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BEST SUSTAINABLE INDOOR AIR QUALITY PRACTICES IN COMMERCIAL BUILDINGS

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Abstract. This paper describes commercial building indoor air quality practices and then discusses them in the context of total building environmental performance. “Green buildings” generally have included some effort to address indoor air quality issues along with an unspecified number of other environmental concerns. Rarely, if ever, is analysis conducted to evaluate trade-offs made among environmental features considered important in “green” buildings even though conflicts occur among design features intended to improve a building’s environmental performance. One “green building” feature may reduce certain environmental impacts while increasing others. A method is needed to examine the total environmental impact of designs. In order to identify best sustainable indoor air quality practices in commercial buildings, a newly-developed, comprehensive approach to building ecology is presented. This approach, tentatively titled the Systematic Evaluation and Assessment of Building Environmental Performance (SEABEP), uses sustainability criteria as the basis for comprehensive evaluation of the environmental performance of design features.

Introduction

Many building design professionals are now involved in “green” building design or “sustainable design” in response to expressed interest or requirements from their clients. Some building design professionals initiate “environmentally-responsible” design based on their own recognition of the need for reducing human impacts on the environment - local and global. This appears to be occurring more frequently in Europe and North America during the past half-decade. In the future, economic criteria and regulatory mandates are likely to motivate more and more designers’ clients, building owners, and other both public and private organizations to create “environmentally-responsible” buildings. As this occurs with increasing frequency, designing buildings with low environmental impacts will become both a necessary and a challenging part of building design professionals’ work. It will also offer new opportunities for developers, product manufacturers, and others in the building industry.

The trend toward environmental protection is gaining momentum. Public opinion in the United States (and around the world) indicates that people are supportive of environmental protection even if they must pay a modest additional economic cost. Innovations in economic analyses are emerging that value environmental resources and quality more highly and modify the outcome of “bottom line” calculations to favor less environmentally harmful behavior (1). In many cases, as for example in the production of aluminum and steel building products, recycling already appears

Table 1. Common “Green Building” Features

Energy conservation features: insulation, efficient lights and mechanical equipment
Solar energy utilization: passive space heating, cooling; water heating; photovoltaic electricity generation
Water conservation features: low consumption fixtures
Incorporation of recycled materials, or materials with large fraction recycled content
Low emitting material selection and ventilation for improved indoor air quality
Reduced building construction waste and re-sourcing waste products
Less environmentally-destructive site development: run-off control, small footprint, preservation of water courses, natural vegetation and habitats
On-site wastewater treatment
Reduced or zero use of ozone-depleting compounds in refrigeration and fire suppression systems
Life cycle assessment (“cradle-to-grave”) of materials or building systems
Formal (regulatory) environmental impact assessment of the total building project
Recycling provisions (in building design) for occupants

to make both economic and environmental sense. It is clear that the environmentally preferred solution is also better economically. Social and political forces will bring additional pressure for more environmentally-sound technological decisions. Regulations will continue to evolve to protect the environment from technological development including the construction, operation, use, and disposal of buildings.

“Green Building” Practices

To date, efforts to implement “green” design practices have consisted largely of adoption or eclectic adaptation of various technologies and solutions to perceived environmental problems. Normally these solutions have been incorporated to reduce harmful environmental impacts (2). Collectively, they have come to be known as the elements of a “green” building design. Some examples of common “green building” features are listed in Table 1.

Indoor Air Quality “Best Practice”

Many building design, construction, and operational measures necessary to create good indoor air quality in commercial buildings are well-established. The challenging opportunity facing designers today is to implement the measures in the context of a so-called “green building” project or “sustainable” building design. Table 2 below provides an overview of the major measures required to create good IAQ in a commercial building. Following the table is an elaboration and discussion of each of the ten best practices. That is followed by consideration of how to integrate these with other sustainable design objectives in a rational and comprehensive fashion. More detailed guidance for indoor air quality can be found in several referenced publications (3-9).

Table 2. IAQ best practice concepts for commercial buildings

1. Relationships between indoor air pollution sources, ventilation, and concentrations.
2. Simple dose response basis for health effects: “the dose makes the poison”
3. Overall design consideration of indoor air quality: from cradle to grave
4. Source identification:
5. Source control options and strategies
6. Ventilation system design and operation
7. Material selection and specification
8. Construction procedures
9. Maintenance and operation
10. Change of Use, Renovation, Adaptive Re-use, and De-mounting

Basic Relationships Between Indoor Air Pollution Sources, Ventilation, and Concentrations

Concentration = source strength/ventilation rate. There is a simple mathematical relationship that clearly expresses the most important relationships in indoor air quality. Concentration is a function of source strength divided by ventilation. There are many types of contaminant removal mechanisms including filtration and air cleaning, deposition on surfaces, and chemical transformation. But the most important concepts are embodied in the simple relationship between source strength, ventilation, and concentration (7-9).

This relationship is expressed in equation 1.

$$\text{Concentration (mg/m}^3\text{) - Emission Rate (mg/h) / Ventilation Rate (m}^3\text{/h)} \quad [1]$$

The emission rate is determined by the emission factor (mg/m^2 h) times the area of the source (m^2). The ventilation rate is the amount of uncontaminated air introduced into the space (or environmental test chamber) per hour.

Source control is most effective. The most effective strategy for achieving good indoor air quality is source control. Identification of pollutant sources is the first step. Then, elimination, reduction or isolation are the next three strategies that should be applied. For example, completely encapsulating a particleboard sheet material used in casework can reduce significantly the emission rates of formaldehyde and other volatile organic chemicals from the product (7-9).

Major sources: The major sources of indoor pollutants include the outdoors, the building itself, the occupants, building equipment, appliances, and consumer products. The most important sources vary from project to project. Building materials are important, particularly when they are new and for many weeks or months afterwards. Some, such as composite wood products, due to their thickness and their pollutant content, can be sources for years after installation. Major pollutant sources and removal mechanisms are listed in Table 3.

Ventilation principles: The most effective exhaust for point or concentrated sources of pollutants is local exhaust. For distributed sources, dilution ventilation is used. An effective air supply strategy is displacement ventilation, usually involving introduction of air low in a space, then relying on thermal forces to transport low air upwards and create a strata of more polluted air just below the ceiling. There the polluted air is collected and removed for exhaust or cleaning and recirculation. It is essential to maintain overall ventilation system balance since it is pressure differences that result in air flows within and between spaces..

Table 3. Determinants of indoor air quality

POLLUTANT SOURCES
- Outdoor Air, Soil, Water
- Building Envelope
- Building Equipment
- Finishes and Furnishings
- Machines and Appliances
- Occupants
- Occupant Activities
- Maintenance and Cleaning

POLLUTANT REMOVAL MECHANISMS
- Sinks
- Ventilation
- Air Cleaning and Filtration
- Chemical Transformation

Other pollutant removal mechanisms: Among the most common removal mechanisms are filtration, usually incorporated into a mechanical ventilation system, the process of particle or chemical deposition on surfaces, and chemical transformations. These are discussed further below.

Simple dose response basis for health effects: “the dose makes the poison”

The dose makes the poison: This is the fundamental principal of toxicology. Everything is toxic, it is just a matter of dose. Thus, there are no “non-toxic” products or chemicals, there are just more or less toxic ones..

Major health effects: Health effects can range from irritation and discomfort to disability or life threatening disease. Table 4 lists the major effects including health effects of exposure to indoor pollutants.

Major indoor air pollutant classes and their effects: The most commonly discussed indoor air pollutants are volatile organic compounds (VOCs), microbial contaminants (fungi, bacteria, viruses), non-viable particles, inorganic chemicals (nitrogen oxides, carbon monoxide, carbon dioxide, ozone), and semi-volatile organic compounds (SVOC - including pesticides and fire

Table 4. Major Health Effects of Indoor Pollutants:

Infectious disease: flu, cold, pneumonia (Legionnaires' Disease, Pontiac fever),
Cancer, other genetic toxicity, teratogenicity - (Ecotoxicity)
Asthma and allergy

CNS, skin, GI, respiratory, circulatory, musculoskeletal, and other systemic effects
SBS (Sick Building Syndrome)

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retardants). The VOCs and the microbial contaminants receive the most attention, and, perhaps, deservedly so. Common industrial solvents, adhesives, and other modern chemical products are abundant in most indoor air, although the concentrations are generally far lower than known thresholds for health effects. Nevertheless, the huge number of chemicals present suggests that there may be effects due to additive or synergistic effects.

SBS: causation hypothesis and interactions: Sick building syndrome has received much attention as it has become more widespread in modern buildings. It is now generally recognized as a multi-factorial problem; that is, it is caused by a constellation of factors, not by a single building-related factor. It is probable that there are additive and even synergistic effects of some of the environmental factors, not just chemicals or microbes, but also the acoustic, thermal, illumination, and other aspects of the indoor environment that affect the incidence of SBS. It is also likely that work stress and other psychological and social or institutional factors play a role in the incidence of SBS (10-15).

Overall Design Consideration of Indoor Air Quality: From Cradle to Grave

Planning through construction, commissioning. A major cause of indoor air quality problems is premature occupancy. Buildings are occupied before construction is complete, either with respect to installation of finishes and furnishings, or with respect to the complete testing, adjusting, and balancing of the HVAC system. By considering the need for thorough curing of new products and complete verification of a properly functioning ventilation system, many IAQ problems can be avoided. This requires planning from the outset for adequate time between scheduled completion and initial occupancy.

Operation Design and operation must be consistent. The design team must make appropriate assumptions about the use of the building, document their assumptions, and pass them along to the operators of the building. Operational schedules must be adequate not only to control thermal conditions but also to remove pollutants accumulated during off-hours. Early morning purging, especially after weekends and other extended unoccupied periods is essential. When maintenance or housekeeping activities involve the application of chemicals such as carpet shampoo, solvents, floor wax, or furniture polish, the accumulated emissions from these processes should be removed before re-occupancy.

Maintenance and housekeeping. Neglected or deferred maintenance is often the source of IAQ problems. Design should provide for access to all components of HVAC systems for inspection, repair, and cleaning. Cleaning of surfaces, especially periodic removal of accumulated dust from concealed surfaces above a suspended ceiling used as a return air plenum, is essential. Vertical fabric covered surfaces such as walls or office workstation panels should be vacuumed since small, inhalable particles deposit as easily on vertical as on horizontal surfaces.

Modification and Renovation. During construction activities, construction dust, fumes, and vapors must be contained and not allowed to contaminant building surfaces or the air in occupied spaces. Temporary ventilation and isolation barriers should be employed.

Adaptive re-use. When the use of a space or building is significantly changed, it is essential to determine whether the building can support the new activities and occupancy loads. This can be done by reviewing record drawings and other documents. If such documents are not available, an engineering assessment should be conducted.

De-mounting and re-source or disposal. Ultimately, buildings or portions of buildings will be demounted and replaced. Care must be taken during demolition to avoid contamination of occupied spaces or of surfaces that will remain in use or be re-used.

Source Identification

Control of indoor air quality requires adequate identification of pollution sources and development of strategies to address each source.

Outdoors. Sources outside the building include ambient air pollution, emissions from neighboring buildings or activities, contamination in soil adjacent to or under the building,

Building fabric. The building structure, envelope, and floor system are major components that must be considered, even though many of their surfaces will be covered by finish materials or will not be visible to the building occupants. Spray-on fireproofing or acoustic materials have very large surface areas and are often exposed to the circulating air within the building. Contaminants can adsorb on these surfaces and subsequently be re-released. Chemical reactions and emissions from the products themselves can occur due to changes in the humidity. Deterioration of aging binders or erosion by air currents can also result in breakdown of these materials and releases of pollutants into the building air.

Building finishes. As is the case with the building fabric, finishes can be sources and sinks for pollutants. Care in their selection is essential, and major surface areas and masses of materials should be identified and carefully considered as potential pollutant sources.

Building equipment: HVAC systems are increasingly recognized as sources of pollutants. Microbial contamination of filters is a potential source of microbes and their metabolic by-products, microbial VOCs. Power, illumination, transport, communication, and security system components can also be significant sources.

Occupants and their activities. The most important source, and the one over which building designers and constructors have the least control is the building occupants themselves. The nature of the occupancy and use of the building is an important indicator of the type of contaminants that will originate from the occupants.

Load documentation and calculations Thermal and pollutant loads should be documented and considered part of the design process as well as the building management process. By creating such documentation and including it with materials submitted to the building owner as part of the design approval process, designers ensure that there is a common understanding of the use of the building and its implications for pollutant sources.

Source Control Options and Strategies

Isolation from outdoors. For pollutants such as pesticides used to treat soil or for radon gas, complete isolation of the building from the outside is the most effective strategy. Moisture intrusion is a major contributor to microbial contamination, and, therefore, should be prevented. The integrity of joints in the construction, of coatings, seals, and other barriers is essential. It is also important to control pressure relationships across the envelope to prevent moisture accumulation on or behind surfaces. The placement of vapor barriers is determined by the indoor - outdoor humidity ratios and the local climate.

Outdoor air cleaning and filtration. Among the most common pollutant removal mechanisms is filtration, usually incorporated into a mechanical ventilation system. This involves circulation of air through a filter where particles are removed primarily because they cannot pass through the openings in the media, usually made from cellulose or man-made mineral fibers. Recent advances in filter technology allows for much more effective filtration of smaller particles, those in the inhalable size range, without concomitant pressure drops that formerly required larger fan capacity and more energy consumption. In some cases air cleaning is done for gases by use of selective sorbent media.

Some pollutants are removed by the process of deposition on surfaces. To some extent these processes, known as sink effects, are usually reversible, at least to some degree, but the sink effect serves to buffer very high concentrations at the cost of extending the pollutant residence time over longer periods. Frequent cleaning of surfaces can reduce the burden on ventilation and filtration or air cleaning and may be found cost effective in some applications. In any case, surfaces should be cleaned to control contaminant concentrations.

Finally, chemical transformations can take place, as is the case when ozone brought in from outdoors or generated by photocopiers and laser printers reacts with certain organic chemicals, often forming more irritating compounds than were present before the ozone interaction. Ozone is often used to convert a “smoking” room to a “non-smoking” room in hotels. What is not well-understood or considered is the nature of the compounds formed by this process.

Outdoor air ventilation rates and schedules. Adequate outdoor air supply involves assessing the quality of the outdoor air as well as the needs to remove pollutants from people and from materials or processes within the building. Starting up to late in the morning or not providing enough ventilation during housekeeping activities can cause unnecessary air quality problems.

Ventilation System Design and Operation

Local exhaust for point sources. The most effective way to control indoor air pollutants from sources within a building is to remove them at the source and not allow them to disperse to other portions of the space or building or to deposit on surfaces (sinks) from which they can be emitted later. Kitchen range hoods and bathroom exhaust fans are good examples. Smoking lounges with one-pass, direct-exhaust ventilation are another example.

Air distribution strategy and ventilation effectiveness. Consider air distribution and ventilation effectiveness before establishing outdoor air ventilation rates. Ventilation effectiveness indicates the portion of the supply air that reaches the occupants' breathing zone. To the extent that ventilation effectiveness is less than 100%, then additional outdoor air needs to be provided to compensate for the shortfalls. The location of supply and return registers will affect air distribution and ventilation effectiveness under some conditions. Local supply directly into the breathing zone of the occupants may be the most effective strategy where feasible. In the long run, it can save energy and even first costs for mechanical ventilation and conditioning.

Outdoor air ventilation rate: It is necessary to ensure that there is adequate dilution for the people-related, activity-related, and the building-related sources. Traditionally ventilation rates have been based only on the number of people. This is not adequate since occupant density does not necessarily correlate with the source strengths of processes, building materials, and other potentially important sources.

Accessibility of all system components. This includes filters, coils, drain pans, ductwork, duct liners, plenums, valves, controllers, etc. They must be accessible for inspection, cleaning, maintenance, and repair. While this may seem obvious, it has frequently been neglected and caused serious IAQ problems.

Operator training. Operation of complex, modern HVAC systems requires competent, well-trained personnel. While operator training is often part of the construction contract, it is often skipped over because the operators are pre-occupied with getting a new building or system running at the time when the training is to occur.

Commissioning. Traditional testing, adjusting, and balancing is simply insufficient to ensure a properly function HVAC system. Increasingly in recent years, construction contracts call for complete HVAC system commissioning before final acceptance of the building. This is found to be both cost effective for the owner and beneficial for the contractor as well. Benefits include reduced call-backs, energy-saving during operation, and avoidance of many common IAQ problems in new buildings.

Material selection and specification

Quantify major materials and identify important sources. Based on mass and area ratios to space volume, target products should be selected for careful review, specification, and installation.

Some sources will be important although small in area or mass. These include many wet products such as paints, sealants, adhesives, caulks, and chemical additives.

Identify major material selection criteria and alternatives. Criteria include emissions when new and service lifetime for estimating total occupant exposure; acoustic, energy, lighting, aesthetics, maintenance, cost, and other factors. Data are available on the emissions of many products and, increasingly, manufacturers are recognizing the need to provide data on the emissions from their products. Low total emissions is useful for screening but compound specific emission rates are necessary to address health, irritation, and odor effects.

Obtain maintenance, durability, and expected service life for candidate materials The durability of a material or product is a major determinant of its potential importance to indoor air quality. The more durable a material, the less likely it will result in indoor pollution. Maintenance product requirements should be considered at least as important as emissions from new materials.

Determine indoor air implications of removal and replacement processes. Ultimately, surface materials will need to be replaced, and their removal and replacement can be a very large source of indoor air pollution. This should be evaluated when products are originally selected.

Specify construction practices Temporary ventilation can reduce adsorption on surfaces and subsequent re-emission of contaminants from building products. Construction filters should be specified and changed before occupancy. Moisture protection for porous materials can reduce microbial growth when materials are installed. Moistened materials should be removed and replaced at the contractor's expense. Proper clean-up of exposed and concealed surfaces exposed to circulating air should be completed before initial occupancy. Indoor air quality can be improved by limiting fleecy and porous materials and by isolating them from high VOC concentrations and particles during construction. Specify finish construction installation practices including adequate ventilation (special temporary if necessary) to control concentrations and avoid excessive sink effects.

Construction Procedures

Review submittals to ensure conformance to IAQ performance specifications. No matter how careful the selection process, materials can be substituted during the construction process. It is necessary to monitor the submittals phase for substitutions that will result in IAQ problems.

Specify and observe construction site practices. It is essential to ensure that porous materials are protected from moisture. Wet or moist construction materials are a common source of microbial contamination once buildings are occupied. Specify and observe adequacy of ventilation conditions during installation of wet products. Specify and observe protection of fleecy and porous surfaces from dust, gases, and vapors. Ensure completion of HVAC Testing, Adjusting and Balancing, and of full HVAC commissioning before occupancy. Ensure ventilation and thermal control systems are operational and effective prior to move-in and initial occupancy. Recommend (if possible, specify) and monitor move-in and initial occupancy procedures to ensure indoor air quality and climate. Assemble the project manual to include full documentation of thermal and IAQ loads; HVAC system design criteria, assumption, and equipment; operational sequences and controls; warranties; record drawings and specifications; and, inspection, maintenance, and replacement requirements.

Maintenance and operation

Inspection, Cleaning, and Replacement. Periodic inspection for IAQ with good record-keeping can create a preventive maintenance environment in which problems are less likely to occur. The records should be archived in an accessible location and protected from deterioration. This inspection should include but not be limited to HVAC systems. It should also be conducted to identify any new or modified indoor pollution sources.

Change of Use, Renovation, Adaptive Re-use, and De-mounting. Evaluate impacts of planned use changes on loads (thermal, IAQ) and determine system design capacities, distribution, etc. and the adequacy for planned changes. Treat renovation projects as new construction with respect to the items discussed above.

TOWARDS A SUSTAINABLE BUILDING PRACTICE

There can be little doubt that buildings are important contributors to environmental deterioration. Buildings contribute from 15% to 45% of the total environmental burden for each of the eight major LCA inventory categories (16). Table 5 shows these contributions.

The data in Table 5 above are from the United States, but the portion of buildings' environmental impacts globally show that this share of total environmental burdens is generally consistent throughout the world (17).

In any design, trade-offs must be made among solutions aimed to optimize building performance for various objectives. Environmental objectives are diverse, complex, inter-connected, and, not infrequently, conflicting. Local, regional, and global objectives may conflict. Natural resource conservation and other objectives often do conflict. Explicitly or implicitly, trade-offs must be made among objectives in choosing a design solution. Decision-making tools such as multiple attribute decision analysis can assist designers and their clients resolve conflicting project goals

Table 5. Environmental Burdens Of Buildings, U.S. Data (16)

RESOURCE USE	*% OF TOTAL*	*POLLUTION EMISSION*	*% OF TOTAL*
Raw materials	30	Atmospheric emissions	40
Energy use	42	Water effluents	20
Water use	25	Solid waste	25
Land (in SMSAs)	12	Other releases	13

that normally are part of any project. Yet no comprehensive, systematic analysis based on empirical data has provided the tools necessary for designers and other decision-makers to evaluate the trade-offs they must make explicitly or unwittingly between and among putative "environmentally-friendly" building features.

Until recently, there has been no comprehensive effort to establish a systematic approach for evaluating total building environmental performance. The two notable exceptions are the "Building for Environmental and Economic Sustainability" (BEES) being developed by Barbara Lippiatt at NIST in cooperation with EPA (18), and EcoQuantum, being developed by W+E Consultants in Gouda, the Netherlands Both are comprehensive in their scope, but both are presently years away from full development.

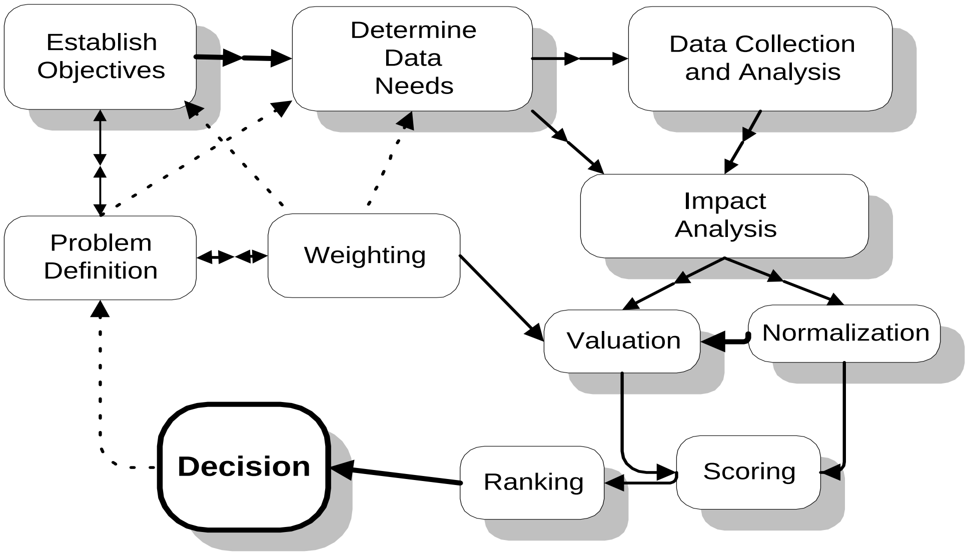
Books and reports abound with discussions, advice, directions, and even scoring or rating systems for assessing the environmental performance of building features. The scoring is usually implicitly or explicitly in terms of a small number of discrete environmental goals. No apparent effort is made to assess the trade-offs among various environmental objectives. This approach, used most notably by BREEAM (19), BSRIA (20), and BEPAC (21), and now proposed by the Green Building Council, provides some guidance to those lacking any other basis for choosing less environmentally harmful building technologies. However, it is clearly an inadequate basis to determine whether a particular design element is "sustainable" or even environmentally benign or beneficial from a comprehensive building environmental performance perspective.

Typically, each green design features addresses a single environmental problem and appears, at least on first glance, to be environmentally beneficial. Often life cycle assessment inventory analysis of the pre-use phase of a product is the basis for the selection. This analysis is performed semi-quantitatively while in-use phase environmental impacts are assessed qualitatively with the usual exceptions of energy and water consumption and waste production. No basis for comparison of the relative importance of energy consumption versus other environmental impacts such as water consumption, soil erosion, habitat destruction, or wastewater production is developed, and, therefore, no basis for weighting the various impacts is available. But because environmental problems are complex and interconnected, optimizing performance of a building material, product, or system may not produce unqualified environmental benefits. It is necessary to weight environmental impacts, normalize sources of similar impacts, and calculate the total environmental performance in order to determine which alternative technology is preferable. Furthermore, it is essential to establish sustainability criteria to determine the performance of an alternative in terms of sustainability.

There are no *a priori* environmentally benign products (22). In fact, a more complete evaluation is required to assess confidently the environmental performance of a particular design. Implementation of some or all the features listed in Table 1, although often labeled "green" design or "green building," are also promoted as "sustainable design" or sustainable building. No evidence is provided to support these claims. No criteria are presented based on calculated environmentally sustainable impacts in relation to ecosphere carrying capacity. Projections and assumptions regarding population growth, per capita consumption, and impacts per unit of consumption must be made. Further, estimates of ecological carrying capacity must be made that, require both scientific knowledge and value judgments that are often unavailable for the former and generally controversial for the latter. Efforts to make such estimates are appearing in Europe, especially in the Netherlands. (23-25). Such an estimate is attached as Appendix A to this paper.

In an attempt to address the shortcomings of previous efforts to guide environmentally-responsible design, we have developed an approach based on building ecology, the study of the inter-relationships of the building to its inhabitants and to the larger environment (26). A new model for assessing building environmental performance is being developed. It attempts to address the need for comprehensive performance evaluation and assessment based on life cycle assessment, comparative risk assessment, industrial ecology, and the work done to date on the BEES model being prepared at by Lippiatt at NIST (18, 27-33). The most rigorous effort to establish relative importance of varioius environmental problems is an international comparative risk assessment completed at Harvard by Norberg-Bohm *et al* (32). The approach, tentatively called the Systematic Evaluation and Assessment of Building Environmental Performance (SEABEP), is intended to be based on similarly rigorous methodologies. Some progress has been made on portions of the model. A diagram representing the approach is shown in Figure 1.

Figure 1. Systematic Evaluation and Assessment of Building Environmental Performance (SEABEP) Decision Model



The valuation of various environmental problems requires construction of a list of problems that is both comprehensive and not too detailed. Such a list is shown in Table 6.

In order to assess the overall impacts of trade-offs, the relative importance of various environmental problems must be determined. Following are criteria recommended to develop a weighted set of environmental problems. These criteria are similar to those used by EPA's

Table 6. Building related environmental problems

ECOLOGICAL PROBLEMS
Top priority
Habitat destruction / deterioration
(directly resulting in Biodiversity loss)
Global warming
Stratospheric ozone depletion
High priority
Soil erosion
Depletion of freshwater resources
Acid deposition
Urban air pollution / smog
Surface water pollution
Soil and groundwater pollution
Depletion of mineral reserves
(esp. oil and some metals)

HUMAN HEALTH PROBLEMS
Building occupants
Indoor air pollution - radon
Indoor air pollution - non-radon
Accidents in buildings (electrical, fire, falls, etc.)
Building workers
Building construction / demolition / material manufacturing, etc.

Science Advisory Board in "Reducing Risk" (29) The first four criteria used for weighting were adapted from reference 28 and the fifth was added here. These are shown in Table 7.

Table 8 shows a sample of "generic" weights created from a global environmental perspective. The weights shown or ones developed by those involved in a project could be used in a scoring system where impacts per problem are to be assessed in a comprehensive environmental analysis. Such weightings can be done on a global scale or on a local, regional, or project scale. The results will often differ. It is important that both sets of weightings be applied. A default set of global weightings can be used, or an original one developed by the project team. The local or project specific weightings must be developed by the project team.

Table 7. Criteria for Weighting Environmental Problems

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. Sinks = receptors, or environmental compartments)

Table 8. Weightings for ten environmental (ecological) problems

Environmental Problem Category	*Weighting*
Habitat destruction / deterioration (Biodiversity loss)	90
Global warming	80
Stratospheric ozone depletion	90
Soil erosion	20
Depletion of freshwater resources	10
Acid deposition	25
Urban air pollution / smog	25
Surface water pollution	25
Soil and groundwater pollution	35
Depletion of mineral reserves (esp. oil and some metals)	50

A similar set of weights should be developed for the environmental problems with direct human impacts, as listed in Table 6 above. One of the most challenging tasks is to develop a single weighting system that integrates both the ecological environmental problems and the human health environmental problems.

Sustainability Criteria for Design Analysis

There are several possible approaches to developing sustainability criteria. Each has its shortcomings, either involving the need for scientific knowledge or data that aren't available or requiring value-based judgments that vary among individuals, cultures, and locations. Nevertheless, each of these leaves "transparent" the basis for the criteria and, therefore, is susceptible to revision by those who wish to apply new or different data, knowledge, or value judgments to the process. Among these are socio-ecological indicators (34), ecological carrying capacity (23), and I=PAT (35) among others. The last two are similar in that they both establish acceptable levels of consumption and pollution generation based on assumed levels of sustainable environmental impacts. Such determinations of sustainable impacts require value judgments that are often considered outside the purview of scientists. However, James Nash asserts that such value judgments are implicit in many of the requisite scientific components of risk assessment (36). By ignoring them, Nash argues, scientists are accepting certain values by default, not avoiding value based decisions. He points out that issues of social, generational, and genetic justice are at the heart of any risk assessment. These three issues are similar to those identified by Azar *et al* as indicators of their fourth socio-ecological principle discussed below (34). They clearly are issues in defining sustainability criteria or any environmental goals.

It is important to understand the implications of projected global population growth and consumption to anticipate the level of environmental impacts to be addressed by technological improvement and/or reduced consumption. Table 9 shows global population projections to the year 2100.

Table 9 United Nations median population projections (billions of people)

Year:	1900	1950	2000	2050	2100	
Industrialized countries	0.6	0.8	1.2	1.3	1.3	Population in billions
Developing countries	1.0	1.7	5.1	8.7	9.9	
World	1.6	2.5	6.3	10.0	11.2	

In Table 10 it is assumed that a doubling of per capita consumption in the industrialized countries and a quadrupling in the developing countries based on a projected 2.5% annual growth rate in industrialized countries and a projected 3.5% annual growth rate in developing countries. These are reasonable estimates based on recent experience. When these consumption rates are multiplied by the population growth rates, there is an overall increase in consumption to 3.5 times current levels. There is also a decrease in the fraction of total consumption occurring in industrialized countries from the present 75% to a projected 43% in the year 2050.

By calculating the effects of combinations of projected population growth rates, per capita consumption rates, and environmental impacts per unit of consumption, one can assess in gross terms the seriousness of the coming crisis. If current stresses on the environment such as greenhouse gas emissions, soil erosion, acid deposition, mineral consumption, etc. are approaching the limits of the earth's carrying capacity, then significant reductions in these stresses is required. Only when the magnitude of these reductions is determined and the results used as targets for technological improvement can sustainability be assessed. One of the major limitations of this approach is the insufficiency of scientific data on most environmental problems. Reasonably good data are available for global climate change and ozone depletion, but even the seriousness of these environmental problems remains controversial, if not among most scientists, at least among many policy-makers in the industrialized countries (35). Other problems such as soil erosion, habitat destruction and biodiversity loss are not only subject to political and regional differences, they are also plagued by insufficient scientific knowledge. Most other global environmental problems are similarly insufficiently characterized from a scientific perspective.

A slightly different approach is proposed by Azar *et al* to avoid focusing directly on environmental impacts because, the authors assert, impacts are so complicated and difficult to assess. The authors argue that there are anthropogenic actions that affect the environment for which establishing acceptable rates based on four simple principles is reasonable (34). These four principles are are presented in Table 11.

Table 10. Global consumption in 2050 based on population and consumption per capita.

	Now	Population factor	Consumption factor	2050
Industrialized countries	75	1	2	150
Developing countries	25	2	4	200
World	100			350

Table 11. Four Socio-Ecological Principles Of Sustainability.

Principle 1: Substances extracted from the lithosphere must not systematically accumulate in the ecosphere
Principle 2: Society-produced substances must not systematically accumulate in the ecosphere
Principle 3: The physical conditions for production and diversity within the ecosphere must not systematically be deteriorated
Principle 4: The use of resources must be efficient and just with respect to meeting human needs

These four principles are the basis of several indicators for each. These indicators, given by Azar et al as mathematical formulas, can be used to calculate criteria for most technologies including building technologies. For each principle, then, the indicators can be used to assess the sustainability of buildings' impacts on the "ecosphere." Table 12 lists each of the "socio-ecological" indicators for the four socio-ecological principles.

Many of the criteria from Table 12 can generally be applied to decisions affecting indoor air quality alone or to the composite environmental impacts of a whole building or collection of buildings. The indicators for principles 1 and 2 can be converted more or less directly into indicators useful for the indoor environment.

Sustainable IAQ Practice

Space limitations do not permit a full exploration of all these IAQ "best practices" persented above. However, we will examine some exemplary ones in order to discover some principles that may demonstrate the application of a systematic evaluation and assessment of building environmental performance based on sustainability criteria.

Table 12. Socio-ecological indicators based on socio-ecological principles (34)

Principle 1: Substances extracted from the lithosphere must not systematically accumulate in the ecosphere	*Principle 2: Society-produced substances must not systematically accumulate in the ecosphere*	*Principle 3: The physical conditions for production and diversity within the ecosphere must not systematically be deteriorated*	*Principle 4: The use of resources must be efficient and just with respect to meeting human needs*
$I_{1.1}$: Lithospheric extraction compared to natural flows	$I_{2.1}$: Anthropogenic flows compared to natural flows	$I_{3.3}$: Transformation of lands	$I_{4.1}$: Overall efficiency
$I_{1.2}$: Accumulated lithospheric extraction	$I_{2.2}$: Long-term implication of emissions of naturally existing substances	$I_{3.2}$: Soil cover	$I_{4.2}$: Intragenerational justice
$I_{1.3}$: Non-renewable energy supply	$I_{2.3}$: Production volumes of persistent chemicals	$I_{3.3}$: Nutrient balance in soils	$I_{4.3}$: Intergenerational justice
	I: Long-term implication of emissions of substances that are foreign to nature	$I_{3.4}$: Harvesting of funds	$I_{4.4}$: Basic human needs

Deciding What's Important In Design

A simple illustration of the application of criteria that might be developed for healthy material selection considering the indoor air quality, indoor environment, and the general environment is shown in Table 13. The importance of each factor for each environment is indicated by the number of marks in the matrix. This exercise shows that there is considerable overlap among the criteria for different environmental compartments.

"Sustainable Design" Guidance

Following is preliminary design guidance that attempts to integrate both indoor and general environmental considerations.

*Resource conservation***.** Selecting building materials and products that are extremely durable and can be expected to perform well over an extended useful life will generally result in a better environmental choice than one that must be replaced twice or even ten times during the same time period. This is evident from the approximately ten-fold greater relative additional resource extraction/consumption, manufacturing, transport, installation, and disposal. A roof used in many European applications may last between one and three hundred years while in the United States typical roofs last ten to thirty years. It is obvious that the environmental impacts of U.S. roofs are roughly ten times that of the European roofs regarding the extraction and disposal of materials. Long-lived products are an inherently preferred solution for resource conservation and environmental protection.

Re-using materials and products that have reached the end of their useful lives is the next most effective way to avoid withdrawal of additional resources and creation of environmental pollution associated with the extraction, transport, processing, manufacturing, installation, and disposal. A longer-lasting material is inherently more desirable from an overall environmental perspective(37).

Table 13. Sample Matrix of Criteria for Healthy Materials Selection

Material Selection Criteria	*IAQ*	*Indoor Env't*	*General Env't*
Resource conservation	X		XXX
Durability	XX	X	XXX
Low emissions/pollution production			XXX
Low emissions/pollution finished	XXX		XX
Maintenance chemical requirements	XXX	X	XX
Replacement frequency	XX	X	XXX
Hard surface (IAQ vs. acoustics)	XX	XXX	
Smooth surface	XXX	XX	X
Energy consumption	X	XX	XXX

Durable materials tend to have low emissions. Therefore, they tend to be better for indoor air quality than less durable ones. They may also require less frequent application of maintenance and surface renewal chemicals and use of less harmful chemicals. There is a sort of multiplier effect from the use of durable materials..

Designs that assume frequent changes in interior partitions should provide for re-mounting durable ones rather than demolition/disposal and new construction.

*Pollutant source control***.** Controlling pollution at the source is generally four times as cost effective as removing pollution from air, water, or soil. This applies both to indoor air as well as ambient air. It also applies to both surface and groundwater water. It is widely accepted that the most effective strategies for indoor air quality involve reducing indoor air pollutant sources and their source strengths or toxicities by one of the following measures: elimination, reduction, substitution, or source isolation. Important considerations for material selection and indoor environmental quality include functional requirements, surface characteristics, total mass, chemical composition and emissions, durability - longevity, and cleaning, maintenance and renovation requirements. Selecting low-emitting materials, especially for those products that will be present in large quantities by mass or exposed surface area, is also important to reduce emissions to the general environment. Typically, low-emitting products will have resulted from production processes involving lower exposures of the manufacturing workers as well.

Design for effective moisture protection is important to prevent intrusion of water from outdoors through cracks, openings, or semi-permeable membranes and eliminate potential for standing water or condensate inside the building from chilled water systems. This will prevent the growth of microorganisms and, therefore, result in better indoor air quality. This will also prolong the life of the building and its components resulting in resource conservation.

*Energy conservation***.** The first step toward reducing energy consumption is conservation. This includes effective building envelope insulation, tightly-sealed openings, and control of air movement and thermal transport mechanisms between the building and the outside and, in some cases, between spaces within the building. This does not mean minimal ventilation; it means reducing the requirements for conditioning ventilation air by avoiding unintentional thermal losses. Energy conservation will produce more comfortable indoor environments. Energy conservation is extremely important in reducing potential emissions of greenhouse gases at power plants, and acid-forming gases that cause acid deposition. This will also reduce the need for refrigeration involving ozone-depleting compounds.

*Energy efficiency***.** Where energy-consuming devices are required (such as fans, pumps, motors, appliances, etc.) it is essential to select efficient appliances. The ratio between the best and worst in a class of products may easily be 2-to-1 or even 3-to-1, so it does make a great deal of difference which product is selected.

*Ventilation***.** Ensure adequate ventilation to control pollutants that reach the indoor air by reducing and removing them through dilution, exhaust (local, general), filtration, and air cleaning. Occupant-controlled ventilation can produce energy savings while reducing occupant stress and building sickness symptoms. Individual occupant desk top air supply that is turned off automatically when a desk is unoccupied can save energy as well efficiently deliver air when and where it is needed. Reduction in overall air supply volumes reduces ductwork materials consumption, air handler capacity, and operating energy. The cost savings achievable with such an approach can easily pay for the additional costs of the individual desktop supply and control.

*Overall design***.** Design for the whole person: The human body and mind integrate all the factors in the physical, chemical, biological, and psychosocial environment. Full integration of environmental considerations in design will include not only indoor air quality but also thermal comfort, lighting, acoustics, and spatial relationships. Such designs will be inherently healthier. A building that meets the needs of its users (occupants, operators, others) will endure longer and not require demolition, replacement, or other resource- and pollution-intensive actions. The more satisfied building users are, the longer the building will remain in service, avoiding the need for additional construction.

Building design and indoor environmental quality issues must be considered throughout the process of planning, design, construction, use, and disposal/re-use/recycling buildings. The major design phases include site selection, project feasibility, budgeting, building configuration, building envelope, environmental control scheme, energy considerations, and environmental impact analysis.

DISCUSSION and CONCLUSION

This paper has emphasized a “building ecology” view of buildings as dynamic, interdependent systems (25). This view suggests the importance of planning during the design phase for varying cycles of building performance and use or requirements during the building’s lifetime. The more specific the analysis, the more relevant its application to any given building design. Generic analyses are helpful but suffer from the potential to miss important characteristics of a particular situation.

It is apparent that in many instances, the design alternative best for indoor environmental quality is also best for general environmental quality. For example, durable materials will be less likely to emit contaminants into the indoor air, will require lower quantities and less toxic chemicals for the maintenance and refurbishing, and, by definition, will be longer lasting. Service life is an extremely important determinant of overall impact on the general environment since each replacement cycle requires the use of additional resources with the concomitant pollutant emissions.

Designers must be aware of the impacts of the building on the larger environment. These will include impacts on biodiversity, global warming, ozone depletion, on the soil, air, and water, on resource depletion, on waste generation, and on energy consumption,. Some of these will ultimately, although perhaps imperceptibly, affect the building itself and its users. Therefore, each building must be planned and designed as though it were being replicated a million times over so that we take seriously the consequences of its impacts on the global environment and, in a very real sense, its own environment.

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Appendix A.: Sustainable versus expected level of environmental impact for selected indicators (Reference 22, p. 25)

Dimension/indicator of environmental impact	*Sustainable level*	*Expected level 2040*	*Desired reduction*	*Scale*
DEPLETION OF FOSSIL FUELS:				
* oil	stock for 50 years	stock exhausted	85%	global
* natural gas	stock for 50 years	stock exhausted	70%	global
* coal	stock for 50 years	stock exhausted	20%	global
DEPLETION OF METALS:				
* aluminum	stock for 50 years	stock for >50 years	none	global
* copper	stock for 50 years	stock exhausted	80%	global
* uranium	stock for 50 years	depends on use nuclear energy	not quantifiable	global
DEPLETION OF RENEWABLE RESOURCES:				
Biomass	20% terr. animal biomass	50% terr. animal biomass	60%	global
	20% terr. primary production	50% terr. primary production	60%	global
Diversity of species	extinction 5 species per annum	365-65,000 species per annum	99%	global
POLLUTION:				
Emission of CO_2	2.6 Gigatonnes carbon per annum	13.0 Gigatonnes carbon per annum	80%	global
Acid deposition	400 acid eq. per hectare per annum	2400-3600 acid eq.	85%	continental
Deposition nutrients	P: 30 kg. per ha. per annum	no quantitative data	not quantifiable	national
	N: 267 kg. per ha. per annum	no quantitative data	not quantifiable	national
Deposition of metals:				
* deposition of cadmium	2 tonnes per annum	50 tonnes per annum	95%	national
* deposition of copper	70 tonnes per annum	830 tonnes per annum	90%	national
* deposition of lead	58 tonnes per annum	700 tonnes per annum	90%	national
* deposition of zinc	215 tonnes per annum	5190 tonnes per annum	95%	national
ENCROACHMENT				
Impairment through dehydration	reference year 1950	no quantitative data	not quantifiable	national
Soil loss through erosion	9.3 billion tonnes per annum	45 to 60 billion tonnes per annum	85%	global