SUSTAINABLE BUILDINGS: DREAM OR REALITY?

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Summary

The design community and stakeholders started to accept the concept of “Green Buildings.” The green buildings incorporate better practical solutions, with respect to the present market or design requirements, that reduce the environmental load. Although the development of green buildings has a considerable success in the today’s market, this concept is only the first step towards the sustainable buildings. Over the past three decades, researchers discussed other approaches for assessing the sustainability of a given development, including buildings. The paper presents a short summary of indices of sustainability with applications to buildings, with emphasis on those based on the second law of thermodynamics. The paper also presents examples from some case studies from the author’s research projects, related to the building envelope and HVAC systems.

1. Sustainable Development

The United Nations report “Our Common Future”, known as the Brundtland report (1987), defined the sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” In a few years, the sustainable development has evolved from an esoteric concept to a philosophy embraced by dozens of multinational corporations and government agencies (Fiksel and Fiksel 2001).

On the other hand, Leadbitter (2002) underlined that the Brundtland definition failed to convey the idea that there are biophysical limits within which society must operate. In his opinion, the sustainable development is only the process of moving towards sustainability. The present situation is characterized by the fast-depletion of resources and the fast-growth of population. Under these conditions, a sustainable system should be defined as one that can continue forever, without any additional impact on resources. The final destination of sustainability must be defined in such a way that some indices could be measured, and finally compared with accepted benchmarks. Hammond (2004a) made reference to work by Parker, who found in the literature more than 200 formal definitions for sustainable development.

There are, however, no accepted standards for measurement of sustainability. The situation is even worst: all definitions and measurements of sustainability must consider the fact that we do not really know how the system works (Hardi et al. 1997), and therefore the decision about what to measure must be based on judgments about what is important, in the absence of full knowledge.

Four ecological principles, known as the Natural Step concept, were defined as criteria for sustainability (Robert et al. 1995): (1) Substances from the Earth’s crust must not systematically increase in the ecosphere; (2) Substances produced by the society must not systematically increase in the ecosphere; (3) The physical basis for the productivity and diversity of nature must not be systematically diminished: and (4) Resources must be used fairly and efficiently with respect to meeting human needs. Hammond (2004b) believes that the Natural Step criteria put severe constraints on economic development, and therefore be viewed as impractical or utopian.

Peacock (1999) concluded that there are three major concepts about sustainability: (1) there is no problem that the technology cannot solve or the “business as usual” concept, (2) the sustainability is the management of scarce resources or the “lifeboat” concept, and (3) the sustainability is the symbiosis between humans and the ecosystem or the “mutualistic” concept. According to the lifeboat concept, the sustainable development is not even theoretically conceivable. The sustainable use of nonrenewable resources means using them as slowly as possible, to delay their complete depletion. The sustainable use of renewable resources means using them slowly enough that the ecosystem can regenerate them. Peacock is the promoter of the mutualistic concept, where humans can produce with hands and voices as plants produce chlorophyll. For instance, through a sensitive design and careful placement in the landscape, a new building can enhance the productive effectiveness of human beings. Cultural factors generated by the construction of a new building such as architecture, art, music, literature or philosophy should also be considered when its sustainability is measured.

Voorspools (2004) analyzed the current efforts towards sustainability of energy services, and concluded that they mainly focus on efficiency improvement and sustainable conversion technologies. In his opinion, these technological efforts most likely cannot provide long-term alternatives, and therefore there are only two long-term sustainable alternatives: (i) the discovery of an infinite energy source, and (ii) the stabilization of demand for energy services.

Norde (1997) warned the reader that the "thermal death" of the universe (when no energy will be available to generate work, and the processes will cease to occur) should not be of concern, because long before this event occurs the Sun will extinguish, and therefore the terrestrial life will be impossible. In his opinion, the future of the Earth on a shorter term should be the real concern. The use of some energy sources such as nuclear energy, which is supposed to be unlimited, will bring in addition to some technical issues another problem: the maintaining of a high flow of energy will require the significant increase of matter entropy, and therefore matter will dissipate over the planet and will not be available any more. Therefore, the thermodynamics lead the reader to the only feasible scenario of sustainable development, in which the economic activities should be adjusted to low-scale energy consumption, and the technological infrastructure should be modified to use only the renewable energy sources (e.g., sun, water and wind).

Other researchers argued that development per se cannot be sustainable or even it is not desired by some developing countries. Finally, other researchers suggested that the sustainability may be just a dream such as happiness (Manning 1990, referred by Peacock 1999). Thring (1990) prefers that humanity would look for a creative and stable world with the aid of equilibrium engineering.

The opinions presented above indicate that there is no consensus on the definition of sustainable development or even on the question if such development could exist. Fowler and Hobbs (2003) tried to respond to the question "Is humanity sustainable?" The authors compared humans with 31 samples of non-human species with respect to the following measures: biomass consumption, global energy consumption, CO_2 production, population size and extent of unoccupied areas. They concluded that humans consume more than the mean of other species and also produce more CO_2 emissions (they are outside the 90-99% confidence limits). This abnormality leads to the conclusion that humanity is not sustainable. Our uniqueness is the source of extreme risks, including extinction.

Glicksman (2003) noticed that there is no general agreement about the meaning of a sustainable building, and developers are more interested in making the building "look green". The coordination between the designer, consulting engineer, and building owner is the important condition to achieve the outstanding sustainability performance of a building. The concept of sustainable development is translated in the building industry as the concept of sustainable buildings or "green" buildings (Brandemuehl 2004).

ASHRAE defined the concept of green design, as applied to building systems, as the design that is aware of and respects nature and the natural order of things. A green building is one that achieves high performance, over the full life cycle, in the following areas (Grumman 2004): (1) Minimal consumption of nonrenewable natural resources, depletable energy resources, land, water, and other materials as well; (2) Minimal atmospheric emissions having negative environmental impacts, especially those related to greenhouse gases, global warming, particulates, or acid rain; (3) Minimal discharge of harmful liquid effluents and solid wastes, including those resulting from the ultimate demolition of the building itself at the end of its useful life; and (4) Minimal negative impacts on site ecosystems. The sustainability is a simple and good general definition when is applied to planet Earth, however, it is difficult to apply the concept, in a meaningful way, to an individual earthly component such as a building. For this reason, the ASHRAE GreenGuide focused on "green" buildings, and was developed specifically directed toward practitioners.

A global vision about the sustainability of built environment requires the implementation of mechanisms to transform the traditional linear development process followed presently by the Architecture, Engineering and Construction (AEC) industry into a closed cyclical system (Vanegas 2003). The sustainable built environment should ensure the collaborative push/pull environment of three components: (1) the sustainable facilities, (2) the sustainable civil infrastructure systems, and (3) the sustainable technologies, systems, products, materials and equipment. Each component should be optimized over its life cycle. A residence that can be a provider of energy rather than a simple user is an example of such collaborative environment. This new goal will pull the development of new technologies and materials, and will push the utility companies to use the excess electricity generated by theses residences.

Larsson (2000) presented the Canadian experience in the integrated building design process as a significant step towards the green building design process. The Commercial Buildings Incentive Program (CBIP) and C-2000 program proved that, at least in the Canadian context, it is possible to improve the energy performance by about 35% without heroic measures.

Although the development of green buildings has a considerable success in the today's market, this should be only the first step towards sustainable buildings. It is important to define at the very beginning the control boundaries used for the definition and analysis of sustainable buildings. There are two extreme cases:

(1) The sustainable building is seen as one component of a larger geo-socio-economical space, and therefore its performance should be evaluated through the contribution to the sustainable development of the village, community, city or country. The goal of design and operation of such building is the

minimization of environmental loads, expressed as energy use (e.g., annual or life cycle operation energy use, life cycle totals energy use including embodied energy and operation energy), life cycle equivalent CO_2 emissions, and life cycle costs that may integrate the external costs related to the environmental impacts (e.g., penalties or taxes, or abatement costs).

(2) The sustainable building is seen as a net producer of goods (e.g., energy) with respect to surroundings, which would sustain the socio-cultural-economical development within its own boundaries. An example of this approach is the Net Zero Energy House.

2. Indices of Sustainable Development

Over the last decade a large number of practical tools such as GBTool, BEES, BREEAM or Athena have been developed to help designers in assessing the environmental impact of buildings. The Green Building Challenge, an international competition organized along with the Sustainable Building conference was of a great success. Designers proved that it is possible to improve significantly the energy performance and reduce the environmental impact. A detailed matrix of indicators was used to compare the performance of buildings in competition. Several building energy rating schemes (e.g., HERS) or environmental rating schemes (e.g., LEED) are today in operation.

The indicator framework of the United Nations Commission on Sustainable Development, which is used by national governments to measure their progress in implementing Agenda 21, includes a list of over 140 indicators grouped in four major categories: social, economic, environmental and institutional (Hardi et al. 1997). In Canada, the sustainable development is measured based on the ecological framework of the Indicators, Monitoring and Assessment Branch of Environment Canada. There are 18 issue areas (e.g., atmosphere, water, living organisms, and natural economic resources) for each ecozone of Canada.

Green Building Council (Larsson 2003) proposed the use of several indicators to measure the building sustainability such as total embodies energy, total primary energy for building operation, area of land for building and related works, annual greenhouse gas emissions from operation and annual consumption of potable water for operation.

Designers and clients look for innovative design solutions, which will make buildings “greener” than before. Following this approach, one may ask questions such as: How much “green” a building should be? What is the ideal building “greenness”? Instead of responding to this question, someone should look from a higher level of concept, which is the concept of sustainable buildings. All efforts and successes obtained so far by designers should open a new search towards the development of sustainable buildings. The goal should be assessed in terms of objective functions that are not affected by economical or political conditions of today such as energy price, labor and material cost, or current standards and by-laws. Over the past three decades, researchers developed several indices that eventually can be used to respond to questions such as: How to measure sustainability or sustainable development, or how to measure the progress towards sustainability? Some of these indices are presented in this section. The emphasis is given to those indices based on the second law of thermodynamics that help assessing the quality of developments and the potential impacts on the environment.

Wall (1977) recommended the use of exergy for the accounting of natural resources. In 1993 he proposed the use of exergy of emissions as an indicator of environmental effects.

Wackernagel and Rees (1996) introduced one single indicator, called the ecological footprint, to assess the sustainability of human developments. The ecological footprint of a given population is the amount of productive land required to produce the energy and materials, and to assimilate all wastes generated by that population, in order to sustain the lifestyle. The calculated value is compared with the overall average of 2.0 hectares per person, which is estimated by dividing the total area of Earth’s productive land by the today’s population. For instance, the average footprint of Canada is 8.8 ha/person (Footprint 2005). This result can be converted into another indicator that is much easier to understand: if every person on the Earth would have the same life style as an average Canadian, we would need more than four planets to sustain that lifestyle.

McMahon and Mrozek (1997) interpreted the Brundtland definition as the call for continued economic expansion without environmental degradation. Presently, the environmental decision models are based on: (1) the axiom of material value (the resources have no intrinsic value apart from their economic value on the market), and (2) the axiom of abundance (the Earth is very large, so the natural capital cannot be depleted or degraded by economic processes within human time frame). As a consequence of the second axiom, it is concluded that technologies will always find substitution among sources of natural capital, and between manmade and natural capital. The authors indicated that the entropy, as a measure of irreversibility, should be the unifying factor of economics, physics and ecology for the foundation of the theoretical concept of sustainability.

Krotscheck (1997) discussed several indicators for eco-sustainability: (1) the critical volume of air, water and soil that is needed to dilute the toxic emissions; (2) the material input (water, air, abiotic material such as concrete, and biotic material such as biomass) per unit of goods produced by the process; (3) the sustainable process index (SPI) that is the area per inhabitant, which is required for the delivery of a service (e.g., area to produce raw materials, area to provide process energy, area to accommodate products and by-products); (4) the appropriated carrying capacity that is the area a region uses to run its economy; (5) the waste potential entropy (WPE) that is measured as the difference between the actual entropy of a system and its final entropy, after it reaches equilibrium with its local environment; and (6) the pollution control (abatement) costs that show the costs for control measures to attain a specific environmental quality.

Rosen and Dincer (2001) represented the relationship between exergy, sustainability and environmental impact as follows: the sustainability increases and the environmental impact decreases as the exergy efficiency of a process increases.

Gong and Wall (2001) found that the Delin's definition of sustainability offers a precise measurement, without being manipulated by political or economical arguments. According to this definition, the thermodynamic conditions of sustainable life-support system require that the incoming energy from the sun must be greater than the outgoing energy, and therefore the exergy must be stored as deposits on the earth. The authors used the life cycle exergy analysis, applied to renewable and non-renewable resources, to define sustainable engineering. If the input of exergy to build, for instance a wind power plant or a solar collector, is less than the output of exergy over the entire life duration, than the deposits that were initially used can be restored, and the development is considered to be sustainable.

Cornelissen and Hirs (2002) applied the exergetic life cycle assessment to analyze the depletion of natural resources through the depletion of copper ore. The depletion of natural resources is calculated as the difference between the life cycle irreversibilities and the depletion of exergy content of renewables.

Lems et al. (2002) presented the overall sustainability coefficient, originally developed by De Wulf, as the average of the renewability parameter and the overall efficiency parameter. The renewability parameter is defined as the exergy value of the ingoing renewable resources as a fraction of the exergy value of all resources used in the process. The overall efficiency parameter is defined as the product of two efficiencies: (1) The first efficiency is calculated as the ratio between the exergy required to run a process and the total exergy of the process including the exergy required for abating the harmful emissions; (2) The second efficiency is defined as the exergy value of the useful products as a fraction of the exergy value of resources required to run the process. Maximum overall sustainability is obtained when all resources used in the process are renewable, and when no exergy is lost in the process and no exergy is required to abate harmfull emissions. Lems et al. (2002) presented a revised quantification method of the sustainability of a technological process that is composed of a set of three independent sustainability parameters, that are not combined into one sustainability coefficient: (1) The parameter of sustainable resource utilization is defined as the product of the average and minimum abundance of resources, which take into account the depletion time of a resource; (2) The exergy efficiency is defined as the ratio between the useful exergy flows coming out of the process and the exergy input; (3) The environmental compatibility parameter is defined as the ratio between the exergy required to run the process and the exergy required to run the process in an environmentally sound way, which includes the extra exergy required for abating the harmful effects on the environment.

Hornbogen (2003) defined the material sustainability index as the inverse of the total entropy of a cycle, relative to the starting conditions. This index can be used to assess the sustainability of a final product (e.g., building) compared with the initial state of raw materials, or can be used to compare the sustainability among several building design alternatives. The analysis should consider both material and energetic entropies, and the life duration of goods. Since the present type of development cannot be sustained, a new condition must be fulfilled for new approaches to development: the entropy should not be raised at a higher rate than the negative entropy that is available from the sun.

3. Examples

This section presents results from some case studies selected from the author's research projects.

Weimin et al. (2005) optimized a commercial building using two conflicting objective functions: (1) the life cycle environmental impact (LCEI) that is expressed by the expanded cumulative exergy consumption; this term takes into account the exergy of all natural energy and non-energy resources consumed in all steps of the production process, and the abatement exergy that is required to remove or isolate the emissions from the environment; and (2) the life cycle cost (LCC). The optimization was performed using Genetic Algorithms, and the solution was presented as a Pareto front (Figure 1).

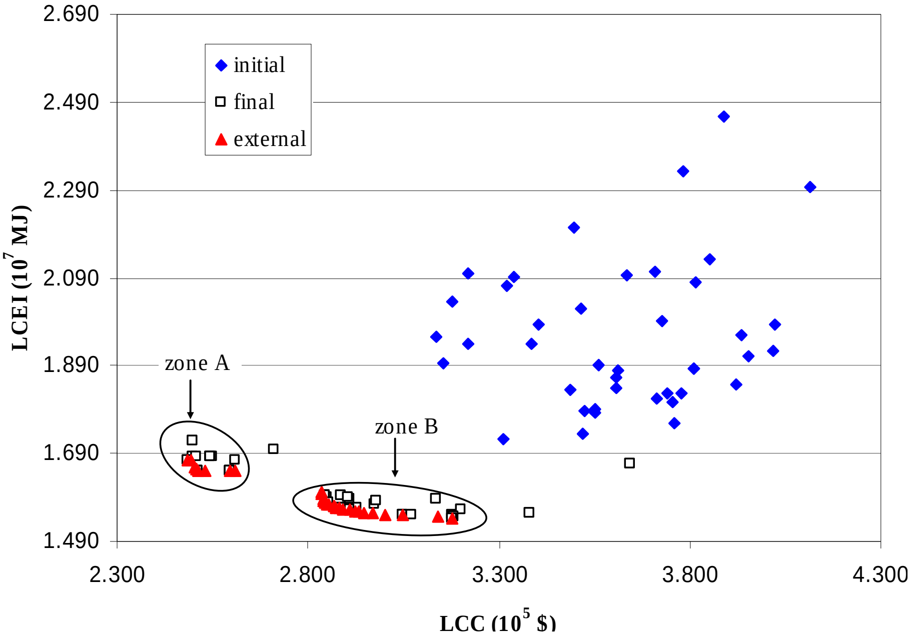

Figure 1. Distribution of the initial and final population or solution.

Zmeureanu and Wu (2005) used the second law of thermodynamics analysis to estimate the performance of nine design alternatives of residential heating, ventilation and domestic hot water (HVAC-DHW) systems for a house in Montreal, Canada (Table 1). System no.1 is composed of electric baseboard heaters, installed in each room, while the domestic hot water is heated by electricity in a standard storage tank. System no.2 uses a gas-fired hot water boiler to supply the baseboard heaters and the storage tank. System no.3 uses a ground source water-to-water electric heat pump (GSHP) to supply the radiant heating floor and the storage tank. Systems no.1 to no.3 do not have a mechanical ventilation system. Systems no.4 to no.6 are similar to the first system, the main difference being the addition of mechanical ventilation system and an electric air heater for heating the cold ventilation air. In addition, in order to reduce the energy use for heating the ventilation air, two heat exchangers are used to preheat the cold air: (1) an air-to-air heat exchanger that uses heat from the exhaust air stream, and (2) an earth tube heat exchanger that uses heat from the ground. System no.7 uses a gas-fired hot water boiler to supply the baseboard heaters and the storage tank (as system no.2) and has a mechanical ventilation system. System no.8 uses an electric boiler to heat the radiant heating floor and an electric heater for domestic hot water. System no.9 uses a ground source water-to-water electric heat pump (GSHP) to supply the radiant heating floor and the storage tank (a gas-fired water heater is used if the demand is not satisfied), and has a mechanical ventilation system.

The following indices are used for the comparison between the seven residential HVAC-DHW systems (Table 1): the Coefficient of Performance, the exergy efficiency, and the environmental compatibility index ξ (Lems et al. 2002). Calculations are based on the primary energy use and related equivalent CO_2 emissions, for the electricity mix of Quebec, where hydroelectricity accounts for about 97% of electricity generation. The reference temperature for the calculation of exergy efficiency is the hourly outdoor air temperature.

The environmental compatibility index ξ is calculated as the ratio between the exergy used for satisfying the heating needs of the sample house and the exergy used for heating the house without polluting the environment. The denominator is composed of the exergy needed for heating the house plus the abatement exergy (a value of 5.86 MJ/kg of CO_2 emissions is used, see Cornelissen 1997). Systems no.2 and no.7 have low values of ξ that indicates a significant exergy demand for abatement, compared with the exergy demand for heating. Both systems use a gas-fired boiler for domestic hot water. The environmental compatibility index ξ indicates that these two systems have significant impact on the environment, compared with others that use hydroelectricity.

If both exergy-related indicators are considered, the exergy efficiency and the environmental compatibility index, it can be concluded that the system no.3 has the lower environmental impact. This system is composed of: a radiant floor heating system; a ground source heat pump; an air-to-air heat exchanger; and an earth tube heat exchanger. This system does not contain a mechanical ventilation system. The addition of a mechanical ventilation system, with or without heat recovery, to any HVAC-DHW system discussed in the paper increase the COP and decreases the exergy efficiency, which indicates a potential damaging impact on the natural environment. The best system, among those evaluated, uses for the HVAC-DHW system 29.5% of the potential of natural energy resources, while 70.5% are wasted in the environment.

Table 1. Comparison of residential HVAC systems under annual operating conditions.

System	COP [-]	η_2 [%]	Environmental compatibility index (-)
No.1	0.71	6.9	0.51
No.2	0.73	8.4	0.18
No.3	1.19	29.5	0.50
No.4	0.66	4.9	0.51
No.5	0.83	5.1	0.51
No.6	0.88	5.6	0.51
No.7	0.90	6.8	0.19
No.8	1.49	25.4	0.51
No.9	1.46	26.8	0.33

Baouendi et al. (2005) developed the Energy & Emission Estimator (EEE) tool that is based on the Life Cycle Assessment and Life Cycle Cost methods. The EEE tool uses information about the house envelope, imported from the HOT2000 energy simulation software (HOT2000 1995), and a built-in inventory database containing values of the embodied energy, the greenhouse gas emissions corresponding to both embodied energy (called “embodied emissions”) and operating energy use, and the initial cost of a number of common building materials. In the present version of the EEE, the life cycle calculations account only for the inventory flows associated with the construction and operation stages of a house. The main results of analysis are (Figure 1): (1) the Life Cycle Energy Consumption (LCEC, in MJ); (2) the Life Cycle Greenhouse Gas Emissions (LCGE, in tons of equivalent-CO_2); and (3) the Life Cycle Cost (LCC, CAN$). The life cycle energy use is given in MJ, and is obtained as the sum of the embodied energy in the exterior envelope and the life cycle operating energy use. The life cycle emissions are given in kg of equivalent CO_2, and are calculated as the sum of the embodied emissions in the exterior envelope and the emissions generated from the house operation over its physical life. The life cycle cost, given in Canadian dollars, is the sum of the initial cost of the exterior envelope and the life cycle cost of energy used for the house operation.

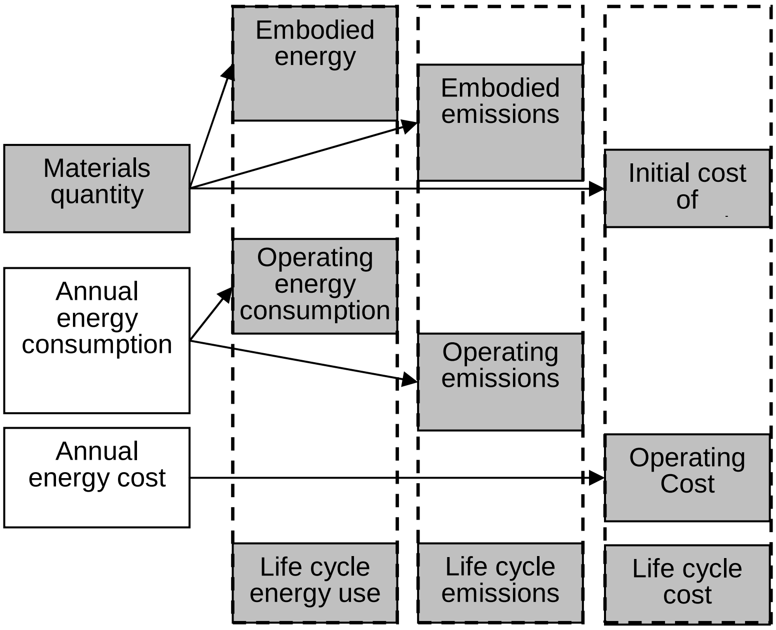

Figure 2. Flowchart of the Energy and Emissions Estimator (EEE)

4. Conclusions

This paper presented a few opinions, collected from the technical literature, concerning the term sustainable development. Although this term is largely used and applied to economical, social and environmental areas, there is still a need for developing simple measuring indicators, especially for assessing the quality of sustainable buildings. All successes obtained so far by designers should be considered as the first step towards the development of sustainable buildings. The goal should be assessed in terms of objective functions that are not affected by economical or political conditions of today. Such criteria should be developed based on the second law of thermodynamics that allows the assessment of the quality of developments and the potential impacts on the environment.

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References

Baouendi, R., Zmeureanu, R., Bradley, B. 2005, Energy & Emission Estimator: a prototype tool for designing Canadian houses. ASCE Architectural Engineering Journal, June, pp.1-10.

Brandemuehl, M.J. 2004, ASHRAE Research Toward Sustainable Buildings, 10(1), pp.1-3.

Cornelissen, R.L. 1997, Thermodynamics and sustainable development — the use of exergy analysis and the reduction of irreversibility. Ph.D. Thesis, Laboratory of Thermal Engineering, University of Twente, Enschede, The Netherlands.

Cornelissen, R.L. and Hirs, G.G. 2002, The value of exergetic life cycle assessment besides the LCA. Energy Conversion and Management, 43, pp. 1417-1424.

Fiksel, J. and Fiksel, D.G. 2001, From Here to Sustainability: A Global Perspective. Chemistry Business, April.

Fowler, C.W. and Hobbs, L. 2003, Is humanity sustainable? Proceedings of the Royal Society of London, 270(1533), pp.2579-2583.

Footprint. 2005, www.earthday.net/footprint/index.asp. Ecological Footprint. Last access on February 27.

Glicksman, L.R. 2003, Promoting Sustainable Building. HVAC&R Research, 9(2), pp.107-109.

Grumman, D.L. 2003, ASHRAE GreenGuide. American Society of Heating, Ventilating and Air-conditioners Engineers, Inc., Atlanta.

Gong, M. and Wall, G. 2001, On exergy and sustainable development-Part 2: Indicators and methods. Exergy, an International journal, 1(4), pp. 217-233.

Hammond, G.P. 2004a, Towards sustainability: energy efficiency, thermodynamic analysis, and 'two cultures.' Energy Policy, 32, pp. 1789-1798.

Hammond, G.P. 2004b, Science, sustainability and the establishment in a technological age. Interdisciplinary Science Reviews, 29(2), pp.193-208.

Hardi, P., Barg, S., Hodge, T. and Pinter, L. 1997, Measuring sustainable development: Review of current practice. International Institute for Sustainable Development. Occasional paper no. 17. Industry Canada, ISBN 0-662-63202-8.

Hornbogen, E. 2003, A definition of sustainability based on entropy production by matter and energy. Metall-Heidelberg, 57(3), pp.124-128.

HOT2000. 1995, User's manual. CANMET, Natural Resources Canada, Canada.

Krotscheck, C. 1997, Measuring eco-sustainability: comparison of mass and/or energy flow based highly aggregated indicators. Environmetrics, 8(6), pp. 661-681.

Larsson, N. 2000, Moving Towards a Green Building Design Process. Sustainable Building Conference, Maastricht, The Netherlands.

Larsson, N. 2003, Sustainability Indicators and Benchmarks for GBC. Background for Discussion. Madrid, Spain, March.

Leadbitter, J. 2002, PVC and sustainability. Progress in Polymer Science, 27, pp. 2197-2226.

Lems, S., Van der Kooi, H.J. and De Swaan Arons, J. 2002, The sustainability of resource utilization. Green Chemistry, The Royal Society of Chemistry, 4, pp.308-313.

McMahon, G.F. and Mrozek, J.R. 1997, Economics, entropy and sustainability. Hydrological Sciences, 42(4), pp. 501-512.

Norde, W. 1997, Energy and entropy: a thermodynamic approach to sustainability. The Environmentalist, 17, pp.57-62.

Peacock, K. 1999, Staying out of the lifeboat: sustainability, culture, and the thermodynamics of symbiosis. Ecosystem Health, 5(2), pp. 91-103.

Robert, K.H., Daly, H., Hawken, P. and Holmberg, J. 1995, A Compass for Sustainable Development. Resource Magazine, 170, pp.31.

Rosen, M.A. and Dincer, I. 2001, Exergy as the confluence of energy, environment and sustainable development. Exergy, an International Journal, 1, pp.3-13.

The Brundtland Commissions 1987, Our Common Future, The Report of the World Commission on Environment and Development (WCOED), Oxford University Press, Oxford.

Thring, M.W. 1990, Engineering in a stable world. Science, Technology and Development, 8(2), pp.107-121.

Vanegas, J.A. 2003, Road Map and priciples for Built Environment Sustainability. Environmental Science and Technology, 37 (23), pp.5363-5372.

Voorspools, K. 2004, Sustainability of the future; rethinking the fundamentals of energy research. Renewable and Sustainable Energy Reviews, 8, pp. 599-608.

Wackernagel, M. and Rees, W. 1996, Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers, Gabriola Island, Canada.

Wall, G. 1977, Exergy - a useful concept within resource accounting. Institute of Theoretical Physics, Goteborg, Report No.72-42.

Weimin, W., Zmeureanu, R. and Rivard, H. 2005, Applying multi-objective genetic algorithms in green building design optimization. Building and Environment Journal, January, pp.1-14.