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DESIGNING HEALTHY BUILDINGS: STRATEGIES AND ISSUES

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ABSTRACT

The design of a buildings for healthy living implies that buildings are designed to be healthy for both their occupants and the larger environment. The design of healthy buildings is a complex task due to the large number of factors that must be addressed and the lack of knowledge about the effects of interactions among the various environmental factors and the human and environmental responses to them. Guidelines to address interactions are lacking. Designers must review the research literature, establish priorities, and design accordingly. Indoor environmental factors of importance are identified by examining the literature on Sick Building Syndrome (SBS) and Building Related Illness (BRI). This allows prioritization of design attention and rationalization of design decisions. Many risk factors for indoor environments can be easily addressed by design. Others require operation and maintenance solutions, although these can be facilitated by good design. Overall, some design solutions will benefit both the quality of the indoor environment and the impact of the building on the larger environment. Some of the most significant solutions are identified and recommended.

INTRODUCTION

"Buildings for healthy living" must, obviously, be "healthy buildings." And "healthy buildings" must be healthy both for their occupants and for the larger environment. The definition of "healthy" can mean either that the building itself is in good health or that the building causes or supports good health. It should mean both. When either the occupants or the environment are harmed by a building, then it can no longer be considered healthy. We have defined a healthy building as one that does not adversely impact either its occupants or the larger environment [12, 14, 18].

Buildings affect occupant health and well-being through the quality of their security, safety, and the quality of the thermal, air, acoustic, and illumination environments. It is obvious that the impacts of the building on occupant health and well-being are extremely important. Buildings affect the larger environment by the resources they consume including (natural, mineral, water, and land resources) and the pollution they create (including air, water, soil, and waste). These impacts are not so obvious. Recent work has shown that building impacts on the general environment range from 15 to 45% of total anthropogenic impacts [19, 24]. Energy consumption for buildings is around 40% of total U.S. national energy consumption and approximately the same fraction of total global energy consumption. Various forms of pollution attributable to buildings tends to be around 25% ±10% of all pollution sources.

Practical limitations do not permit a full exploration of the wide range of issues for healthy buildings here. This paper will focus primarily on the indoor environment. Some of the broader environmental issues have been addressed previously [12, 14, 18]. One conclusion from our previous work has been that durability of building materials and products and of the building itself tends to produce a healthier building both in terms of indoor environmental quality and general environmental quality [18]. There is also an important connection between the quality of the indoor environment and energy conservation, although the precise relationship should be better quantified. Energy conservation, daylighting and passive ventilation can all provide improved indoor environmental conditions without as much dependence on consumption of fossil fuels or other forms of energy with their concomitant resource consumption and pollution output.

CRITERIA FOR HEALTHY BUILDINGS

In order to design buildings for healthy living, designers must have criteria. Some factors for which criteria are requited are listed in Table 1. It can be seen that this list, although it encompasses only fairly broad categories of indoor environmental factors, is rather lengthy. When the details of each of these factors is articulated, it is clear that the design of healthy buildings is a complex and challenging task. While data and standards exist to guide design relative to the separate factors [1, 2, 7, 11, 31) there is little guidance for designers that allows understanding of the complex interactions among these factors and the combined effects of multiple environmental exposures on building occupants.

Table 1. Criteria for Healthy Buildings: Important factors for which 'Healthy Building' criteria should be established

Environmental focus	*Criteria focus*
Indoor environmental quality	Thermal environmental quality
	Indoor air quality
	Illumination
	Acoustics
	Functional support
	Security
	Privacy
	Way-finding
General environmental quality	Mineral resource consumption
	Energy consumption
	Natural resource consumption
	Habitat destruction, Biodiversity loss
	Land use
	Atmospheric pollution
	Water pollution
	Soil pollution

Humans respond to all facets of the indoor environment: The human body integrates its responses to environmental factors as mediated through various receptors: visual, tactile, aural, thermal, and posture. Most research separately addresses these various receptors and the related human responses. Standards and criteria generally available for design are derived from this focused research. Very little research has addressed the interactions among the multitude of factors. Thus, the designer is challenged to discover the inter-relationships among various factors and ascertain the effects of interactions among environmental factors and the human responses to them. This is not a trivial task, and little guidance exists to assist designers effectively to address the inherent problems. The various indoor environmental factors to which the human body responds are listed in Table 2.

Table 2. Non-air quality environmental factors to which the body responds

Factor	*Examples*
THERMAL	Temperature Air velocity Radiant asymmetry Moisture
ELECTROMAGNETIC ENERGY	Visible light Ultraviolet light Infrared radiation Cosmic radiation Extremely low frequency Ionizing radiation Electrostatic fields
MECHANICAL ENERGY	Noise Vibration

There may also be interactions among the human responses to the environment. For example, odor, taste, and irritation may interact when air pollutants are inhaled. Endocrine system responses to environmental factors will mediate subsequent responses to the environment. Cold temperatures will reduce the human response to odor. It is an understanding of these and many other interactions among environmental factors and human responses that is sorely lacking from the research data available to guide designers of buildings for healthy living.

MULTIPLE FACTORS AFFECT THERMAL COMFORT

Addressing just one of these major factors is complex. For example, several different environmental and personal factors affect the human response to the thermal environment [1, 11]. The factors that affect thermal comfort are listed in Table 3.

Table 3. Thermal comfort determined by several interactive factors

ENVIRONMENTAL FACTORS:	Air temperature Relative humidity Air velocity Radiant asymmetry
PERSONAL FACTORS:	Metabolic rate Clothing (Clo value)

The designer can attempt to design for control of all indoor environmental factors, but inevitably has no control over the personal factors, individual preferences, metabolic rate, and clothing. Yet, clearly, metabolic rate and clothing have very important effects on thermal comfort. Therefore, the designer can only assume the normal or average condition of most typical occupants relative to their metabolic rate and thermal comfort. In the end, no matter what the designer does, some fraction of the occupants will desire either warmer or colder thermal conditions. At best, according to the available standards from ASHRAE and ISO [1, 11], no more than 94% of the occupants will be satisfied at the "optimum" temperature. In fact, field research has shown that even fewer occupants are likely to be satisfied in most indoor thermal conditions.

To complicate matters further for designers, non-physical factors may affect the acceptability of the indoor environment even more than physical factors. For example, Hodgson [10] recently reported the results of field work in office environments showing that work stress may be a more important factor determining thermal comfort than the physical environment. According to Hodgson, work stress was a better predictor of occupants' thermal comfort response than the "predicted mean vote" (PMV) of thermal comfort calculated from the measurements of the thermal comfort parameters used as the basis for the ASHRAE and ISO thermal comfort standards widely used to guide building design. Thus, designs for thermal comfort may be good, factors outside the designer's control may be even more important determinants of occupants' reactions.

An important example of complex interactions is illustrated in the work of Berglund and Cain [4]. They reported that "...the comfort of occupants in buildings will depend upon almost all perceptible influences." They found that increasing temperature adversely affects occupants' perception of the chemical quality of the air (fresh vs. stale, stuffy, etc.) They found that the concentration of chemical contaminants "...will also influence judgments of air quality, but in some instances may actually prove secondary to temperature and humidity." The occupants rated the air quality as more stuffy and less fresh (more stale) even though air quality was held constant in the experiments. A one degree increase in temperature had about the same impact as a 5% increase in relative humidity. Their work shows that while thermal comfort may be acceptable at temperatures above 25 °C, overall the indoor environment may not be acceptable.

INDOOR AIR QUALITY

Air quality is the most recent indoor environmental factor to receive attention. This results in part from many disastrous indoor air quality incidents during the past 20 years. Among these are building closings, expensive and extensive corrective renovations, multi-million dollar law suits resulting from poor indoor air quality, and even building abandonment such as that following the 1976 epidemic of Legionnaires disease at the Bellvue-Stratford Hotel, Philadelphia. There has been widespread concern in Europe and North America about asbestos, radon, environmental tobacco smoke (ETS), volatile organic compounds (VOCs) PCBs, pesticides, and other semi-volatile compounds (SVOC). Sick building syndrome (SBS) has been a major concern for office and school building occupants. Table 4 lists the major effects attributed to exposure to indoor air pollutants.

Table 4. Major effects attributed to exposure to indoor air pollutants:

- Building Related Illness (BRI)
- Sick Building Syndrome (SBS)
- Irritation
- Discomfort
- Communication interference
- Task disruption

Building-related illness (BRI) refers to clinically diagnosed diseased with presumed etiology in building exposures. Air is an important route of infection by airborne pathogens. Important diseases such as tuberculosis, pneumonia (including Legionnaires disease), many types of influenza, and the common cold are transmitted through the air and exposure is by inhalation. Carcinogens including radon, asbestos, and environmental tobacco smoke (ETS) are among the indoor air pollutants causing BRI. Exposure to airborne allergens is also a function of the quality of indoor air. Concern is growing in Northern Europe and North America because asthma has become more prevalent. Some Scandinavian countries have reported strong evidence of steadily increasing asthma among their populations. Many authorities believe that much of the increase in the incidence of asthma is due to poor indoor environmental quality. Attention has focused particularly on control of moisture and resulting building infestation by micro-organisms and dust mites. Pets, particularly cats and dogs, have also been a concern. These same exposures can also result in an increase in allergen exposure. All of these exposures can be controlled, at least to some degree by good design.

Productivity impacts of poor indoor environmental quality

One of the most important motivations for the design of healthy buildings is the potential impact of poor environmental quality on productivity. A building must not interfere with the ability of office workers or students to perform their tasks, the ability of retail establishments to make profits from sales, and the ability of others to do the tasks for which a building is constructed. The connection between the indoor environment and productivity is often difficult to measure directly. But there are many indirect indicators of productivity, as listed in Table 5.

Table 5. Indoor environment - productivity linkages

Death,
Job injury
Illness
Doctor visits
Days absent due to work-related illness
Task performance
Attention span
Lost time spent addressing IAQ and other indoor environmental problems
Loss of concentration
Impairment of memory
Reduced creativity
Other task-related to components of worker productivity

DETERMINING IMPORTANT INDOOR ENVIRONMENT PARAMETERS

Understanding the relationship between indoor air quality and occupant responses is complex. Many studies have been inconclusive, others have found contradictory results. However, it is important for designers to interpret the available information in order to address the most plausible risk factors. Previous efforts to identify key risk factors for Sick Building Syndrome (SBS) have resulted in the list shown in Table 6. The author(s) who has identified this risk are indicated in the right hand column and the key is given below the table. With the exception of Mendell (USA) and Seppänen (Finland), all of the authors are from Sweden where SBS has been studied longer than anywhere else.

Table 6. SBS risk factors identified in major studies and reviews. (Levin, 1995)

GENERAL FACTOR	*SPECIFIC PROBLEM*	*AUTHOR*
BUILDING FACTORS		
	Low ventilation rates (< 10 L/s p)	(L, M, Se, Su
	Ventilation operations (<10 h/d)	(Su)
	Insufficient materials control	(L, N)
	Fleecy materials	(N, Sk)
	Carpets	(M, N)
	Air-conditioning	
BUILDING ENVIRONMENTAL FACTORS		
	High temperature	(M, Sk)
	High humidity	(L)
	Low relative humidity	(M)
	Volatile hydrocarbons	(N)
	Microbial VOC	(L)
	Dust	(N)
BUILDING USE / OCCUPANCY FACTORS		
	High occupant density	(M)
	VDT use	(M, St, Su)
	Photocopiers present	(St, Su)
OCCUPANT FACTORS		
	Perception of "dry air"	(St, Su)

Notes: Initials of lead authors of articles listed in the Reference section.

L= Lindvall M= Mendell N= Norback Sk=Skov
Se= Seppanen Su=Sundell St= Stenberg

Reporting on investigations of many large and intractable problem buildings, Woods [30] identified the predominant environment stressors as shown in Table 7. Table 8 shows Woods' assessment of the HVAC system shortcomings that contributed to the indoor air quality problems in these same buildings.

Table 7. Types of Predominant Environmental Stressors for Indoor Air Quality Problems [30]

Type of Environmental Stressor	*Frequency (%)*
Chemical and Particulate Contaminants	75
with odor discomfort	70
Thermal discomfort	55
Microbiological contaminants	45
Nonthermal humidity problems (with eye irritation and mold growth from low- and high relative humidities respectively)	30

Table 8. HVAC System Causes of IAQ Problems in Buildings [30]

Problem Category	*Physical cause*		*Frequency (%)*
Design			
	System problems		
		Inadequate outdoor air	75
		Inadequate supply air distribution to occupied spaces	65
		Inadequate return/exhaust air	75
	Equipment problems		
		Inadequate filtration of supply air	65
		Inadequate drain lines and drain pans	60
		Contaminated ductwork or duct linings	45
		Malfunctioning humidifiers	
		Inadequate access panels to equipment	60
Operations			
		Inappropriate control strategies	90
		Inadequate maintenance	75
		Thermal and contaminant load changes	60

Although designers cannot control all the factors affecting occupant response, there are many things that can be done during design. In order to target design efforts so that they will be most effective, it is important to gain some understanding of the most important sources and types of indoor pollution. Then, design efforts can be prioritized accordingly.

To design effectively, it is important to understand the basic determinants of indoor air quality. A practical way to address indoor air quality problems by design involves identifying pollutant sources so that they can be eliminated or minimized and pollutant removal mechanisms so that they can be utilized effectively. This is similar to the way structural design or thermal control design is done. Loads are identified and means are provided to eliminate, control, or remove them. Table 9 lists the major categories of pollutant sources and removal mechanisms.

Table 9. Determinants of indoor air quality

POLLUTANT SOURCES	
	Outdoor Air, Soil, Water
	Building Envelope
	Building Equipment
	Finishes and Furnishings
	Machines and Appliances
	Occupants (clothes, hygiene)
	Occupant Activities
	Maintenance and Cleaning
POLLUTANT REMOVAL MECHANISMS	
	Sinks
	Ventilation
	Air Cleaning and Filtration
	Chemical Transformation

The potential for indoor air contaminants to affect occupants depends on their exposure. Exposure is the product of the concentration of the contaminant and time of the exposure. Equation (1) describes this relationship [3].

$$\text{Exposure} = \text{Concentration} \times \text{Time} \qquad (1)$$

The major determinants of indoor air quality are the relationships between the rate at which pollutants are generated in the space or brought into it and the rate at which they are removed from the air. These relationships are described in equation (2) known as the Mass Balance Equation.

$$\text{Sources} - \text{Sinks} = \text{Steady State Concentration} \qquad (2)$$

Building Material and Product Selection

Designers have begun to address indoor air pollution control by carefully selecting building materials and furnishings with low emissions of volatile organic chemicals (VOCs) into the air after installation in the building [6, 8, 9, 15-17, 20, 25, 27], Emissions tests are conducted, and the emission factors are determined. These emission factors are expressed in mg/m^2 h. The emission rate is then determined by multiplying the emission factor times the area of the material in the space. Many factors affect the concentration of a chemical emitted from a material or product [5, 16, 25, 26]. In addition to the source strength, these include several characteristics of the space. These factors are listed in Table 10.

Table 10. Factors affecting concentration of a pollutant emitted into a space

- SOURCE STRENGTH
  - Mass available in the material
  - Vapor pressure (function of temperature)
  - Source type (fast or slow emitting, thickness, density)
  - Age and environmental exposure history
- CONCENTRATION
- VENTILATION RATE
- SINKS
- CHEMICAL REACTIONS
- AIR MOVEMENT

At steady state, for constant emissions, the relationship between source strengths, ventilation rates, and air concentrations is given by the equation 3.[3].

$$C = (EF \times L)/Q \tag{3}$$

Where

C = concentration (mg/m^3)

EF = emission factor (mg/m^2 h)

L = loading ratio (m^2/m^3)

Q = air exchange rate (h^{-1})

These relationships are shown in Figure 1 for the range of typical VOC source strengths and ventilation rates found in modern buildings [16, 17, 20, 22, 23, 28]. it is important to know source strengths and ventilation rates in order to control concentrations to some established target or regulatory value. It is also extremely important to maintain minimum ventilation rates under all conditions of building occupancy. Typically, office buildings have 0.9 air change per hour (ach) [23], schools have around 3 ach, and residences have from 0.5 to 3.0 ach [22]. The values and the fundamental relationships depicted in Figure 1 are not limited to VOCs. They apply to microbial contaminants, particulate matter, SVOCs, inorganic gases, or any other contaminant. Note that the concentrations get very large at the lowest ventilation rates. This requires that either extreme care be exerted to avoid the presence of strong sources when ventilation is very low or that ventilation not be allowed to go so low. Also note that the dramatic reductions in concentrations do not occur as the ventilation rates are increased incrementally toward the right hand side of the graph.

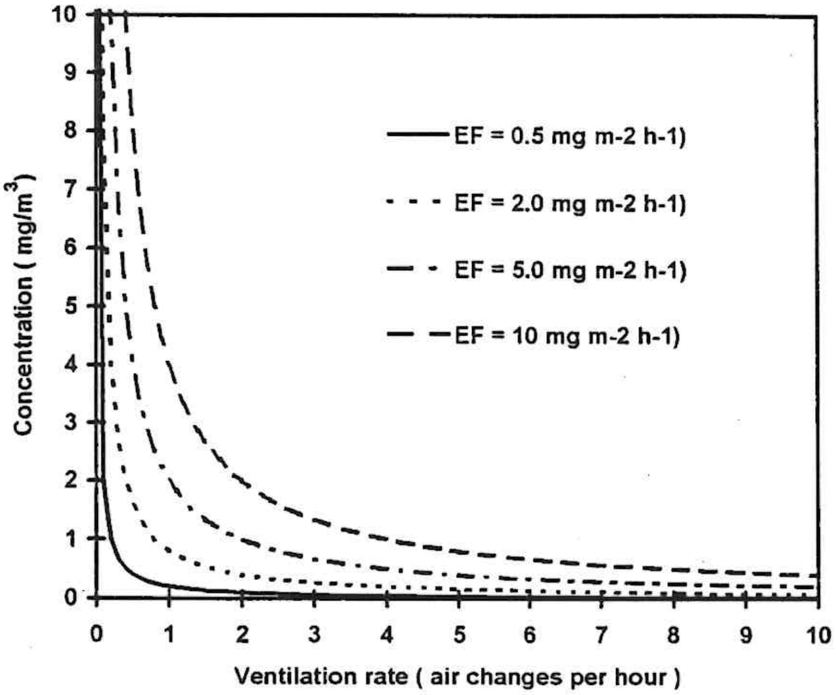

Figure 1. VOC concentrations as a function of source strength and air exchange rate.

Since not all products used in a building can be effectively evaluated, it is essential to identify those products with the largest surface area or mass and to carefully evaluate them [15, 16]. It is also useful to identify the products with known odorous, irritating, or toxic emissions and pay special attention to their selection and installation. Providing additional ventilation during the installation of strong emitters can significantly reduce occupant exposure to pollutants [16].

Importance of Ventilation

While there has been controversy about the significance of many of these factors due to conflicting findings in various studies, nearly all quality building studies have indicated that the prevalence of symptoms increases at ventilation rates below 10 litres per second per person (L/s/p) and decreases above 10 L/sp [21]. Tables 6 and 8 as well as Figure 1 all strongly support the need for maintaining minimum ventilation rates while buildings are occupied.

Life Cycle Emissions and Exposure

It is important to recognize that the emission characteristics of various building materials and other sources of indoor air pollutants vary over the life of a building. Since total occupant exposure is more dependent on life cycle emissions than on initial emissions alone, in some instances the cleaning or refinishing products used to maintain a product's surface and to extend its useful life may be far more important sources of indoor air pollutants over the life of the product than the emissions from the product itself. This can be visualized by the example of floor coverings that require frequent refinishing or surface coating and even more frequent waxing or polishing with chemical products. Figure 2 illustrates the life cycle of materials and other indoor air pollution sources. Each plus in the cradle-to-grave lifecycle is intended to represent a time when the emissions from the particular source is at or near its strongest level, assuming that most building product and material sources will decay over their lifetimes. Thus, some sources are fairly steady, others are periodic or episodic, as depicted in the table.

Figure 2. Life cycle perspective on indoor pollution sources

Source	*Cradle - - - - - - - - - - - - - to - - - - - - - - - - - - - - Grave*
Outdoor air, soil gas	+++
New materials emissions	+++ + +++ + ++ +
Furnishings	++ ++ ++ ++ +
Occupants and their activities	++++++++++++++++++++++++++++++++++++++ ++++++++++++++++++++++++++++++++++++++
Equipment operation	+++++++++++++++++++++++++++++++++++++++
Housekeeping	+ +
Maintenance	+ + + + + + + + + +
Surface renewal	+ + +
Renovation	+ +

From a life cycle perspective, it appears to be more important to select products that will require minimal chemical cleaning and refinishing and that will last for a long time. That will eliminate the periodic emission of the chemicals used in the cleaning or finishing products and the release of the strong emissions from the products when they are new. Thus, durability and ease of cleaning and maintenance become important criteria for material selection. Designers can require manufacturers to provide information on their product's maintenance, renewal, and cleaning requirements, expected useful life, and installation procedures to assist in making product selections [16, 18, 20].

Moisture Problems

Moisture control has become recognized increasingly as a critical factor of indoor environmental problems. The potential for microbial contamination leading to occupant health effects and to material deterioration warrant significant design, construction, and building maintenance efforts to control moisture intrusion, leakage or condensation, and other sources of excess indoor moisture. Ventilation helps prevent microbial growth when indoor moisture sources are strong, but ultimately the best remedy is to prevent moisture intrusion or condensation by design and proper use of the structure. Flat roofs are a significant risk factor for moisture problems and should only be used where rainfall is very low or other roofing options are not viable.

DESIGN STRATEGIES

1. The overall design should be based on a determination of what is important and established priorities for design efforts to create healthy buildings:
    - This should include an assessment of the amounts of surface area and mass of major building materials and products that will be used.
    - It should include an overview of the use of the building and the appropriate ventilation strategy.
    - It should include a detailed plan for the operation and maintenance of the building over its entire life cycle.
2. Material selection should include evaluation of the following
    - Identification of quantities of major materials and products being used
    - Emissions of new materials and decay profiles
    - Maintenance and cleaning requirements
    - Surface renewal requirements
    - Durability - Expected useful life
3. Develop guidelines to protect air quality during construction and renovation
    - Isolate construction areas
    - Provide abundant air exchange during installation of "wet" products
    - Protect building surfaces (sinks) from adsorption of emissions
    - Exhaust construction fumes to outdoors
    - Provide extra ventilation during and after installation of new materials

4. Develop guidelines to protect against important airborne pathogens, allergens, and asthmagens

- Evaluate effectiveness of building design and construction methods for moisture control
- Evaluate effectiveness of ventilation and filtration to prevent infection from specific important inhaled pathogens such as rhinovirus, Legionella pneumophila, B. tuberculosis.
- Evaluate effectiveness of housekeeping in protecting against dust and allergens

Individual Occupant Control of the Indoor Environment

Some experts believe that satisfying the majority of occupants is not sufficient. They argue that designers can and should attempt to satisfy virtually all occupants. Therefore, they recommend individual control of the indoor environment in order to increase the overall satisfaction or acceptability rate. This approach is advocated for office workers and it is claimed to be the only way to satisfy the overwhelming majority of building occupants. The control may involve any of the indoor environmental variables discussed above - thermal, air quality, acoustic, or light. Various hardware options exist for both delivering and allowing for control of the indoor environment at an individual occupant level. The most basic, of course, is the operable window. But more sophisticated technology now exists for application where operable windows are not an option.

Durability of Materials

Durable materials are beneficial from the perspective of the total environment impact of buildings since the more durable the material, the less resources will be required from natural and mineral reserves and the less waste will be generated over the total life of the building [18]. Durable materials also generally require less toxic cleaning and maintenance materials be used to support their continued functioning. In general it may be said that the more durable a material, the lower its total lifetime emissions of VOCs and other contaminants.

PREDICTION OF FUTURE TRENDS

Increasing attention to microbial contamination will lead to more careful planning of building envelopes to avoid moisture intrusion. Measurements of VOC emissions from microbial contaminants will become more common and may assist in determining the causes of many occupant health and comfort complaints. Standardization of emissions testing from building materials and products will provide more reliable data for selection of products. More emphasis on the total life cycle of the building will become routine as larger environmental issues are made more important as design criteria. Indoor air chemistry will be better understood as more research is completed. Designers will then be able better to contribute to creation of healthy buildings.

CONCLUSION

Thoughtful consideration of the major sources of contaminants and means of control can result in good indoor air quality. Adding concerns for other indoor and general environmental factors, while complicating the designer's job, can result in a clearer set of criteria for decision-making and result in a healthier building environment. Work still must be done to better understand the interactions among various environmental factors. In the meanwhile, designers can achieve buildings for healthy living by emphasizing the control of sources, provision of adequate ventilation, preventing intrusion of moisture, selecting durable building materials, and providing for individual occupant control of the environment.

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