Building and Environment 60 (2013) 202–210

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Exergy-based index for assessing the building sustainability

Ahmed El shenawy*, Radu Zmeureanu

Department of Building, Civil and Environmental Engineering, Concordia University, 1455 de Maisonneuve Blvd. W, Montreal, Quebec H3G 1M8, Canada

ARTICLE INFO

Article history:
Received 15 June 2012
Received in revised form
3 October 2012
Accepted 25 October 2012

Keywords:
Sustainable building
Assessment
Single index
Exergy
Energy
Emissions

ABSTRACT

Over the past decade, efforts have been made in developing the Sustainable Building (SB) assessment tools which enable all stakeholders to be aware of the consequences of various design choices and to assess the building performance. Currently, a large variety of existing SB tools, approaches, rating systems, indices and methods of assessment are available and used in the construction industry. Despite usefulness of existing assessment methods in contributing towards a more sustainable building, some limitations have led towards a scientifically-based SB assessment tool. This paper proposes an exergy-based definition of a sustainable building, the calculation method of a new Exergy-based Index of building Sustainability (ExSI), and the rating scale. Finally, the results from five case studies are presented.

1. Introduction

A significant number of environmental problems are caused by or related to the intensive use for materials, water and conventional energy resources through building construction and operations. In Canada, buildings account for 33% of energy production, 50% of extracted natural resources, 25% of landfill waste, 10% of airborne particulates, and 35% of green house gases [1].

The rating systems and assessment methods of the environmental impacts of building were initially conceived of as a way for owners to demonstrate that they are trying to make a difference in environmental impact [2]. The need for assessment systems of environmental impacts received more attention and support from policy makers [3]. Voluntary rating systems became market-driven systems. Some rating systems differentiate the building-related environmental impacts from user-related environmental impacts [4]. Building designers, architects, engineers and researchers use these rating and assessment tools to test design strategies against different sets of criteria. Some of these ratings (e.g., BREEAM) assess the absolute performance whereby others (e.g., LEED) seek to determine the improvement in the design as a percentage [5].

Rating systems and assessment tools started to be specified by public agencies as performance requirements, and as potential incentives for development approval. Rating systems and assessment methods are currently used by banking, financial and insurance companies as a basis for risk and mortgage appraisals and real estate valuations. Muldavin [6] demonstrates that a green rating creates building value. He elaborates on assessment methods functions and shows that asset managers and real estate directors are now struggling to assess the performance of their properties, identify opportunities for improvement, determine where and when the repair, rehabilitate or replacement is necessary to insure a healthy working for building users, and make necessary changes to consider sustainability issues in their property decisions.

The lack of general consensus on the definition of sustainable buildings is a good reason to return to the fundamental definition of sustainable development as given by the Brundtland report [7]. This definition does not identify the current and future needs, and the type and availability of renewable or non-renewable resources that would be used.

Since there is no general consensus on the definition of sustainable buildings, the literature review starts with the most currently used methods based on multi-criteria, weights and scores (e.g., BREEAM, LEED and SBTool), followed by a discussion about the potential use of a single index for assessing the progress towards building sustainability. Since our proposed methodology is based on the application of exergy concept, the literature review covers also studies on the use of exergy on the evaluation of sustainability.

In this context of lack of a unique metric for sustainable buildings, several assessment methods and tools were developed and are in use by different stakeholders. Forsberg and Malmborg von [3] classified those assessment tools in two categories: qualitative tools

* Corresponding author. Tel.: +1 514 848 2424x7266; fax: +1 514 848 7965.
E-mail address: ahmed_elshenawyy@yahoo.com (A. El shenawy).

0360-1323/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2012.10.019

and quantitative tools; the first category is based on multi-criteria, weights and scores (e.g., BREEAM, LEED and SBTool), and the second category is based on life cycle assessment with quantitative input and output data of flows of matter and energy.

Those assessment methods and tools can be analyzed in terms of structural organization, functional performance, approach, scale, scope, indicators and methods of measurement, weighting factors, and reporting results. For instance, LEED [8] uses fixed benchmarks which are periodically reviewed and eventually modified in order to comply with new standards, while SBTool [9] requires third party to define some user-defined benchmarks to comply with regional applications. LEED allocates equal weights to each criterion, while SBTool allocates weights through a subjective voting process. Some tools use a binomial approach (e.g., in LEED, the building design receives points of performance if certain requirements are met or looses points if it fails to satisfy the predefined requirements) or a rank-based approach (e.g., SBTool evaluates the level of performance using values from -1 to $+5$). Those tools assess mainly the relative performance against specific requirements rather than measuring its performance against carrying capacity [10–12].

The use of a single index for assessing the progress towards building sustainability is not a common practice. Two such sustainability metrics are the monetary and biophysical metrics. They utilize a common currency/denominator (e.g., money, land or energy). Pearce et al. [13] argued that money is a useful metric because it is relatively easy to be understood by non-experts and relevant stakeholders. However, Alberti [14] showed that monetary tools are over-dependent on subjective valuations, and inadequate since sustainability assessment goes beyond economic efficiency. Howarth [15] added that discounting is an important controversial part that is performed to compare future values with present ones.

Among the biophysical metrics, we mention here (i) the Ecological footprint [16] that uses the area of land as a limiting factor; (ii) the emergy synthesis [17] that converts the value of all ecological and economic aspects of services and commodities in common unit of solar energy; and (iii) the exergy analysis.

Exergy has been widely used as a thermodynamic property of a system. The term was introduced in the mid 1950s by Rant [18], while the exergy analysis can be traced to 19th century where the pioneering work of Gibbs and Carnot took place. The exergy analysis can evaluate quantitatively the causes of the thermodynamics imperfection of the process, and the impact of energy resource utilization on the environment. A few examples of such studies are presented below. Kotas [19] and Szargut et al. [20] used the cumulative exergy consumption analysis to the evaluation of depletion of environmental resources induced by product generation. Wall [21] suggested the application of an exergy tax as a first step to decrease environmental destruction and to improve the present resource use. Cornelissen [22] suggested that exergy losses should be minimized to obtain sustainable development; and that environmental effects associated with emissions and resource depletion can be expressed in terms of one exergy-based indicator. Dewulf et al. [23] used a set of three independent sustainability indicators to express the sustainability of technological processes: (i) α for renewable resource utilization, (ii) η for the conversion of the energy in the process, and (iii) ξ for the environmental compatibility of the process. Those independent sustainability parameters were not combined into one sustainability index. Rosen and Dincer [24] illustrated how sustainability increases and environmental impact decreases as the exergy efficiency of a process increases. Gong and Wall [25] proposed that the thermodynamic condition of a sustainable system is achieved when the input of exergy to any building application is less than the output of exergy over the service life of that application. Dewulf and Van Langenhove [26] considered two sustainability indicators to reflect the integration of the process within the natural ecosystem: the re-use indicator and the recoverability indicator. Cornelissen and Hirs [27] concluded that the exergetic life cycle assessment can be applied to determine the depletion of natural resource. Dincer et al. [28] concluded that the effectiveness of exergy analysis in addressing sustainability issues is substantial. Rosen et al. [29] expressed the sustainability index of fuel resource as the inverse of the depletion number, which is the ratio of exergy lost and exergy input to the system.

Section 2 proposes a new exergy-based index of building sustainability, and Section 3 presents the results from a few case studies. The paper concludes on the main results and need for future work.

2. Exergy-based index for assessing building sustainability

This paper presents a new prototype framework for the estimation, at conceptual design stage, of the building sustainability over its assumed life span $L_{service}$, which allows the potential design alternatives to be explored in the search for a sustainable alternative.

The proposed framework is a combination of three categories with the scope of measuring the building sustainability: (1) Multi-criteria assessment that uses the holistic approach to cover all of the building aspects which help the designer to understand the building within its wider context; the SBTool is the selected tool as the initial starting point of this category; (2) Life Cycle Analysis (LCA) that allows the assessment over the life cycle of buildings; ATHENA Impact Estimator is the selected tool for this category, and (3) an exergy-based index is used as single commodity to aggregate the multi-criteria scores into one single score.

The new definition of building sustainability is based on the concept of strong sustainability, in opposition to the weak sustainability, which requires that different types of natural capital must be maintained indefinitely for future generations. In this context, the solar radiation, which is renewable and supposed to be available on very large time scale, is that natural capital available for the building construction and operation. The use of exergy of solar radiation brings together the amount of energy received and used, as well as the quality of energy flows. The available solar exergy, which is harvested on the building footprint, is used exclusively to define the maximum natural capital, and the building sustainability is defined with respect to that maximum value. According to this new definition, a building is considered as sustainable if the overall exergy lost, due to construction and operation over the life cycle, is substituted by the available solar exergy. The exergy lost is calculated for all material and energy flows, and for the abatement of environmental impacts generated through the construction of operation of the building. Therefore a 100% sustainable building has the exergy index of sustainability ExSI equal to 100.

The new thermodynamically-based index of building sustainability gives the upper limit of theoretical performance that a building can achieve, for instance in the case of strong sustainability by using renewable energy sources only. Although such a performance will never be achieved, the rating scale can measure the distance between any technical or economical solutions and theoretical upper limit. This index is not affected by geo-political or market conditions.

The proposed index along with a rating scale would enable the designer:

i) to measure the building sustainability within its wider context, in relation with energy and non-energy natural resources;