International Journal of Sustainable Built Environment (2014) 3, 207–224

HOSTED BY ELSEVIER

Gulf Organisation for Research and Development

International Journal of Sustainable Built Environment

ScienceDirect
www.sciencedirect.com

CrossMark

Original Article/Research

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

Bahareh Reza, Rehan Sadiq *, Kasun Hewage

School of Engineering, University of British Columbia, 1137 Alumni Ave, Kelowna BC V1V 1V7, Canada

Received 9 August 2013; accepted 12 September 2014

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

* Corresponding author. Tel.: +1 (250) 807 9013; fax: +1 (250) 807 9850.
E-mail address: rehan.sadiq@ubc.ca (R. Sadiq).
Peer review under responsibility of The Gulf Organisation for Research and Development.

http://dx.doi.org/10.1016/j.ijsbe.2014.09.001
2212-6090/

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