DESIGN AND CONSTRUCTION OF HEALTHY AND SUSTAINABLE BUILDINGS

Article

Hal Levin
Building Ecology Research Group

DESIGN AND CONSTRUCTION OF HEALTHY AND SUSTAINABLE BUILDINGS

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

ABSTRACT

Considerable progress has been made during the past thirty years toward a more complete understanding of design and construction requirements for “healthy” buildings. Buildings are now being built with available technology that consume only 10% to 25% of the energy consumed in today’s average buildings while being more comfortable, healthier for their occupants, and less harmful to the environment. Awareness of environmental problems has shifted design and construction toward so-called “green” or “sustainable” building practices, yet there is scarce evidence that such practices actually produce less overall environmental damage. Very limited attention to rigorous analysis of buildings’ actual impacts has resulted in the establishment and increasingly widespread acceptance of many purportedly “green” practices of undetermined environmental impact. Dissemination and adoption of advanced building practices require overcoming resistances of habit and opposition from vested interests. Methods are being developed and tested that can provide more evidence-based decisions for improving buildings’ overall environmental performance, but much improvement is still needed.

KEYWORDS: Building ecology, environment, life cycle assessment, sustainability

INTRODUCTION

The energy crises of the 1970s and recognition of local and global environmental problems have stimulated considerable progress toward a more complete understanding of design and construction requirements for “healthy” buildings. In spite of growing evidence of global climate change resulting, in significant part, from combustion processes to produce electricity, heat, and cooking in buildings, the new technological knowledge and its application remain very limited.

Many “environmental-friendly” design and construction principles are widely accepted, but designers and constructors often fail to recommend or their clients fail to adopt state-of-the-art practices. Reasons for these failures include short-term financial considerations, lack of expertise, or preference for and adherence to traditional practices. Meanwhile, awareness of environmental problems has produced an emerging shift toward purportedly “green” building practices that presume to include buildings that are “healthy” for their occupants and measures intended to minimize buildings’ impacts on local, regional, national, and global environments.

To date, there has been far too little rigorous analysis of buildings’ actual environmental impacts. “Green” building practices are typically applied in unsystematic and inconsistent ways, often without resolution of inherent conflicts between and among such practices.

Designers, product manufacturers, constructors, and owners declare their buildings and the applied technologies to be beneficial to the environment without validating these claims. Those seeking guidance to construct “green” buildings accept these claims without further analysis. This has resulted in the establishment and increasingly widespread acceptance of many practices that are of undetermined environmental impact. It has also produced a number of guidance documents and tools that have begun to codify these practices and bestow an air of authority upon them. Much more work is required to determine the total environmental impacts of the buildings that are built based on such guidance. This work should include detailed and rigorous evaluation of the embodied and life cycle resource consumption, pollution emissions, and land encroachment required for the construction, operation, and use of such buildings.

“Healthy buildings”

There can be little doubt that enormous progress has been made since the 1970s in improving the understanding of the design and construction practices that produce healthy buildings in terms of the impacts of buildings on occupant health and well-being. A broader definition of “healthy buildings,” first introduced by Levin in 1995, included not only the impacts of buildings on their occupants but also on the larger environment [1]. “A healthy building is one that adversely affects neither the health of its occupants nor the larger environment.” [1]

Today there is substantial knowledge to design and construct buildings that consume between 10% and 25% of the energy used to operate the average buildings being built today. A few such buildings have been built, and their energy performance has been verified. These more resource-efficient buildings can be more comfortable, more satisfying to their occupants, and more productive places of work, study, or recreation. These buildings typically provide their occupants with more control over their personal or local thermal and lighting environment than most buildings being built today and in the recent past. Some of them provide better air quality. Many of them cost less to build and to operate. They are built using materials requiring far less consumption of non-renewable resources and with far fewer apparent impacts on the natural environment. These environmental and economically improved buildings can be built using currently available technology.

We must ask ourselves: “What is preventing us from more widely implementing these practices? What is preventing us from constructing such buildings that are better for their occupants and for the earth’s ecosystems?”

Barriers and costs of a sustainable society

The barriers are understood to include, among others, an excessive emphasis on short-term economic considerations. Globalization of economies, political realities, and corporate criteria for profitability have all shifted the decision-makers’ focus toward consumption and away from preservation of ecosystem productivity and environmental values. The tendency to focus on short-term considerations is exacerbated by a limited understanding of the extent of the environmental improvements required to achieve sustainable building practices and sustainable economies in general. In 1992, Dutch authors Weterings and Opschoor estimated the resource consumption and pollution emissions reductions required for a sustainable world in the year 2040 at 75% to 95% of 1990 levels [2]. In their work the Dutch authors provide a transparent methodology for development of targets for sustainable development. No other estimate of this sort is known to exist, and the present author has found no other such comprehensive estimates in the open literature.

The cost of achieving satisfactory living conditions for all humans is not beyond the easy reach of the world today. It is estimated that an annual expenditure of US\$200 x 10^9 would be sufficient to provide food, shelter, potable water, and health care to all those in the world who do not presently have these basic human needs adequately met. To put this in one context, it is also estimated that global annual expenditures on military defense total approximately USD600 x 10^9 [3].

We know that concerns about global climate change (among other environmental problems) require that we apply our knowledge to reduce the large amount of energy consumed in buildings and the concomitant emissions of greenhouse gas emissions associated with global climate change. Yet short-term economic analysis and the absence of realistic targets for carbon emission reductions keep us from implementing many of the available technologies.

Building energy consumption

The major technologies resulting in building energy consumption patterns are electric and fossil fuel powered ventilation, cooling, space and domestic hot water heating, and illumination. In the United States, these building-related energy uses account for about 30% of all energy consumed. Part of the problem is that standards based on laboratory research now lead us to believe that we must use enormous amounts of such energy to create comfortable and functionally-adequate buildings. Yet nothing could be further from the truth.

Assumptions about acceptable indoor environmental conditions and the means to achieve them have become increasingly limiting. These assumptions are based on laboratory studies of thermal comfort that have been translated into rigid (standards and code) requirements. Yet field studies have shown that buildings designed according to these standards and codes commonly fail to achieve their presumed objective of ensuring thermal comfort for the vast majority of building occupants. Fixed, narrow ranges of temperature limits derived from the laboratory study results ignore people’s behavioral, physiological, and psychological adaptation to indoor and general climatic conditions. The codification of these set points (as in ASHRAE Standard 55 and ISO Standard 7730) produces an unnecessarily limited and often unsuccessful set of design and operational requirements. These requirements are energy wasteful while they also fail to produce their purported objective of guiding design to deliver thermal comfort to the vast majority of building occupants.

It is more than likely that with good design, construction, and operational practices, buildings can provide healthy indoor air quality with far less outdoor air ventilation than is commonly recommended or required. Guidance on appropriate outdoor air ventilation rates is based on large scale building occupant surveys that include buildings that are designed, constructed and operated poorly along with those done well. Quite predictably, measured ventilation rates derived from such studies reflect both poor practice as well as average and good practice.

In order to protect people in buildings with strong pollutant sources and in buildings where design, construction, or operational practices are of poor quality, all buildings are then required to provide more ventilation than might actually be necessary for healthy, comfortable indoor environments in well-designed, -constructed, and -operated buildings. Because high ventilation rates are generally not achieved in passively- (or naturally-) ventilated buildings, there is a growing tendency to require mechanical ventilation systems. Meanwhile, ventilation systems themselves have often been shown to be major contributors to the poor air quality found in “problem buildings.”

Environmental lighting

It is quite likely that lighting standards are unnecessarily high and result in excessive energy consumption to produce the illumination as well as the by-product waste heat that must then be removed from buildings in most temperate and warm climates. Illumination standards’ criteria levels steadily increased during the period 1950–1975 based on research sponsored primarily by the manufacturers of electrical illumination devices.

Standards for illumination in buildings are also based on laboratory studies and reflect the visual acuity based on electrical illumination sources rather than daylight. The study subjects are generally accustomed to and adapted to prevailing lighting standards. Therefore the subjects are unlikely to adapt to lower illumination levels during the short exposure periods in the studies. Generally it takes three weeks or more for people to adjust to significant changes in illumination levels, whether the changes are to lower or to higher levels of illumination. The studies also tend to ignore the influence of light source spectral distribution in establishing criteria for illumination requirements. Research during the past 15 years by Sam Berman of Lawrence Berkeley National Laboratory and Don Jewett, formerly at the University of California, San Francisco, has shown that the composition of dominant electric fluorescent illumination sources has been inefficient at providing visibility while producing perceived “brightness” and illumination levels.

After the 1973 Arab oil embargo, criteria for lighting levels in offices were reduced from 700 lumens to 450 lumens. Prior to the 1960s they were set at 300 lumens. After the widespread introduction of personal computers into office work places during the 1980s, criteria for lighting levels were reduced even further as it was found that bright workplaces often resulted in glare on computer display screens. The shift away from predominantly general or overhead light sources to user-controlled task lighting provides the opportunity for individual office workers to adjust the light level and effectively and conveniently to address its potential for glare. No single illumination level can be “optimum” or “preferred” by more than 50% of office workers. Therefore, it is only by providing occupant control of illumination levels that a higher level of satisfaction and, presumably, worker productivity, can be achieved.

Total building-attributable energy consumption

The total fraction of U.S. national energy consumption attributable to building-related uses is around 40%. Therefore, a reduction of energy consumed for the construction and operation of buildings could significantly reduce total national energy consumption. A study done by the Worldwatch Institute found that global energy consumption attributable to buildings is of the same order as that of the United States [4, 5].

MAJOR FACTORS AFFECTING BUILDING-RELATED RESOURCE CONSUMPTION

Beyond the energy used to operate buildings, an additional 8 to 12% of total U.S. national energy consumption is required for the manufacture and use of building construction and maintenance products and their ultimate disposal. These energy uses include mining or extraction of raw materials, manufacturing, transport, and installation or application of materials and products in buildings.

Buildings consume approximately 25% to 80% of representative categories of major industrial materials consumed nationally in the United States. Table 1 shows the consumption of major industrial materials attributable to buildings.

Sustainability is ultimately a question of mass flows. Thus, the best way to make buildings (and societies) more sustainable is to reduce mass flows [6]. There are four major strategies for reducing mass flows in buildings. These are shown in Table 2 below.

Building size and resource consumption

Many resource consumption metrics are stated in terms of units per unit area-year. This type of metric inherently favors larger structures and penalizes smaller ones. Consider, for example, two equal size families living in houses of $60m^2$ and $120\ m^2$ respectively. If they both consume the same total amount of energy, the larger structure appears twice as efficient while having consumed roughly twice as much material for construction. If the larger one consumes 2 times the energy consumed by the smaller one, it appears equally energy efficient when its annual consumption is reported in joules per square meter. Of course the quality of the indoor environment and source and type of energy (renewable or non-renewable, CO_2 emitting or not, etc.) are also important indicators of overall building environmental performance.

The average house size in the USA increased >50% from 1970 to 1999, while the average number of occupants per house decreased by more than 25%. Thus, when resource or energy efficiency calculations are made on the basis of consumption per unit area per year (e.g., joules per square meter per year), the results may be misleading regarding the resource use intensity per person.. For this reason, a more informative unit of measure would be a functional unit such as resource or energy consumption per resident per year. Thus, environmental performance measures for work, residential, and recreational environments, etc. could also be reported in terms of the number of people-years served. Energy consumption would not be compared solely on a joules per $m^2\ y^{-1}$ basis. Instead, they would be reported in terms of energy per residential square meter-person year. If two individuals shared a $60\ m^2$ residence, the performance units would be based on $30\ m^2$ per person-year.

MAJOR DETERMINANTS OF INDOOR AIR QUALITY

Good indoor air quality (IAQ) can be achieved by addressing its fundamental determinants and applying available technologies along with common sense. Indoor air quality is a function of the ventilation rate and quality of outdoor air, the type and strength of sources of indoor pollutants, and the quality of operation cleaning, and maintenance of the building itself. The major determinants of indoor air quality are shown in Table 3.

Ventilation and indoor air quality

While much has been written and discussed about the relationship between recommended or measured building ventilation rates and occupant reactions, in the end the amount of ventilation required is determined by the purpose of the ventilation, the health status of the exposed population, and the strength of contaminant sources including those entering from outdoors. Table 4 presents a modified and expanded list of ventilation rates and their purposes originally developed by Thomas Lindvall in 1989 [7].

Researchers during the past ten years have consistently found an overall trend toward improved occupant health in buildings with higher ventilation rates. The major reviews of ventilation rates and SBS symptom rates have all found that outdoor air ventilation rates lower than 10 liters per second per person (L/s/p) are associated with increased rates of reported building-associated health effects. Yet the number of IAQ determinants indicates that more case-specific design ventilation rates can produce acceptable environments at lower ventilation rates.

The most fundamental relationships between sources, ventilation, and pollution concentrations are shown in Figure 1. It is apparent from inspection of Figure 1 that reducing source strengths can significantly reduce the outdoor air ventilation requirements to achieve a given chemical concentration in indoor air. Armed with such knowledge, the building designer or operator can make informed choices about building materials in specific building applications. The adoption of generic ventilation rates without the details of a specific building's occupancy, sources, and ventilation system will necessarily result in over- or under-ventilation of various buildings since no building exactly fits a generic model.

Buildings change over time in terms of their users, uses, and the strength of the sources within them. Only by looking more specifically at the concentrations and ventilation can appropriate decisions be made regarding ventilation rates to achieve good indoor air quality.

A major barrier to adopting approaches based on real-time measurements of contaminants and ventilation rates is the absence of reliable health effects-based guidance on appropriate concentrations of contaminants. Much reliance has been placed on the so-called total volatile organic compound (TVOC) concentration. However, it is now accepted among most scientists in the field that such measures cannot be used as indicators of health effects [8]. Specific individual compounds must be measured and guidelines must be developed for interpretation of the concentration data.

Emissions and life cycle contaminant exposure

In the past twenty years, increased attention has been paid to emissions from building materials as sources of indoor air contaminants. However, over the life cycle of a building, the emissions from new building products and materials may be far less important in determining total occupant exposure to chemical and biological contaminants than the performance of the material as a sink or reservoir for chemical or microbial growth. Periodic cleaning and maintenance products as well as waxes, polishes, and re-finishing of surfaces and later emitted into air may be far more important determinants of occupant total VOC exposure than emissions from new building products themselves. Far more attention must be paid to life cycle performance of building materials throughout their entire anticipated service lives.

ASSESSING BUILDINGS ENVIRONMENTAL IMPACTS

Methods are being developed and tested that provide more evidence-based guidance for decisions that will improve buildings' overall environmental performance [9]. Much still remains to be done. Ultimately, practicing architects, engineers, and other building professionals cannot conduct time-consuming life cycle assessments of building materials in order to choose among alternatives. They are dependent on researchers and specialists who will conduct such studies and distill their findings into appropriate guidance documents and design tools. The ultimate goal is to incorporate such guidance into the computer aided design and drafting (CADD) software that is used routinely by design and construction professionals. Then, when such software is used, the designer or builder can be informed of the environmental trade-offs choosing among different materials or design alternatives.

Life cycle assessment of building materials

Databases contain generic information on products and processes so that the results of even rigorous life cycle assessments (LCAs) fail to inform designers about preferred brand-specific products. While an LCA may show that one product type is generally better than another, for example vinyl floor coverings versus carpet or linoleum, it does not conclusively show that all vinyl floor coverings are better or worse than all carpets or linoleum products. Furthermore, value differences among designers, builders, governments, or nations cannot be easily separated from the analytical results.

Indoor air quality and other direct human exposure to emissions from products during the use phase of building materials and products have not been addressed adequately or even at all by the LCAs that have been published on building materials so far [10]. It is not easy to discern the relative importance of one environmental problem or issue versus another; e.g., local air or water pollution versus global climate change or stratospheric ozone depletion. It is also not clear how to make the necessary trade-offs between human and ecological health or between manufacturing worker exposure versus building occupant exposure to emissions from building materials.

The expected service life of a building material determines the relative importance of the embodied environmental impacts (from the extraction, processing, and installation phases) and the use phase environmental impacts of the material. Many materials affect energy consumption during buildings' operational phase, and this characteristic can dominate the total life cycle impact if the service life is sufficiently long. The service life is in the denominator in any calculation of life cycle impact of a product or material for the "embodied" impacts. Long service life is apparently a generally desirable quality. Therefore, choosing quality materials and using them in ways that permit their long-term use should be an objective in creating healthy buildings. Since durability is often associated with low emissions, such products may also be generally preferable for indoor air quality considerations.

The need for an ecology of buildings

In order to better understand buildings, building scientists, architects, engineers, and constructors must adopt an approach similar to that used by ecologists to look at ecosystems. This includes a more dynamic, inter-dependent, systems view of buildings, their occupants, and the larger environment. Such a view has been described as "building ecology" as long ago as 1981 [11]. In such a view, the impacts of the building on its occupants as well as the impacts of the occupants on the building are to be considered. Similarly, the mutually-dependent impacts of the building and the larger environment must also be considered.

CONCLUSION

While currently there is a trend toward increasing attention paid to both occupant and general environmental health effects of buildings, it is clear that efforts to improve building environmental performance remain the practice of only a small fraction of designers and constructors. Furthermore, there is much still to be learned in order to achieve the goals of creating buildings that are healthful for their occupants and sustainable in terms of their general environmental impacts.

RFERENCES

1. Levin, H., “Building ecology: an architect’s perspective on healthy buildings” in Maroni, *et al*, (eds) *Proceedings of Healthy Buildings ‘95*, *Proceedings of the Fourth International Conference on Healthy Buildings*, Milan, Italy, September, 1995.

2. Weterings, R.A.P.M., J.B. Opschoor, “The ecocapacity as a challenge to technological development.” Rijswijk, the Netherlands: Advisory Council for Research on Nature and Environment (RMNO), 1992.

3. Azimi, Nassrine, Personal communication. UNU/UNITAR Series On Sustainable Development In Practice, United Nations University/United Nations Institute for Training and Research, New York, 1998.

4. Roodman Malin, David, Nicholas Lenssen, “A building revolution: how ecology and health concerns are transforming construction” March, World Watch Institute, Washington, D.C., 1995.

5. Levin, H., A. Boerstra, and S. Ray, “Scoping U.S. buildings inventory flows and environmental impacts in life cycle assessment” Presented at Society for Environmental Toxicology and Chemistry (SETAC) World Congress, Vancouver, BC, November 1995.

6. Kohler, Niklaus, An observer’s perspective on the relevance of GBC ’98. Plenary Lecture, Presented at Green Building Challenge ’98. October 1998, Vancouver, BC. http://www.greenbuilding.ca/gbc98cnf/, 1998.

7. Lindvall, T. “The sick building syndrome - overview and frontiers.” in H. Knöppel, and P. Wolkoff, (eds.) *Chemical, Microbiological, Health and Comfort Aspects of Indoor Air Quality - State of the Art in SBS.* Kluwer Academic Publishers, Dordecht, 1992.

8. Bornehag, C.-G., *et al*, “TVOC and health in non industrial indoor environments;” Report from a Nordic scientific consensus meeting at Lângholmen in Stockholm. Borås: Sweden, National Testing and Research Institute, 1996.

9. Koortman, J. and Mak, J., :EcoQuantum,” *Bouw*, October, 1996.

10. Jönsson Å**.** **“**Life cycle assessment and indoor environment assessment,” *Proceedings, CIB World Congress 1998***,** Gävle, Sweden, 7-12 June 1998**.**

11. Levin, H, "Building ecology," *Progressive Architecture*, 62(4):173-175. 1981.

Table 1. Buildings’ share of national use of major industrial materials [5]

Material	*Buildings Share (%)*
Clay	80
Polyvinyl chloride	75
Timber	67
Sand	55
Polystyrene	38
Copper	34
Aluminum	25
Steel	25

Table 2. Strategies to reduce building-related mass flows

Strategy	*Instead of…*
Re-use existing buildings	Build new buildings
Build smaller buildings to accommodate the same functions	Overbuild - waste space
Re-use building materials	Dispose of them
Recycle building materials that cannot be re-used	Instead of landfilling or incinerating them

Table 3. Major determinants of indoor air quality

Building Characteristics	*IAQ Considerations*
Site characteristics:	Outdoor air and ground source pollutants
Occupant activities:	Type, schedule, location within building
Building environmental control:	Ventilation, thermal comfort, pollutant source control`
Building materials and furnishings:	Emissions, durability, maintenance and cleaning requirements.
Appliances and equipment:	Supplies, lubricants
Construction IAQ requirements:	Construction: material protection, temporary ventilation, commissioning
Building operational manuals:	Completeness, clarity, IAQ inventory

Table 4. Various recommended and adopted ventilation rates (after Lindvall, 1989) [7]

Ventilation Rate (L/s)[a]	*Basis or recommending/adopting group and year*
> 0.3	2% CO_2, (respiration)
> 0.5	1% CO_2 (performance)
> 1	0.5% CO_2, (TLV)
> 3.5	0.15% CO_2, (Pettenkofer Rule, 1858; body odor)
2.5	ASHRAE Standard 62-1981
3.5	Swedish Building Code 1980
4	Nordic Building Regulation Committee 1981
5 - 7-	Berglund et al. (body odor))
8	Fanger et al. (body odor
7.5	ASHRAE Standard 62-1989
5 - 10	Swedish Building Code 1988
10 – 30	Swedish Allergy Committee 1989
10, 20	Nordic Building Regulation Comm., preliminary 1989
16 – 20	Weber et al.; Cain et al. (Tobacco smoke, annoyance)
14 – 50	Fanger *et al.* (total odor)

[a] 1 liter per second ~ 2 cubic feet per minute

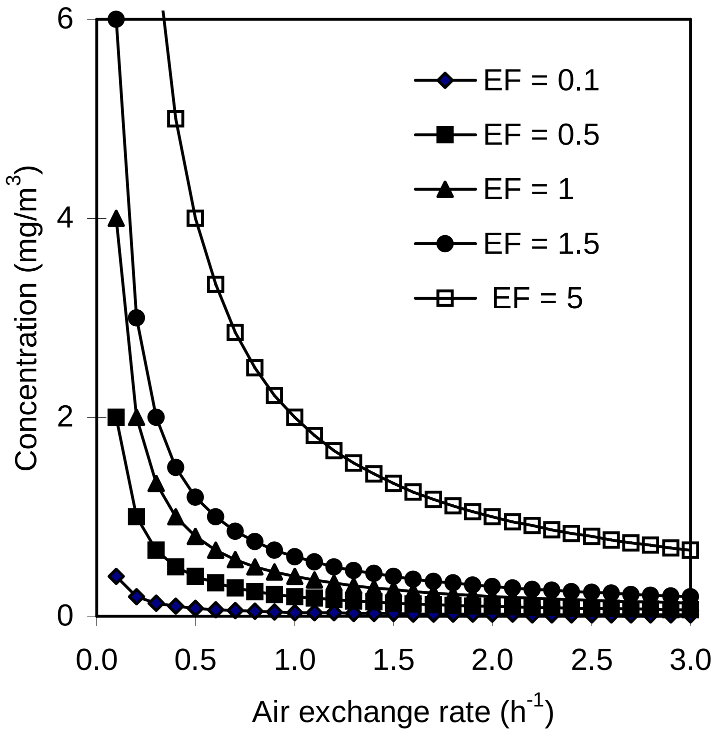

Figure 1. Pollutant concentration from various source strengths as a function of building ventilation rate. EF = emission factor (mg/m^2 h^{-1})