Healthy buildings—from science to practice

Olli Seppänen*

Helsinki University of Technology, Finland

ABSTRACT
The activities of indoor environmental research have increased significantly since the first energy crisis of the early 1970s. Since then, research has produced many significant results that have already been put into practice. These include the health effects and prevention of environmental pollution by tobacco smoke, formaldehyde, radon, asbestos, etc. The health risks of these contaminants have been verified, and appropriate measures have been taken by the authorities, as well as by the building industry and product manufacturers. Recently, the focus of research has not only been on specific compounds in the air, but also on the indoor environments of buildings. Research has identified several risk factors relating to building design, construction and operation that may have an adverse effect on health and productivity. A major challenge is to discover how best to utilize this information in practice; that is, how to transfer the information familiar to scientists to practitioners in the field. In this dissemination process, various methods should be utilized. This paper presents an overview of building and environmental factors associated with health and productivity. These include ventilation rates, ventilation system types, hygiene of air-handling systems, control of moisture and mould, and emissions from building materials. Also discussed are the practical measures that can be taken into account in the design, construction and operation of buildings with a view to creating a better indoor environment. Various measures and methods of disseminating scientific information to those involved in the practical aspects of indoor environment control are discussed and evaluated. These methods include voluntary and mandatory strategies such as using test and demonstration buildings, stipulating criteria for healthy buildings, integrating healthy building concepts into the building process, devising labelling schemes, etc. Examples are given of successful activities at the national level, with an emphasis on the activities of the Finnish Society of Indoor Air Quality and Climate.

INDEX TERMS
Air quality; Building process; Design; Cleanliness; Guidelines; Health effects; Legislation; Material emissions; Standards; Target level

INTRODUCTION
Deteriorated indoor climate is commonly related to increases in sick-building syndrome symptoms, respiratory illnesses, sick leave, reduced comfort and losses in productivity. The cost of deteriorated indoor climate for society is high (Fisk and Rosenfeld, 1997; Fisk, 2001). Some calculations (Seppänen, 1999) show that the cost is higher than the heating energy costs of the same buildings. Building-level calculations have shown that many measures taken to improve indoor air quality and climate are cost-effective when the potential monetary savings resulting from an improved indoor climate are included as benefits gained. Improvements to the indoor environment may result in potential financial benefits: reduced medical care costs, reduced sick leave, better performance of work, lower turnover of employees and lower building-maintenance costs due to fewer complaints about indoor air quality and climate. The pathways to these potential benefits from changes in building technology and/or indoor climate (Figure 1) are routed via several human responses to the indoor environment such as

*E-mail: olli.seppanen@hut.fi

infectious diseases, allergies and asthma, sick-building syndrome symptoms, perceived air quality and thermal environment. A conceptual model to evaluate the costs and benefits is presented in an accompanying paper (Seppänen and Fisk, 2003). The epidemiological research has been helpful in the identification of the risk factors and also of the factors that are beneficial to health and productivity. Even though all mechanisms between building factors and indoor environment and health are not yet known, there are a lot of data available for use by the building industry to benefit the health and productivity of building occupants. The problem is how to disseminate this information to practice.

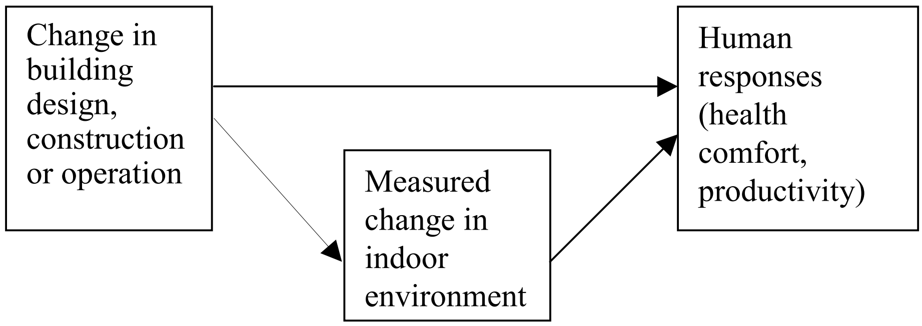

Figure 1 Research has shown the effect of indoor air environment and building factors on health, productivity and comfort.

SOME HEALTH DETERMINANTS RELATED TO INDOOR AIR QUALITY AND THEIR CONTROL

In the following, the most important factors of indoor air quality are briefly discussed. The list is not complete. For example, the thermal factors that are important in many respects are discussed in the accompanying paper (Seppänen *et al.*, 2003).

Environmental Tobacco Smoke

The health effects of environmental tobacco smoke (ETS) are well known. The exposure to ETS increases the risk of heart and lung diseases. Exposure can also trigger asthma and worsen the symptoms of respiratory allergies. The control of ETS is probably the most cost-effective method to improve indoor air quality. The positive effects of the control include reduction of energy consumption due to lower requirements of ventilation. Positive effects are independent of country and climate. Good examples of the effect of legislation and information campaigns can be seen from the experience gained in a number of European countries.

Dust Mites

Fragments and faeces of dust mites (including the families *Dermatophagoides*, *Pyroglyphidae*, *Tarsonemoidae* and *Acaridae*) are probably the most common and best known indoor generated allergens in Europe. Dust mites are common all over world, but more in moderate and humid climates. The reasons of growth and control methods are also known. The generally accepted method of controlling the growth of dust mites is to limit the indoor relative humidity below 45%. The control measures are primarily focused on the control of relative humidity indoors by controlling moisture sources, ventilation, heating or dehumidification.

Mould

The term *mould* covers usually moisture-related microbial growth in buildings including fungi and some bacteria. Even though all mechanisms of the health effects of mould growth or damp buildings are not yet known, the scientific evidence shows that moisture damage in buildings is a health risk. The control of mould growth is, in principle, very simple: keep the building dry. The limit value of the microbial growth varies between 65 and 95% relative humidity depending on the species. The control methods are the same as those for dust mites, but, in addition, the building structures should be kept dry and ventilated properly. Mould problems are common all over the world, in humid, cold and moderate climates.

Pollen

Pollen is probably the most common allergen. The sources differ by country. In northern Europe, the most common source is birch trees. More than 50% of children are allergic to pollen from birch. The diameter of the pollen is relative large, i.e. 1–10 μm, which makes it easy to filter them from indoor air. Control of pollen indoors requires an airtight building envelope, mechanical ventilation and air cleaning or portable air cleaners.

Nitrogen Oxides

Strong scientific evidence shows the negative health effects of exposure to nitrogen oxides. The source of nitrogen oxides is combustion; the main outdoor source is traffic and energy generation. Indoor sources are related to open flame combustion either in the kitchen or for heating. The most feasible control method is to avoid unvented combustion indoors. Kitchen range hoods and effective ventilation reduce indoor concentrations. Incoming outdoor air can be cleaned, but the long-term performance of doing so is not known.

Formaldehyde

Formaldehyde is a well-known irritant and carcinogen. Its primary source used to be particle boards, a commonly used construction material in buildings and furniture. The emission control and labelling systems for particle boards have significantly reduced the formaldehyde concentrations indoors. However, other sources have become significant. These include textiles used for interior decoration, furniture, tobacco smoke and household chemicals. These sources can be controlled through testing and labelling programmes. The labelling programmes of building materials used in some countries also include the limit values of formaldehyde emissions.

Volatile Organic Compounds (VOCs)

Several studies have found the association between symptoms and indoor concentrations of VOCs. Recent research indicates that the VOCs may react in the indoor air with other substances, and generate compounds more harmful than those participating in the reaction. Sources of VOCs exist everywhere in buildings; however, the main sources are building materials. Labelling programmes have been effective and resulted in a dramatic reduction of emissions of VOCs from building materials.

Asbestos and Manmade Mineral Fibres

Asbestos is a well-known carcinogen. It still exists in insulation and other building materials, and should be removed from buildings using special technology. Less known are the sources of mineral fibres and their irritating effects. Manmade vitreous mineral fibres may be made from glass, rock and other mineral materials. Typically, the fibre diameter is 2–5 μm, while its length is typically over 20 μm. Mineral wools are used commonly in buildings for acoustical purposes and also for thermal insulation. Mineral fibres are irritants. If the mineral wool is uncoated, the fibres may be released into the air, deposited on surfaces and get to the respiratory track and eyes causing irritation. The fibre release can be prevented by coating or otherwise treating materials appropriately.

Indoor Generated Particulate Matter

Indoor concentrations of particulate matter may exceed the limit values for outdoors, particularly in spaces with high occupant density and large amounts of fleecy surfaces. The indoor levels of particulate matter vary widely, depending on country and micro-climatic conditions. The health effects of the particulate matter in the air depend on its composition, but, in general, high dust concentrations are related to higher prevalence of symptoms. Airborne particles may also carry bacteria and viruses. Some VOCs are also bound to particles. The particle concentration may also affect the concentration of VOCs and microbial contamination in the air. The primary method of controlling dust concentration is to control the source. Wall-to-wall carpets should be avoided, particularly in public buildings and working places. Proper cleaning is an effective method of reducing dust concentration in the air as well. Cleaning during occupancy should be avoided to reduce exposure.

Carbon Monoxide

Sources of carbon monoxide are incomplete combustion in fireplaces, stoves, ovens and other heating appliances and tobacco smoking. Control of CO emission involves the control of combustion and limiting smoking.

SOME HEALTH-RELATED BUILDING FACTORS AND THEIR CONTROLS

Epidemiological research has shown that some factors related to buildings may have an effect on health, productivity and comfort, even though the mechanisms are not known. Some of these are described in Table 1, while a few (building materials, ventilation, air-handling systems and moisture) are described in more detail below.

Table 1 Some building factors that may have effect on health, productivity and comfort

Building factor	Possible effects on indoor environment	Possible positive effects on health, productivity and comfort	Possible adverse effects on health, productivity and comfort
Building materials*	Increase of chemical compounds and dust in the air		Irritation, SBS symptoms and other health effects depending on the exposure
Ventilation*	Decrease of all indoor generated pollutant concentrations in the indoor air	Decrease of infectious diseases and SBS symptoms, improved perceived air quality and productivity	Noise, daft
Air-handling systems*	Control of indoor air temperature and humidity, may be a source of chemical, particulate and microbial pollutants	Control of temperature and humidity	SBS symptoms, Legionella, Pontiac fever, humidifier fever, noise, draft
Damp buildings and moisture damages*	Dampness is always a heath risk. Moisture is the controlling factor of microbial growth in buildings		Asthma, respiratory allergy, infectious diseases, inflammatory diseases
Space cleaning	Decreases dust and fibre concentration on the surfaces, and may decrease the dust and pollutant concentration in the air	Less irritation symptoms due to cleaner air and surfaces	SBS symptoms due to cleaning agents
Wall to wall carpets and other fleecy surfaces	May increase the dust concentration in the air, and may act as a reservoir of pollutants and microbes	Control of acoustic environment	SBS symptoms
Distance of working place from window	Affects the perception of space and contact visual outdoors	Long distance reduces the glare from daylight	SBS symptoms due to long distance
Operable windows	Individually controlled indoor environment improves user satisfaction	Less SBS symptoms with operable windows	More SBS symptoms with sealed windows
Maintenance	Has a great influence on the overall perception of indoor climate. Lack of maintenance may create serious problems related to moisture and air quality	Less complaints with good maintenance	More complaints with bad maintenance and adverse health effects
Individual control of the indoor environment	Individually controlled indoor environment improves user satisfaction	Less SBS-symptoms, better productivity, less complaints	

*More following.

Building Materials

Material emissions have been recognized as having an influence on the total pollution loads of a building. Danish studies have showed that approximately one-third of pollution loads originate from building materials (Fanger *et al.*, 1988). During the last decade, research has shown that almost all materials emit pollutants. Focus has been on paints, varnishes and flooring materials. The research and development activities in the area of material emissions started with formaldehyde emissions from particle boards about 20 years ago. The harmful emissions are not limited to the finishing materials, but also include furniture, partitions, etc. In some cases, sealants and injection putties have created high-emission problems. Large variations of emissions have been measured from the materials intended for the same purpose, which proves the importance of product development and control.

Analytical methods are well developed from a given collected sample. The problem in emission measurement lies in the question: What are the relevant pollutants to be measured? The majority of material emissions and chemical evaluations of indoor air quality has been conducted by measuring the concentration of total volatile organic compounds (TVOC), the relevance of which has been questioned by a prominent group of Scandinavian scientists (Andersson *et al.*, 1997).

The chemical reactions of pollutants in the air are not well known. It has been suggested that oxidized VOCs, for example, are more harmful than those actually measured.

Sensory assessment of material emissions have been used as a complementing method to chemical analysis, mainly because chemical measurements do not seem to be sensitive enough to evaluate the emissions. While its relevance has been questioned, a European working group (ECA, 1997) nevertheless considers it a method relevant to the evaluation of material emissions.

In practice, an architect or engineer needs information, not only from one layer of material, but from the whole structure. The emission of a concrete floor structure with a levelling agent, glue and flooring material, may be completely different from the emissions of its single compounds.

The problems of material emissions are not limited to air chemistry and toxicology. The system of emission control should be easy to understand. For the user of the materials, the system should be simple. This is achieved, for example, by means of a labelling or classification system. These kinds of programmes exist for some material groups and in some countries. Best known in Europe may be the Finnish and Danish labelling programmes.

Ventilation

Health effects

The reviews of ventilation rates and human responses (Seppänen *et al.*, 1999; Fisk, 2001) summarize the results of four studies available at that time on the health effects of ventilation rates. All of them reported a significant association between low ventilation rates and an increase in health problems: pneumonia, upper respiratory illnesses, influenza and short-term sick leave. The consistent findings are a strong indication of the association of ventilation rates with health effects. The strongest evidence is provided by the most recent study of these (Milton *et al.*, 2000). The association with sick leave was analysed for 3720 employees in 40 buildings using 115 independently ventilated ventilation areas. Among office workers, the relative risk of short-term sick leave was 1.53, with the estimated ventilation of 12 l/s per person compared to a ventilation rate of 24 l/s per person.

Reviews (Seppänen *et al.*, 1999; Wargocki *et al.*, 2002) on the association of ventilation rates and human responses show that ventilation rates below 10 l/s per person are associated with negative health effects. Available studies further show that increases in ventilation rates above 10 l/s per person, up to approximately 20–25 l/s per person, are associated with a significant decrease in the prevalence of SBS symptoms, or with improvements in perceived air quality.

Improvement of ventilation

Pollutant removal efficiency

Task ventilation has been commonly used in industry for years and various applications have been presented in several guidebooks for industrial ventilation. Task ventilation is one method of extracting pollutants at source and to supply clean conditioned air directly to the occupied zone or work station. In that way, conditioning and ventilating a large space to the same level as a work station becomes unnecessary as long as the work stations are well conditioned. One residential application of local ventilation is the commonly used range hoods in kitchens. They improve air quality by preventing the pollutants from spreading to living areas. The same principle can be applied to other pollution sources too.

During the past few years, increasing attention has been paid to air distribution systems that condition the immediate environment of office workers and their work stations. A comprehensive guide to task ambient systems has been written by Bauman and Arens (1996). The major advantages of the task conditioning system are:

1. It offers occupants the possibility of controlling their environment individually.
2. The task/ambient system saves heating, cooling and fan energy if properly designed and used.
3. Task/ambient systems have been reported to improve working efficiency and alleviate the SBS symptoms.

Ventilation efficiency

The importance of ventilation efficiency has been widely recognized, and is now proposed to be included in the ventilation standards (CEN, 1996; ASHRAE 62n, 2001). Poor room air distribution can significantly reduce the air quality in a room, if the supply airflow spreads the pollutants generated in a room to the breathing zone, or if the supply air flows directly towards the return air openings (short-circuiting flow). According to the original definition, the air change efficiency for complete mixing is 50%. In the draft standards, complete mixing was taken as a reference and the value 1 given to effectiveness of ventilation. Accordingly, the values for the other flow patterns are given in Table 2.

Table 2 Values of ventilation effectiveness for various flow patterns

Flow pattern	Air change efficiency, %	Zone air distribution effectiveness (ASHRAE 62n, 2001); ventilation efficiency (CEN, 1996)
Complete mixing	50	1
Piston flow	100	2
Displacement flow	50–100	1–2
Short circuiting flow	<50	0–1

When these numbers are applied to the airflow calculations, the same air quality can be achieved in the best cases with half the airflow, or contamination concentration can be reduced to half with the same airflow by improving the ventilation efficiency.

One way to improve the effectiveness of ventilation is the displacement or low velocity air distribution system. The displacement air distribution system is widely used in North European countries, and recommended also all over Europe (REHVA, 2002). Detailed measurements and CFD simulations have shown that the benefits of displacement ventilation can be even greater than evaluated, just by using air-change efficiency.

Distribution of airflows in the building

Ventilation rates per person or floor area vary a lot in office buildings. Even if the average outdoor airflow is correct in a building, the outdoor air is often unevenly distributed due to improper balancing of the airflow or the recirculation of return air (Teijonsalo *et al.*, 1996).

An imbalance in outdoor airflows leads to high energy consumption in the rooms with high outdoor rates and degrades air quality in the rooms with low outdoor airflow rates. This is particularly the case in the ventilation systems without air circulation. By balancing the airflows the average air quality in a building can be enhanced and energy efficiency improved.

Pollution from air conditioning systems

In a recent summary, Seppänen and Fisk (2002a,b) show that most studies completed to date indicate that relative to natural ventilation, air conditioning, with or without humidification, was consistently associated with a statistically significant increase in the prevalence of one or more SBS symptoms, by approximately 30–200%.

One explanation for the association of SBS symptoms and mechanical HVAC-systems is that VOCs and other chemical pollutants are emitted by HVAC components and ductworks. The emissions may originate from any component in the HVAC system. The measurements of chemical emission from typical materials used in HVAC systems are sparse. Measurements indicate (Morrison and Hodgson, 1996; Morrison *et al.*, 1998) that emission rates of VOCs emitted by the materials varies a lot. The high emitting materials in their measurements were used as duct liners, neoprene gaskets, duct connectors and sealants. The high surface area materials such as sheet metal had lower emission rates.

Olfactory measurements of the pollution generated by various components are more abundant. The measurements have shown that both new and used components are sources of sensory pollutants (Björkroth *et al.*, 1998). The new components are typically not cleaned after manufacturing and the surfaces may be coated with oils or chemicals that pollute the air. The laboratory tests have shown (Pasanen, 1998) that a new round sheet metal duct decreases perceived air quality as much as an old used one. The effect of cleaning has been demonstrated by washing the duct; after washing, the perceived quality of air flowing through the duct is actually improved (Björkroth *et al.*, 1998).

Because many factors affect the quality of supply air, the following cleanliness requirements of the components should be se:

1. A component shall not induce pollutants harmful to health or comfort in the air-handling system or supply air.
2. A component shall not produce odours, or gaseous or particulate pollutants that deteriorate the quality of supply air.
3. A component shall be easy to clean.

Moisture

Moisture accumulation into building structures or material may lead to microbial growth on materials, subsequent microbial emissions and other contamination of buildings. In epidemiological studies, moisture damage and microbial growth in buildings have been associated with a number of health effects including respiratory symptoms and diseases and other symptoms (Bornehag *et al.*, 2001). The health effects associated with moisture damage and microbial growth seem to be consistent in different climates and geographical regions (Flannigan and Morey, 1996). However, the causal agents or cellular mechanisms of the health outcomes are not well understood.

It has been shown with relatively good certainty that building-related moisture and microbial growth increases the risk of respiratory symptoms, respiratory infections allergy and asthma. The underlying mechanisms are irritation of mucous membranes, allergic sensitization and non-specific inflammation. Also toxic mechanisms may be involved, especially in connection with toxin producing fungi and bacteria. Certain building materials seem to support the growth of potentially toxic microbes, and even induce toxin production more readily other materials.

While microbial growth and health outcomes are consequences, the common nominators for them are different forms of undesired moisture behaviour. Water intrusion, dampness and moisture and related phenomena are not only harmful for the occupants' health but also a serious risk to the condition of the building structures. All these may decrease the indoor air quality of the building. In addition to risks of rot to wooden structures, building materials may also be deteriorated by chemical processes induced by moisture.

The technical causes of water damage, dampness, or moisture control failure are often closely connected to the climate. The prevailing temperature, humidity, rain and wind conditions regulate much of the principles and practices of construction, e.g. foundation, insulation, structure of the building envelope and ventilation system. Indoor humidity is also physically connected to the outdoor climatic conditions. Therefore, the whole issue and problematics of building moisture and dampness, microbial contamination, repair and control practices varies strongly according to the climatic zone. However, regardless of the climate, the prevention and control of moisture problems, and subsequent effects, should be addressed in early phases of building construction practices, and in sustained maintenance of building. Some methods of controlling moisture in new buildings are described in Table 3.

Table 3 Methods of controlling moisture (control of dust mites and microbial growth) in new buildings with focus on cold and moderate climate

Method	Effect on construction cost	Effect on energy consumption
Building construction		
Improve thermal properties of windows	Increases	Decreases
Ventilate exterior walls and other building components to prevent condensation and mould growth	Negligible	No effect or small decrease
Design the structures to stand external and internal moisture loads (vapour barriers, etc.)	Negligible	No effect or small decrease
Improve thermal insulation of building envelope to increase indoor surface temperatures to prevent condensation	Increases	Decreases
Prevent moisture migration from the ground	Negligible	No effect or small decrease
Improve protection against rain, roofing, walls, windows	Negligible	No effect or small decrease
Ventilation		
Provide openable windows in all living rooms and kitchen	Slight increase	May increase or decrease
Provide adequate, controllable average ventilation for the residence	Slight increase	May increase or decrease
Ventilate all rooms—e.g. use ventilation where needed	Slight increase	May increase or decrease
Provide effective kitchen-range hood	Slight increase	May increase or decrease
Provide possibility of controlling ventilation by demand	Slight increase	Decreases
Use mechanical exhaust ventilation in warm and moderate climate—tighten the building envelope to prevent excess ventilation	Slight increase	Decreases due to reduced air leakage
Use mechanical supply and exhaust ventilation with heat recovery in cold climate	Slight increase	Decreases
Heating		
Install central heating in cold climate	Slight increase	Slight increase
Do not use open flame unvented heaters	No effect	No effect
Control heating and cooling with thermostats	Slight increase	Decrease
Encourage the use of district heating and cooling	Negligible	Decreases the use of primary energy
Require chimneys for all heating boilers and furnaces	Slight increase	Better efficiency—decrease in primary energy
Improve the control of fire places with dampers, etc.	Slight increase	Decrease

FROM SCIENCE TO PRACTICE

The quality of indoor climate is affected equally by heating, ventilation and air conditioning equipment, construction engineering, quality of construction work, building materials as well as the operation and maintenance of the building. Good indoor climate requires taking these aspects into consideration during all the stages of the design, construction and use of the building. Some of the problems may originate from the buildings themselves, some are caused by actions of the occupants or operation and maintenance of the buildings. Lot of information on how to build a healthy building is available but the problem is how to utilize this information. Various measures and methods (Table 4) of disseminating scientific information to those involved in the practical aspects of indoor environment control are discussed and evaluated in this section. Examples are given of successful activities at the national level, with an emphasis on the activities of the Finnish Society of Indoor Air Quality and Climate.

Table 4 Some actions to disseminate scientific results to the practice

Action category	Contents	Target group
Integrate IAQ and construction process	Guidelines for design and construction, model building specification, commissioning process, etc.	The whole building industry including designers and contractors
Develop guidelines and standards	Specify the target values and criteria for products and systems for healthy indoor environments	Designers, construction industry, manufacturers
Activate IAQ societies and patient organizations	Wide range of activities to motivate and educate members and involved parties	General public, patients with IAQ-related illness (asthma, allergy, etc.)
Develop labelling schemes	Construction materials, HVAC components, green building labelling	Material and equipment manufactures
Increase the public awareness	Information and training campaigns to public	General public (employees, residents, teachers, students, etc.)
Training and information through professional societies	Training, model specifications, agreements, guidelines, etc.	Architects, HVAC engineers, occupational health personnel, medical doctors, etc. (paediatricians, lung and allergy specialists, etc.)
Develop professional skills and certification programmes	Qualification requirements, training, examinations	Designers, contractors, building investigators, etc.
Accomplish information and training campaigns	Bulletins, mass media, training courses, etc.	All players for good IAQ
Build and monitor demonstration buildings with improved indoor environment	Apply and follow up design and construction of buildings with best knowledge on healthy construction	Construction companies and building owners
Initiate integrated research programmes	Integration of building, material, and health sciences in common research projects as well as research community and practitioners	Funding agencies, building research institutes, heath research institutes, governmental agencies

IAQ and Building Process

The most important stage in the construction process in respect of good indoor climate is the specification of the quality of indoor climate at the beginning of the project. This should be done during the first discussions between the building owner and those responsible for indoor climate design in the project. The value of a good indoor climate is not always evident to a building owner. The professionals should themselves understand what the decisions concerning the HVAC systems really mean during the operation of the building and should take care to explain their meaning to the layman in language he can readily understand.

A building is a complex product. Its design and construction requires the involvement of various disciplines and trades. Several designers and contractors are often working on the project simultaneously in different companies. The coordination of these many participants is important for a good overall result, but is often neglected. This leaves room for serious faults to develop during the building process, particularly where the work of different designers, contractors or suppliers overlaps.

Guidelines and Standards

Dissemination of scientific information to practice requires several steps towards more practical guidelines and 'easy to apply' information (Table 5). It is important to facilitate developments and encourage the adoption of standards and the use of codes, with specific attention to ventilation, controls of sources, maintenance requirements and other relevant aspects. In this area, it is beneficial if the information on indoor air and climate can be added to the existing guidelines, building codes and standards. This makes the dissemination process faster than writing totally new guidelines for the control of indoor air quality.

Table 5 Some national and international standards, guidelines and working groups related to indoor environment

Publishing organization	Title	Contents	Status
International guidelines and working groups			
CEN Technical report CR 1752	Ventilation for buildings: design criteria for indoor environment	Target value for indoor air quality and climate	Published 1996
CEN prEN 13779	Ventilation for non-residential buildings: performance requirements for ventilation and room-conditioning systems	Target value for indoor air quality and climate and prescriptive criteria for ventilation systems	Final voting in 2003
CIB TG 42 and ISIAQ	Criteria of buildings for health and comfort	IAQ in the construction process	Review in 2003
ECA, urban air, indoor environment and human response	Ventilation, good indoor air quality and rational use of energy	Rational design and construction of ventilation systems	Final draft in 2003
ISO 205	Building environment design—indoor air quality—methods of expressing the quality of indoor air for human occupancy	Target values of indoor environment at large	On-going work
WHO	Air quality guidelines for Europe	Limit values of some pollutants	Published 2000
WHO	Guidelines for air quality	www.who.int/peh/	Published 2000
National standards and guidelines			
American Lung Association	Builders guide to improve IAQ in homes	General and detailed instructions for design and construction	Published 2001
ASHRAE standard 62 and its addenda	Ventilation and acceptable indoor air quality	American standard for indoor air quality and ventilation of buildings	Published 1999 but is continuously reviewed
ASHRAE standard 62.2	Ventilation and acceptable indoor air quality in low rise residential buildings	American standard for indoor air quality and ventilation of residential buildings	Final voting in 2003
ASHRAE GP 10	Guideline project committee for criteria for achieving acceptable indoor environments	Guidelines for and target values for indoor environment	On-going work
DIN 1946, several parts	Raumluttechnik, Gesundheitstechnische Anfordungen, Luftungsregeln	Target values for indoor air climate, and specification of ventilation systems	Published1991 and revised
Finnish Society of Indoor Air Quality and Climate (FiSIAQ)	Classification of indoor climate and construction process	Target values, labelling criteria, cleanliness of construction, design criteria	1995, revised in 2000
Finnish Building Code D2	Indoor climate and ventilation	Target values for indoor air climate, and specification of ventilation systems	Forced in 2003
Japan Building Management Education Center	Law for maintenance of sanitation of buildings	A guide how to apply the Japanese law from the year 1987	Published 1999
US Environmental Protection Agency	Building air quality—a guide for building owners and facility mangers	A comprehensive guide with checklists and data sheets	Published 1991
VDI 6022	Hygienic standards for ventilation and air-conditioning systems—offices and assembly rooms. VDI. Verein Deutscher Ingenieure (Association of German Engineers)	Hygienic requirement for buildings and training requirements of operation personnel	Published 1997

Finnish Classification of Indoor Climate, Construction and Finishing Materials
Target values for IAQ are important in the implementation and in verification of the end result, but their use as performance criteria is very limited, because tools for transforming target values to practical measures are not adequate or are not used. In Finland, the first attempt to convert target values to practical guidelines was the Classification of Indoor Climate, Construction, Building Materials and HVAC Components issued by FiSIAQ first in 1995 and revised in 2001 (FiSIAQ, 2001). The classification (Figure 2) consists of:

1. target and design values for IAQ;
2. criteria for construction cleanliness and moisture control;
3. criteria for material emissions;
4. criteria for clean of HVAC components.

The classification provides a performance-based approach combined with descriptive measures by defining classes for measurable or approvable quality such as IAQ, thermal comfort, moisture control, cleanliness, etc. Classes are defined for indoor climate (S1, S2, S3), cleanliness of construction and HVAC system (P1, P2) and for material emissions (M1, M2). Such classification of quality makes it very flexible to specify relevant quality levels in designs and especially in contractor's agreements. Each class may contain design and target values and instruction for working phases. In practice, an additional effect of the classification has been a tendency to guide towards better quality level.

The classification which has a status of a guideline (to be used in completely voluntary bases) was first accepted in practice by designers and consultants, then by building owners, material and HVAC manufactures and finally also the general contractors were forced to accept it. The Finnish Classification of Indoor Climate, Construction, and Finishing Materials is written in code language so that the text can easily be transferred to building specifications and guidelines.

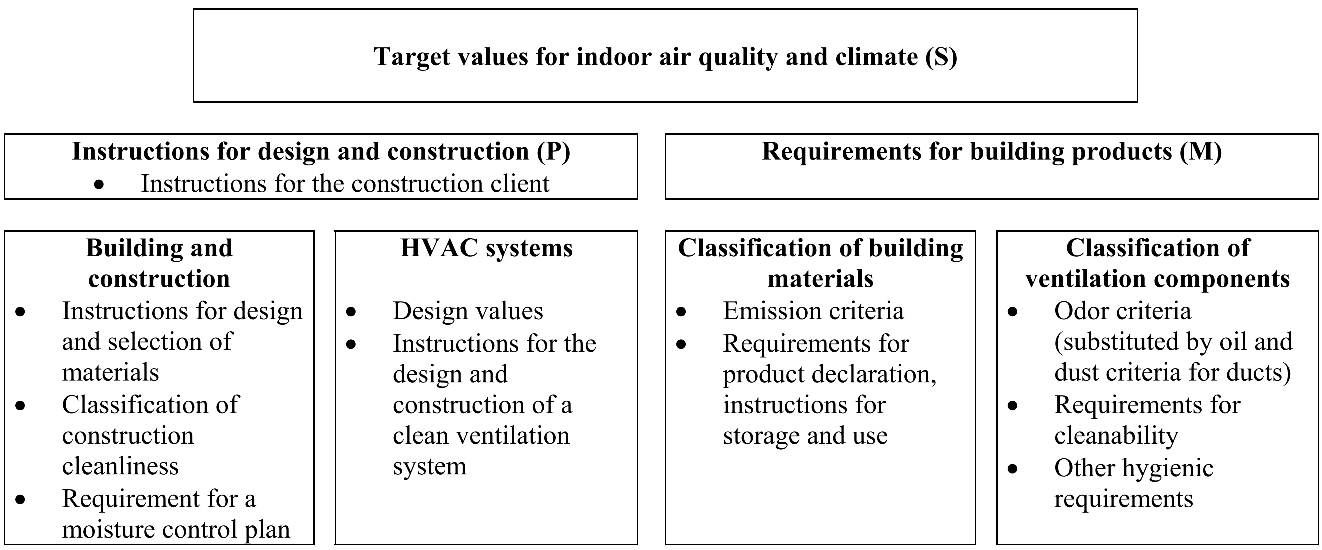

Figure 2 Structure of the Finnish Classification of Indoor Climate, Construction, and Finishing Materials (Säteri, 2002).

ISIAQ-CIB TG 42 Criteria of buildings for health and comfort
The International Council for Research and Innovation in Building and Construction (CIB) established a task group with the International Society of Indoor Air Quality and Climate

(ISIAQ) to develop document 'Performance criteria of buildings for health and comfort'. The draft document is now available (Table 6). The report covers the main technical design and construction issues that are relevant in creating a healthy and comfortable indoor climate. In the beginning of each topic there is a short rationale and description of the essential requirements for healthy and comfortable indoor climate. These requirements are intended as minimum basis for setting more detailed performance levels. Some possible definitions of performance levels are presented next for each topic. These target and design values for indoor climate support the work of building owners, designers, equipment manufacturers, contractors and maintenance personnel. They can be referred to when writing specifications of construction and mechanical systems. For several parameters, the target and design values have been divided into three categories: basic, medium and high. This has been done to allow variation according to the needs of the client.

Table 6 Contents of the report from the ISIAQ-CIB task group on criteria of buildings for health and comfort. http://hvac02.hut.fi/TG42.html

1 Target values
- Target values for indoor air quality
- Target values for thermal comfort
- Interactions between IAQ and thermal comfort
- Special requirements for allergic and hypersensitive people

2 Ventilation
- General requirements for ventilation
- Design principles for air change rates, noise levels
- Filtering in relation to outdoor air quality
- Air distribution
- Ventilation efficiency
- Criteria for design and documentation
- Construction criteria
- Maintenance and operation

3 Cleanliness of air-handling components and systems
- Cleanliness of components
- Cleanliness of the HVAC systems and building during the construction phase
- Verification and measuring methods for cleanliness

4 Emission from building materials
- The emission criteria of building materials
- Classification of materials
- Measuring methods
- Use of the materials to achieve good indoor air quality

5 Protection against moisture damages and microbial growth
- Design strategy to achieve structures with good moisture performance
- Moisture loads and moisture physics
- Protection of materials in the building site
- Moisture control and drying during construction process, protection of materials
- Measurements of moisture contents of materials at construction site

6 Commissioing, operation and maintenance
- Commissioning of HVAC system
- Commissioning phase for building and technical installations
- Operation and maintenance
- Preventive maintenance programme

IAQ Societies

In Finland,[1] one of the key elements in information transfer has been the Finnish Society of Indoor Air Quality and Climate (FiSIAQ). It was founded in 1990 and is a non-profit

[1]For the reference: population of Finland is 5 million.

organization. FiSIAQ promotes work aiming at healthy and comfortable indoor air quality and climate, and disseminates information from research to practice.

FiSIAQ has about 100 invited researchers and officials working in the field of indoor air as individual members. Companies are accepted as non-voting supporting (industrial) members. The number of supporting members has risen from 14 in 1994 to over 150 in March 2003. The list of the supporting members is included in the FiSIAQ newsletter, in which supporting members can also advertise their products and activities for good indoor air quality.

FiSIAQ has a close cooperation with other Finnish societies related to the indoor air field. This has been easy as FiSAIQ is not competing with any of the professional organizations. A key issue in this had been the relatively small number of individual members in the society. FiSIAQ has not tried to increase its membership numbers.

FiSIAQ arranges annually a 2-day Indoor climate seminar, where 60–70 technical papers are presented and which is attended by 600–700 participants. In connection of the seminar, exhibition of about 25 companies is arranged. The technical papers are published in the seminar proceedings, which is distributed to the participants free of charge.

FiSIAQ newsletter is published quarterly, and in addition one or two special issues are published each year. The newsletter is the only IAQ newsletter in Finland and it has over 7000 subscribers. The costs of the newsletter are covered by advertisement income. The newsletter includes a reference list of corporations working on indoor climate issues. The home page of FiSIAQ presents also the links to the home pages of the supporting members.

The budget of FiSIAQ with five full-time employees is ca. EUR 400 000. The structure of organization and summary of its activities is presented in Figure 3.

FiSIAQ is active in development work on indoor climate. The most well known is the Classification of indoor climate 2000. FiSIAQ has arranged two international conferences: Indoor Air in 1993 and Healthy Buildings in 2000. The ISIAQ Secretariat is also located at the FiSIAQ office.

SIY Indoor Air Information Ltd. is owned 100% by FiSIAQ. It was founded for publishing purposes; four to five reports are published annually. It also has also a book store, and a permanent exhibition with brochures of the supporting members is located at the office building. SIY Indoor Air Information Ltd. has IDA Indoor Climate and Energy software sales and support, and it gives consulting for companies. Indoor Air Information has published

- annual proceedings of Finnish indoor climate seminar (60–70 papers each year);
- quarterly newsletter;
- guidelines for practitioner;
- classification of indoor climate, construction works and finishing materials;
- textbooks;
- educational material for specific target groups;
- simple instructions and guidelines for public.

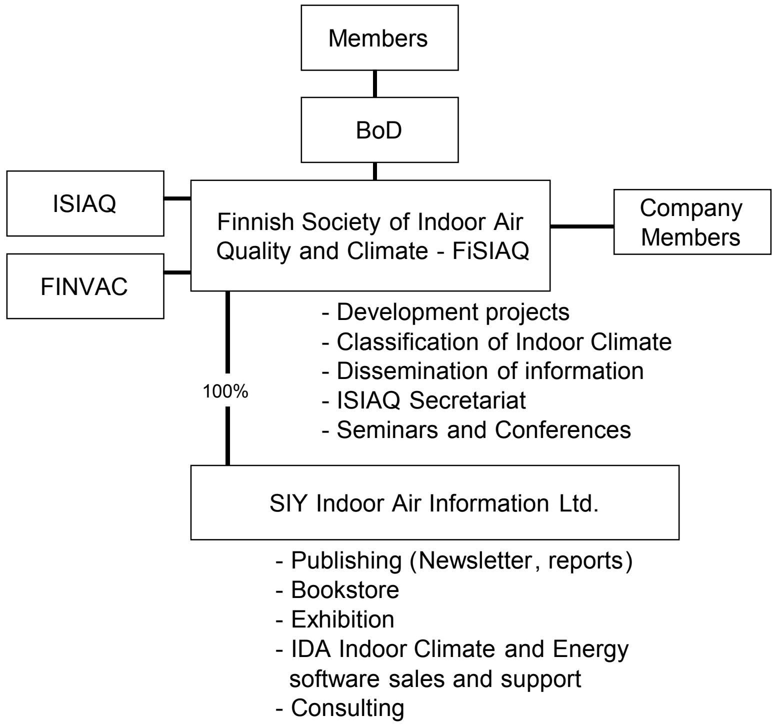

Figure 3 Structure and activities of the Finnish Society of Indoor Air Quality and Climate.

Labelling Schemes

Decisions concerning the design for good indoor air quality are often complex, and a building owner may not have all the technical knowledge necessary to understand the decisions as to details. One possible way of solving this problem is to classify indoor climate and label the products so that the selection of the category of indoor climate specifies not only the target values but also the most important technical details that have an influence on the indoor air quality and climate.

Low emitting building materials

The major pollutants in buildings are pollutant-emitting building materials. To limit these emissions, the use of low-emitting building materials should be encouraged. It is also important to support the industrial production and use of low emitting materials with incentives at the market level.

In Finland, this has been done with a voluntary classification. The Finnish classification and labelling system of materials (FiSIAQ, 2001) was developed by the Finnish Society of Indoor Air Quality and Climate and the Finnish Building Information Institute in 1995. The classification system of finishing materials has three classes, category M1 being the best and category M3 containing materials with the highest emission levels. Because the total emission and concentration of room air depend on the amount of materials used, the classification gives guidelines for the use of various materials. When the best category for indoor air, category S1, is selected, the use of higher-emitting materials (categories M2 and M3) is limited.

The best category, M1, is designated for natural materials, such as stone and glass, which are known to be safe with respect to emissions, and for materials which fulfil the following requirements:

1. the emission of TVOC is below 0.2 $mg/m^2/h$;
2. the emission of formaldehyde is below 0.05 $mg/m^2/h$;
3. the emission of ammonia is below 0.03 $mg/m^2/h$;

4. the emission of carcinogenic compounds (IARC) is below 0.005 mg/m^2/h;
5. The material is not odorous (dissatisfaction with the odour is below 15%).

The Finnish material classification and labelling of materials programme is integrated into The Classification of Indoor Climate, Construction, and Finishing Materials, which is intended to be used during the design and contracting phases of construction works and mechanical systems for buildings. By summer 2003, about 600 materials have been granted the best, class M1, label (Figure 5). The material manufacturers use the classification certificates and labels in their own marketing. The labelling system has reduced significantly emissions from building materials (Figure 4).

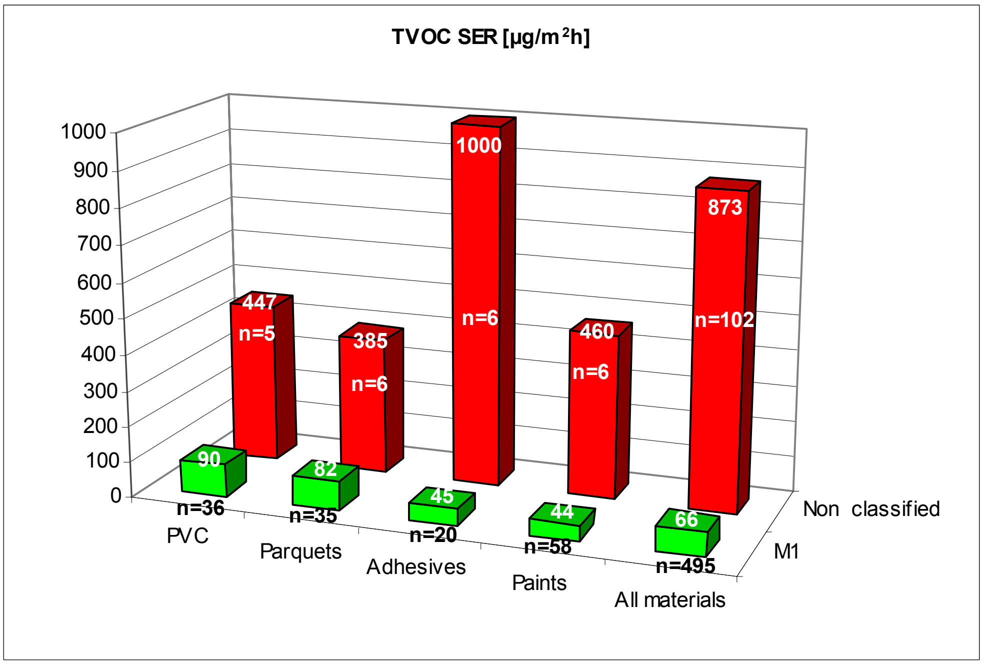

Figure 4 The effect of the Finnish material labelling system on emissions (SER) of some building material groups. Those labelled M1 are those that have met the criteria (Saarela, 2003).

Labelling of air-handling components

One section of the Finnish Classification of Indoor Climate (FiSIAQ, 2001) deals specifically with the cleanliness of air-handling components. It includes the cleanliness requirements for these components and the cleanliness requirements set for the design and installation of the air-handling system.

The requirements concern sheet metal ducts and their accessories manufactured using traditional techniques (oil-based lubricants). The general requirements and the criteria below will be applied to products manufactured using other methods or materials. The inner surfaces of classified ducts and accessories will satisfy the requirements of Table 7.

Table 7 The requirements of the cleanliness classification for ducts and accessories at factory. The exact instructions for sampling and analysis are determined in the protocol for testing air-handling components (Björkroth *et al.*, 2002a,b; RTS, 2002)

Pollutant	Classification criterion
Surface density of oil in ducts[a]	0.05 g/m^2
Surface density of oil in accessories, terminal units, and air and fire dampers[b]	
• Parts manufactured by cutting, bending or jointing	0.05 g/m^2
• Parts manufactured from deep-drawn sheet metal, processes requiring oil	0.3 g/m^2
Mineral fibres released into airflow (MMMF)[b]	10^4 fibres/m^3
Amount of surface dust	<0.5 g/m^2

[a]The requirement is based on measurements concerning the correlation between odour intensity and the total mass of oil residuals carried out on the lubricant 'Solvac'. If other lubricants are used, their odour threshold will be shown to be lower than that of Solvac.
[b]The concentration of mineral fibres in the airflow applies only to components which have been manufactured using materials containing fibres. The general requirements are applied to fibres other than mineral fibres.

The labelling system qualifies a component as accepted to get the label (M1) (Figure 5). In order to receive a cleanliness label, each component must fulfil both the general and specific requirements for the component group presented in the testing protocol. Up till now, these requirements have been specified for ducts, fittings, air and fire dampers and filters. Requirements for terminal units, heating and cooling coils, and revised requirements for filters are expected by summer 2002.

Figure 5 The cleanliness class M1 label for building materials on left and for air-handling components on right.

Public Awareness = Information and Training Campaigns
Information transfer from science to practice is important, and various avenues are needed to reach the public. The information work has to be persistent. For this purpose long-term information programmes should be established to raise public awareness, and assist the citizens to take reasonable measures to reduce their health risks from indoor air pollution.

One example is *Indoor Climate Year 2002* which was organized together with Finnish Ministry of the Environment, Ministry of Social Affairs and Health and three patient organizations. The objectives of this information and training campaign were:

- to improve the consumers' understanding of the health effects of indoor climate and their possibilities to improve it;
- to increase the knowledge and sense of responsibility of building owners and key management and maintenance personnel in solving indoor climate problems;

- to increase the level of know-how of construction professionals in indoor climate issues;
- to increase the knowledge of health care professionals in diagnosing symptoms and illnesses caused by poor indoor climate;
- to supply information and tools for guidance and control of indoor climate to municipal decision makers and authorities.

The campaign was initiated and planned by the Allergy and Asthma Federation, the Asumisterveysliitto AsTe (Association for healthy living environment), the Finnish Society of Indoor Air Quality and Climate, and the Pulmonary Association, Heli. In addition to these organizations, the representatives of all the target groups were invited to join the work. Over 60 expert and consumer organizations responded positive. These organizations took up indoor climate issues in their activities during the campaign year. They produced informative material, arranged events, gave advice and organized education. The activities were coordinated by the Finnish Society of Indoor Air Quality and Climate. The Campaign was financed by the Ministry of Social Affairs and Health, the Ministry of the Environment and the participating organizations.

The main results of the campaign were:

- dissemination of information through mass media and professional journals increased the number of media hits on indoor climate by 60% from 1300 to 2100 per year;
- fifteen local indoor climate events with 1900 participants;
- nationwide net of 160 information stands;
- production and distribution of informative material: 10 leaflets, 30 000 copies each;
- local networks of municipal experts in 83 (out of 450) communities;
- over 7000 answered telephone and internet enquiries;
- web service www.sisailma2002.net;
- production of educational material and organization of professional education;
- participation in events and trade fairs;
- linking all interested organizations and their activities to the campaign.

The results of the campaign were good and the objectives were fulfilled.

Training of Professionals

When the demand for products and services for better indoor quality and climate increases, it is important to develop at the same time programmes to ensure the reliability and effectiveness of building products and services promoted for the control of indoor air quality. This applies to all services and products. Certification programmes, testing methods, performance criteria are all needed. International collaboration would be particularly useful in this area.

Building professionals are in key positions to transferring research results into practice. Each country should develop guidance and training for professionals

- involved in building design, operation and maintenance;
- responsible for community health as well as individual patient care;
- providing building diagnostics as mitigation services.

In Finland, the training of professionals has been conducted in close co-operation with existing professional organizations. Experience has shown that each profession is more likely to participate in a training event organized by its own organization than somebody else's. In addition, the individual training programme of the annual Finnish Indoor Climate Seminar draws more and more participants from a variety of professions and offers a forum for multidisciplinary exchange of information.

Demonstration Buildings
The demonstration of healthy building practice is an important way to convince people of the research results. It is outmost important that these demonstration projects are followed up by an independent team, and that the results are evaluated scientifically, and published. The tradition of demonstration projects and their follow up procedure has been well established in the area of energy efficient buildings. Similar methods should be used also in the area on indoor air and climate. Some successful projects from Finland, Italy, Sweden and the USA have been reported in literature, specifically in the proceedings of the previous Healthy Buildings conferences.

Integrated Healthy Buildings Research Programmes
The problems related to indoor air quality and climate are often multifactorial; therefore, to solve these complex problems, multidisciplinary research is needed. In Finland, a healthy building research programme was accomplished in 1998–2002 with the following general objectives:

- To enhance know-how and health expertise associated with indoor air and building physics to a level where it becomes a key success factor internationally. This will be achieved through collaborative work in the real estate and construction business, the public health sector, manufacturing industry and the research sector.
- To develop and implement indoor air and health criteria for buildings, and for products and services used in buildings, and establish quality classifications to support these.
- To develop key spearhead products and processes that are competitive and exportable.
- To develop processes for diagnosing and improve indoor air quality and the health properties of buildings.

Preparatory work for the technology programme was started at the beginning of 1997 and the programme itself was launched in spring 1998. The budgeted volume of projects in the programme was EUR 4 million per annum, totalling EUR 21 million over the programme period. The final number of projects was 123, with a total volume of EUR 22.8 million, including EUR 12.3 million funding from the National Technology Agency.

Key areas were set for the programme's operational targets and steering in practice. These key areas were:

- services and business concepts (31 projects, 27% of volume);
- ventilation and building services (25 projects, 32% of volume);
- moisture (44 projects, 32% of volume);
- emissions from construction materials (11 projects, 5% of volume).

At the same time an environmental health research programme was also initiated in Finland. Health questions relating to indoor air quality, particularly to microbial contamination, are part of this programme.

CONCLUSIONS

As the building tradition, building materials, climate, the problems relating to indoor air quality and climate vary from country to country it is important to assess the present situation of indoor air quality in order to establish appropriate goals and methods for the reduction of adverse health effects of indoor air. The paper has presented several proven methods based on scientific evidence how the indoor climate can be improved and its benefits increased.

ACKNOWLEDGEMENT

This work was supported by the Finnish Technology Agency and the Finnish Work Environment Fund, project Productive Office 2005. The author would like to presents thanks to Jarek Kurnitski, Markku Rantama, Leila Sarajarvi, Jorma Sateri and Ruth Vilmi.

REFERENCES

Anderson, K., Bakke, J., Bjorseth, O., Bornehag, C.-G., Clausen, G., Hongslo, J., Kjelman, M., Kjargaard, S., Levy, F., Mølhave, L., Skerfving, S. and Sundell, J. (1997). TVOC and health in non-industrial indoor environment. Report from a Nordic scientific consensus meeting in Långholmen in Stockholm. *International Journal of Indoor Air Quality and Climate* **7** (2), 78–91.

ASHRAE 62 (2001). ANSI/ASHRAE standard 62-2001. Ventilation for acceptable indoor air quality. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers.

ASHRAE 62n (2001). Proposed addendum ‘Ventilation rate procedure’ to ASHRAE standard 62.2-2001. Ventilation for acceptable indoor air quality. Public review draft. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers.

Bauman, F. and Ahrens, E. (1996). Task/ambient conditioning systems: engineering and application guidelines. University of California. California Institute of Energy Efficiency.

Björkroth, M., Seppänen, O. and Torkki, A. (1998). Chemical and sensory emissions from HVAC-components and ducts. *Design, Construction, and Operation of Healthy Buildings—Solutions to Global and Regional Concerns*. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers.

Björkroth, M., Asikainen, V., Seppänen, O. and Säteri, J. (2002a). Cleanliness criteria and test procedures for cleanliness labeling system for clean ventilation products. *Indoor Air 2002*.

Björkroth, M., Seppänen, O., Säteri, J., Neuvonen, P., Pasanen, P. and Railio, J. (2002b). Labelling system for clean ventilation components. *Proceedings of Indoor Air 2002*.

Bornehag, C.-G., Blomquist, G., Gyntelberg, F., Jarvholm, B., Malmberg, P., Nordvall, L., Nielsen, A., Perhagen, G. and Sundell, J. (2001). Dampness in Buildings and health. Nordic interdisciplinary review of the scientific evidence on associations between exposure to ‘dampness’ in building and health effects (NORDDAMP) *Indoor Air Journal* **11** (2), 72–86.

CEN (1996). Technical report CR 1752. Ventilation for buildings: Design criteria for indoor environment. Brussels: European Committee for Standardisation.

ECA 18 (1997). Evaluation of VOC Emissions from building products. 1997 (EUR 17334 EN) European Collaborative Action. *Indoor Air Quality and its Impact on Man*. Report No. 18.

Fanger, P.O. (1988). Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and out doors. *Energy and Buildings* **12**.

FiSIAQ (2001). Classification of Indoor Climate 2000. Espoo, Finland: Finnish Society of Indoor Air Quality and Climate (FiSIAQ), publication 5 E.

Fisk, W.J. (2001). Estimates of potential nationwide productivity and health benefits from better indoor environments: an update. In: Spengler, J., Sammet, J. and McCarthy, J. (eds), *Indoor Air Quality Handbook*. New York: McGraw Hill.

Fisk, W. and Rosenfeld, A. (1997). Estimates of improved productivity and health from better indoor environments. *International Journal of Indoor Air Quality and Climate* **7** (3).

Flannigan, B. and Morey, P. (1996). Control of moisture problems affecting biological indoor air quality. ISIAQ guideline. Task Force I. Ottawa, Canada: International Society of Indoor Air and Climate.

Milton, K., Glenross, P. and Walters, M. (2000). Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaint. *International Journal of Indoor Air Quality and Climate* **10**, 211–221.

Morrison, G. and Hodgson, A. (1996). Evaluation of ventilation system materials as sources of volatile organic compounds. *Proceedings of the 7th International Conference of Indoor Air Quality and Climate*, Vol. 3, pp. 585–590.

Morrison, G., Nazaroff, W., Cano-Cruiz, A., Hodgson, A. and Modera, M. (1998). Indoor air quality impacts of ventilation ducts: ozone removal and emissions of volatile organic compounds. *Journal of the Air & Waste Management Association* **48**, 941–952.

Pasanen, P. (1998). Emissions from filter and hygiene of air ducts in the ventilation systems of office buildings. Doctoral dissertation, University of Kuopio, Faculty of Natural and Environmental Sciences, Finland.

REHVA 2002. Skistad, H., Mundt, E., Nielsen, V., Hagström, K. and Railio, J. (2002). Displacement Ventilation in non-industrial premises. Federation of European Heating and Air-conditioning Associations. Guidebook 1/2002.

RTS (2002). Protocol for Cleanliness Testing of Air-Handling Components. Building Information Foundation RTS. Finland; www.rts.fi

Saarela, K. (2003). Emissions from construction materials. Results from the national 'Healthy Building' Programme. *Proceedings of Healthy Buildings 2003*, Singapore.

Säteri, J. (2002). Finnish classification of indoor climate 2000: revised target values. *Proceedings of Indoor Air 2002*, Vol. 3, pp. 643–648.

Seppänen, O. (1999). Estimated cost of indoor climate in Finnish buildings. *Proceedings of Indoor Air '99*, Vol. 4, pp. 13–18.

Seppänen, O. and Fisk, W. (2002a). Association of ventilation type with SBS symptoms in office workers. *International Journal of Indoor Environment and Health* **12** (2), 98–112.

Seppänen, O. and Fisk, W.J. (2002b). Relationship of SBS symptoms and ventilation system type in office buildings. *Proceedings of Indoor Air 2002*.

Seppänen, O. and Fisk, W.J. (2003). A Conceptual model to estimate cost effectiveness of the indoor environment. *Proceedings of Healthy Buildings 2003*, Singapore.

Seppänen, O., Fisk, W. and Mendell, M. (1999). Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings. *International Journal of Indoor Air Quality and Climate* **9**, 226–252.

Seppänen, O., Fisk, W.J. and Faulkner, D. (2003). Cost benefit analysis of the night time-ventilative cooling in office building. *Proceedings of Healthy Buildings 2003*, Singapore.

Teijonsalo, J., Jaakkola, J.J. and Seppänen, O. (1996). The Helsinki office environmental study: air change in mechanically ventilated buildings. *International Journal of Indoor Air Quality and Climate* **6**, 2.

VDI 6022 (1997). Hygienic standards for ventilation and air-conditioning systems—offices and assembly rooms. VDI, Verein Deutscher Ingenieure (Association of German Engineers).

Wargocki, W., Sundell, J., Bischof, W., Brundrett, G., Fanger, O., Gyntelberg, F., Hanssen, S.O., Harrison, P., Pickering, A., Seppänen, O. and Wouters, P. (2002). Ventilation and health in nonindustrial indoor environments. Report from a European Multidisciplinary Scientific Consensus Meeting. *International Journal of Indoor Environment and Health* **12**, 113–128.