SUSTAINABLE BUILDING AND INDOOR AIR QUALITY

E. Hasselaar[1)] and L. Morawska[2)],
[1)]OTB Research Institute for Housing, Urban and Mobility Studies, University of Technology Delft, The Netherlands;
[2)]Environmental Aerosol Laboratory, Queensland University of Technology, Brisbane, Australia.

ABSTRACT

The quality of indoor air is linked to detrimental health effects. Indoor air is a research and design issue in healthy housing, rarely considered in sustainable building. By analysing the relation between sustainable building and indoor air, a framework for discussion is constructed. The question is how the relation between healthy indoor air and sustainable building can be improved.
The authors conclude that fresh air can be treated as an essential consumption good, which is produced by building services. Fresh air must be "created" in situations when the collected outdoor air needs to be filtered, heated, transported, consumed and replaced. After its use, the air is exhausted as waste material. The energy consumption, pollution process and re-cycling can be accounted for in life cycle assessment calculations. From the perspective of flows, airflows can be added to the flows of materials, energy and water during the entire life cycle of the building. The integration of flows in terms of consumption of fresh air will result in a better balance between strategies on the level of each flow. In this way it will be possible to make a stronger link between healthy indoor air and sustainable building.

KEYWORDS

Sustainable building, healthy housing, indoor air quality, life cycle assessment.

INTRODUCTION

The built environment creates many health risks, due to noise, polluted air, microbial growth in water or radiation. Indoor air quality has developed into a major research field, because of challenges related to the need for provision of clean air and thus prevention of a growing number of cases where inadequate air quality is linked to detrimental health effects. The quality of indoor air can be improved through practical implementation of healthy housing concepts. In the process of sustainable building, the restructuring of urban areas and the renovation of existing buildings, many opportunities can be used to improve the health standard of the environment. Sustainable building is focussed however on energy, materials use and waste and does not explicitly include health risks. This paper analyses the relationship between sustainable building and healthy housing, with a special focus on healthy indoor air.
The research questions are:

1. What is the relation between indoor air quality and human health?
2. Is indoor air quality an aspect of sustainable building?
3. Can the quality of indoor air be improved by better integration of healthy housing concepts in sustainable building?

MATERIAL AND METHOD

The article is based on the experience and empirical data of two experts, one in the field of indoor air (fine particulate matter) and one in the field of sustainable building and healthy housing (architect and building physicist). The confrontation of views provokes a framework for the discussion about the relation between sustainable building and healthy housing, especially healthy indoor air. The article shows possibilities for better integration and poses questions for the development of new instruments.

RESULTS, THE RELATION BETWEEN INDOOR AIR AND HUMAN HEALTH

An increasing number of studies conducted in many countries have demonstrated that the quality of the indoor environment is directly related to health and wellbeing. A comprehensive literature review by (Fisk, 1999) showed that there is moderate to strong evidence that characteristics of the indoor environment significantly influence rates of a large number of health effects. The list of health effects that have been linked to indoor exposures include (Maroni, 1995):

- allergy and other effects on the immune system,
- cancer and effects on reproduction,
- respiratory effects (other than cancer and allergic effects),
- irritating effects on skin and mucous membranes of eyes, nose and throat,
- sensory effects on the nervous system,
- effects on the cardiovascular system.

In addition to the specific health effects listed above, there are also syndromes and sensitivities exhibited or acquired in indoor environments: Sick Building Syndrome (SBS), Building Related Illness (BRI) and Multiple Chemical Sensitivity (MCS). The term syndrome is used, because the relation between cause and effect is yet unknown. While there is large variation in the magnitude of the effects and while direct comparison of results between individual studies is not always possible due to the differences in methodologies used, the occurrence and the potential for serious health effects caused by the poor quality of indoor environments is no longer questioned. Human susceptibility to illness from exposure to air pollutants will vary but will be especially critical for the very young or old, the asthmatic and people with allergies and chemical sensitivity.

AIR QUALITY

Good air quality means above all, low concentrations of pollutants that are detrimental to human health and wellbeing. There are thousands of pollutants in the air of anthropogenic as well as natural origin and they can be classified and characterised in many different ways. For example according to physical state the pollutants exist either in gaseous/vapour or particle form (solid or liquid). However, they can also be classified according to their chemical or biological composition or by the effect they have on humans (toxic, carcinogenic, etc). There are further complexities existing within each class of pollutants. For example, airborne particulate matter can be further classified into fine particles, which are usually defined as those with an aerodynamic diameter equal to or below 2.5 µm, coarse particles, which are above 2.5 µm, and ultra fine particle, which are those below 0.1 µm. In the terminology of the standards used in many countries, PM_{10} and $PM_{2.5}$ fractions are mass concentrations of airborne particulate matter with aerodynamic diameter smaller than 10 μm and 2.5 μm respectively. Fine particles typically contain a mixture of components including soot, acid condense, sulfates and nitrates, as well as trace metals and other toxins.

One important factor, which contributed to the deterioration of the quality of the indoor environment, was tightening of the building envelopes. Leaky building structure is considered as one of the major sources of energy losses, allowing heated or cooled air to escape from the building. In order to save energy, particularly during the energy crises, the trend emerged to tighten buildings. While these measures resulted in lowering of energy wastage due to escape of the conditioned air, it also lead to some developments undesirable from the point of view of human health. In particular, air change rates decreased, which in turn lead to the elevation of concentrations of pollutants present in indoor air. An additional problem experienced in tight building structures is an increased moisture presence, which results in favourable conditions for microbial growth. This is the case when conditions are created under which condensation occurs on relatively cold surfaces, when water becomes entrapped in some parts of the building construction or in furnishing, leading to infestation with moulds or bacteria. Microbial growth produces different substances, some of them allergenic and even toxic. Humans subsequently inhale the gaseous and airborne particulate matter.

OUTDOOR VERSUS INDOOR AIR

Outdoor and indoor air is often considered separately, not only because of the differences between these two types of environments, but most importantly, because usually different regulatory bodies are responsible for indoor and outdoor environments. The importance of outdoor air was recognised in the fifties of the twentieth century and outdoor air quality was first regulated in the USA in 1970 (Clean Air Act). Indoor air quality emerged as an issue sometime later and was soon recognised as having at least equal importance to outdoor air quality. There is evidence that most people spend over 90% of their time indoors and that the indoor environment is often more polluted than the outdoor environment. Now, indoor air pollution is ranked among the top five environmental risks to public health (EPA, USA). Despite this recognition, only limited progress has been achieved in regulating indoor air quality in many parts of the world, particularly in residential and non-industrial environments like offices and school buildings.

In many countries most people live in urban areas. World wide over 50% of the population lives in cities and this number is expected to increase to 75% in 25 years. For example in Australia, one of the most urbanised countries in the world, over 86 percent of the population lives in urban areas, and over 50 percent in the five largest cities (Newton et al 1998). Noise is perceived to be a serious pollution problem in cities, affecting large parts of residential communities. Airborne particles are emitted copiously by motor vehicle engines, particularly those operated on diesel fuel. Exhaust air of industrial and occupational buildings is polluted. The "fresh" air outdoors is vented into houses, thus forming a base load of exposure to pollution in urban houses.

There are numerous indoor air pollution sources that can contribute to significant concentrations of many pollutants including Volatile Organic Compounds (VOC), Carbon Monoxide (CO), particles or biological agents. Emissions from heating and cooking equipment, from paint, cleaning fluid and other solvent based materials all play a part (ATSE, 1997). Important indicators for indoor air quality in residences include:

- Formaldehyde concentration in construction materials and furniture;
- Nitrogen dioxide concentrations from non-vented gas appliances;
- Bacteria-infested aerosols from drinking water systems (legionella);
- House dust mite allergens in housing in coastal climates;
- Small dust particles with radio-active nuclei;
- Benzene concentrations from adjacent garages;
- Several volatile organic compounds from paints, cleaning agents and many other products used in housekeeping.

HEALTHY HOUSING AND SUSTAINABLE BUILDING

Taking the existing knowledge about the profound effect of the quality of the indoor environment on health and well being of the occupants and the knowledge available in the areas of building science and technology, it is an imperative for future development to combine these two areas together to achieve true sustainability of the building sector.

The strategy of sustainable development is defined in terms of avoidance, reduction and protection. The time horizon is long term, for instance 10% CO_2 reduction in 30 years time. The scale is the global environment. This is in contrast with the strategy of healthy housing, which is to create a healthy indoor environment for the present occupants of a building. Sustainable building is one of the means to reach the goals of global sustainability. The global CO_2 reduction agreement was translated into well-defined goals and strategies for the building sector and that made energy-saving into a dominant issue in sustainable building. Where this strategy implicates an increased risk for the indoor environment, the health aspects must play a more dominant role.

The strategies for sustainable building and healthy housing cause several confrontations:

- the short term need of sufficient indoor air can conflict with energy conservation strategies;
- ecological balance demands for green areas, but pest control or protection against pollen asks for open and controllable environments;
- collecting waste material in several fractions, including a fraction of kitchen and garden waste, attracts insects and pest animals and produces mould spores;
- re-use of domestic water or the use of rain- and surface water for housekeeping creates higher risk of contamination of drinking water;
- hot water for showers and baths can be produced at around 42^{o}C, but this temperature is optimal for the reproduction of the legionella-bacteria.

Sustainable building and healthy housing strategies can provide mutual support. Thermal insulation of a building would greatly reduce the need for heating and reduce the emissions on rooftops. A well-insulated construction protects against condensation of moist air on heat barriers and thus prevents mould growth. The use of environmentally friendly products and systems, for instance non-volatile paints, wood from fast growing trees and solar heating instead of wood-burning stoves will reduce emissions in the house as well as in the global atmosphere. These confrontations and mutual support demand for a joint development of sustainable and healthy buildings. The design aids and quality regulations for sustainable building must be complemented by healthy housing design aids and regulations.

The back-to-basics approach of sustainable development focuses on the ecological quality, leaving out health, which is considered a social-cultural aspect. Others argue that in sustainable development, the value of providing for the needs of the present generation without obstructing the quality of life of future generations links the quality of human life to ecological quality. Therefore, health aspects must play a role in sustainable development.

In planning processes in the city of The Hague in The Netherlands, health aspects are integrated in sustainable building. A matrix is used, with energy, materials (including water) and health as the parameters. See table 1. Participants in workshops discuss the present and desired quality, by filling out a sustainability matrix (Hasselaar et al., 2001). Participants discuss the present situation and present ideas, steps and strategies to improve the sustainable quality. By putting health in the "quality" field and air in the "flows" field, the matrix comes out as in table 1 and can be used to discuss air quality aspects. See table 1.

Strategy for sustainable and healthy building renovation											
	Flows										
Qualities	**energy**			**materials and water**					**air**		
	Low use of fossil fuel	Renew-able energy	Energy efficient	Re-source Protect-ion	High quality	Efficient use	Waste managem ent and re-cycling	Closing the Water-cycle	outdoor condit-ions	Efficient condition-ing for clean indoor air	Low emission/ pollution by exhaust air
Conserv-ation	Well Insulated Compact building	Solar Thermal and pv	Low temp. Heating Efficient heaters	Low material use	Function and life span agree	Long life, Low maint-enance	High function for re-use	Low consumpt-ion, Aware-ness of user	Use fresh air directly	Efficient use of re-sources, simple, low energy	
Durable and func-tional	Long life, well insulated structure	Passive solar heating, Wind-water-power	Natural Gas, free cooling	Use of wood	Comfort-able, funct-ional, aesthetic	Low mainte-nance	Flexible	Efficient Use, keep water within neigh-borhood	Natural flows, adapted building design	Control by occu-pants, low flows	Well insulated against noise, non pollutive
Recycled	Cellulose insulat-ion	natural materials like wool	Bio-gas	Recycle building material	Re-use of com-ponents	Fits technical and funct-ional life span	De-mount-able compo-nents	Use of rain water in the house, recycle in area	Flow from user area to service area	Recupe-rate heat	Filter exhaust air if dusty or toxic
Healthy	No open fires	Cooling with fresh air, Solar heating	Radiant heat from large surface	Low emission Low radiation No dust	User friendly, comforta ble, safe	user control, flexible, adaptable	Avoid polluted recycle products	Safe drinking water, bacteria free bathing	Take air in from clean area	hybrid venti-lation, summer and winter systems	Non toxic, dust free low noise

Table 1. Sustainability matrix

SUSTAINING HEALTHY HOMES

The integration of health criteria will benefit from the development of "sustaining healthy homes". Good indoor air is an essential quality, and also the protection against high sound levels, drinking water pollution, violation or accidents and extreme climate and radiation conditions. Fresh air is a natural resource. Instead of looking at indoor air as a material we propose to see it as an essential consumption good, which is produced by the building itself. Fresh air must be "created" in situations when the collected outdoor air needs to be filtered first, heated, transported, consumed and replaced. Fresh air is consumed and released as polluted air. This pollution is an emission from the building that can be accounted for in life cycle assessment tools.

In general terms, as discussed above, air pollutants are generated inside the building either by human presence and their activities or by emissions from the building elements or its furnishings; they can be also introduced to the building from outside. Different measures can be taken in relation to these different aspects of indoor air pollution.

The most efficient way to reduce pollution resulting form the emissions is to use low emitting material for building construction as well as for furnishing of buildings. This is according to the principle that source control is the most efficient way of pollution control. More and more information becomes available about material properties in relation to emissions (Haghighat & De Bellis, 1998), which should serve as a guide for building designers and building owners. In choosing low emitting materials it should also be ensured that consideration is taken of the conditions under which the building operates, particularly in terms of the meteorological conditions of the area and the function of the building. For example, the materials, which are suitable for climatic conditions of temperate zones, are not necessarily applicable to tropical areas and vice versa. Since zero emissions are usually not achievable, and a build up of the emitted pollutants could lead to concentrations affecting human health, it is the role of the ventilation system to remove contaminated air.

The most significant pollutants resulting from human presence are exhaled CO_2 and biological agents such as bacteria, viruses, hair or skin cells. Pollutants generated as part of the human life cycle are removed from indoor air by ventilation. There are guidelines and norms in different countries, as to the required rate of ventilation, expressed as air change rate (ACH), which is necessary to ensure desirable air quality as a function of human occupation, their activities, and the indoor source strengths. Some examples include a minimum airflow rate of 10 l/s per person or 1 $l/s.m^2$ of room area.

In proximity to roads carrying high traffic flows, but also in the vicinity of industrial or agricultural operations, polluted air should be prevented from entering an indoor environment. Concentration levels of pollutants in outdoor air vary significantly in place and time and depend on the strengths of the outdoor sources, patterns of operation of the sources, the distance between the sources and the building and meteorological conditions, particularly wind direction (Wallace, 1985). The most efficient way to ensure good outdoor air quality is, again, through source control, meaning reduction of motor vehicle or industrial emissions. If this option is not available, the next best option is to locate the building at a sufficient distance from the outdoor pollution source, so its impact on air quality in the vicinity of the building is minimal. The final resort is to filter the outdoor air provided to the building. These choices could be optimised by calculating the environmental effects of the location of the building, and of the heating and air conditioning services, that "produce" the conditioned air.

THE ROLE OF OCCUPANTS

The relation between human health and the building is indirect. Certain building components and functions create nuisance or pollution, and health effects depend on the exhibition of the occupant. In turn, the occupant behaviour determines the exhibition, for instance through the use of the ventilation system. This behaviour however is very much influenced by the functionality of the technical building services. Therefore, air quality is the result of the building and the way human occupants relate to it. See figure 1.

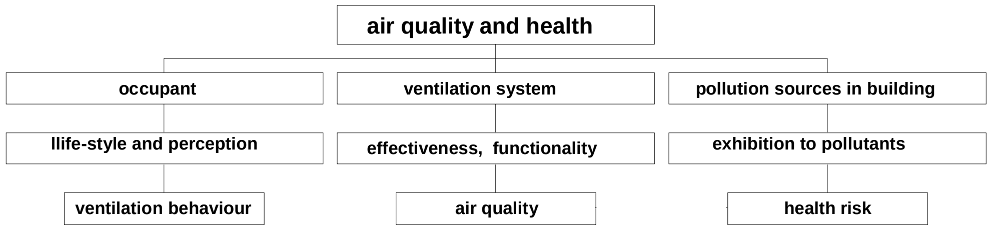


Fig. 1. The relation between indoor air quality and health (Hasselaar, 2002).

One of the difficulties in creating a healthy indoor environment is that human response, in terms of health effects as a response to multiple physical and psychological factors in the indoor environment is very individual, complex and often not well defined. While there is a general knowledge about the qualitative associations between exposure and health effects, in quantitative terms, information is often very limited. More information is needed about conditions in sustainable buildings and the indicators of these conditions. Human responses are left out in many surveys, thus creating a paradigm of individual responsibility. Within this paradigm, the occupants must be educated to ventilate better and must be informed about how to use new energy-efficient solutions. This paradigm discloses the conflict between manufacturers and consumers, who demand user friendly systems. The design of sustainable houses, especially low-energy houses, is sometimes in certain ways not user friendly: some air conditioning systems cannot be used properly, because of the high noise level, and sun-oriented rooms tend to collect too much heat and cannot be cooled properly by opening windows. Occupant behaviour should not be a limiting factor for progress in creating healthy indoor environments, but should be the starting point in building design and planning. Good ventilation can be the result of simple tools that are easy to understand and work efficiently, or follow the strategy of smart solutions, with automated control of the indoor air quality. Solutions with high sustainable quality can provide good environments, if products and services take user friendliness, comfort and health aspects into account, thus serving the needs of the present occupants.

TOOLS AND DESIGN AIDS

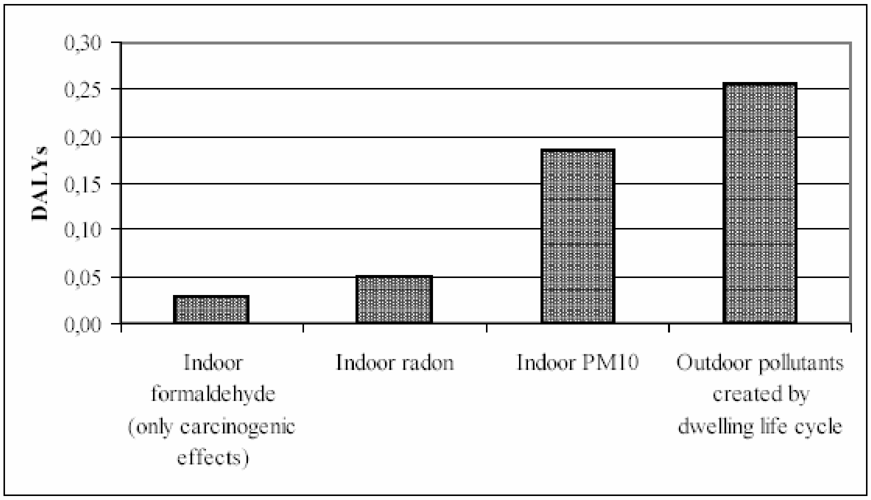
In European countries, a need is expressed to define indicators of healthy environments, in order to facilitate the integration of health aspects in sustainable building (Cochet, 2002). France focuses on 14 targets for sustainable buildings, in clusters called eco-construction, eco-management, comfort and health. Indoor air quality is one of the 14 targets. Health criteria support the selection of building materials. Cleaning and maintenance of air systems is integrated in design requirements. One of the targets says that air systems must be user friendly for the physically handicapped and must support the care for senior citizens. Important indicators in The Netherlands concern indoor air quality, thermal comfort and noise. After 12 years of policy development in the field of sustainable building in The Netherlands, the health issue has turned into an important research topic, stimulated by the conflict between energy conservation and indoor air quality. Health assessment tools are being developed, to support the design of healthy new buildings and to select health-responsible energy-saving measures in existing buildings. Also, an assessment tool in support of individual occupants is available, which provides better insight into the quality of ventilation systems (Rijsbergen et al, 2001). These tools promise better integration of health aspects in sustainable building and management of existing buildings.

We propose to consider fresh air as a natural resource, that is (re)produced by building services. The question than can be put in two ways:
1. How to optimise the sustainable quality of the production technique for 1 m3 of indoor air?
2. What is the environmental impact of the service “healthy indoor air”?
The second question can be answered by life cycle assessment (LCA-) studies. The first question can be answered by using tools for the calculation of environmental impacts. These tools are based on life cycle assessment studies of the many different components that constitute for instance the heating and ventilation systems. A comparison could be made, for example on the question, if natural ventilation or balanced flue ventilation for new buildings has better sustainable quality. In cold climate many new buildings are equipped with balanced flue ventilation systems and the heat from exhaust air is recuperated, to save energy. This system requires the construction of more metal ductwork, fans and recuperation units and extra maintenance work. Will the environmental impact counterbalance the energy saved for heating of the vented air? Also, balanced flue ventilation requires a well sealed building envelope and this aspect can contribute to unpredicted health effects. How can we account for these health effects? Köhler ventured a life cycle assessment study of produced fresh air (Köhler, 2002). He estimated that the production of fresh air, utilising a balanced ventilation system, which is very energy efficient, has a lower integrated sustainability quality than naturally produced fresh air, even when this needs five times more energy to be heated. Köhler used this example to stress the need of life cycle assessment for indoor air.
Eco-Quantum is an LCA-tool that calculates the environmental quality of a complete building. Twelve impact categories can be calculated: depletion of raw materials, depletion of fuels, global warming, ozone depletion, photo-oxidant formation, human toxicity, ecological toxicity, acidification, desiccation, energy consumption, non-hazardous waste and hazardous waste. The reduction in toxicity, hazardous waste and photo-oxidants are useful aspects for the quality of air, but the tool does not calculate the quality of indoor air.
A design tool like Enervent can be used to calculate indoor air quality, but this tool is not compatible with life cycle assessment tools. Integrating health impacts in LCA-methods deserves attention in further development of these tools.

The effects of air pollutants on airway-diseases and child mortality have been studied well and data can be used in LCA. Meijer et al. studied the effect of indoor formaldehyde, radon and PM_{10} on the health of occupants and compared the effect with outdoor pollutants, created by the dwelling life cycle. Indoor air has a large influence on the total health effect of a dwelling (Meijer et al, 2002). The LCA for a reference (simple type) residential building resulted in Disability Adjusted Life Years (DALY’s) in figure 1. The research is being continued, with a focus on emissions from building components and on ventilation strategies.
Despite the large number of existing mathematical models there is a need for improvement in terms of better model validation, accuracy, input requirements, and also a need for development of new simulation tools capable of progressing with the new developments in the multi-disciplinary and complex field of indoor environments. By calculation the environmental effects of air conditioning on the scale of a building, given a specified air quality, but produced by different means, the building quality can be optimised. Also, by

calculating the total impact of the building life cycle on indoor air, the environmental load and the health impact can be calculated.

Figure 2. The effects of air pollutants on health (Meijer et al, 2002).



CONCLUSIONS

The first research question explores the relation between indoor air quality and human health. There is proven evidence about the impact of indoor air pollution on human health. Also, there is a convincing, but not yet a proven relation with different syndromes such as Multiple Chemical Sensitivity. Indoor air quality has developed into a major research field, because of challenges related to the need for provision of clean air and thus prevention of a growing number of cases where inadequate air quality is linked to detrimental health effects.

If air quality can be treated as an aspect of sustainable building is until now a matter of opinion. The authors propose to treat air as a natural resource and indoor air as a flow in sustainable development, in the same way as energy, materials and water are treated. By considering indoor air as a resource, that is consumed and (re)produced by a building, indoor air quality can be integrated in design tools for sustainable building.

Can the quality of indoor air be improved by better integration of healthy housing concepts in sustainable building? In many countries, where sustainable building has developed into a main policy, the quality of indoor air is being studied, because of the conflicts between energy conservation in buildings and healthy indoor air. Progress is being made and design tools for the integration of health aspects are being developed. Information is available about the impact of singular agents on human health. There is some indication, but not enough evidence yet, that the quality of indoor air will be improved by better integration of health aspects in sustainable building.

The research on the impact of the building life cycle on air and health must be continued. Also, further development of the method for optimising the building on the basis of optimised production of conditioned indoor air is needed.

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