewable minerals (N_m) such as limestone and iron ore.
ii. Non-renewable petroleum (N_p) such as gasoline and oil.
iii. Non-petroleum fuel (N_f) including fuel from sources other than crude oil, such as natural gas.
iv. Local, slowly-renewable natural resources (N_r) such as soil organic matter, animals, wood, and water use.
v. Indigenous renewable energy (R) such as hydroelectricity.

In this step, all inventory data related to resource use needed to be classified based on the five above-mentioned

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[2] It was assumed that heated area of buildings excludes basements and garages.

[3] It is necessary to mention that the proposed categorization was only aimed to facilitate calculating emergy indices. Thus, biosphere (natural) and technosphere (manmade, e.g. gasoline, hydroelectricity) resource inputs were not classified as separate categories.

Table 2
Emergy-based impact indicators for building system.

Indicator	Description	Unit
N_m	Non-renewable minerals per unit area	seJ/m^2
N_r	Slowly-renewable natural resources per unit area	seJ/m^2
N_f	Non-petroleum fuel per unit area	seJ/m^2
N_p	Non-renewable petroleum fuel per unit area	seJ/m^2
R	Renewable energy per unit area	seJ/m^2
EL_{HH}	Emergy equivalent of human health loss per unit area	seJ/m^2
EL_{EQ}	Emergy equivalent of ecological loss per unit area	seJ/m^2
EL_{SW}	Emergy equivalent of natural loss due to solid waste discharge on land per unit area	seJ/m^2
Es_{air}	Ecological services for dispersal of air pollutants per unit area	seJ/m^2
Es_{water}	Ecological services for dispersal of water pollutants per unit area	seJ/m^2
F_S	Emergy equivalent of purchased services per unit area	seJ/m^2
F_L	Emergy equivalent of labour per unit area	seJ/m^2
N	Non-renewable Emergy inputs per unit area: $N_m + N_f + N_p + N_r$	seJ/m^2
F	Emergy Feedback (from economy and ecology): $F_l + F_s + ES_{air} + ES_{water}$	seJ/m^2
EL	Emergy equivalent of natural and human capital losses per unit area: $EL_{HH} + EL_{EQ} + EL_{SW}$	seJ/m^2
Y	Yield Emergy per unit area: $N + R + F$	seJ/m^2
EYR	Emergy yield ratio: Y/F	–
ELR	Environmental loading ratio: $(N + F + EL)/R$	–
ESI	Emergy sustainability index: EYR/ELR	–
E_c	Emergy per capita: $(Y + EL)$/people	seJ/person
E_P	Empower: $(Y + EL)$/Lifetime	seJ/yr

categories. In addition to Athena LCI results for resource use, the effect of land use (soil erosion or loss of soil organic matter) has been evaluated considering the loss of organic matter content in the built area equivalent to an average 3% of 1 m depth ground volume as proposed by Pulselli et al. (2007). Accordingly, weight of 1 m depth of total excavation has been multiplied by 3% of organic substance, 22.6 kJ energy content per each gram of soil organic matter (Reza et al., 2014). After classifying all inventory data related to resource use, UEV for each inventory item must be extracted from the emergy database (Odum, 1996) and adopted based on the global biosphere emergy baseline[4] (Odum, 2000). Eventually, using UEV of each input pathway, all resource inputs in the inventory are converted to emergy values using Eq. (2).

3.3.2. Quantifying emissions and wastes or downstream impacts

The consequences of airborne and waterborne emissions and solid waste generation can be quantified based on two potential effects that can harm the ecosystem, people, and the economy:

i. The natural and human capital losses or preliminary damage (e.g. acidification, eutrophication of lakes, ecotoxicity, and human health) (Bakshi, 2002; Liu et al., 2011a,b).
ii. The ecological services needed to dilute emissions (Ulgiati and Brown, 2002; Ulgiati et al., 1995).

In this research, the approach of *Eco-indicator 99* has been used to evaluate the preliminary damage due to natural and human capital losses. According to Eco-indicator 99, emission impacts on ecosystem quality and human health can be expressed by two indicators:

- Potentially disappeared fraction (PDF) of species in the affected ecosystem[5]
- Disability adjusted life years per unit emission (DALY).

Then these two indicators, PDF and DALY, can be converted to a corresponding emergy equivalent of (human or natural capital) loss (EL) as proposed by Liu et al. (2011a,b). Emergy equivalent of loss in support of local ecological resources can be measured Eq. (3) as proposed by Liu et al. (2011a,b):

$$EL_{EQ} = \sum m_i \times \text{PDF}(\%)_i \times E_{\text{bio}} \tag{3}$$

where EL_{EQ} denotes emergy equivalent of loss of regional natural resources due to given emission, m_i is the amount of ith chemical released, PDF (%) is calculated as PDF $\times$ m^2 $\times$ yr $\times$ kg^{-1}, and E_{bio} represents the unit of annual emergy allocated to regional natural capital[6]. The emergy equivalent of loss in support of human resources

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[4] Global biosphere emergy baseline is the total emergy driving the biogeosphere. So far a few different global biosphere emergy baselines have been suggested by emergy practitioners. In this research the sum of solar, tidal, and deep heat sources is considered to be equal to the value of 15.83E24 sej/yr as suggested by Odum (Odum, 2000).

[5] The PDF can be interpreted as the fraction of species that has a high probability of no occurrence in a region due to unfavorable conditions caused by acidification and eutrophication.

[6] To understand the environmental accounting procedure (based on emergy synthesis) of natural capital and ecosystem services see (Campbell and Brown, 2012), (Brown and Ulgiati, 1999), and for the Canadian provinces that used in this paper see (Hossaini and Hewage, 2013).

can be calculated using Eq. (4) as proposed by Liu et al. (2011a,b):

$$EL_{HH} = \sum m_i \times \mathrm{DALY}_i \times E_\mathrm{P} \tag{4}$$

where EL_{HH} represents emergy equivalent of human health loss due to given emission m_i, DALY represents the disability adjusted life years per unit emission (yr × g^{-1}), and E_P is the total annual emergy per population (e.g., annual emergy per population for Canada is 1.73E+17 seJ/yr/pop (Hossaini and Hewage, 2013).

In addition, damage associated with solid waste generation can be quantified based on land occupation for landfill and disposal using Eq. (5):

$$EL_{SW} = \sum m_i \times L_\mathrm{OC} \times E_\mathrm{L} \tag{5}$$

where EL_{SW} represents emergy equivalent of natural loss due to discharge of solid waste on land, m_i is given solid waste total mass (tonne), L_{OC} represents land occupation factor (ha per tons of waste), and E_L is the emergy value of land restoration per area (seJ/ha) assuming 50 years recovery time. Approximately 2.85E+4 tonnes of industrial solid waste occupy 1 ha land, and the average emergy value due to land erosion and replacement can be measured using the UEV of 1.05E+15 seJ/ha (X.H. Zhang et al., 2010).

The second method to quantify emission impacts by means of emergy synthesis is measuring the ecological services (feedback) that are required to prevent or fix reversible damages incurred and charged to a process (Ulgiati and Brown, 2002; Ulgiati et al., 1995). In other words, the impact of emissions can be addressed based on the ecosystem services needed to dilute undesired by-products generated by a process to an acceptable state or concentration level (X.H. Zhang et al., 2010). Ecological services for diluting airborne/waterborne pollutants can be calculated based on required mass of dilution of air/water using Eq. (6):

$$M = d \times (m/c) \tag{6}$$

where d represents air/water density, m is the amount of given emission from the process, and c is the acceptable or background concentration according to regulations. Then the energy value of ecological services (feedback) required to dispose of airborne emissions can be determined by calculating kinetic energy of the services required to dilute airborne pollution, using the average value of wind speed in the area (2 m/s for the under study area). Finally, the *emergy value of the required ecological service for air dilution* (ES_{air}) can be determined by multiplying achieved wind kinetic energy by its UEV (2.52E+3 seJ/J) Odum, 1996.

Ecological services for diluting waterborne emissions can be derived with the same concept. The amount of energy required to dilute water pollutants can be achieved by calculating average surface runoff energy in the area (X.H. Zhang et al., 2010). Finally, the *emergy value of the required ecological service for water dilution* (ES_{water}) can be determined by multiplying achieved surface runoff energy by its UEV (3.05E+4 seJ/J) (Odum, 1996).

3.3.3. Evaluating monetary resources and purchased labour and services

Often, labour and services[7] are not accounted for in a final impact assessment in a conventional LCA. However, every process consists of investing emergy (F) from the economic system due to different activities such as extracting and refining the resources, manufacturing and producing goods, and providing labour and services for construction, rehabilitation, and maintenance. Odum (1996) presents a new approach based on emergy synthesis to account for the effects of labour and services based on the level of personnel training and education, and related emergy required to support them (Odum, 1996).

According to Ulgiati and Brown (2012), if we trace back far enough through the web of energy and material flows of a system, it can be revealed that all the money invested in a process is used in order to purchase labour and services (indirect labour). They emphasize that it is not necessary to assess the monetary value for each input item in the supply chain, and services can be accounted for from the price of final inputs to the foreground.

In order to evaluate emergy value of labour and services, their associated monetary cost must be multiplied by national/regional *emergy money ratio (EMR)*, which represents emergy investment per unit of GDP generated in a country, region, or process. Emergy value for direct labour and local services (e.g. design and tendering, and ownership cost) and labour can be accounted for based on local currency (local EMR). Emergy value for other services (e.g. material and energy costs for construction, maintenance, rehabilitation, and operation related services) associated with national flows of material and energy inputs can be determined based on national currency (national EMR). National EMRs for different regions have been reported in the NEAD[8]database. EMRs for Canadian provinces are reported in Hossaini and Hewage (2013).

3.4. Step 4: flow summary and calculation of emergy-based indicators (EMII)

In the final step of the proposed Em-LCA, the emergy of different items of the examined buildings is combined and aggregated to obtain emergy-based impact indicators (EMII). Several EMII can be calculated from the flows of emergy supporting processes and products. In this study

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[7] According to Brown et al. (2012) labour can be define as an activity that directly applied to a process, while services can be recognized as activities that indirectly applied to a process from the larger scale of the economy.

[8] NEAD can be found in the following web page: http://sahel.ees.ufl.edu/frame_database_resources_test.php?search_type.

EMII will be used to compare different building alternatives and scenarios.

Various EMII have been calculated by emergy practitioners and each of them has a specific sustainability meaning (e.g., see Ulgiati et al., 1995; Huang and Hsu, 2003; Brown and Ulgiati, 2010, 1997; X. Zhang et al., 2011). In this study, the common EMII have been slightly modified to consider the contribution of three upstream, downstream, and socio-economic impacts for different building systems as presented in Table 2.

In this study, three impact categories identified in Section 3.1 have been used to analyse long-term impacts of residential building practices in Vancouver (BC). Later the analysis is repeated by considering the first impact category for three other provinces in Canada (Ontario, Alberta, and Quebec), where the three large cities of Toronto, Calgary, and Montreal are located. As an example, the emergy evaluation process for different impact categories of the single-family house in Vancouver, BC has been described in several emergy evaluation tables in “Appendix” section (Tables 6–10).

4. Results and discussion

Emergy-based indicators of a multi-unit residential building and single family house in Vancouver, BC have been summarized in Table 3. Fig. 3 indicates different categories of life cycle resource consumption (upstream impacts) of the multi-unit residential and single-family house in Vancouver, BC. According to this figure, the multi-unit residential building is more resource demanding with regard to the non-renewable mineral (N_m) consumption and fuel consumption (N_f and N_p), while the single-family house is considerably more resource demanding according to the slowly-renewable natural resources (N_r) as it causes further land use or loss of soil organic matter in the construction phase. On the other hand, while total non-renewable resource uses in the two building types

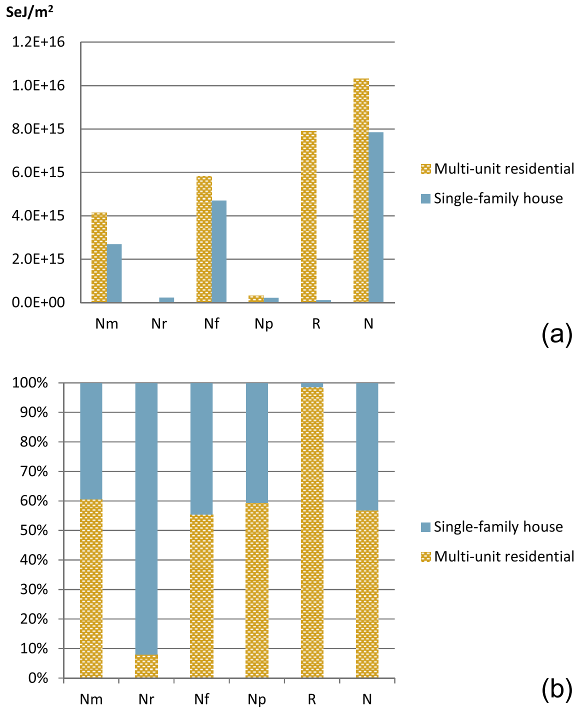


Fig. 3. Upstream impacts of multi-unit residential and single-family house (Vancouver, BC), (a) absolute values, (b) relative percentages (Non-renewable minerals (N_m), non-renewable petroleum (N_p), non-petroleum fuel (N_f) Local, slowly-renewable natural resources (N_r), indigenous renewable energy (R)).

Table 3
Emergy-based indicators of multi-unit residential building and single family house in Vancouver, BC.

Indicator	Description	Unit	Multi-unit residential	Single-family house
N_m	Non-renewable minerals	seJ/m^2	4.1E+15	2.7E+15
N_r	Slowly-renewable natural resources	seJ/m^2	2.0E+13	2.3E+14
N_f	Non-petroleum fuel	seJ/m^2	5.8E+15	4.7E+15
N_p	Non-renewable petroleum fuel	seJ/m^2	3.2E+14	2.2E+14
R	Renewable energy	seJ/m^2	7.9E+15	1.2E+14
EL_{HH}	Emergy equivalent of human health loss	seJ/m^2	6.2E+14	2.4E+14
EL_{EQ}	Emergy equivalent of ecological loss	seJ/m^2	2.5E+13	1.1E+13
EL_{SW}	Emergy equivalent of natural loss due to solid waste discharge on land	seJ/m^2	1.9E+03	1.0E+04
ES_{air}	Ecological services for dispersal of air pollutants	seJ/m^2	3.9E+13	1.8E+13
ES_{water}	Ecological services for dispersal of water pollutants	seJ/m^2	1.0E+14	4.9E+13
F_S	Emergy equivalent of purchased services	seJ/m^2	3.5E+16	1.9E+16
F_L	Emergy equivalent of labour	seJ/m^2	1.3E+15	5.6E+14
N	Non-renewable Emergy inputs: $N_m + N_f + N_p + N_r$	seJ/m^2	1.0E+16	7.9E+15
F	Emergy Feedback (from economy and ecology): $F_l + F_s + Es_{air} + Es_{water}$	seJ/m^2	3.6E+16	1.9E+16
EL	Emergy equivalent of natural and human capital losses: $EL_{HH} + EL_{EQ} + EL_{SW}$	seJ/m^2	6.4E+14	2.5E+14
Y	Yield Emergy: $N + R + F$	seJ/m^2	5.4E+16	2.7E+16
EYR	Emergy yield ratio: $Y/F_l + F_S$	-	1.5E+00	1.4E+00
ELR	Environmental loading ratio: $(N + F + \mathrm{EL})/R$	-	6.0E+00	2.3E+02
ESI	Emergy sustainability index (EYR/ELR)	-	2.5E−01	6.3E−03
E_c	Emergy per capita $(Y + \mathrm{EL})$/residents	seJ/person	1.8E+18	1.4E+18
E_P	Empower intensity: $(Y + \mathrm{EL})$/lifespan	seJ/m^2/yr	9.1E+14	4.5E+14

are comparable, the portion of renewable resource use (*R*) as compared to nonrenewable resource use (*N*) is considerably greater in the multi-unit residential building in Vancouver, BC. This is because a significant portion of annual operation energy in the multi-unit residential building in Vancouver was electricity (i.e. hydroelectricity in BC province), which is a renewable source of energy (see Table 1).

Fig. 4 compares different downstream impact categories of the single-family house and multi-unit residential building in Vancouver, BC. According to this figure, the multi-unit residential building causes more natural and human capital losses due to emission to air and water, and discharge of solid waste on land, while needing more ecological services (ES_{air} and ES_{water}) to dilute emissions. Altogether, the multi-unit residential building causes more downstream impact per unit area as compared to the single-family house in Vancouver, BC. Comparing Figs. 3 and 4 it is clear that the total upstream impact is significantly more than that of the total downstream impact of building stock in Vancouver, BC.

The life cycle monetary costs were calculated based on average cost of labour and services in Canada. The impacts of life cycle costs (socio-economic impacts) are considered as emergy investment (*F*) from the economic system due to different activities such as extracting and refining the nonrenewable resource, manufacturing and producing goods, and providing labour and services for construction, rehabilitation, and maintenance. Emergy value for local services (i.e. design and tendering, and ownership cost) and labour has been accounted for based on local currency (BC emergy/GDP is 2.67E+12 seJ/CAD$ (Hossaini and Hewage, 2013). The emergy value for other services (i.e. construction, maintenance, rehabilitation, and operation related services) associated with national flows of material and energy inputs has been determined based on national currency (Canada emergy/GDP is 4.22E+12 seJ/CAD$ (Hossaini and Hewage, 2013).

Fig. 5(a) compares emergy investment from the economic system to purchase labour (F_L) and services (F_S), while Fig. 5(b) compares the total emergy investment (*F*) associated with different life cycle stages of the two buildings. According to these figures the emergy costs per unit area associated with the life cycle of multi-unit residential building are about twice the single-family house. Moreover, the ownership cost per unit area is the highest life cycle cost, which is about ~2 times higher for the multi-unit residential (rental suites) as compared to the single-family house in a 60 year time period.

Fig. 6 compares emergy-based indicators of the two buildings. According to this figure, a multi-unit residential building causes more significant upstream, downstream, and socio-economic impacts per unit area (altogether) throughout its life cycle. The yield emergy (total life cycle emergy) per unit area of the multi-unit residential building is twice the single-family house in Vancouver, BC.

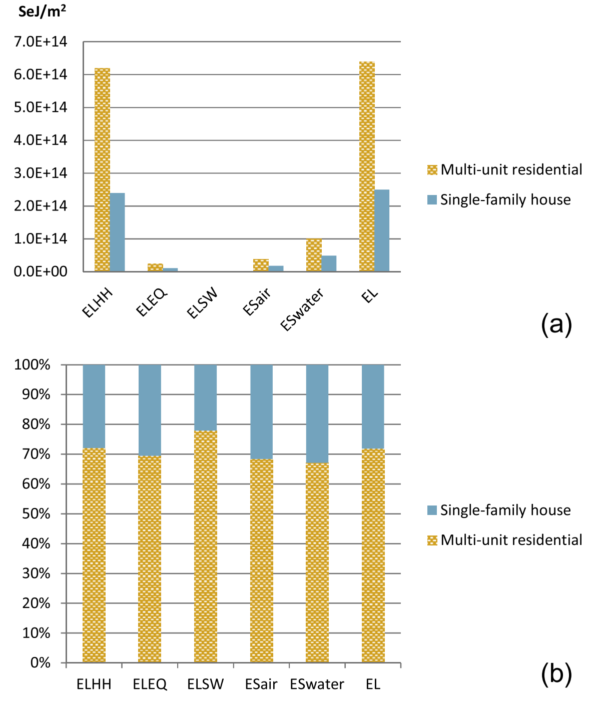
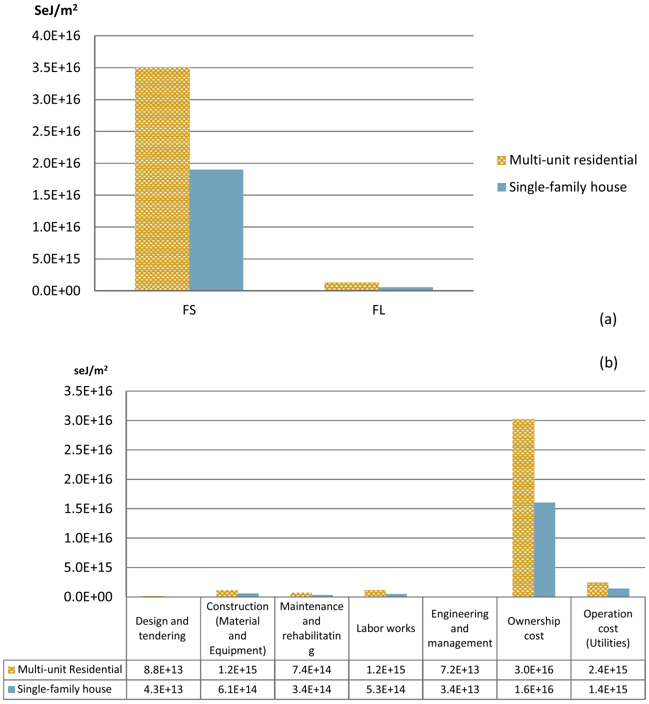


Fig. 4. Downstream impacts of multi-unit residential and single-family house (Vancouver, BC) (a) absolute values, (b) relative percentages (EL_{HH}: emergy equivalent of human health loss per unit area, EL_{EQ}: emergy equivalent of ecological loss per unit area, EL_{SW}: emergy equivalent of natural loss due to solid waste discharge on land per unit area, ES_{air}: ecological services for dispersal of air pollutants per unit area, ES_{water}: ecological services for dispersal of water pollutants per unit area).



	Design and tendering	Construction (Material and Equipment)	Maintenance and rehabilitation g	Labor works	Engineering and management	Ownership cost	Operation cost (Utilities)
▨ Multi-unit Residential	8.8E+13	1.2E+15	7.4E+14	1.2E+15	7.2E+13	3.0E+16	2.4E+15
■ Single-family house	4.3E+13	6.1E+14	3.4E+14	5.3E+14	3.4E+13	1.6E+16	1.4E+15

Fig. 5. Investing emergy from the economic system to purchase labour and services for multi-unit residential and single-family house (Vancouver, BC) (F_S: emergy equivalent of purchased services per unit area, F_L: emergy equivalent of labour per unit area).

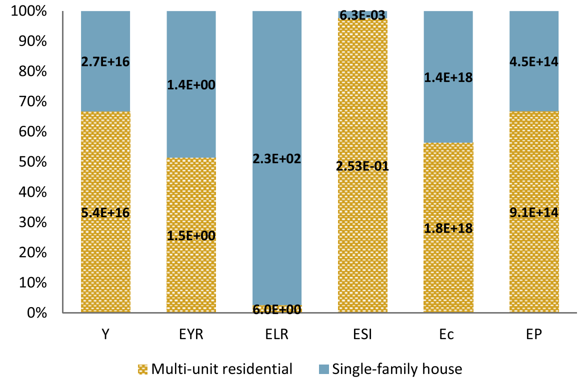


Fig. 6. Emergy-based indicators of multi-unit residential building and single family house in Vancouver (BC) (Y: yield emergy per unit area (SeJ/m^2), EYR: emergy yield ratio, ELR: environmental loading ratio, ESI: emergy sustainability index, E_C: emergy per capita: (SeJ/person), E_P: Empower (SeJ/yr)).

However, emergy per capita (E_c) of two building is comparable, which is only ∼11% greater for the multi-unit residential building in Vancouver, BC. This means the two building types cause similar life cycle impacts in providing housing for each resident. In addition, the emergy yield ratio (EYR), which indicates total emergy released per unit of emergy invested, for the multi-unit residential building is comparable, which is only ∼7% greater for the multi-unit residential building in Vancouver, BC.

In contrast, the environmental loading ratio (ELR), which indicates total emergy equivalent of natural and human capital losses plus nonrenewable and invested emergy per unit of local renewable resource, for the single-family house is significantly greater than ELR for the multi-unit residential building. Moreover, according to the emergy sustainability index (ESI) that indicates emergy yield per unit of environmental loading, the multi-unit residential building shows higher ESI than the single-family house in Vancouver, BC. This is because a considerable portion of annual operation energy in the multi-unit residential building in Vancouver is electricity (i.e. hydroelectricity), which is a renewable source of energy. Therefore, the operation of the multi-unit residential building is highly dependent on local renewable energy sources, whereas the main source of energy in the single-family house in Vancouver is natural gas, which is a non-renewable source of energy. As a result, based on the nationally and regionally averaged annual energy use data, the multi-unit residential building consumes energy in a more sustainable manner than the single-family house.

In order to investigate the validity of Em-LCA results in other Canadian provinces, steps 1–4 of Em-LCA framework have been repeated for the two types of building in other large and populous cities in three other regions of Canada, i.e. Toronto (located in Ontario or ON), Calgary (located in Alberta or AB), and Montreal (located in

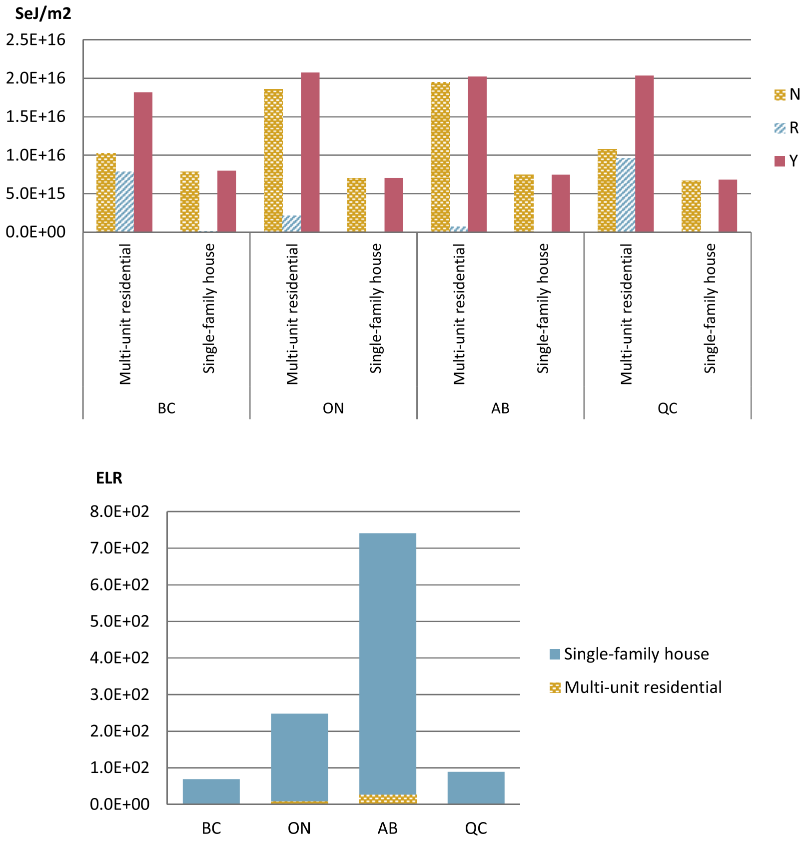


Fig. 7. EMII for single-family houses and multi-unit residential buildings in different provinces of Canada (BC: British Columbia, ON: Ontario, AB: Alberta, QC: Quebec).

Québec or QC). From the previous analysis it was realized that the first categories of impacts (upstream impacts) are dominant (e.g., compare "N" with "EL" in Figs. 3 and 4). Hence, only upstream impacts have been considered for the second run of Em-LCA.

The results of upstream impacts have been combined and aggregated to obtain EMII to compare the life cycle effects of single-family house and multi-unit residential building in different provinces of Canada (Fig. 7). Results show that life cycle resource use or upstream impacts caused by different building types in three other Canadian provinces (AB, ON, and QC) follow the same pattern as for BC.

According to Fig. 7, the yield emergy (total life cycle emergy per unit area) of multi-unit residential buildings is ∼2–3 times greater than the single-family houses in different Canadian provinces. While total non-renewable resource uses per unit area in all provinces are greater for multi-unit residential buildings, the portion of renewable resource use (*R*) as compared to nonrenewable resource use (*N*) is considerably greater in multi-unit residential building in all provinces. This is because operation energy use in multi-unit residential buildings was considered to be a combination of electricity and natural gas, while in single-family houses was considered to be natural gas based on the average national energy data (see Table 1). As a result, the environmental loading ratio (ELR), which indicates total emergy equivalent of natural and human capital losses plus nonrenewable and invested emergy released per unit of local renewable resource, for the single-family houses is always greater than ELR for multi-unit residential buildings. On the other hand, ELR for residential buildings in AB and ON is considerably greater than in BC and QC. This is because the electricity in BC and QC is hydro, which is a renewable energy source, while a significant portion of electricity in AB and ON is produced from nonrenewable sources, i.e. coal and nuclear energy.

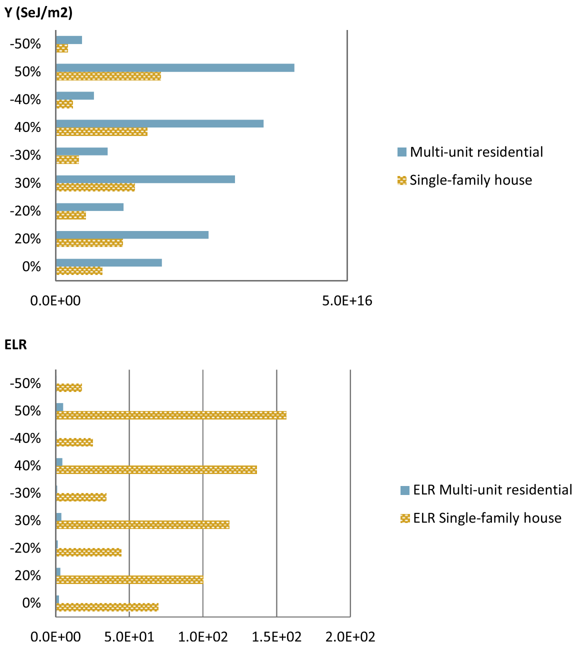


Fig. 8. Sensitivity analysis (effect of variable annual operational energy on Y and ELR indices).

Table 4
Bill of material report for typical single-family residential in Vancouver, BC.

Material	Quantity	Unit
#15 Organic felt	530.4549	m^2
1/2″ Regular gypsum board	974.4204	m^2
5/8″ Regular gypsum board	228.3303	m^2
6 mil polyethylene	573.3610	m^2
Aluminium	0.9535	Tonnes
Batt. fibreglass	4725.2731	m^2 (25 mm)
Cold rolled sheet	0.9929	Tonnes
Concrete 20 MPa (flyash av)	49.7196	m^3
EPDM membrane (black, 60 mil)	223.9296	kg
Galvanized sheet	0.2063	Tonnes
Joint compound	1.2004	Tonnes
Large dimension softwood lumber, kiln-dried	6.3607	m^3
Low E tin argon filled glazing	165.4599	m^2
Metric modular (modular) brick	256.4363	m^2
Mortar	6.7362	m^3
Nails	0.3679	Tonnes
Organic felt shingles 25 yr	488.5769	m^2
Paper tape	0.0138	Tonnes
PVC	1197.8257	kg
Rebar, rod, light sections	1.6778	Tonnes
Screws, nuts & bolts	0.0856	Tonnes
Small dimension softwood lumber, kiln-dried	12.8069	m^3
Softwood plywood	890.9060	m^2 (9 mm)
Water based latex paint	906.8422	L
Welded wire mesh/ladder wire	0.1213	Tonnes
Wide flange sections	1.8786	Tonnes

Table 5
Bill of material report for typical multi-unit residential in Vancouver, BC.

Material	Quantity	Unit
1/2″ Regular gypsum board	470.8000	m^2
5/8″ Regular gypsum board	704.8800	m^2
Aluminium	34.3954	Tonnes
Ballast (aggregate stone)	142366.3043	kg
Batt. fibreglass	7182.8192	m^2 (25 mm)
Concrete 20 MPa (flyash av)	180.6732	m^3
Concrete 30 MPa (flyash 25%)	1040.9091	m^3
Concrete 30 MPa (flyash av)	1921.9318	m^3
EPDM membrane (black, 60 mil)	1651.3817	kg
Extruded polystyrene	3583.6763	m2 (25 mm)
Galvanized sheet	7.5265	Tonnes
Galvanized studs	4.0241	Tonnes
Glazing panel	110.0253	Tonnes
Joint compound	1.1734	Tonnes
Nails	0.0952	Tonnes
Paper tape	0.0135	Tonnes
Polyester felt	0.8259	Tonnes
Polyethylene filter fabric	0.1764	Tonnes
Polyiso foam board (unfaced)	1325.4797	m^2 (25 mm)
PVC membrane 48 mil	5203.5291	kg
Rebar, rod, light sections	264.8485	Tonnes
Screws, nuts & bolts	1.2485	Tonnes
Water based latex paint	22333.6454	L
Welded wire mesh/ladder wire	0.7835	Tonnes

Table 6
Emergy equivalent of resource use or upstream impacts (single-family house in Vancouver, BC).

Resources (Unit)	Type	UEV Odum, 1996 (seJ/unit)	Manufacturing	Construction	Maintenance	Operating energy		End-of-life	Total	Emergy (seJ)	Emergy density (seJ/m^2)
						Annual	Total				
Limestone (kg)	N_m	1.69E+12	1.8E+04	–	3.8E+03	–	–	–	2.2E+04	3.7E+16	1.9E+14
Clay & shale (kg)	N_m	4.10E+12	3.4E+04	–	6.4E+00	–	–	–	3.4E+04	1.4E+17	7.0E+14
Iron ore (kg)	N_m	4.43E+12	1.0E+03	–	8.0E+02	–	–	–	1.8E+03	8.0E+15	4.0E+13
Sand (kg)	N_m	1.69E+12	3.3E+03	–	1.9E+03	–	–	–	5.3E+03	8.9E+15	4.5E+13
Ash (kg)	N_m	2.35E+13	1.3E+02	–	–	–	–	–	1.3E+02	3.1E+15	1.5E+13
Gypsum (natural) (kg)	N_m	1.69E+12	3.7E+03	–	–	–	–	–	3.7E+03	6.2E+15	3.1E+13
Gypsum (synthetic) (kg)	N_m	2.35E+13	5.3E+03	–	–	–	–	–	5.3E+03	1.2E+17	6.2E+14
Semi-cementitious material (kg)	N_m	3.70E+12	1.1E+03	–	–	–	–	–	1.1E+03	4.1E+15	2.0E+13
Coarse aggregate (kg)	N_m	1.69E+12	5.0E+04	–	–	–	–	–	5.0E+04	8.5E+16	4.2E+14
Fine aggregate (kg)	N_m	1.69E+12	5.1E+04	–	–	–	–	–	5.1E+04	8.7E+16	4.3E+14
Land use (soil erosion) (J)	N_r	1.05E+05	–	2.3E+11	–	–	–	–	2.3E+11	2.4E+16	1.2E+14
Water (L)	N_r	2.10E+09	1.1E+05	–	4.8E+04	–	–	–	1.6E+05	3.4E+14	1.7E+12
Obsolete scrap steel (kg)	N_m	7.80E+12	2.7E+03	–	2.9E+02	–	–	–	3.0E+03	2.3E+16	1.2E+14
Prompt scrap steel as feedstock (kg)	N_m	7.80E+12	1.7E+03	–	1.7E+02	–	–	–	1.9E+03	1.5E+16	7.3E+13
Wood fibre (kg)	N_r	1.40E+12	1.6E+04	–	–	–	–	–	1.6E+04	2.2E+16	1.1E+14
Metallurgical coal as feedstock (kg)	N_p	1.69E+12	1.8E+02	–	2.8E+02	–	–	–	4.5E+02	7.7E+14	3.8E+12
Natural gas as feedstock (MJ)	N_f	8.05E+10	1.2E+04	–	2.8E+04	–	–	–	4.1E+04	3.3E+15	1.6E+13
Crude oil as feedstock (MJ)	N_p	9.27E+10	2.9E+04	–	6.3E+04	–	–	–	9.2E+04	8.5E+15	4.3E+13
Hydro (MJ)	R	2.67E+11	4.0E+04	2.1E+03	4.3E+04	1.56E+01	9.39E+02	1.20E+01	8.61E+04	2.30E+16	1.15E+14
Coal (MJ)	N_p	6.71E+10	5.7E+04	5.3E+02	2.6E+04	2.28E+02	1.37E+04	1.70E+02	9.74E+04	6.54E+15	3.27E+13
Diesel (MJ)	N_p	1.21E+11	3.7E+04	6.8E+04	1.4E+04	8.10E+02	4.86E+04	2.60E+04	1.94E+05	2.34E+16	1.17E+14
Gasoline (MJ)	N_p	1.11E+11	1.7E+02	–	4.1E+01	0.00E+00	0.00E+00	–	0.00E+00	0.00E+00	0.00E+00
Heavy fuel oil (MJ)	N_p	1.11E+11	1.7E+04	1.5E+03	1.2E+04	1.01E+02	6.08E+03	5.80E+02	3.72E+04	4.12E+15	2.06E+13
LPG (MJ)	N_p	8.05E+10	4.2E+03	6.9E+01	1.2E+02	4.75E+01	2.85E+03	2.60E+01	7.27E+03	5.85E+14	2.92E+12
Natural gas (MJ)	N_f	8.05E+10	2.7E+05	3.1E+03	6.1E+04	1.30E+05	7.82E+06	1.10E+03	8.15E+06	6.56E+17	3.28E+15
Nuclear (MJ)	N_f	2.00E+11	3.4E+05	1.3E+02	1.1E+06	5.76E+01	3.46E+03	4.50E+01	1.44E+06	2.89E+17	1.44E+15

Table 7
Emergy equivalent of air emission downstream impacts (single-family house in Vancouver, BC).

Airborne Pollution	Damage category HH	DALY/g	Damage category EQ	PDF%	Manufacturing	Construction	Maintenance	Operating energy		Total effect	Emergy equivalent of loss (seJ)		Ecological services (seJ)
								Annual	Total		EL_{HH}	EL_{EQ}	Es_{air}
Carbon dioxide, biogenic g	CC	2.10E−10	–	–	2.2E+03	0.0E+00	2.7E+00	–	–	2.2E+03	7.9E+10	–	2.2E+07
Carbon dioxide, fossil g	CC	2.10E−10	–	–	3.3E+04	5.4E+03	1.2E+04	4.5E+03	2.7E+05	3.2E+05	1.2E+13	–	1.5E+10
Nitrogen oxides g	RD	8.87E−08	AC	5.71E+00	9.9E+04	3.7E+04	4.1E+04	3.4E+02	2.0E+04	2.0E+05	3.1E+15	6.4E+14	1.2E+14
Sulphur dioxide g	RD	5.46E−08	AC	1.04E+00	1.8E+05	2.0E+02	9.1E+04	4.0E+04	2.4E+06	2.7E+06	2.5E+16	1.5E+15	3.2E+15
Sulphur oxides g	RD	5.46E−08	AC	1.04E+00	2.5E+04	5.5E+03	2.1E+04	7.3E+01	4.4E+03	5.8E+04	5.4E+14	3.3E+13	6.9E+13
Particulates, >2.5 μm, and <10 μm g	RD	3.75E−07	–	–	1.5E+04	6.4E+02	1.4E+03	2.8E+02	1.7E+04	3.5E+04	2.3E+15	–	1.3E+13
Particulates, <2.5 μm g	RD	3.75E−07	–	–	1.3E+05	3.8E+02	1.1E+05	1.4E+01	8.2E+02	2.4E+05	1.6E+16	–	9.0E+13
Methane g	RD	1.28E−11	–	–	8.6E+04	9.4E+01	2.8E+04	2.0E+04	1.2E+06	1.3E+06	3.0E+12	–	5.7E+11
Methane g	CC	4.40E−09	–	–	8.6E+04	9.4E+01	2.8E+04	2.0E+04	1.2E+06	1.3E+06	1.0E+15	–	–

Notes: HH: human health; CC: climate change; RD: respiratory disorders; EQ: ecosystem quality; AC: acidification.

Table 8
Emergy equivalent of water emissions downstream impacts (single-family house in Vancouver, BC).

Waterborne pollution	Damage category human health	DALY/g	Damage category ecosystem quality	PDF%	Manufacturing	Construction	Maintenance	Operating energy		Total effect	Emergy equivalent of loss (seJ)		Ecological services (seJ)
								Annual	Total		EL_{HH}	EL_{EQ}	Es_{water}
Arsenic, ion (mg)	Carcinogenic impacts	6.57E−05	Ecotoxic	1.14E+01	6.7E+03	1.6E+03	2.8E+03	1.6E+03	9.8E+04	1.1E+05	5.5E+06	6.9E+11	6.5E+12
Cadmium, ion (mg)	Carcinogenic impacts	7.12E−05	Ecotoxic	4.80E+02	1.2E+03	2.3E+02	7.1E+02	2.4E+02	1.4E+04	1.6E+04	2.0E+14	4.3E+12	4.9E+13
Cyanide (mg)	Carcinogenic impacts	4.60E−08	–	–	3.4E+05	4.1E−01	3.6E+05	5.3E−01	3.2E+01	7.0E+05	5.6E+12	–	4.2E+14
Lead (mg)	–	–	Ecotoxic	7.39E+00	1.7E+05	3.4E+03	8.8E+04	2.3E+03	1.4E+05	4.1E+05	–	1.7E+12	1.2E+14
Mercury (μg)	–	–	Ecotoxic	1.97E+02	1.7E+04	5.6E+03	8.9E+03	1.5E+03	8.9E+04	1.2E+05	–	1.3E+13	7.3E+15
Oils,	unspecified (mg)		Carcinogenic impacts		4.16E−08	–	–	1.0E+07	1.3E+05	1.1E+07	1.4E+05	8.5E+06	3.0E+07
2.2E+14	–	1.8E+15											

Ultimately, a sensitivity analysis has been conducted for buildings' annual operational energy use as the largest emergy inputs to the building system (refer to Appendix, Table 6). The sensitivity analysis has been done assuming a variation of the energy input and related UEVs by ±10%, ±20%, . . ., ±50%, and assessing to what extent such a variation affected the final conclusion (e.g., see Fig. 8). Results of sensitivity analysis in this study verify that the final conclusions are analogous, and in all cases prototype multi-unit residential buildings considered in this study cause greater yield emergy (seJ/m^2) while bringing about a smaller environmental loading ratio. In other words, prototype multi-unit residential buildings considered in this study consume significantly higher non-renewable resources and cause greater associated emission impact throughout their life cycle. However, based on the average national energy data, prototype multi-unit residential buildings consume energy in a more sustainable manner (use more renewable sources) as compared to the prototype single-family houses considered in this study.

All in all, the results of this study are in agreement with previous LCA studies that reported the 'amount' and 'type' of annual operating energy as the main factors of building sustainability (e.g. Norman et al., 2006; Hossaini et al., 2014). In addition, the results of Em-LCA confirm that building sustainability does not significantly depend on the type of land use or land development. In contrast, building sustainability considerably depends on the use of renewable resources for operation, as well as the total amount of operation energy use throughout the building lifespan.

5. Summary and conclusions

This paper proposed and applied an improved step-by-step emergy synthesis based on the LCA framework, considering both upstream and downstream ecological and human health impacts, as well as life cycle socio-economic impacts related to human labour and services. This research developed a comprehensive methodology to estimate and integrate a number of TBL sustainability objectives over the life cycle of buildings. Part of those sustainability objectives and their related impacts (e.g., ecological impacts, work of ecosystems to provide 'freely available' services and products, downstream ecological and human health impacts, and life cycle socio-economic impacts) were ignored in other previous LCA studies, emergy research, and economic analysis (e.g. life cycle costing (LCC)) related to sustainability assessment of buildings (e.g. Hossaini et al., 2014; Reza et al., 2011; Pulselli et al., 2009, 2007; Norman et al., 2006; Pulselli et al., 2008). The proposed Em-LCA framework is capable of integrating a wide range of environmental impacts (both ecological and human health effects) and a number of socio-economic aspects, i.e. life cycle monetary cost related to human labour and services, and estimates overall life cycle impact with an unbiased and unified measure that is impossible with many other existing methods. However, it is also true that some of the social sustainability aspects (e.g. effects of multi-unit residential on resident comfort, marriage durability, mental health, social and cultural acceptance, etc.) were not considered in this study as they were out of the authors' area of expertise and need to be further studied by social scientists.

Em-LCA benefits from LCA's capabilities, including standard life cycle inventory (LCI) databases and life cycle impact assessment (LCIA) techniques such as classification, characterization, and end-point impact assessment factors that yield impact categories such as resource use, energy consumption, and air/water/land emission. On the other hand, Em-LCA employs emergy synthesis as an upstream and downstream impact estimator and provides a comprehensive framework to evaluate the life cycle streams and their associated TBL impacts within the same quantitative framework.

The developed Em-LCA framework has been applied for two types of residential buildings (i.e. multi-unit residential and single-family house) in four Canadian provinces. The results of this paper only reflect the overall life cycle impacts of typical multi-unit and single-family residential buildings in Canada and may not be the same in other regions of the world (e.g. more populous cities where the life cycle costs of house ownership is not affordable, or in regions with milder weather where service energy use is not considerable).

Table 9
Emergy equivalent of ecological loss due to solid waste discharge on land (single-family house in Vancouver, BC).

Solid waste	Manufacturing	Construction	Maintenance	Operating energy		End-of-life	Total effects	Land occupation	Emergy equivalent of loss (seJ)	EL_{SW} density (seJ/m^2)
				Annual	Total					
Bark/wood waste kg	1.2E+02	6.7E+02	1.1E+02	–	–	–	9.1E+02	3.2E−08	3.3E+07	1.7E+05
Concrete solid waste kg	2.6E+03	–	–	–	–	–	2.6E+03	9.1E−08	9.6E+07	4.8E+05
Blast furnace slag kg	4.0E+02	–	1.3E+02	–	–	–	5.3E+02	1.9E−08	1.9E+07	9.7E+04
Blast furnace dust kg	3.0E+02	–	1.6E+01	–	–	–	3.2E+02	1.1E−08	1.2E+07	5.9E+04
Steel waste kg	1.3E+01	–	6.2E+00	–	–	–	1.9E+01	6.7E−10	7.0E+05	3.5E+03
Other solid waste kg	2.0E+03	5.1E+01	2.1E+03	4.6E+01	2.8E+03	1.9E+01	6.9E+03	2.4E−07	2.5E+08	1.3E+06

Table 10
Emergy evaluation of single-family house life cycle costs (Vancouver, BC).

Purchased input	Type	UEV Hossaini and Hewage, 2013 (seJ/unit)	Design	Construction	Maintenance	Operating		Total	Emergy (sej)	Emergy density (seJ/m^2)
						Annual	Total			
Design and tendering services	F_s	2.67E+12	3251.7	–	–	–	–	3.3E+03	8.7E+15	4.3E+13
Construction Services (material and equipment)	F_s	4.22E+12	–	29011.2	–	–	–	2.9E+04	1.2E+17	6.1E+14
Maintenance and rehabilitating services	F_s	4.22E+12	–	–	16328.2	–	–	1.6E+04	6.9E+16	3.4E+14
Labour works	F_L	2.67E+12	–	25184.1	14174.2	–	–	3.9E+04	1.1E+17	5.3E+14
Engineering and management works	F_L	2.67E+12	–	1625.9	915.1	–	–	2.5E+03	6.8E+15	3.4E+13
Ownership cost	F_s	2.67E+12	–	–	–	20048.3	1202897.0	1.2E+06	3.2E+18	1.6E+16
Operation cost (utilities)	F_s	2.67E+12	–	–	–	1800	108,000	1.1E+05	2.9E+17	1.4E+15

It is necessary to mention that this study did not intend to draw a conclusion on which type of residential dwelling is more sustainable. Indeed a more comprehensive case study considering different aspects of urban development and a more inclusive historical data is needed to compare different types of residential dwellings in Canada.

Em-LCA provides a comparative quantitative framework for sustainability appraisal of building systems with minimum subjectivity (human judgment). It also provides a set of quantitative sustainability indicators for building systems to aggregate cumulative effects of life cycle environmental and socio-economic impacts, and to advocate sustainable use of natural resources. Ultimately, Em-LCA for building systems delivers a quantitative characterization of building metabolism (resource input and emission/waste output) and their associated TBL impacts that can be used to support long-term decision-making related to the building industry and asset management. The future use of Em-LCA includes, but is not limited to, the following studies:

- Selecting the most sustainable type of building development (multi-unit, single-family, townhouse, condominium, etc.) for different regions and based on different scenarios (e.g. service life energy and structural system).
- Selecting the most sustainable building structural system (e.g. wood-frame, concrete-frame, steel-frame, hybrid, etc.) based on the different scenarios (regional resources, transportation, manufacturing, climate, etc.).
- Selecting the most sustainable building material based on the different scenarios (regional resources, transportation, manufacturing, climate, etc.).
- Selecting the most sustainable and high efficiency operation energy system (e.g., natural gas, electricity, geothermal, solar) for building energy supply, storage, co-generation, distribution, and recovery (e.g. sewer heat recovery) based on the different scenarios (regional resources, climate, etc.).

In order to implement the Em-LCA approach for other buildings or in other regions of the world, an appropriate life cycle inventory database (e.g., Athena was used as a Canadian database for building life cycle and may not be appropriate for European buildings), as well as a set of related UEVs are required.

The most challenging part of the emergy accounting is to calculate the UEVs or transformities that could be changeable according to time, process, geography, and other variables. Reza et al. (2013a) discussed different

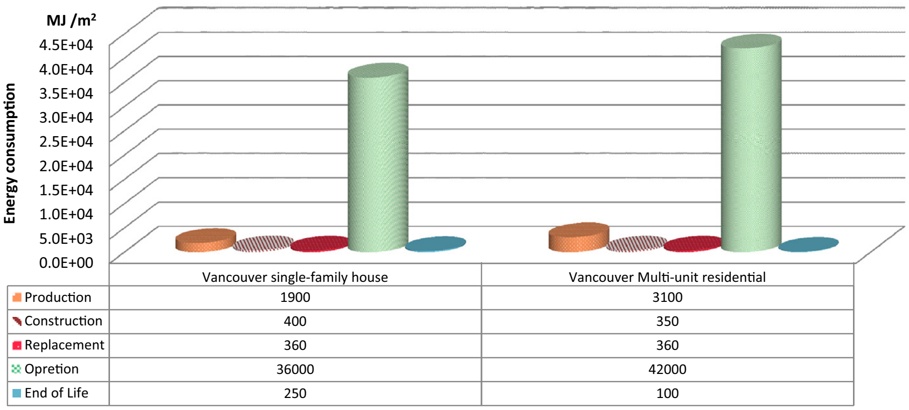


Fig. 9. Energy consumption (MJ/m^2) of multi-unit and single-family residential by building life cycle stages (in Vancouver, BC).

sources of uncertainty in UEVs and explored the utility of fuzzy-based methods to propagate uncertainty in emergy synthesis. Most of the UEVs used in this paper were extracted from the published literature (e.g., Odum, 1996). A number of possible future studies are apparent in order to propagate uncertainty and variability of UEVs and EMRs, as well as some other variable parameters such as average annual costs, DALY, PDF, average wind speed, and average runoff energy.

Appendix

(See Tables 4–10 and Fig. 9.)

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