SUSTAINABILITY ASSESSMENT FRAMEWORKS, EVALUATION TOOLS AND METRICS FOR BUILDINGS AND ITS ENVIRONMENT – A REVIEW

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ABSTRACT

Measurement science is vital in evaluating environmental impacts to assess sustainability. There are several types of frameworks, analytical tools and metrics that have been developed to assess the achievement of sustainability. The purpose of such frameworks, tools and metrics is to evaluate impact to the environment at different scales depending on project boundaries. This paper provides a detailed review and in-depth mapping of a variety of sustainability frameworks, analysis tools and metrics currently in use related to building and environment. Such a mapping offers clarity to modelers on the hierarchy of measurement sciences in the yet-to-be-formulated “science of sustainability.”

INTRODUCTION

An ecosystem is a complex interconnected setting where both living and non-living networks operate together. Such networks exchange materials and energy, and through feedback systems, self-organize connectivity in space and time (Ulgiati and Brown, 2009). Owing to excessive human exploitation and interventions, this fabric of self-sustenance is stretched and conceivably to irreparable order if unchecked. Harvesting beyond biological limits has caused significant decline to natural ecosystems such as depletion of fish stocks, forest cover, grasslands, wetlands, etc. (WRI, 2000).

Sustainability, in its broadest scope, through balanced development and through promoting environmental health and societal equity seeks to offer a solution to the ruin of ecosystems. An “ideal metric” should aid such a balancing act. Currently, there are no universally accepted metrics that characterize the natural environment and its interactions with social, economic and technical environments (Giannetti et al., 2010). This may be in part due to lack of a unified accepted definition of sustainable development (Parris and Kates, 2003) and opposing approaches to quantitative analysis in the field of sustainability (Giampietro et al., 2006). However, renewed interests in environment and sustainability have provided increasing momentum to the field, specifically in data gathering and characterization, for the development of sustainability metrics. Several research efforts in the field of sustainability, particularly in environmental decision-making, performance monitoring, policy evaluation and benchmarking comparisons, are evolving within the scientific community. In essence, such a mapping offers clarity to assessors or modelers on the hierarchy of measurement sciences in the yet-to-be-formulated “science of sustainability.”

Sustainability is an emerging field. However, the urgency of the dire state of the world has boosted research effort in the field of sustainability through the emergence of distinct research branches – not yet unified. Although natural science, social science, humanities and engineering fields have focused research efforts towards sustainability, a unified framework assessing economic, environmental and social issues and equity is yet to become a standard and / or a legal requirement worldwide (Giannetti et al., 2010). Ness et al (2007) attempted “Sustainability Science” through appropriate discussions including categorization of sustainability assessment tools. This is due to the unique nature of assessing the economic, environmental, and social considerations simultaneously that calls for a “science of sustainability” which develops the scientific basis for dealing with this relatively new concept (Giannetti et al., 2009).

Lack of a “science of sustainability” has led to debate at philosophical and ethical levels of sustainability; for example, substitutability between the economy and the environment, or “natural capital” and “manufactured capital” or between “weak” and “strong” sustainability (Ayres et al., 1998). Debate about the economy and the environment, or “natural capital” and “manufactured capital” lie in the difference between eco-centric or anthropocentric viewpoints respectively. “Weak” sustainability is attained through the substitutability of economic, natural and social capital for natural capital, “strong” sustainability conserves natural capital such as natural resources and environmental quality (Brekke, 1997; Daly and Cobb 1989). In other words, strong sustainability rejects substitutability of natural capital. Further to this concept, a “very strong” sustainability implies that every subsystem of the natural environment is preserved (Pearce and Atkinson, 1995). However, the quantification of natural capital and its contribution to economic activity is critical for environmental sustainability (Hau, 2005).

Measurement science is vital in evaluating environmental impacts to assess sustainability. There are several types of frameworks, analytical tools and metrics that have been developed to assess the achievement of sustainability by a project under consideration. The purpose of such frameworks, tools and metrics is to evaluate impact to the environment at different scales depending on the project boundaries. When it touches projects at a larger–scale (for example, policy-making at town or city–levels), sustainability frameworks play a major role. Such frameworks use structured protocols in addition to varied analytical tools for evaluation. These analytical tools are specific to the problem at-hand in terms of magnitude and purpose.

The selection of a tool will be determined based on the objective of the problem such as a reductionist or non-reductionist approach. A reductionist tool measures the performance by compiling and then integrating measurable characteristics of the project. Examples of reductionist tools include economic and monetary tools, biophysical models and thermodynamic methods, and performance evaluation tools. Non-reductionists tools integrate methodological choices which are subjective in nature, and may be particularly influenced by the analyst performing the analysis. Multi Criteria Analysis (MCA) is an example of such a tool.

Finally, metrics measure the achievement of a project in sustainability terms. For example, the project may perform in an energy efficient manner during its life-time. There are metrics available specific to the efficient use of energy in building operations and those may be applied to the project to measure and describe the project's level of achievement in energy efficiency. This paper provides an in-depth mapping of a variety of sustainability frameworks, analysis tools and metrics currently in use related to building and environment.

SUSTAINABILITY ASSESSMENT

Environmental considerations have gained significant importance for assessing a project's impact, both positive and negative, on the environment. The framework for sustainability assessment tools may contain the following – temporal characteristics for evaluation of past and / or future outcomes; focus areas such as a product or a proposed change in policy; and integration of nature-society systems. Based on the above, Ness et al (2007), categorized three major areas – (a) indicators and indices, (b) product-related assessment tools, and (c) integrated assessment. The proposed assessment tool framework is based on the temporal and object focus of the tool. Under this umbrella of sustainability assessment tools, indicators are simple measures which then can be aggregated to an index. Examples include Ecological Footprint Analysis (EFA), Wellbeing Index (WI), Environmental Sustainability Index (ESI), Human Development Index (HDI), etc. The product-related assessment tools focus on production and consumption of goods and services. Examples include Life Cycle Analysis (LCA), Life Cycle Costing (LCC), product material flow analysis, etc. Integrated assessment tools are used for supporting decisions related to a project or a policy. Examples include MCA, Cost Benefit Analysis (CBA), etc.

However, categorizing the tools may pose significant problems such as whether the objectives of sustainability assessment are fulfilled and if established guidelines are available for tool practitioners, etc (Ness et al., 2007). More importantly is the selection of assessment approaches based on the sustainability requirements or interpretations of those requirements. As research progresses in the field of sustainability owing to demand for this knowledge, new tools emerge and become accessible. The challenge is whether all of the fundamental sustainability objectives mentioned above were integrated into the method and easily employed by assessors or modelers over a diverse set of problems.

Sustainability assessment approaches may be categorized based on the hierarchical structure in their application, e.g., frameworks, analytical tools and metrics. In other words, these approaches can be assessed using frameworks or structured protocols to study several options within the framework using analytical tools, and to define such project occurrences using metrics.

The first level category includes the assessment frameworks. These are integrated and structured assessment models that aid in the comparison of various alternatives for projects and policies. Examples include Environmental Impact Assessment (EIA) and Strategic Environmental Accounting (SEA).

The second level category is comprised of analytical evaluation tools that assist in decision-making or in finding potential solutions to specific problems within the framework (Gasparatos et al., 2010). However, to preserve the generic nature of the framework, it does not identify the analytical tools that may be used; rather it provides the protocols for assessment. These tools are discussed under two second level sub-categories - reductionist and non-reductionist tools.

The third level category of sustainability measurement science includes environmental metrics. Three sub-categories are used to categorize the metrics at varied scales or measurement boundaries. They are the ecosystem, building - environment, and building scales. Examples of ecosystem scale metrics include EFA, Surplus Biocapacity Measure (SBM), ESI, WI, etc. Examples of building - environment metrics include rating systems such as Green Globes, LEED™, BREEAM, etc. Finally, the building scale metrics include net energy, zero energy, Renewable Emergy Balance (REB), etc.

This paper may not discuss all possible frameworks, tools and metrics that are currently in use. Only those with established methodologies, adequately tested and applied are included with applications in this paper. The following sections map the various sustainability frameworks, analytical tools, and metrics and offer tool users clarity on the hierarchy of measurement sciences for buildings and environments.

SUSTAINABILITY ASSESSMENT FRAMEWORKS

In most cases, prior to proceeding with major projects, environmental impact studies are conducted by specialists. Such studies are part of the larger sustainability framework to assess project impact on the environment. Such approaches are well structured, integrated, and organized to respond to three inquiries (Ness et al., 2007) namely – (are the tools capable of integrating nature-society systems?; is the tool capable of assessing different scales or spatial levels?; and, are the tools able to address both the short and long-term perspectives?) One significant and noticeable characteristic of frameworks is that they do not explicitly specify the different analytical tools that may be used for such analysis. Selection of a tool is of utmost importance, because if it is not properly identified for the stated purpose, it may provide a distorted sustainability evaluation (Gasparatos, 2010).

Among others, two major frameworks that have gained traction are the EIA and SEA. They are part of the legal requirements for evaluating many projects and policies (Gasparatos et al., 2010). For example, Directives 97/11/EC and 2001/41/EC have rendered both EIA and SEA as legal requirements in the European Union. Through comparison of different project alternatives' environmental impact, these frameworks evaluate and assist in the decision-making process.

EIA outcomes are presented on an objective basis which then is used for decision-making. At the end of the assessment, an audit is conducted to compare actual impacts with those that were predicted during the assessment. Additionally, the success of mitigation measures is validated. EIA is undertaken for larger global projects and primarily focuses on the environmental elements affected. However, it is to be noted that the "scale" at which the EIA study is conducted is vital for the study outcome. Scale as spatial extent and scale as geographical detail or granularity affect project analysis. Scale issues are discussed in Joao (2002). Several EIA study examples at varied scales can be found in academic literature such as water quality (Osterkamp, 1995), landscape studies (Meentemeyer and Box, 1987), ecology (Fernandes et al., 1999), etc.

In an SEA framework, the strategic decision-making takes into account the environmental considerations in support of environmentally sound and sustainable development (UNECE, 2007). The framework uses a step-by-step, methodological approach through mapping plan / policy or program / project making them relevant to sustainability assessment. The steps include definition of objectives; formulation of alternatives; scenario analysis; environmental analysis; valuation and conclusions (Nilsson et al., 2001). However, it does not recommend the "best" analytical tool to be used for the analysis. The quality of the analysis through the use of the analytical tools is critical as it is the vehicle that provides necessary information to decision-makers. Gasparatos (2010) discussed the SEA as an example to show differences between evaluation tools and frameworks. Such assessments have been effective for evaluating several applications including energy policies (Nilsson et al., 2001).

Both EIA and SEA frameworks may be used to evaluate impact to the environment particularly at a larger scale. Depending on the project to be evaluated, evaluation tools and metrics may be selected to be part of the framework. The selection must coincide with project objectives and specific outcomes that are required to enable environmental decision-making. The following sub-sections discuss a set of evaluation tools and metrics specific to buildings.

SUSTAINABILITY EVALUATION TOOLS

Sustainability evaluation tools have been developed to support conscious environmental decision-making. As discussed earlier, they may be broadly classified as reductionists and non-reductionists tools. The selection of the evaluation tool lies with the analyst's particular worldview or subject of expertise, which is ultimately projected upon a particular project. Thus, the tool becomes the yardstick to evaluate the sustainability of the project at hand (Gasparatos, 2010).

Reductionists Tools

A reductionist tool uses a single measureable indicator, a single dimension, a single objective, a single scale of analysis and a single time horizon (Munda, 2006). For example, CBA is a type of reductionist tool where "cost" is the single indicator used for evaluation. In other words, it can be stated that a "common denominator" approach is taken to deduce diverse aspects to a set of numbers for analysis. There are several types of reductionists tools namely economic and monetary tools; biophysical models and thermodynamic methods; performance evaluation tools. Economic and monetary tools use cost as an indicator for evaluation. Examples include CBA and Whole Life Costing (WLC). Biophysical models and thermodynamic methods use some physical quantity as the indicator to determine what was required for the production of goods / services. Examples include exergy analysis, thermo-economics, LCA, embodied energy, thermodynamic input-output analysis, and emergy (spelled with an "m") analysis. The economic and biophysical tools, although they use a reductionist approach, have dissimilar perspectives in their evaluations. While the former uses currencies, the latter uses physical units. In other words, economic models use an "anthropocentric perspective" approach to valuation while the biophysical tools use an "eco-centric perspective" (Gasparatos, 2010). Performance analysis tools use energy as an indicator for evaluation. Such tools can be either of prescriptive or performance type. While the prescriptive approach confirms within energy standards, the performance option goes beyond minimum energy standards. Building energy analysis tools are a type of performance analysis tools. These tools enable whole-building energy analysis for in-depth assessment of building energy.

Economic And Monetary Tools

Economic and monetary tools use "currencies" as a common denominator. Thus, by measuring performance of projects using a common denominator, the project is evaluated. Since these use a single measurable indicator, they are examples of reductionist tools. CBA and WLC are types of economic and monetary tools. These tools are approaches to economic decision-making. CBA is evaluated based on the public's willingness to pay (to benefit from) or to accept a compensation (to avoid) consumption of the commodity. The relevant costs and benefits are computed at present value. Therefore, in order to determine future costs and benefits, a discount rate is introduced. Typically the discount rate (interest) applied is drawn from financial markets which may, at times, prove contentious as they may not adequately correspond to future environmental impacts. In other words, it is primarily focused on efficiency in the allocation of resources. Similarly, the objective of WLC is to minimize costs throughout the life of the asset. This tool uses both initial and operational costs. This is comparable to LCC which refers to the total cost of ownership. However, it oversimplifies environmental problems by collapsing them into a monetary dimension. For environmental building design that focuses on sustainability at a geobiosphere level, biophysical models and thermodynamic methods may be suitable when compared to CBA and WLC.

Biophysical Models and Thermodynamic Methods

Biophysical models and thermodynamic methods for analysis of a good/service provide an acceptable measurable method to evaluate resources used in the production of the same. The common denominator in this case is a physical measure of the "natural capital" or resources invested for the production of the good/service. Most biophysical models allow substitution within the same form of natural capital or resource and not between different forms of capital, emergy being the exception, since the normalization of quality between different resource types is performed when converting any quantity into emergy. Several tools such as exergy analysis, LCA, embodied energy and thermodynamic input-output analysis, emergy analysis, etc., are examples of biophysical models.

Exergy, like energy and entropy, is a thermodynamic concept. The concept of energy does not show the quality and consumption aspects as it focuses entirely on quantity (of use). Exergy provides some data related to the quality of inputs and offers information on efficiencies. For each energy transfer, there is a corresponding exergy and entropy transfer. Exergy analysis is another thermodynamic-based framework that may be adopted as an evaluation tool for environmental building design. Exergy heat transfer depends on both the system and the (temperature of) the reference environment. In other words, it depends on the temperature at which an action happens relative to the background temperature of the external environment. Several exergy-based research studies have been made to investigate building components such as heating system evaluation (Balta et al., 2008); residential buildings (Saidur et al., 2007; Zmeureanu and Wu, 2007); heating and cooling systems (Schmidt et al., 2004); daylighting, electric lighting and space cooling systems (Taufiq et al., 2006), etc.

LCA is a tool to assess the environmental impacts and resources during a product's life-time. Its primary objective is identifying emissions and their impact during the life cycle of a process. LCA evaluates the potential environmental impacts of a product. It involves selection of impact categories, assignment of the inventory data to impact categories for appropriate classification and quantification of the contributions from the product to the chosen impact categories. Through expanding the boundaries of the study and with suitable information on allocation, environmental accounting may be pursued. However, Burgess and Brennan (2001) provide in-depth data related to the shortcomings of LCA. Other issues include setting the boundaries, allocation through proportionally distributing the responsibility for inputs used (resource consumption) and undesired outputs (emissions) of a process, costs of data collection as LCA strongly relies on the quality of the data, etc. Nevertheless, several attempts were made to use LCA for building evaluation, the most recent and notable being the Life Cycle-based Zero Energy Building or LC-ZEB (Hernandez and Kenny, 2010). LC-ZEB is a simplified methodology to include embodied energy of building components together with energy use in operation. For a building to achieve LC-ZEB status, the annual energy use must be negative to such an extent to compensate for the already-consumed embodied energy in buildings, which may, in reality, unachievable.

Although the research approach attempts to follow ecological modeling principles, there are shortcomings such as non-inclusion of material formation in LCA; the selection of primary energy as an indicator, in particular when renewable energies are considered; and the approach does not quantify progressive replacement of non-renewable by renewable resources to achieve net energy. The most significant inadequacy is that LCA lacks a rigorous thermodynamic framework which is elemental for analyzing ecosystems and in certain situations may even violate thermodynamic laws (Hau, 2005).

Embodied energy, sometimes referred to as thermodynamic input-output analysis, includes the primary energy use such as fuel, nuclear, hydro-electric, etc., for the production of raw materials to construction completion. Embodied energy includes the primary energy used for the production of raw materials to complete construction. Primary energy is extracted or captured from sources such as fossil fuel, nuclear, and hydro-electric power, etc. Secondary energy is human-induced energy transformation from primary energy source. For example, electricity generated from burning coal is secondary energy. However, labor and environmental work of the geobiosphere is not included. Additionally, embodied energy does not include the energy used by the built environment's space conditioning requirements and other uses (Stein et al, 1981). However, labor and environmental work of the geobiosphere is not included. Such limitations do not offer a solution for in-depth analysis of a given product / service over its entire life-time and is disadvantageous.

Emergy is an environmental accounting quantity that is based on the summation of all the available energy of one kind required directly and indirectly for the production of a product or service. Emergy analysis provides a "total environmental analysis" that goes beyond typical thermodynamics and includes all environmental and human energies involved in the system under investigation. Emergy is the available solar energy previously used, both directly and indirectly, in order to make a service or a product (Odum 1996; Odum, 1971; Odum 1983). Solar energy is used as a common denominator for all resources, services and goods. Only a handful of research efforts have focused on assessing buildings using emergy analysis: evaluation of recycling and reuse of building materials (Buranakarn, 1998); emergy associated with the operation of a Building (Meillaud et al., 2005); building manufacturing, maintenance and use – development of Em-building indices (Pulselli et al., 2007); energy and emergy based cost-benefit evaluation of building envelopes relative to geographical location and climate (Pulselli et al., 2009); emergy evaluation of a green façade (Price and Tilley, 2010); maximizing renewable resource use for Renewable Emergy Balance or REB (Srinivasan, 2011a) and energy balance framework for NZE buildings (Srinivasan et al., 2011b).

Performance Evaluation Tools

Performance tools use computer-based simulations and related protocols to assess building performance. Moreover, building performance indices and definitions characterize buildings based on their overall energy consumption over a period of time (for example, NZE buildings). Energy analysis tools may be broadly classified into System Sizing Tools and System Performance Evaluation Tools (Axley, 2004). While System Sizing Tools help in sizing individual components, System Performance Evaluation Tools simulate a system to specified excitations.

Tools may be differentiated into Macroscopic Analysis Tools – those that utilize fundamental conservation principles providing a whole-system analysis rather than room-specific data, and Microscopic Analysis Tools – those that utilize Partial Differential Equations to evaluate spaces. The US Department of Energy's DOE-2 engine and US Department of Defense's BLAST engine aided the development of building energy analysis tools. ENERGYPLUS engine is the convergence of DOE-2 and BLAST. Currently, building energy analysis tools include the software tools for building energy and renewable performance simulation. Although most of these tools have undergone mandatory validation per US Department of Energy's requirements, they still do not comprise all possible design strategies implemented (Crawley et al., 2005). Recent development in equation-based, component level algorithms alleviate issues inherent to current monolithic simulation programs (Wetter, 2011).

Non-Reductionists Tools

Non-reductionists tools integrate methodological choices which are subjective in nature that is they are particularly influenced by the analyst performing the analysis. MCA is an example of such a tool. In the case of MCA, subjective criteria are applied to data selection, criteria definition, aggregation and weighting (Messner et al., 2006). It is a family of indicator based techniques similar to composite indicators (Gasparatos, 2010). A type of MCA was used for renewable energy assessment (Gamboa and Munda, 2007; Madlener and Stagl, 2005). Since the aggregation of individual indicators does not take place, MCA is closer to the concept of strong sustainability (Gasparatos, 2010).

SUSTAINABILITY METRICS

The third aspect of sustainability measurement science is metrics. Sustainability metrics rate the sustainability of a system. Since the measurement boundaries vary for systems, they can be categorized into three types namely ecosystem scale, building-environment scale, and building scale.

Ecosystem Scale

Ecosystem-scale metrics enable the measurement and evaluation at a larger neighborhood or even at a regional aggregation. Examples of ecosystem–scale metrics include EFA, SBM, ESI, WI, etc.

The human demand on Earth's ecosystems is measured in terms of Ecological Footprint Analysis or EFA (Rees and Wackernagel, 1996). In other words, it represents the natural resources of the earth that are required to sustain human populations. For example, a specific lifestyle may require a greater demand of Earth's resources. This demand can be plotted and compared against others for judging relative sustainability. EFA for several countries were developed as a measure of sustainability. Measurement boundaries vary depending on the stakeholder's requirements. The calculation procedures are standardized for widespread implementation and available at the Global Footprint Network.

The Surplus Biocapacity Measure assesses the sustainability of consumption patterns. In short, SBM is the difference between the country's ecological footprint and domestic productive area. Thus, it can be stated that the SBM of a country is a combination of its consumption, ecological space and population.

The Environmental Sustainability Index uses several indicators that assess the environmental, socio-economic, and institutional aspects of sustainability. It was developed by the World Economic Forum's Global Leaders for Tomorrow Environment Task Force, the Yale Center for Environmental Law and Policy, and the Columbia University Center for International Earth Science Information Network (WEF, 2010).

The Wellbeing Index assesses the wellbeing of humanity and ecosystems, equally weighed. While the Human Wellbeing Index (HWI) uses the health, population, household and national wealth, knowledge and culture, community, and equity, the Ecosystem Wellbeing Index (EWI) consists of land, water, air, species and genes, and resource use (Prescott-Allen, 2001).

While the Ecosystem Services Product (ESP) is the economic value of ecosystem services, the Subtotal Ecological-Economic Product is the sum of Gross Domestic Product (GDP) and ESP. These two sustainability metrics enable the evaluation of countries regarding their sustainability.

Building-Environment Scale

Examples of Building-Environment scale include rating systems such as Green Globes, LEED™, BREEAM, etc. Green Globes is a building environmental design and management tool. The online tool provides assessment to new and existing buildings. LEED™ was developed by the US Green Building Council and this rating system uses a point-based system to evaluate the building and its environment in sustainability terms. Recently, the system has been revised with new weighting methodology and represented as points for tallying. Based on the points, the building is certified. On the other hand, BREEAM is a UK-based building rating system akin to LEED™. These rating systems assess the building and its environment.

Building Scale

The building scale metrics include net energy, zero energy, LC-ZEB, NZE, REB, etc. Net Energy is a technique for evaluation which compares the amount of energy delivered to society by a technology to the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a socially useful form (Cleveland et al., 2006). Thus, Net Energy is the true value of energy to society (Odum, 1983). The difficulty with Net Energy is the definition of the boundary, similar to LCA methodologies such as non-inclusion of energy related to material formation. However, several terms have been developed to capture the essence of the larger Net Energy concept such as energy payback, energy return on investment (Hall, 2008), energy yield ratio, etc. The Zero Energy metric is applied to balancing the energy delivered to a grid and energy used. This balance is maintained on an annual basis and specifically includes the life cycle energy associated with delivering the building and its components in addition to building operation. This is the significant difference with the NZE metric.

Yet another way of measuring building performance is using performance indices and definitions. While performance indices provide assessment opportunities for improved performance exploration, performance-related definitions offer broader compliance methodology. For example, "Em-building indices" were formed through a comprehensive evaluation of building materials, technologies and structural elements (Pulselli et al., 2007). Additionally, indices such as building emergy per person ("em-building per person"), building emergy/money ratio ("em-building money ratio"), building emergy per volume ("em-building volume"), etc., were developed for emergy assessment of a building. Recently, a "renewable substitutability" index was developed; it is material portion that can be substituted with renewable resources and used for REB calculation (Srinivasan, 2011a).

CONCLUSION

This paper provided an in-depth mapping of a variety of sustainability frameworks, analysis tools, and metrics currently in use to building and environment. Frameworks use structured protocols and a variety of evaluation tools to assess the project under investigation. The tools relate specific to the problem at-hand. The paper discussed the reductionist tools, specifically biophysical models and thermodynamic methods. This is due to the fact that elaborate bookkeeping is crucial for environmental decision-making solutions. This is especially true as we acknowledge that only a finite mass of material resource exists irrespective of the multitude of transformation needed to make a product. Thus, a building, like an organism or an ecosystem must seek self-sustenance to prevail with limited availability of energy and materials.

Among the tools discussed in the paper, emergy analysis coupled with LCC may be suitable for assessing building and its environment. The emergy approach is well structured, integrated, and organized. The tool is capable of integrating nature-society systems. It is capable of assessing different scales or spatial levels. More importantly, emergy analysis provides a "total environmental analysis" that goes beyond typical thermodynamics and includes all environmental energies involved in the system under investigation. However, as pointed by Hau and Bakshi (2004), additional research and widespread application of emergy concepts is needed to strengthen the assessment tool.

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