INDOOR ENVIRONMENT AND SUSTAINABLE BUILDINGS

Hal LEVIN
Building Ecology Research Group, 2548 Empire Grade, Santa Cruz, CA 95060 USA
hal.levin@buildingecology.com

Summary

Integration of indoor environmental concerns in sustainable buildings requires a comprehensive, science-based assessment of building environmental performance. Indoor environmental quality must be assessed in the context of total building performance and the aggregated impacts on the indoor and total environment. This requires articulated targets established on the basis of the carrying capacity ("ecocapacity") of the local and global environment and agreed targets for indoor environmental performance. These "sustainable" targets can be used with total building environmental performance assessment tools in building design and evaluation of completed buildings to create better indoor environments and reduce impacts on the general environment recognizing local context and global environmental concerns. Targets will be based on priorities that vary considerably in developed and less developed countries (Ehrlich and Kennedy 2005). The local context will affect regional and local targets and should be considered in established sustainability targets for resource consumption and pollution emissions. This paper presents an approach to determining sustainability targets based on a Building Ecology framework and an established approach to determine targets for overall global, national, and building sector sustainability. Establishing benchmarks or targets that are sustainable using the environmental capacity concept is shown by example for the building sector.

Keywords: Indoor Environment, Sustainability, Life Cycle Assessment, Ecospace, Building Ecology

1. Introduction

Indoor environmental quality usually focuses on thermal conditions, sound and vibration, light and other electromagnetic radiation, and indoor air quality. While interest in thermal conditions, noise, and light in the indoor environment have received considerable attention for many decades from the building community in the more developed countries, the recent surge in interest in indoor environmental quality has increased attention to building design and construction for so-called "sustainable" buildings. Together with knowledge gained during the past three decades about the impacts of indoor air quality on building occupants, this has resulted in a substantial increase in attention to indoor environmental quality. In developing countries, the indoor environmental quality issues are generally related to more extreme conditions, especially very strong pollution sources such as biofuels used for cooking, poor or nonexistent sanitation, and low levels of control of thermal conditions. However, most efforts to address sustainable building issues -- particularly those addressing indoor environmental quality – do not address the relationship between indoor environment and a building's overall sustainability. Indoor environmental improvements are commonly proposed or implemented in both developed and developing countries without considering the impacts on the larger environment. Addressing sustainability requires identification of the indoor environmental control measures <u>and</u> the related environmental impacts.

The projected environmental impacts of population and consumption assuming modest growth projections result in requirements for reductions in consumption on the order of 50 to 90% of current consumption levels to achieve sustainability (Wetterings and Opschoor 1992; Levin 2000a, Graedel and Klee 2002). Even the most "environmentally-friendly" buildings constructed to date are not sustainable under either dictionary or common sense definitions of the term (Kohler 1998). Therefore, it is essential to reduce dramatically building-related pollutant emissions and resource consumption .

Many technologies used to control indoor environmental quality are resource and energy intensive as well as strong sources of pollutant emissions and land encroachment. Fossil fuel and other non-renewable energy sources based on combustion are strongly related to greenhouse gas emissions (noted hereinafter as carbon emission equivalents – C_{eq}) and their contribution to global climate change. Hydropower systems disrupt and even destroy aquatic ecosystems and adjacent or dependent habitats. Nuclear power generation presents problems of widely-accepted means for ultimate disposal of the radioactive waste products. Regardless of how comfortable, healthy, or productive the indoor environment might be, building sustainably requires that harmful impacts on the general environment be minimized. Truly sustainable buildings will have dramatically reduced energy consumption and related pollutant emissions compared to the current building stock.

Many non-energy-related, non-renewable resources are approaching the point of exhaustion and/or are accompanied by potentially serious impacts on humans and non-human living organisms (Holmberg *et al* 1995; Azar *et al* 1996). Even renewable resources must be managed and used carefully in order to avoid threats to their continued availability. Science-based, systematic efforts to define sustainable levels of resource utilization, land encroachment, and pollution emission must be developed and utilized to assess a building's sustainability (Foley *et al* 2005). The use of such assessments has not been reflected in designs or evaluations of buildings to date.

Most so-called "sustainable" designs are developed without comprehensive assessment of building environmental performance necessary to make informed and wise decisions about the inevitable trade-offs that characterize all design processes. Current designs generally do not integrate much of the knowledge developed in the indoor air sciences during the past three decades. Life cycle assessments (LCAs) and Life Cycle Impact Analysis (LCIA) have collapsed the categorical evaluation with implicit valuation but without explicit discussion of the trade-offs between various environmental problems of concern. These separate problems or impacts are identified in Table 1.

Table 1. Building-related ecological and human health problems

Ecological problems	**Human health problems**
Habitat destruction / deterioration	
(directly resulting in Biodiversity loss)	***Building occupants***
Global climate change	Indoor air pollution – radon
Stratospheric ozone depletion	Indoor air pollution - non-radon
Soil erosion	Accidents in buildings (electrical, fire, falls, etc.)
Depletion of freshwater resources	
Acid deposition	
Urban air pollution / smog	
Surface water pollution	
Soil and groundwater pollution	***Building workers***
Depletion of mineral reserves	Building construction / demolition / material
(esp. oil and some metals)	manufacturing, etc.

LCAs of building materials have often failed to consider the operational phase of a building's life cycle which, for a long-lived product like a building, is the dominant phase in terms of total life cycle environmental impacts. It is certainly the most important in terms of indoor air quality. To date, there have been few efforts to establish the relative importance of ecological and human health impacts. Nearly all "green building" rating systems and design guides fail to address the overall performance of a building design and to identify the necessary trade-offs and the relative importance of the impacts of the built environment on humans versus the impacts on ecological systems.

In order to develop measures to improve IAQ and to avoid negative ecological impacts there must be a consistent framework for systematic, comprehensive evaluation of building environmental performance. Once such systems have been applied to a range of representative buildings, rating systems or other "green" scorecard approaches can be developed relying on the results of such evaluations. To date, such rating systems have relied most heavily on design professionals' judgment and manufacturers' claims about materials and on minimal ventilation and thermal comfort requirements adopted by professional and international societies. In less developed countries, the connections between indoor environmental quality and impacts of its attainment on the general environment are rarely analyzed or even discussed.

The remainder of this paper presents the background and a proposal for a more rigorous, science-based, data-driven assessment and evaluation process of designs and completed buildings. The framework builds on the concept of Building Ecology (Levin 1981, 1997, 2000a, 2000b) integrating all aspects of building performance into a comprehensive approach that includes human and non-human impacts. The framework draws from the sustainability target-setting approaches developed by Wetterings and Opschoor (1992); FOE/NL (1994), and Holdren *et al* (1995), and more recently used by Graedel and Klee (2002).

1.1 Prior Work

A variety of existing tools and methods can be combined to form a framework for comprehensive and systematic building environmental performance assessment. The basis is a specific construct of the concept "sustainability" that goes beyond the oft-cited but hopelessly vague Brundtland Commission definition (Dobson 1996). One can draw from the wide-ranging exploration of sustainability by Bryan Norton (2003), and the sustainability framework outlined by Andrew Dobson in 1996 and revised in 1998. Methods and tools that can be adapted include life cycle assessment (LCA) (Heijings et al 1992; Weitz and Warren 1994), normalization for assessment of impacts in the LCA process (Lindeier 1996), socio-ecological indicators (frequently cited as The Natural Step) (Holmberg 1995, Azar *et al* 1996); Goals and specific environmental performance targets are established using the "Ecocapacity" (environmental capacity) and "Ecospace" (environmental space) concepts developed in the Netherlands in the early 1990s (Wetterings and Opschoor 1992) and used by Friends of the Earth/Netherlands (FOE/NL 1994) and by Friends of the Earth/Europe (FOE/EU 1995). The Dutch approach to setting sustainable development targets was adapted and applied with three worked examples by Graedel and Klee (2002) (although these later authors did not acknowledge the earlier work). Wackernagel and Rees' Environmental Footprint (1996) has been used elsewhere and has its own set of environmentally sustainable consumption and pollution limits. A useful review of some of these precedents is Marshall and Toffel's conceptual framework for sustainability assessment (2005) and Upham's critique of the so-called "Natural Step" process in evaluating the most appropriate and useful tools (2000).

1.2 Need for Weighting Criteria

Missing from nearly all prior efforts is a process for establishing the weighting or prioritization of environmental goals. The trade-off between human and non-human impacts is one of the biggest challenges because it is both so fundamental and so difficult. It is always done implicitly but rarely identified or discussed. Within and between various ecological and human environmental impacts, it is also essential to establish priorities and weightings in order to evaluate proposed designs or building performance in a consistent, transparent manner. This requires the establishment of criteria as illustrated in the comparative international risk assessment by Norberg-Bohm et al (1992) and our previous publications (Levin 1995b, 1997).

2.0 Results

Using the basic environmental carrying capacity ("ecocapacity") approach described by Wetterings and Opschoor (1992) and by Friends of the Earth/Netherlands (1994), environmental space per capita ("ecospace") targets for sustainability have been developed. The target values address the amount of resource consumption or pollution emission per person that the environment can support sustainably (meaning "indefinitely"). The approach proposed originally by Wetterings and Opschoor was adapted by Graedel and Klee into four steps:

1. Determine the virgin material supply
2. Allocate the virgin material
3. Identify the regional recapture of the resource base
4. Compare current consumption rates to sustainable living rates

The first three steps and the first part of the fourth step can be based on available data. However, the establishment of sustainable targets, as in establishing "Ecocapacity" in Wetterings and Opschoor, requires numerous assumptions, among them 1) planning time frame, 2) distribution of environmental goods and services among nations, and 3) assumptions and knowledge of the environment's capacity to replenish natural stocks and absorb pollution emissions. Most of these require value-based assumptions and the use of highly uncertain data. An important but missing piece is an on-going, open dialogue to establish the values framework for making these assumptions. As time passes, better data will be available and revisions may be made both to the value-basis as well as to the estimated carrying capacity. Ehrlich and Kennedy (2005) have called for such a dialogue pointing out that values and assumptions vary greatly among cultures and nations.

2.1 Time Frame:

Wetterings and Opschoor adopted a 50-year time frame based on the availability of reasonably credible and accepted projections of population, resources, and environmental impacts. Graedel and Klee adopted a 50-year time frame based on a projection of two generations. Holdren *et al* assumed a 1,000 year time frame for fossil fuel supply allocation stating that this was longer than normal planning frames and shorter than the geological time scale relevant to the formation of fossil fuels. The 50-year and certainly the 1,000 year time frames allow periodic re-assessment of targets utilizing newly-available data.

2.2 Distribution

Wetterings and Opschoor assumed a shift in the current, inequitable 30-to-1 distribution ratio of per capita use of environmental capacity between individuals in OECD and in developing countries. They adopted a more equitable 10-to-1 ratio over the 50-year time frame, although they did not propose the means by which to achieve this shift. Graedel and Klee adopted a target of equal distribution of ecospace to all projected inhabitants of the earth. Both groups used population assumptions from the then most recent United Nations population projections available at the time of their research. Between 1992 and 2002, the 50-year projections of global population were reduced from around 12 billion to around 10 billion.

2.3 Replenishment:

Each of the environmental resources is estimated on an individual basis and the pollution loads that will not exceed the ability of ecosystems to survive are estimated based on the best available science.

2.4 Calculating Maximum Carbon equivalent (C_{eq}) Emissions Targets

Graedel and Klee calculated carbon emissions in terms of a virgin materials supply limit as follows: Assuming that a stable atmosphere could have a CO_2 concentration no greater than 550 ppmv by the year 2100 related to calculated maximum global anthropogenic emissions of ~7.8 x 10^{15} g (7-8 Pg) of carbon per year. For a projected 7.5 * 10^9 people on earth in 50 years, they would allocate about 1 Mg carbon equivalents per person-year (C_{eq}/p-y). Carbon re-capture was not considered established at this time, so zero recapture was included in their calculations. Inhabitants of the USA produce an average of 6.6 Mg C_{eq}/p-y, "…clearly well beyond the estimated global sustainable rate of 1 Mg C_{eq}/p-y."

In Switzerland, emissions are approximately 2.0 Mg C_{eq}/p-y, still approximately twice the calculated sustainable limit. This calculation provides a target for "sustainable" societies and helps identify the scale of reductions required for a sustainable rate of carbon emissions. The CO_2 emission limits calculations by Graedel and Klee are somewhat higher than the estimate by Wetterings and Opschoor made ten years earlier to allow a sustainable global average per capita carbon emission of 0.4 Mg C_{eq}/p-y. Scaling the Dutch estimate based on the more recent population projection used by Graedel and Klee results in a target value of ~0.5 Mg C_{eq}/p-y.

Using these two figures as the upper and lower boundary, an estimate weighted toward the more recent and environmentally just calculation of Graedel and Klee produces a global average target value of ~0.8 Mg C_{eq}/p-y. This requires an approximate 8-fold reduction in the annual average per capita carbon emissions in the USA and about half that in most of Europe and in Japan. As the Dutch authors suggested, with a transparent target-setting process, the targets can be revised when new data become available and when different values are used to inform the target-setting process.

2.5 Allocation of resources within societies/nations:

The next critical question is the allocation of carbon emissions among various sources. An initial estimate can be made using the current proportion of emissions among major activities and sectors. Buildings' share is assumed to be ~40% of total C_{eq}/p-y (Levin 1995, Roodman and Lenssen 1996). The relative opportunities for improvements through conservation, more efficient technologies, and behavioral changes among the major sectors – industry, buildings, transportation, and agriculture – could be used to adjust the allocations among and even within these sectors.

An initial annual target of ~0.35 Mg C_{eq}/p-y is assumed for all building-related purposes including construction, operational energy, and the energy required to manufacture, install, maintain, and replace materials over a building's life cycle. Depending on the service life of a building and its components, a reasonable estimate of the life cycle energy and related carbon emissions will be in the range of 50 to 90% during the use phase. The longer the use phase, the lower the annualized energy and carbon emissions costs of embodied energy. In buildings with long service lives, presumably the most sustainable buildings, then the 90% reduction value would result in an allocation of 0.35 Mg C_{eq}/p-y.

Further research can establish the potential efficiency improvements in each sector and provide incentives and sanctions for utilization of this “virgin material supply limit” allotment. For example, the transportation and building sectors have enormous room for improvements due to the large inefficiencies in the current vehicle fleet and building stock respectively. Over time, the limits can be reviewed and revised as more complete, accurate, and current data become available.

2.6 Building use type targets

Allocation of the per-person target among various building types could be accomplished in several different ways. A simple, readily-available way is using the current distribution of energy use among building types as a basis. Using the data in the U.S. Department of Energy’s *Buildings Energy Databook* (2004), the residential-to-commercial ratio is currently about 1.17. Within residential, there is as much as a 2 to 1 ratio between the energy used per m^2 per household member in single family detached dwellings and in multi-family dwellings in buildings with 5 or more units per building. This kind of disparity should be considered in allocations made according to existing distributions, according to equal energy use per capita, or according to some weighted distribution that encouraged more efficient energy use. Within commercial building types, energy use per m^2 varies by a factor of 6 with food sales being the highest at around $5.7*10^6$ btu/m^2-y and warehouse and storage the lowest at around $1*10^6$ btu/m^2-y. Offices are at about $2.3*10^6$ btu/m^2-y and educational facilities at $1.5*10^6$ btu/m^2-y.

Again, the per capita share of each use should also be considered in making calculations, but this could be further adjusted by consideration of the time spent in and the nature of each environment. For example, health care facilities are quite different from public assembly spaces in terms of the impact of the indoor environment on occupants and the occupancy patterns. It can also be argued that economic outcomes such as “productivity” (or more accurately, “task performance”) should be considered.

Allocations can be based on the distribution of person-hours spent in each building type. But some buildings are inherently more energy intensive than others, e.g., laboratories and health care facilities compared to houses or offices. Thus, an adjustment would have to be made. Again, weighted allocations could be used as a policy tool to encourage more efficient energy use patterns.

2.7 Building-specific performance targets

Building-specific environmental performance targets can be established for individual projects or building-types or for political or bioregional divisions or for whole nations. A convenient convention would be to calculate a building’s ecospace allocations based on multiplying its use of ecospace by the total of all buildings of the same use type and comparing it to global targets. This can be done with the reciprocal of its area or its units of person-hours of use. For example a school of 1,000 m^2 and 500 students could be allocated its share of the total ecospace for schools based either on total educational facility area or total students in the municipality, region, nation or world. Allocation between various types of facilities and individuals should also be determined by the relative intensity of activity requiring the resource use or pollution emission as modified by local conditions of climate and the relevance of the particular resource or emission to the geographical and political contextual basis for the allocations. Here the strong connection between indoor environmental control and sustainability becomes clear. Air pollution problems differ between large urban areas and small towns or rural areas, and climate and other factors can affect the ability of a region to absorb pollutants without exceeding established limits.

2.8 Applying the C_{eq} Emission Approach to Other Environmental Concerns

The approach used for C_{eq} emissions targets per building can be applied to other pollutant emissions and resource consumption. Once the allocation of permissible resource consumption and pollutant emissions is established, alternative designs can then be evaluated against comprehensive environmental performance goals. Specific environmental goals are articulated and project-specific targets are established for use with some of the LCA and other tools already available during design.

2.9 Indoor Environmental Quality and Sustainable Targets

Each of the four main categories of indoor environmental quality – thermal conditions, acoustics, , illumination, and indoor air quality – involve significant implications for energy and other resource consumption and associated pollutant releases. No solution to indoor environmental quality problems can be evaluated in terms of sustainability without consideration of these implications. This requires modeling for the entire life cycle of a building and comparing various alternative design, construction, and operational options. In the end, there will inevitably be trade-offs among environmental goals.

For example, increasing electric illumination or dilution ventilation and close regulation of thermal conditions by mechanical means will require more energy consumption with all the associated environmental impacts. Increasing illumination increases heat loads, thus requiring more cooling in large commercial buildings where cooling loads dominate throughout most of the year. Increasing outdoor air ventilation in humid climates can increase energy requirements for removing excess moisture in order to control humidity within acceptable limits for comfort and to avoid mold growth. In dry climates, increasing ventilation can result in indoor air that is too dry resulting in occupants' symptoms and complaints related to dry eyes and mucus membranes.

Indoor environmental quality has not been addressed in life cycle assessment tools. Its evaluation in "green building" rating systems is limited to incomplete, imprecise indicators of potential indoor pollution and its effects. LCAs use equivalencies for various pollutants that contribute to (cause or exacerbate) an environmental problem. Indoor pollutants can be treated in a similar manner using a risk-based approach to evaluation of various products' contributions to indoor pollution. The permissible contribution of any source of any given type of pollutant in an indoor environment must be determined in the context of all other sources of that pollutant in the particular building in question.

Reducing entry of noise from outdoors may require reducing natural or passive ventilation and result in increased levels of pollutants from, indoor sources while natural ventilation can result in elevated levels of pollutants with outdoor sources such as combustion products from motor vehicles or electric power plants. Increasing daylight illumination using windows or skylights can increase thermal loads requiring more energy to provide comfortable and productive conditions for occupants. Each indoor environmental control technology should be analyzed at both indoor and general environmental problem levels according to the list in Table 1. Furthermore, each aspect must be analyzed in terms of the collective impact of the total building design and performance.

3. Discussion

No matter which framework, rating system, or assessment tool is used, the relative importance of various identified environmental problems must be weighted in order to inform the trade-offs that inevitably must be made. Resource limitations and conflicting solutions to various environmental problems require these trade-offs. Norberg-Bohm's framework for comparative risk assessment (1992) and the US EPA's Reducing Risk report (1990) were among the sources of the criteria shown in Table 2 for weighting environmental problems The EPA criteria were adopted along with a fifth criterion, "the status of the affected sinks." These criteria are reasonably similar to those used by Norberg-Bohm in her international comparative risk assessment (1992) that included both man-made and natural environmental hazards.

Table 2. Criteria for evaluating the importance of various environmental impacts:

The Spatial Scale of the Impact (Global, regional, local - large worse than small)
The Severity of the Hazard (More toxic, dangerous, damaging being worse)
The Degree of Exposure (Well-sequestered substances being of less concern than readily mobilized substances)
The Penalty for Being Wrong (Longer remediation times of more concern)
The Status of the Affected Sinks (Already overburdened sinks more critical than less-burdened ones)

One of the biggest challenges facing those who would develop a systematic approach to building environmental performance evaluation is sorting out the relative importance of building-related impacts on ecosystems versus those on human health, welfare, and comfort (see Table 1). This is a particularly significant challenge for those interested in indoor environmental quality. While much of the recent literature on sustainability mentioned or referenced here has adopted an anthropocentric perspective toward ecosystems, there has been very little progress toward establishing a broadly-accepted basis for trade-offs between human and non-human health and welfare. A risk assessment approach applied both to human and non-human systems can be used, but ultimately, science alone will not be able to identify clear, widely-acceptable valuation of different environmental impacts *viz*, the spotted owl vs. logging old growth forests in the American northwest.

To what extent can we presume to increase the threat to the survival of an endangered species or damage an ecosystem in order to increase human comfort or health or to stimulate economic activity? A balance must be established, but the process of defining the balance will involve technical and political decisions as well as the use of highly uncertain data. In Europe the “precautionary principle” is established in the Constitution of the European Union. It urges opting for safety in the absence of certain science.

> “Union policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Union. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay.” (European Union 2004).

In the United States, in contrast, the free market and commerce are favored until certainty is obtained to suggest restrictions to protect human health or the environment.

4. Conclusion and Implications

Sustainability goals and targets can be developed with a focus on the particular environmental, social, and economic context where the building will be built and on the current understanding of the impacts of human activities on the environment. In this manner, trade-offs based on potential conflicts between and among various measures intended to improve indoor and general environmental performance can be made in a rational and consistent manner. The overall result is an approach to building design that aims to produce a better indoor environment as well as reduced environmental impacts with emphasis on both local needs and global environmental concerns. Using the approach we have called Building Ecology, indoor environmental quality goals can be attained without compromising the ability of the building to minimize harmful impacts on the general environment, and designers and policy-makers can be confident that building environmental performance is moving the toward a more sustainable future.

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