INTEGRATING INDOOR AIR AND DESIGN FOR SUSTAINABILITY

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ABSTRACT
Integration of IAQ concerns in so-called sustainable designs has suffered from a lack of a comprehensive, science-based assessment methodology for building environmental performance. Guidance and rating systems for "green" buildings fail to address systematically the trade-offs necessary for assessment of the overall performance of a building or its design. This paper presents a framework constructed on the basis of Building Ecology for such an assessment. Using the environmental capacity concept developed and used in the Netherlands in the early 1990s, environmental performance targets can be established. Specific environmental goals including those for indoor air quality can be articulated and targets established for use with life cycle assessment tools. The overall result is an approach to building design and evaluation of completed buildings that can create better indoor environments as well as reduced impacts on the general environment with appropriate and clearly-articulated emphasis on the local context as well as global environmental concerns.

INDEX TERMS
Indoor Air Quality, Sustainability, Life Cycle Assessment, Ecospace, Building Ecology

INTRODUCTION

During the past decade or more, increased interest in indoor air quality (IAQ) has resulted from increased attention to building design and construction for so-called "sustainable" buildings. In fact, such buildings constructed to date are not sustainable under either dictionary or common sense definitions of the term. Science-based, systematic efforts to define sustainable levels of resource utilization, land encroachment, and pollution emission have been proposed and examples provided. Yet such efforts have not been reflected in designs or evaluations of buildings to date.

The integration of IAQ concerns in so-called "sustainable" designs suffers from a lack of comprehensive assessment methods for building environmental performance and a lack of integration of the knowledge developed in the indoor air sciences during the past three decades. Life cycle assessments (LCA) have collapsed the categorical evaluation with implicit valuation but without explicit discussion of the trade-offs between various environmental problems of concern. LCAs of building materials have generally failed to consider the operational phase which, for a long-lived product like a building, is the dominant phase in terms of total 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 adequately 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. These separate impacts are identified in Table 1.

In order to develop measures to improve IAQ and to avoid negative ecological impacts there must be a consistent framework for evaluation of building 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.

This paper presents a framework for a more rigorous, science-based, data-driven assessment process for evaluation of designs and completed buildings. The framework builds on the concept of Building Ecology (Levin 1981; 1995) integrating all aspects of building performance into a comprehensive framework including human and non-human impacts.

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Table 1. *Building-related ecological and human health impacts*

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 (esp. oil and some metals)	Building construction / demolition / material manufacturing, etc.

METHODS

A variety of tools and methods have been reviewed and combined to form a framework and outline for a comprehensive approach to systematic building environmental performance assessment. These 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 – more frequently associated with the Natural Step (Holmberg 1995, Azar et al 1996); and the sustainability framework outlined by Andrew Dobson (1996). Goals and specific environmental performance targets can be established using the environmental capacity (“Ecocapacity”) concept developed in the Netherlands in the early 1990s (Wetterings and Opschoor 1992) and applied by them as well as by Friends of the Earth/Netherlands (FOE/NL 1994) and Friends of the Earth/Europe (FOE/EU 1995). This approach was presented again and illustrated with three new worked examples by Graedel and Klee.(2002), although these later authors did not acknowledge the earlier work. Wackernagel and Rees’ Environmental Footprint (1996) was also reviewed. Finally, we reviewed Marshall and Toffel’s (2005) conceptual framework for sustainability assessment and Upham’s critique of the so-called “Natural Step” process in evaluating the most appropriate and useful tools.

RESULTS

Using the basic environmental carrying capacity (“ecospace”) approach described by Wetterings and Opschoor (1992), later by Friends of the Earth/Netherlands, and finally by Graedel and Klee (2002), environmental performance targets for sustainability can be developed. (This process does not differ in many fundamental respects from the process of establishing concentration limit values for indoor air pollutants.) 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) the time frame for planning, 2) the distribution of environmental goods and services among and within nations, and 3) the ability of the environment to replenish or absorb natural stocks and pollution emissions. Many require value-based assumptions and/or the use of highly uncertain data.

Time Frame: Wetterings and Opschoor used a 50-year time frame based on reasonably available 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 and utilization of new data.

Distribution: Wetterings and Opschoor assume a shift in the current, inequitable 30-to-1 distribution ratio of per capita environmental capacity between OECD and developing countries to a more equitable 10-to-1 ratio. 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 most recent United Nations population projections.

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

Example: Maximum CO_2 emissions
Graedel and Klee calculated carbon emissions in terms of a virgin materials supply limit as follows: Assuming that a stable atmosphere could have aCO_2 concentration no greater than 550 ppmv by the year 2100 resulting in a calculated maximum global anthropogenic emissions of ~7.8 x 10^{15} g (7-8 Pg) of carbon per year. For a projected 7.5 billion people on earth in 50 years would allocate about 1 Mg carbon equivalents/person-year (p-y). Carbon re-capture was not considered established at this time, so zero recapture was included in calculations. Since the U.S. produces on average 6.6 metric tons of carbon equivalents/p-y, this is "clearly well beyond the global sustainable rate of 1 Mg of carbon equivalents/p-y. Switzerland produces approximately 2.0 Mg of carbon equivalents/p-y, still approximately twice the calculated sustainable limit. This calculation provides a target for "sustainable" societies and they point out the scale of reductions required for a sustainable rate of carbon emissions. The CO_2 emission limits calculations by Graedel and Klee are of the same order of magnitude as those by Wetterings and Opschoor ten years earlier.

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. Based on data by Levin et al (1995) and Roodman and Lenssen (1996), such an allocation would result in an annual allotment of about 0.4 Mg of carbon equivalents/p-y for all building-related purposes; these include operational energy as well as the energy required to manufacture, install, maintain, and replace materials over a building's life cycle. 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 fleet and building stock respectively. Over time, the limits can be reviewed and revised as more complete, accurate, and current data become available.

Building-specific environmental performance targets
Building-specific environmental performance targets can be established on a project by project basis or building-type bases for a political or bioregional division or for a nation as a whole. A convenient convention is to calculate a single building's allocation based on multiplying its use of ecospace by the total of all buildings of the same use type. 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, or nation. Of course allocation between various types of facilities and individual 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. Air pollution issues differ between most 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 some established limit.

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.

Indoor air quality
Indoor air quality has not been addressed in life cycle assessment tools and its evaluation in various building rating systems is limited to incomplete and imprecise indicators of potential indoor air pollution. Life cycle assessments attempt to develop 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 air pollution. The permissible contribution of any source of any give 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.

DISCUSSION
No matter which framework or tool is used, the relative importance of various environmental problems, to the extent that they have been identified and characterized, must be weighted in order to inform the trade-offs that inevitably must be made due to resource limitations and, at times, conflicting solutions or resolutions to prevent or

mitigate the environmental problems. Norberg-Bohm's framework for comparative risk assessment (1992) and the US EPA's Reducing Risk report (1990) were the source of criteria for weighting environmental problems

The EPA criteria along with a fifth criterion, "the status of the affected sinks," are shown in Table 2. 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	(An already overburdened sink more critical than a less-burdened one)

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. This is a particularly significant challenge for those interested in indoor air quality. While much of the recent literature on sustainability mentioned or referenced here has had an anthropocentric orientation toward ecosystems, there has been very little work to establish a broadly acceptable 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.

CONCLUSION AND IMPLICATIONS

The sustainability goals are 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 environmental performance can be made in a rational and consistent manner. The overall result is an approach to building design that results in a better indoor environment as well as reduced impacts on the general environment with special emphasis on local needs as well as global environmental concerns. Using this approach which we have called Building Ecology (Levin 1981, 1995), indoor air 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 moves toward a more sustainable direction.

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