Practical ways building designers address indoor air quality issues?

Hal Levin
Building Ecology Research Group
2548 Empire Grade
Santa Cruz, CA 95060-9748

SUMMARY

With increasing interest in so-called "green buildings" and "sustainable design", indoor air quality (IAQ) issues are receiving even more attention from building owners and designers. More information about building-related causes of occupant health and comfort problems has led building occupants, employers, and owners to expect building design professionals to address IAQ concerns. This has resulted in the need for design professionals and owners to control the major sources of pollution and to utilize the most practical means to minimize occupant exposure to indoor air pollutants. The importance of IAQ considerations in building design is not only for the purpose of providing healthier, more productive environments but also for avoiding professional liability and costly callbacks. Serious failures to address IAQ result in expensive litigation and large damage awards that can threaten the economic status of even the largest of design firms. Too often insufficient attention is paid to IAQ until a lawsuit or damage claim is filed.

There are many simple, practical ways for building designers to address IAQ issues. These include application of relevant ASTM and ASHRAE standards with a focus on material selection guidelines and adequate ventilation. When good materials are selected and properly specified, ventilation requirements are reduced and the capital and operating costs of the building are reduced. Manufacturers are increasingly aware of the need to characterize their products' IAQ performance and to provide the data designers need to evaluate those products. Procedures and criteria for reviewing the data are being developed and can be used by designers to select better materials. The result is a win-win-win building in which designers, their clients, and the occupants are all beneficiaries of good design resulting in good indoor air quality.

Finally, the attention to indoor environmental quality must be integrated into the emerging concern about broader environmental impacts of buildings. The fraction of total or global environmental burden attributable to buildings is on the order of 30% to 40% or more. Population growth and economic development combine to increase the burdens society places on the planet's resources and its ability to metabolize pollution. Extinction of species is occurring at a rate 1,000 times historical rates, and the trend is toward increasing extinction rates as population and consumption expand. Most of those concerned about reducing buildings' impacts on the environment have paid little more than lip service to indoor environmental quality. Ultimately, indoor, local, regional and global environmental issues must be addressed in a systematic, integrated fashion. Building ecology provides a framework for understanding how to create healthy buildings.

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 (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 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 "green" building design. Some examples of common "green building" features are listed in Table 1.

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

Among the motivations for so-called “green design” are increasing concerns about indoor air quality. Lawsuits and workers’ compensation claims have raised awareness of the importance of good indoor air quality among building owners, operators, and employers. More enlightened building owners recognize the superior marketability of buildings that can provide tenants assurance of good indoor air quality. Indoor air quality problems have cost building owners and employers significant economic and productivity losses due to downtime, costly investigations and remediation projects, worker illness and absence, and health care costs. A recent study found that office worker productivity on typical tasks can increase by 6% where IAQ is improved.

INDOOR AIR QUALITY "BEST PRACTICES"

Many building design, construction, and operational measures necessary to create good indoor air quality are well-established. Table 1 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 building design

1. Understand relationships between exposure, dose, and occupant susceptibility that determine health effects:
2. Recognize relationships between indoor air pollution sources, ventilation, and concentrations.
3. Clear overall design concept for indoor air quality: cradle to grave.
4. Identify pollutant sources:
5. Consider source control options and strategies and select the most effective,
6. Carefully specify ventilation system design and operation,
7. Select and specify materials for good total life cycle IAQ,
8. Specify construction procedures to control short-term emission effects.
9. Identify and specify critical maintenance and operation requirements.
10. Consider IAQ in change of use, renovation, adaptive re-use, and de-mounting

Exposure, dose, and occupant susceptibility determine health effects:

Virtually everything can be toxic. If you drink too much water, you can harm or even kill yourself. Health effects are a matter of exposure, dose, and individual susceptibility. There are no "non-toxic" building products or chemicals, there are just more or less toxic or irritating ones. And their use or application and the occupants’ exposures and susceptibility will determine the effects. Exposures may be either short-term, “peak” exposures, long-term, chronic exposures, or some combination or variation of the two. Consider the neuro-toxicity of alcohol. Drinking one beer an hour for 12 hours will result in inebriation above legal limits for operating a motor vehicle. But drinking 12 beers in one hour during a 12-hour period, you may be close to unconsciousness. Similarly, an odorous compound released at a sub-threshold detection level steadily for 12 hours will not result in its detection. Yet the same quantity of the compound released during a short time period is far more likely to result in detection of the odor.

Major health effects:
Health effects can range from irritation and discomfort to disability or life threatening disease. Table 3 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 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 typically present in indoor air suggests that there may be effects due to additive or synergistic effects.

Table 3. 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)

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).

Relationships Between Indoor Air Pollution Sources, Ventilation, and Concentrations

Concentration = (source rate – removal rate) / ventilation rate.
There is a simple mathematical relationship that clearly expresses the most important relationships in indoor air quality. The concentration of a pollutant will be function of the sum of all the pollutant source contribution rates minus the sum of all the pollutant removal rates divided by the ventilation rate. The simplest form of this relationship states that concentration is a function of source strength divided by ventilation rate without accounting for outdoor sources nor for removal by sinks or indoor air chemistry. 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:

$$\underset{(mg/m^3)}{\text{Concentration}} = (\underset{(mg/h)}{\text{Emission Rate}} - \text{Removal Rate}) / \underset{(m^3/h)}{\text{Ventilation Rate}}$$

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.

In reality, the process is more complex than is suggested by this mathematical expression and should also include all the source terms and removal terms.

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). This is discussed further later in this paper.

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 weeks or months afterwards. Some, such as composite wood products, due to their thickness, density, and their pollutant content, can be sources for years after installation. Major pollutant sources and removal mechanisms are listed in Table 4.

Table 4. 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 (dilution, exhaust)
- Air Cleaning and Filtration
- Chemical Transformation

Ventilation principles:
The most effective way to remove 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 difference that result in air flows within and between spaces.

Other pollutant removal mechanisms:
Among the most common removal mechanisms are air cleaning and 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.

Deposition on surfaces
Some pollutants are removed by the process of deposition on surfaces. Filters designed to remove particles function by “catching” the particles on their surfaces. The particles must be tightly bound to the filter media to eliminate re-entrainment in the air stream. Gases are removed by adsorption on charcoal or other media or by chemical transformation through contact with catalytic surface materials. Deposition of gases and particles also occurs on indoor surfaces. The rates vary with the nature of the gas or particle, the surfaces, the airborne concentrations, and the nature of the surfaces themselves. Fine particles deposit equally on horizontal and vertical surfaces while larger particles fall to the horizontal surfaces below them due to gravitational forces.

Sink effects
To various degrees, processes of removal are going on at all times for most pollutants by deposition on indoor surfaces. These processes, known as sink effects, are usually at least partially reversible. The sink effect serves to buffer very high concentrations by allowing chemicals to deposit on surfaces when concentrations are high. But the downside of this buffering effect is the extension of the pollutant residence time in indoor air over much longer periods.

Different gas-phase chemicals and different surface materials produce different sink dynamics based on variable adsorption and desportion rates. Generally pesticides and other large or “heavy” molecules tend to be less volatile and, therefore, are found on surfaces more than in the air. As the air concentration diminishes, the chemical tends to leave the surface and re-enter the air. This works well to maintain a desired level of a pesticide in air but also results in some unwanted prolongation of the presence of pesticides and other toxic chemical substances such as PCBs, dioxins, and furans.

An excellent example of the sink effect is the deposition of particles and gases in environmental tobacco smoke (ETS) on surfaces. Non-smokers know that if they spend time in a smoke-filled environment, upon arrival at home they recognize the smell of ETS on their clothing. Some of the heavier molecules in ETS tend to be both the most toxic and the most difficult to eliminate.

Overall Design Concept to Achieve Good Indoor Air Quality: From Cradle to Grave

Much of what it takes to achieve good indoor air quality is simply common sense when all of the relevant factors are considered in the design, construction, and operation phases. Many indoor air quality problems occur simply because IAQ was not considered adequately during the process. By developing an overall project concept for IAQ and carrying it through from beginning to end, most common problems can be eliminated and the risk of unusual ones can be vastly reduced.

Planning through construction, commissioning
A major cause of indoor air quality problems is premature occupancy. Buildings are often 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. There is strong evidenced that the closer a building is operating to the design intent, the less likely occupants will report SBS symptoms. There are many steps from design to occupancy during which deviations from design intent can occur. Causes of failure include: lack of translation from design intent into clear, detailed design specifications; inadequate communication among contractors; deviation from specified materials and equipment by substitution or error; improper installation of materials and equipment; and failure to commission fully and properly, among others.

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 contaminate 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.

Pollutant 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, A thorough review of the

adjacent and other buildings in the immediate neighborhood of the project can often reveal obvious sources of pollution. Prominent among these are industrial and agricultural processes, dry cleaners, restaurants, gasoline service stations, parking garages, bus stations, heavy-use roadways, and a number of other common facilities. By avoiding sites where such obvious sources of pollutants are likely, far less stringent air cleaning and filtration will be required to achieve good quality indoor air.

Outdoor air quality exceeds the National Ambient Air Quality Standards (NAAQS) under the Clean Air Act in the communities where approximately 1/3 of all Americans live. Therefore, bringing in contaminated outdoor air is likely. Even where air may meet the NAAQS, it may still be desirable to remove some of the particles, ozone, carbon monoxide, or other contaminants before using it to dilute and replace polluted indoor air.

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 adhesives and 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. While some materials can act as sinks that reduce airborne concentrations, they do not necessarily reduce exposure. An example would be carpet fibers that serve as sinks for airborne chemicals but where children play and receive exposure through skin contact or by breathing the air close to the carpet where the concentration may be higher.

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 and should generally be placed on the side of greatest moisture content or generation to avoid migration through the envelope and condensation on the dew point plane. A drain plane should be provided to prevent the entry of rain water that enters the exterior wall through cracks or other gaps in the outer boundary.

Outdoor air cleaning and filtration

Rather than bringing polluted air into a building, air cleaning and filtration can be used to remove some gases and particles. 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.

Surface cleaning

Frequent cleaning of surfaces can reduce the burden on ventilation and filtration or air cleaning and may be found cost effective in some applications. Where sink effects are a dominant removal mechanism, as for some pollutants in ETS, surface cleaning may be necessary for aesthetic reasons related to both appearance and odor. In any case, surfaces should be cleaned to control contaminant air concentrations of previously deposited particles and gases.

Indoor Air chemistry

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 often inadequately understood or considered is the nature of the compounds formed by this process. While ozone may be effective in eliminating some or all of the odor associated with ETS and other pollutants, some of the reaction products formed may be more toxic than the chemicals from which they are derived.

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 too 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, the highest ratio products and materials should be selected as “target” products for careful review, specification, and installation. Some

other products or pollutant sources will also 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.

Evaluate products based on life cycle emissions profiles
From the complete bill of materials, select those that are of IAQ importance on the basis of the largest interior total surface area or mass: Use the material quantity take-offs from the cost estimate normally done as part of the architectural design services contract during the Design Development Phase. Use the quantity take-offs to prepare a spreadsheet analysis of the area and mass of major materials per unit of volume in the spaces to which they relate. Use this process to identify the high use materials and prioritize the material evaluation activities. Add major wet products even though they may not rank high in terms of mass or area, e.g., seam sealers, glazing compounds, caulks, etc. Identify, what are the major interior surface materials (except for concrete, masonry, metal, stone, tile, and glass). Identify any of these materials that have potential to be strong emitters of pollutants in the short term (such as adhesives, paints, caulks, sealants, and other “wet” products.)

Follow the steps outlined below to evaluate products and materials.

1. ***Obtain information on the chemical contents and emissions of IAQ Target Materials***
    - Request information from product manufacturers. Use products only from those manufacturers who provide the requested data.
    - Have product data sheets and volatile organic chemical (VOC) emissions tests been provided for dry products such as composite wood products?
    - Have chemical contents lists been requested of manufacturers of wet products?
    - Have all major “target” products been reviewed for their chemical contents and potential emissions?
    - Can any of the “wet” products be eliminated or their use reduced?
    - Can installation of necessary “wet” products occur with temporary or permanent ventilation system operation?
    - Will there be extensive use of composite wood products? If so, have low-emitting products been selected?
    - Are composite wood products sealed, laminated, or otherwise isolated from indoor air?
    - Is carpet specified? If so, is it required to meet the Carpet and Rug Institute’s Green Label criteria? Can carpet be eliminated in any cases of its use?”

2. Obtain Information on Cleaning and Maintenance (C&M) Requirements:

- Request product manufacturers' instructions or guidelines on cleaning and maintenance of the major surface area materials (floors, walls, ceilings).
- Identify chemical products required and obtain chemical composition of these products.
- Include these C&M products in the assessment of emissions below.

3. Review chemical data for presence of strong odorants, irritants, acute toxins, and genetic toxins.

- Use standard references (examples include Sax, NIOSH RTECS, EPA IRIS, California OEHHA, ACGIH TLVs, OSHA PELs, etc.) to determine status of chemicals that will be emitted at significant rates (to be defined). Useful information is available from http://www.chemfinder.com/. There are listings on that site for a very large number of government and other databases and information sources on chemical properties including odor, irritation, and toxicity. Information on over 600 common chemicals is also available from EPA's Integrated Risk Information Service database (IRIS) on the web at http://www.epa.gov/ngispgm3/iris/.

4. Calculate Concentrations of Dominant Emissions:

- Use basic indoor air model to calculate emissions of worst case chemicals at 24 hours and 30 days. (Such a model is available at no cost from EPA's web site http://www.epa.gov/iaq/iaqinfo.html#IAQINFO or by contacting Sparks.Les@epa.gov.
- Another IAQ model (CONTAM) is available from the National Institute for Standards and Technology (NIST). www.bfrl.nist.gov/863/contam.
- Compare various sources and focus on those with the largest impact on IAQ.

5. Evaluate Calculated Concentrations and Total Potential Emissions Against Criteria:

- Use the following sources for criteria concentrations:
  - Odor – Devos et al, 1990 – Mutiply threshold by factor of 2.
  - Irritation – ACGIH TLVs for current year for irritants only; divide TLV by 40.
  - Cancer – Use latest lists from NTP, IARC, EPA, and CalOEHHA. Exclude known carcinogens, using concentration or total potential emissions criteria to be established by City of Oakland.
  - Toxicity – Use CalOEHHA, IRIS, and the Danish National Institute of Occupational Health VOCBase lists.

6 Assess total Potential Emissions: (Alternative to steps 4 and 5 above)

- Multiply mass present in the product times the vapor pressure for chemicals to get a dimensionless number. Multiply this number by the reciprocal of 1/40 TLV. Select from among the candidate products the one(s) with the lowest ratio. Note: this is an alternative method for comparing products when emissions data are unavailable, but it is not a true substitute for the detailed process outlined above.

7. Select Products and write installation specifications. For selected products, write specification for acquisition, storage, transport, handling, and installation.
Acquisition: This should include criteria used for selection in the specification
Storage: Ensure storage includes moisture and dust protection, adequate ventilation, absence of direct sunlight, moderate temperatures (freeze protection) and relative humidity.
Transport: should include same criteria as storage.
Handling: Protection against mechanical damage or chemical contamination.

8. Installation: Specify the installation of no greater quantity of wet products (paints, adhesives, caulks, sealants, surface preparation materials, etc.) than that required for the application and use of the product or material in question.
Ventilation: For all "wet" products and major floor covering products, specify no less than 3 air changes per hour during the installation and for 72 hours afterwards.

9. 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.

10. 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.

"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 typical roofs last ten to thirty years. It is obvious that the environmental impacts of 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		X
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 was written from 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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