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European Indoor Air Quality Audit Project in 56 Office Buildings

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Abstract A European project started at the end of 1992, in which, in addition to current methods, trained sensory panels were used to investigate office buildings all over Europe. The main aim of this EC-Audit was to develop assessment procedures and guidance on ventilation and source control, to help optimize energy use in buildings while assuring good indoor air quality.
In each of nine countries, six or more office buildings were selected. Measurements were performed at five selected locations in each building. The buildings were studied while normally occupied and ventilated to identify the pollution sources in the spaces and to quantify the total pollution load caused by the occupants and their activities, as well as the ventilation systems. The investigation included physical and chemical measurements, assessment of the perceived air quality in the spaces by a trained sensory panel, and measurement of the outdoor air supply to the spaces. A questionnaire for evaluating retrospective and immediate symptoms and perceptions was given to the occupants of the buildings. The building characteristics were described by use of a check-list. The annual energy consumption of the buildings and the weather conditions were registered.
This paper presents results and conclusions of the audit in 56 buildings in Europe. However, the analysis and discussions of the results are a summary of the work done, and are focused mainly on comparison between sensory assessments and the other measurements performed.
Furthermore, this paper brings the results of the study based on a two-factor analysis. A paper dealing with results on a multifactorial analysis is in preparation.

Key words Indoor air quality; Sensory evaluation; Pollution sources; Source control; Ventilation requirements; Energy consumption

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Introduction

Over the past twenty years indoor air quality has received growing attention. Many complaints with respect to indoor air quality arise and the causes of these complaints are often not identified, despite thorough measurements of indoor air. To some extent, these complaints have been blamed on energy-efficiency measures.

In a workshop on Indoor Air Quality Management organized by the European Commission, it was identified that the attainment of health and comfort in the indoor environment, combined with energy efficiency, requires both minimization of human exposure to indoor air pollution, i.e. source control, and a well functioning and energy-efficient heating, ventilating or air-conditioning system (Bluyssen, 1991). As a result of this workshop, the "European Audit Project to Optimize Indoor Air Quality and Energy Consumption in Office Buildings" was started.

Fifty-six office buildings in nine European countries were audited during the heating season of 1993-1994 (Bluyssen et al., 1995a). The audits were performed according to a standard procedure, within the framework of the "European Audit Project to Optimize Indoor Air Quality and Energy Consumption in Office Buildings", sponsored by the European Community through the Joule II programme. The main aim of this EC-Audit was to develop assessment procedures and guidance on ventilation and source control, to help assure good indoor air quality and optimize energy use in office buildings. Fifteen institutes from 11 countries (the Netherlands, Denmark, France, Belgium, United Kingdom, Greece, Switzerland, Finland, Norway, Germany and Portugal) participated. Europe-wide agreement was reached on a common method that was developed to investigate mainly indoor air quality in office buildings, including a questionnaire and walk-through survey checklist (Clausen et al., 1993). By determining the pollution load (chemical and sensory) and the ventilation conditions, and by identifying the pollution sources, recommendations can be

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made to ensure good air quality by means of source control and ventilation.

Procedure

The Audit procedure as described in the final manual (Clausen et al., 1993) was prepared to ensure that the field tests were carried out with the same minimum requirements in each country. Only then could proper comparison between the results from each country be made.

To enhance the chance that all data required represented one environmental condition, the research plan concentrated on the investigation of one building per day with minimum required measurements. To obtain a reasonable database of European buildings, at least six buildings were investigated per participating country, five representative locations being selected in each building for the measurement of, among other factors, pollution loads and ventilation. To achieve similar conditions with regard to temperature in the buildings in the different countries, the studies in all nine countries were conducted during the heating season. The buildings were studied while normally occupied and ventilated to quantify the total pollution load caused by the occupants and their activities, the ventilation systems, and the sources in the spaces themselves. The investigation included physical and chemical measurements, assessment of the perceived air quality in the spaces by a trained sensory panel, and measurement of the outdoor air supply to the spaces. The physical and chemical measurements in the spaces included measurements of noise, concentrations of carbon dioxide (CO_2), carbon monoxide (CO), total volatile organic compounds (TVOC), and the thermal parameters: operative temperature, air temperature, relative humidity and air velocity. Airflows between the selected spaces and adjacent spaces were measured when necessary. Additional measurements in the adjacent spaces included measurements of CO, CO_2 and TVOC and assessments of the perceived air quality. In the mechanically ventilated buildings the perceived air quality of the supply air in the five selected spaces was assessed by a sensory panel. At one of the five selected locations in each building, the measurements further comprised measurement of individual volatile organic compounds (VOC), and of airborne particulate matter. All chemical measurements were also performed outdoors. A questionnaire for evaluating retrospective and immediate symptoms and perceptions was given to and collected from the occupants of the buildings on the day of the audit. The building characteristics were described by use of a check-list. The annual energy consumption of the buildings and the weather conditions were registered.

Questionnaire

The occupants surveyed were selected as being representative of occupants in the building as a whole. To obtain a valid sample of at least 100 occupants, buildings with 125 or more occupants were selected.

A week before the day of the audit, the occupants selected to take part were notified by letter. On the day of the audit, the selected occupants were given a questionnaire and on the same day the questionnaires were collected by the research staff.

The selection of occupants to be surveyed was made in three steps. First the population of a selected building was studied, then the rooms and then the workstations. The population study included all the people who worked at the same time during the week in the building studied, or in the selected areas of the building. The study population was limited to selected areas if these areas were sufficiently different from other areas as to be regarded as equivalent to a separate building. For example, they may have been fitted out completely differently or occupied by a different organization, doing a different type of work. In addition, certain people were excluded if they were atypical of the workforce. In practice, however, it was necessary to sample workstations as a proxy of persons, because a staff list was rarely available.

If between 125 and 150 workstations were available, a questionnaire was delivered to each user. If 150-300 workstations were available, then researchers could choose whether to deliver a questionnaire to each workstation or to select a sample. Where over 300 workstations were available, a sample was drawn in general. This sample was drawn in two steps. First by room, then by workstation.

Selection by rooms comprised first of all the rooms where the measurements would take place. Any additional rooms were similar in character and workforce to at least one of the measurement rooms. To be representative of the building, a range of floors and facades were included.

If the selection of floors provided more workstations than required, selection was in general made during the distribution of the questionnaires.

The 8-page questionnaire developed for the EC-Audit project included a short description of how to fill in the questionnaire and a section for personal information such as gender, occupation, employment, smoking habits, allergies, etc. The main questions concerned the occupants' health and their environmental conditions during the past month (retrospective), the occupants' health and their environmental conditions at this point in time (here and now), and other aspects of the office environment.

A retrospective building-related symptom was defined as a symptom experienced at least once during the month preceding the audit, the symptom being less prominent on days away from the building. In the present-time part of the questionnaire, a symptom was identified if the answer was yes to the question: At this moment, are you experiencing the symptom at all? There was a total of 12 symptoms for both parts of the questionnaire comprising: dry eyes, watering eyes, blocked or stuffy nose, runny nose, dry/irritated throat, chest tightness or breathing difficulty, flu-like symptoms, dry skin, rash or irritated skin, headaches, lethargy or tiredness, other symptoms.

Environmental perceptions, both in the retrospective and the present-time part of the questionnaire, comprised: thermal sensation, perception of the indoor air quality and light as well as noise perceptions. Thermal comfort was expressed in several ways, e.g. on the thermal 7-point sensation scale. The acceptability of the indoor air quality was expressed on a scale ranging from "clearly not acceptable" to "clearly acceptable" with a border between "just not acceptable" and "just acceptable". In addition, indoor air quality was rated on 7-point scales: dryness (*1*=dry and *7*=humid), stuffiness (*1*=fresh and *7*=stuffy), odour (*1*=odourless and *7*=smelly). Light and noise perceptions were given on a 7-point scale from *1*=satisfactory overall to *7*=unsatisfactory overall.

The mean number of building-related symptoms, from the list of 12 symptoms, during the month preceding the audit was defined as the BSI_{ff}, whereas the mean number of symptoms at the time of the audit was defined as the BSI_{sf}. BSI is an abbreviation for Building Symptom Index.

Sensory Measurements

The perceived air quality was assessed by a panel of trained persons assessing the air quality in decipol (Bluyssen, 1990). Twelve to fifteen persons were selected from a group of at least 50 applicants of ages ranging from 18 to ~30 years old. There was no restriction on distribution of gender or smoking habits. The 12-15 selected persons (panel members) were trained for three to five days in smaller groups of three to seven persons. Each day they received one to two hours of intensive training. The panel members were exposed to 10 to 15 2-propanone concentrations during the training period. The panel members were furthermore trained to assess air polluted with samples of building materials and to assess the air quality of real spaces. On the third day of training the subjects were exposed to a performance test with 2-propanone. After all panel members had passed this individual test, the whole panel was exposed to a second test, based on pollution sources typically found in buildings.

Ventilation Measurements

The ventilation-related information corresponded to the period of time during which the other evaluations were performed and consisted of determining all airflow rates involved. An objective of these ventilation measurements was to provide the necessary information for calculation of the source strength for each considered pollution source. The ventilation airflow rates to be considered for each selected room were therefore the following: air supplied by the ventilation system; infiltration through the building envelope; and air coming from adjacent rooms. Various methods were used by the different participants to assess these airflow rates. Basic principles were, however, provided in the manual (Clausen, et al., 1993), and were respected as far as possible. However, uncertainties ranged from 5% to 200% (mainly caused by tracer gas mixing problems encountered in open offices).

Physical Measurements

The physical measurements were made in the occupied zone of the selected spaces.

The thermal measurements included air temperature, operative temperature, relative humidity and air velocity. Air temperature and air velocity were measured at 0.1 m, 0.6 m and 1.1 m above floor level, corresponding to foot, middle and head level of a seated person. Operative temperature and relative humidity were measured at 1.1 m above floor level. At one of the selected measurement locations, continuous measurement of operative temperature and relative humidity were performed on the day of the experiment. All other measurements were allowed to be spot measurements, typically with a duration of 5-30 minutes. The amount of respirable particulate matter was measured during eight hours in one of the selected spaces. Several methods exist, but to avoid incomparability of results between the participating countries, it was recommended that a gravimetric method be used. Filters used in most cases had a diameter of 37mm. The nominal pore size of the filters ranged from 0.5 to 5 μm. Reported accuracies ranged from 3-6 $\mu g/m^3$.

The A-weighted equivalent sound pressure level L_{eq} was measured for at least 2 minutes in each of the selected spaces during occupancy with a sound level meter.

Most countries used instruments from Bruël & Kjaer (B&K) to measure the indoor climate parameters. In addition, some countries used sensors connected to data loggers to collect the parameters continuously.

Table 1 Summary of main characteristics of 56 selected buildings

Characteristics	Percentage [%]	Characteristics	Percentage [%]
Situation		*Age*	
country side	14	2 years<age ≤5 years	29
suburbs	25	5 years<age ≤10 years	21
downtown	54	10 years<age ≤20 years	11
industrial area	7	> 20 years	39
Total floor area		*Number of floors*	
≤2, 500 m^2	16	1<floors ≤3	21
2, 500<floor area ≤7, 500 m^2	30	3<floors ≤7	48
7, 500<floor area ≤15, 000 m^2	29	7<floors ≤10	13
>15, 000 m^2	25	>10 floors	18
Number of occupants		*Smoking*	
≤200 occupants	36	yes	59
200<occupants ≤500	34	certain areas	23
500<occupants ≤1000	16	no	18
>1000 occupants	14		

Chemical Measurements

The concentrations of carbon dioxide (CO_2) (as an indicator of the number of occupants present), carbon monoxide (CO) (as an indicator of the number of smoking occupants present) and TVOC (the chemical pollution load in a building can be reflected in a TVOC index, expressed as TVOC/m^3 air) were measured in the selected rooms, in adjacent spaces from which air flowed into the selected rooms, and outdoors. Furthermore, the concentrations in the ventilation supply air were measured for mechanically ventilated buildings. All chemical measurements in spaces were made at 1.1 m above floor level. In all but one measurement location per building, the measurements were allowed to be spot measurements (duration of a few minutes). At one measurement location per building continuous (8 h) measurements were made.

In general, two methods were used to measure TVOC: (1) integrated samples on Tenax-TA followed by thermal adsorption, gas chromatography, FID quantification and MS identification of the most abundant VOCs, and (2) direct measurement of infrared absorption using photoacoustical detection. However, for the international analysis only the results of the first were used. One sample from an office room in each building was selected for VOC screening. The 15 VOCs displaying the highest toluene equivalent indices in each selected sample were tentatively identified from their mass spectra. All analyses were made at one laboratory (BIGA in Switzerland). Analytical quality was verified using the consistency of the spiked internal standard signal. External quality control was obtained by completing 12 sampling and sample integrity checks with two external laboratories (CSTB in France, VTT in Finland), in addition to running 19 parallel analyses of actual samples obtained during the audits with one external laboratory (CSTB). Five results were rejected. The average relative difference in TVOC index for the remaining 26 samples was 26% (Bernhard et al., 1995).

Six different instruments were used for either continuous or spot CO_2 measurements. Accuracy ranged from 10 to 50 ppm. Differences between reported spot and averaged continuous carbon dioxide levels were frequent and in some audits excerpts from the continuous records were used as spot values to avoid the problem.

Instruments used to measure CO ranged from dispersive (filter) IR (infrared) to direct reading colorimetric tubes and included NDIR and colorimetric direct reading detectors. Sensitivities were at the 1 ppm level when stated and detection limits were in the 0.2 ppm (IR) to 1 ppm range.

Energy Consumption

The total annual energy consumption of the audited buildings for all final energy forms (oil, coal, gas, electricity, district heating, etc.) was provided by the building owner or the technical manager. To compare (as far as reasonably possible) the energy use in buildings of various dimensions, an energy consumption index was calculated by:

Energy index=total yearly energy use/gross heated floor area [MJ/m^2][1]

The gross heated floor area included all heated spaces of the building considered, calculated with external dimensions. Unheated spaces such as garage, storage rooms and machinery rooms were not included. An electricity energy index was defined in a similar way, dividing the yearly electricity consumption by the gross heated floor area. For buildings not electrically heated, a heating index was obtained by subtracting the electricity index from the total energy index.

Table 2 Summary of information on ventilation systems of 56 selected buildings

Characteristics	Percentage [%]	Characteristics	Percentage [%]
Ventilation system			
natural ventilation	12	design air change<0.5 h^{-1}	0
exhaust system only	2	0.5 h^{-1}<design air change<1 h^{-1}	18
supply system only	5	1 h^{-1}<design air change<3 h^{-1}	51
balanced VAV system	9	design air change>3 h^{-1}	31
dual ducts balanced	20	des. outdoor airflow rate<7 L/s.pers.	14
induction units	18	7 l/s.pers.<airflow<10 L/s.pers.	25
simple balanced	30	10 l/s.pers.<airflow<20 L/s.pers.	28
other system	4	20 l/s.pers.<airflow<30 L/s.pers.	17
		30 l/s.pers.<airflow<50 L/s.pers.	11
		design outdoor airflow>50 L/s.pers.	6
Cooling system		*Heating system*	
no cooling	25	no heating	0
supply of cooled air	48	hot water heating	50
local fan coil units	18	air heating	43
cooled ceilings	5	direct electric heating	7
cooling convectors	4	other system	0
Recirculation		*Heat recovery*	
no recirculation	61	no heat recovery	42
up to 25% recirculation	6	rotating wheel	27
25%<recirculation<50%	12	plate exchanger	8
50%<recirculation<75%	12	others	23
recirculation>75%	10		
Openable windows		*Ventilation principle*	
cannot be opened	32	no planned principle available	2
can but may not be opened	14	displacement ventilation (incl.natural)	12
can be opened	54	mixing ventilation	87
Control of ventilation system		*Sensor-controlled ventilation*	
		no sensors	55
manual on and off	23	temperature sensors	41
clockwork	77	humidity and other sensors	4

Buildings Selected

For the selection of the buildings in each country, the following questions should have been answered "Yes":

- Has the building been occupied continuously for more than two years? (to avoid high and unstable emissions in new buildings, the buildings shall be at least two years old).
- Is the site free from external pollution (smells, noise, vibration)?
- Is the work carried out essentially "non professional" office work?
- Do at least 125 people work in the building?
- Do they each spend a minimum of 20 hours/week in the building?
- Will the sensory panel have ready access to "outdoor" air?
- Is yearly energy consumption data available?

No other restrictions were placed on the building selection. Public or private sector buildings were equally acceptable. There was no restriction on the type of ventilation used in the building. The selected office spaces were to be representative of the building. These were large open-plan offices or cellular offices. Both smoking and non-smoking workplaces were included. The main activity of the office workers was general office work. Computer terminal rooms and photocopying rooms were avoided. A location near the office spaces studied was required for refreshing the senses of the panel (a nearby office space where it is possible to open the windows or a location outside the building). In general, the selection of office spaces was done in parallel to the selection of the occupants to be surveyed.

A summary of the main characteristics of the 56 selected buildings and their ventilation systems is presented in Tables 1 and 2. More detailed information can be found in the national reports (Bluyssen and Cox, 1994; Lagoudi et al., 1994; Roulet et al., 1994; Groes et al., 1994; Skaret and Blom, 1994; Kovanen and Heikkinen, 1994; Finke and Fitzner, 1994; Aizlewood et al., 1995; Kirchner et al., 1995). As can be seen from Table 1, the majority of the buildings selected were located in towns and had less than 500 occupants. Fifty per cent of the selected buildings were older than ten years, the majority had less than eight floors, and smoking was allowed in more than 80% of them. The statistical information given in Table 2 has been extracted from the checklists. The presented recirculation, air change and airflow rates are design values. Most of the information given is based on more than 50 buildings. The majority

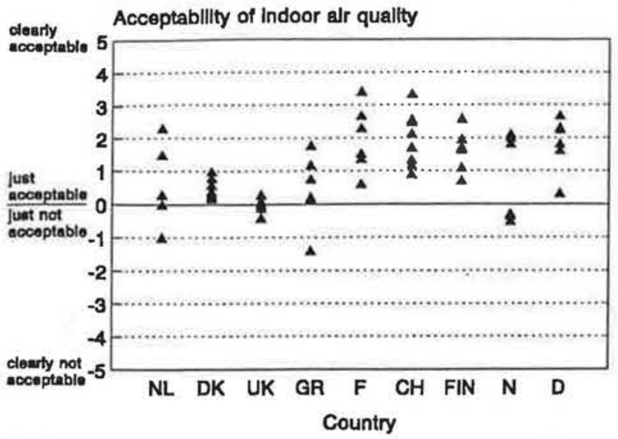

Fig. 1 Indoor air acceptability, at the time of the audit, on a scale from –5 to +5.

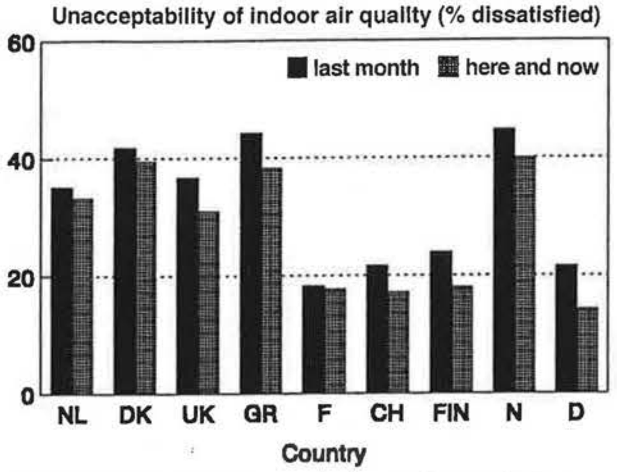

Fig. 2 Indoor air acceptability rated by the occupants in the European IAQ Audit buildings presented in percentage of dissatisfied.

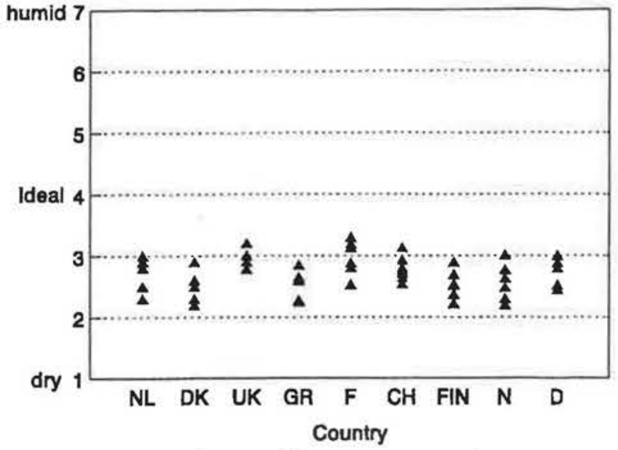

Fig. 3 Air dryness, at the time of the audit, on a scale from 1 to 7.

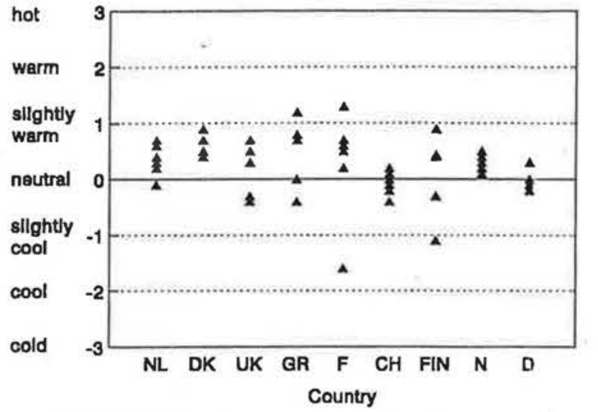

Fig. 4 Thermal comfort rate, at the time of the audit, on a scale from –3 to +3.

of the selected buildings had mechanical ventilation with cooling and without recirculation. The design air change was, in ~50% of the selected buildings, between 1 and 3 ach; the design outdoor airflow rate was more than 10 L/s·person in 60% of the buildings. Only 12% of the investigated buildings had planned natural ventilation only.

Results

Questionnaire

In all, 6 537 occupants in office buildings representing more than 30 000 occupants in the audited buildings, participated in the questionnaire survey (Groes et al., 1995). The response rate varied between 54% and 97% with an average of 79%. The occupants of the office buildings comprised, on average, 47% males and 53% females. The mean percentage of smokers ranged in all investigated buildings per country from 22% to 48%, with an average of 31%. The mean age of the respondents for all countries was 39 years. The average of occupants who had ever experienced eczema for all investigated buildings was 27%. The average of occupants who experienced asthma was 10%. Hay fever was experienced on average by 25% of the occupants.

In Fig. 1, the acceptability rating for the "now" response is shown for all buildings. Figure 2 shows the mean percentage of dissatisfied for the retrospective and the present-time response for each country. In this figure, all occupants who voted below zero on the scale from –5 to 5 were taken to be dissatisfied with the air quality. On average, 27% of the occupants found the indoor air quality not acceptable at the time of the audit, and 32% found the indoor air quality not acceptable during the month preceding the audit. In all buildings the air was perceived as dry by the occupants as shown in Fig. 3 (the mean rate was 2.7). In half of the buildings the air was perceived as being on the stuffy side. The indoor air was not perceived strongly odorous by the occupants (the mean rate was 2.7 rated at the time the audit was performed). The mean thermal sensation varied in general between slightly cool and slightly warm at the time of the audit, as shown in Fig. 4. Noise and light conditions were in general perceived as satisfactory. The occupants generally rated their control of ventilation as little.

Table 3 Building-related symptoms for all of the buildings

Country	NL	DK	UK	GR	F	CH	FIN	N	D	Mean
Past month										
• dry eyes	35%	42%	45%	47%	30%	44%	28%	40%	40%	39%
• watering eyes	10%	12%	22%	21%	30%	19%	18%	10%	15%	17%
• stuffy nose	26%	23%	50%	31%	41%	39%	28%	25%	38%	33%
• runny nose	11%	13%	27%	17%	32%	19%	16%	10%	18%	18%
• dry throat	29%	30%	42%	36%	47%	42%	24%	31%	41%	36%
• chest tightness	12%	5%	14%	30%	26%	16%	8%	8%	12%	15%
• flu-like symp.	18%	14%	31%	33%	38%	27%	16%	14%	31%	25%
• dry skin	16%	23%	24%	27%	29%	26%	22%	33%	28%	25%
• irritated skin	6%	5%	14%	14%	22%	8%	11%	9%	12%	11%
• headache	33%	42%	58%	55%	54%	39%	21%	38%	36%	42%
• lethargy	37%	42%	61%	61%	63%	49%	41%	59%	52%	52%
• other symptoms	11%	11%	15%	6%	15%	14%	13%	11%	11%	12%
Here and now										
• dry eyes	27%	33%	27%	27%	22%	28%	27%	27%	20%	26%
• watering eyes	3%	3%	6%	7%	16%	7%	9%	5%	3%	7%
• stuffy nose	26%	27%	36%	21%	28%	36%	37%	29%	38%	31%
• runny nose	7%	9%	12%	10%	18%	13%	14%	9%	10%	11%
• irritated throat	27%	29%	30%	27%	31%	35%	30%	31%	24%	29%
• chest tightness	8%	3%	6%	20%	19%	11%	7%	7%	7%	10%
• flu-like symp.	11%	7%	9%	14%	15%	19%	18%	10%	25%	14%
• dry skin	21%	39%	30%	21%	25%	34%	51%	39%	29%	32%
• irritated skin	10%	10%	12%	9%	15%	11%	19%	12%	9%	12%
• headache	17%	24%	27%	23%	23%	15%	13%	17%	13%	19%
• lethargy	22%	29%	41%	31%	31%	27%	28%	48%	24%	31%
• other symptoms	8%	9%	10%	6%	8%	9%	8%	10%	5%	8%

The mean prevalence of symptoms for each country during the month preceding and at the time of the audit is given in Table 3. On the day of the building audit the three most prevalent building-related symptoms were dry skin (32%), blocked or stuffy nose (31%), and lethargy or tiredness (31%). The three most prevalent building-related symptoms for the month preceding the building audit were lethargy or tiredness (52%), headache (42%), and dry eyes (39%). The BSI-index at the time of the audit was 2.1, whereas the BSI-index for the month preceding the audit was 3.3 on the list of twelve symptoms. In Fig. 5 it can be seen that the prevalence of symptoms monthly was generally higher than the symptoms at the time of the audit. A significant correla-

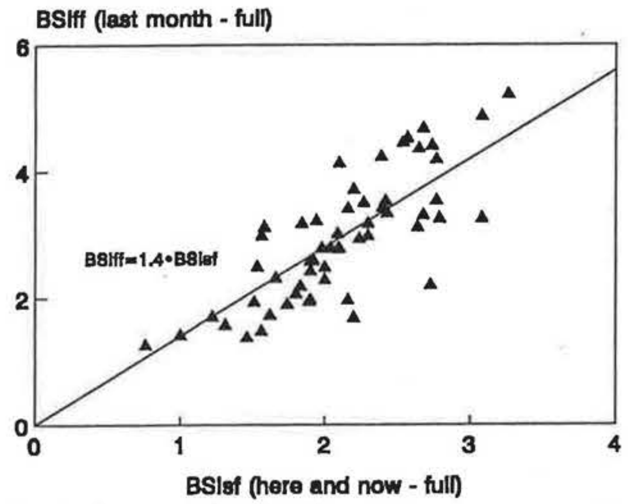

Fig. 5 The mean number of building-related symptoms during the month preceding the audit (BSI_{ff}) vs. the mean number of building-related symptoms at the time of the audit (BSI_{sf}).

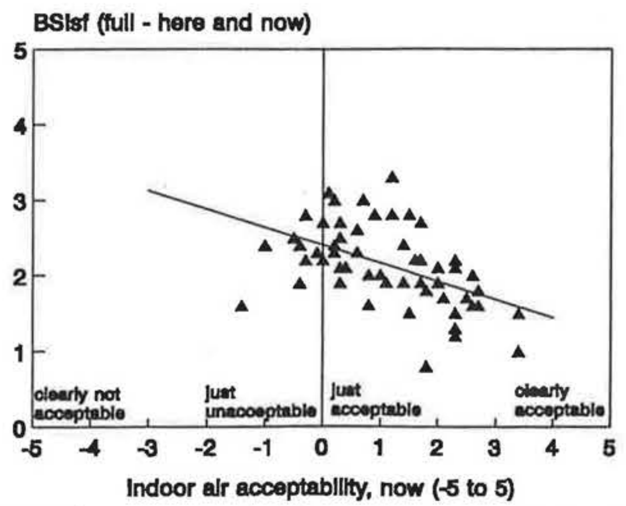

Fig. 6 The mean number of building-related symptoms at the time of the audit (BSI_{sf}) vs. indoor air acceptability, at the time of the audit.

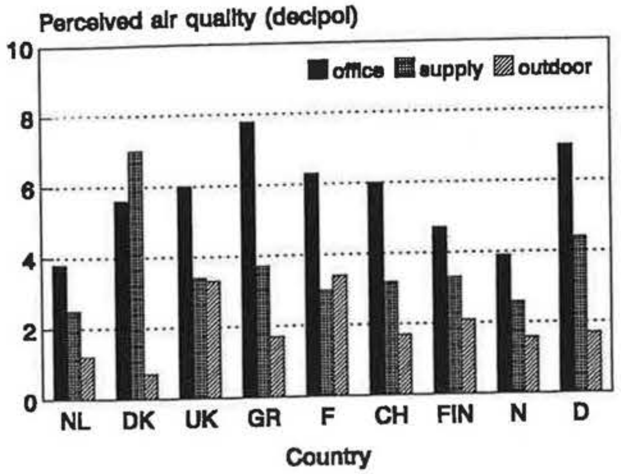

Fig. 7 Mean perceived air quality (decipol), as given by the sensory panels in the selected offices, the supply air and the outdoor air.

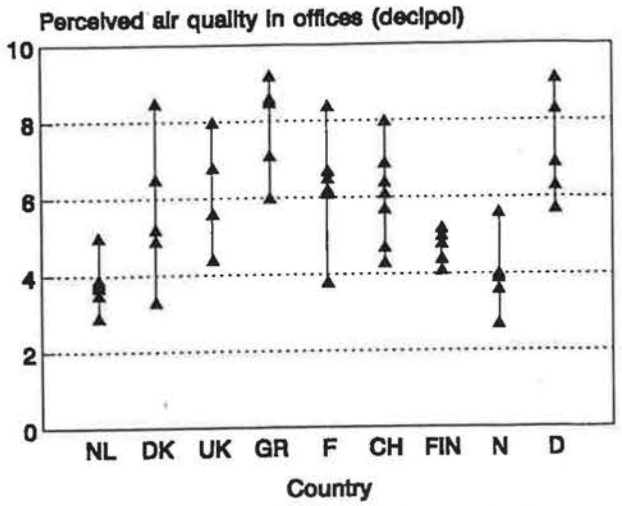

Fig. 8 Mean perceived air quality (in decipol) as given by the sensory panels in the selected offices in the 56 European IAQ Audit buildings.

tion (R^2=0.95, P<0.0001) was found. An even better relation was found between the indoor air acceptability rating during the month preceding the audit and at the time of the audit. A correlation between occupants' symptoms and perception of indoor air quality was found. The significant (R^2=0.26; P<0.0001) relation between the number of symptoms at the time of the audit (BSI_{sf}) and indoor air quality at the time of the audit is shown in Fig. 6. Correlations are based on building means. The occupant responses showed substantial variation between buildings, and sometimes even between countries; however, there were no systematic regional differences.

Sensory Evaluation

The mean air qualities as perceived by the trained panels for the investigated buildings per country are given in Fig. 7. Figure 8 shows the variation of the perceived air quality (decipol) in the selected spaces of buildings within countries as well as between countries. The mean perceived air quality for all 56 European IAQ Audit buildings was ~ 6 decipol for office air, 4 decipol for supply air and 2 decipol for outdoor air. This corresponds to roughly 50%, 40% and 25% dissatisfied visitors with the perceived air quality (ISO/CEN 1994). No correlation between the perceived air quality in the offices and the perceived air quality outdoors seemed to be present. Also, the perceived air quality in offices did not correlate with the perceived air quality in the ventilation supply air.

General Indoor Air Quality

The average TVOC, CO_2, CO and particulate matter concentrations found in buildings per country are presented in Table 4.

Average TVOC indices per building were log-normally distributed. Average TVOC indices per building in the investigated rooms ranged from 40 to 1840 µg/m³ with a median of 202, a geometric mean of 228 and a geometric standard deviation of 2.4. Outdoor air samples ranged from 10 to 420 µg/m³, with a median at 80, a geometric mean of 86 and a geometric standard deviation of 2.5. The selected room samples did not differ essentially from the other room samples in a building. With only 15 compounds per sample (one per building), more than half of the TVOC index could be accounted for in 90% of the buildings. Pooling all samples resulted in a comparatively short list of 66 partially or completely identified compounds (see below). Levels for individual VOCs and even the cumulative TVOC indices all ranked orders of magnitude below current workplace exposure limits (ACGIH, 1994).

Reported outdoor CO_2 levels ranged from 250 to 570 ppm, with 51 out of 54 reported values in the usual 300 to 520 ppm range. The average was 390±60 ppm. No evidence of geographic differences could be found along north-south or east-west axes or between maritime and more continental settings. The average indoor level was 673 ppm.

The average indoor CO level was below 1 ppm. No single value approaching the current workplace exposure level (25 ppm 1 hour time-weighted average (WHO, 1987)) was observed, even during short-term episodes.

The particulate matter values were log-normally distributed, with a geometric mean of 66 µg/m³, a large geometric standard deviation of 2.7, and a median at 62 µg/m³. In general, the particulate concentration remained below 120 µg/m³ (WHO, 1987), except for several buildings in Greece and Switzerland.

General Indoor Climate

The average results of the thermal and noise measurements per country are shown in Table 5. The mean air temperatures measured in the buildings per country were in general in the upper limit of the recommended values given in the thermal comfort standard ISO/CEN 7730 (ISO/CEN, 1994) for the winter (20-24°C). Small differences between operative and air temperature were generally observed (except for France), indicating low differences between radiant and air temperature. The measured operative temperature (mean 22.5°C) and air velocities (mean 0.08 m/s) met, in general, recommen-

Table 4 Average CO_2, CO, particulate matter and TVOC concentrations found in buildings in each country

	NL	DK	UK	GR	FR	CH	SF	N	D
CO_2 [ppm]									
• offices	656	736	516	587	778	744	737	628	674
• supply air	437	•	•	544	550	523	535	448	386
• outside air	418	382	327	400	344	382	473	440	402
CO [ppm]									
• offices	0.5	0.6	0.7	•	1.9	<1	0.8	1.4	0.7
• supply air	0.5	•	•	•	2.5	<1	0.6	1.4	0.5
• outside air	0.5	0.5	•	•	1.5	<1	0.9	1.3	0.5
Particulate matter [µg/m³]									
• offices	72	88	20	149	76	181	51	20	61
TVOC [µg/m³]									
• offices	179	135	436	495	413	518	118	528	146
• supply air	88	38	329	137	306	310	82	148	228
• outside air	79	33	128	158	82	251	62	155	155

Table 5 The average results of the thermal and noise measurements in each country

	NL	DK	UK	GR	FR	CH	SF	N	D
Air temperature [°C]									
• offices	22.3	23.7	22.9	23.5	23.5	22.9	22.3	23.4	21.7
• supply air	19.5	25.1	•	31.2	22.5	•	21.9	20.2	•
• outside air	6.6	5.6	10.4	14.7	12.4	7.2	•	−0.6	•
Operative temp. [°C]									
• offices	22.3	23.5	23.1	•	21.9	21.4	22.4	23.6	22.0
Rel. humidity [%]									
• offices	31	29	36	33	44	39	19	17	41
• supply air	34	•	•	27	42	•	15	•	•
• outside air	57	71	74	40	54	68	•	•	•
Air velocity [m/s]									
• offices	0.10	0.07	0.11	0.08	0.07	0.12	0.08	0.07	0.06
Noise [dB(A)]									
• offices	48	46	55	54	46	45	39	42	51

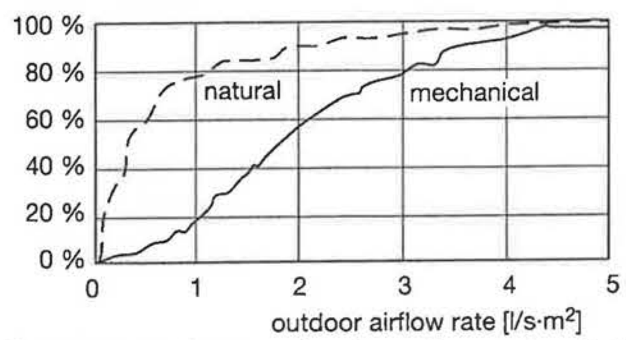

Fig. 9 Cumulated frequencies of outdoor airflow rates in audited rooms split into two populations: 30 naturally ventilated rooms and 196 mechanically ventilated rooms.

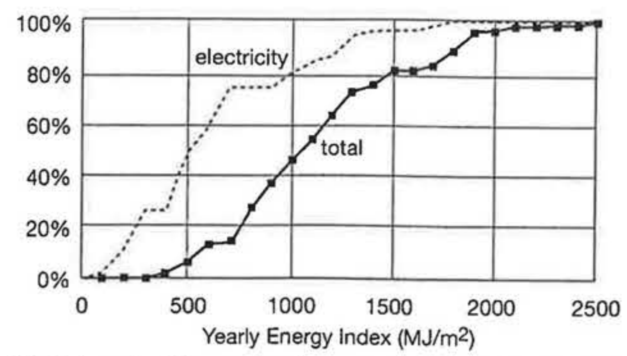

Fig. 10 Cumulated frequencies of energy indices of audited buildings.

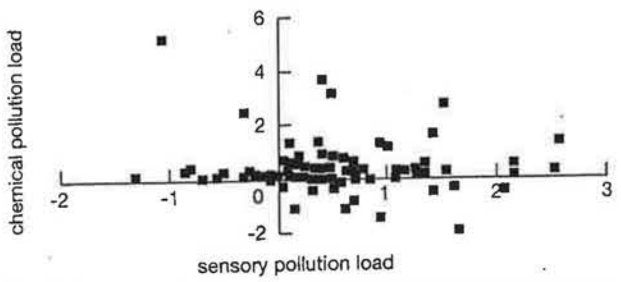

Fig. 11 Comparison between chemical and sensory pollution loads for the selected spaces in 174 audited rooms, expressed in µg/s·m² and olf/m² respectively.

dations in the ISO/CEN standard (ISO/CEN 1994) and requirements in prENV 1752 (CEN, 1994). The Nordic countries (Denmark, Finland and Norway) had a relative humidity indoors below 30%, which is not uncommon in these countries. Highest relative humidities indoors were found in France and Germany. The average noise level was 47 dB(A).

Ventilation

It should be said that the conditions for ventilation measurements are not ideal in occupied buildings. Even with improved techniques for measurement and interpretation, the results cannot be perfect. Therefore, in some cases results were reported with large uncertainties.

The results shown in Fig. 9 are based on measurements of 226 rooms from 56 buildings. Since some rooms were equipped for one person only, and others were large open offices, airflow rates in rooms varied by several orders of magnitude. To be able to compare the airflow rates, specific airflow rates were calculated for each audited room.

Outdoor airflow rate is most interesting from the point of view of both energy consumption and indoor air quality. It is defined as the sum total of the outdoor airflow rates from infiltration and mechanical or natural supply. Naturally ventilated rooms presented generally a low air change rate (Fig. 9). Their average outdoor airflow rate was 1.0 L/s·m², while it was 2.1 L/s·m² in mechanically ventilated rooms. Eighty percent of mechanically ventilated buildings had more than 1.0 L/s·m², while only 20% of naturally ventilated buildings exceeded this limit. The average outdoor airflow rate was 1.9 L/s·m² or 25 L/s·person. The outdoor air change rate of the audited rooms averaged 2.5 h^{-1}.

Actual values often differed from design values (Table 2), in particular for recirculation rates.

Energy Consumption

From the energy consumption data for the year 1993, a huge variation in values appears at first glance. There was a 7:1 ratio in total energy index between the highest and the lowest and a 20:1 ratio between the highest and the lowest energy use per person. Figure 10 shows that the lowest quartile of the audited buildings had an index not greater than 800 MJ/m², and the limit for the highest quartile was 1400 MJ/m². The median value was little above 1000 MJ/m². If only electricity is taken into account, 25% use 299 MJ/m² or less, the median being about 500 MJ/m². Figure 10 shows a large theoretical energy-saving potential: buildings can be operated with less than 500 MJ/m² total energy use and less than 100 MJ/m² for electricity.

The main source of energy for audited buildings was electricity (*ca.* 48%). The remaining was more or less equally distributed between district heat, heating oil and natural gas, each for 15% to 19%. No relation between the building year or climate and energy use was found. Average values for buildings erected before and after the oil price crisis (1973) did not differ significantly. Reasons for this may include today's low cost of energy and energy retrofit of old buildings. No systematic differences were found across Europe (except Greece).

Analysis and Discussion

Questionnaire-sensory Measurements

The occupants' acceptability rating and number of building-related symptoms did not show statistically significant correlation with perceived air quality in the offices evaluated by the sensory panel. It could be debated whether a relation between the perceived air quality and the occupants' perceptions and symptoms was to be expected. It is important to remember that the occupants and the sensory panel did not evaluate the same air. The perceived air quality was measured by a trained sensory panel at only five locations in a building with ~200 to 500 occupants, whereas the occupants evaluated the air quality in their own office room. The sensory panel gave the initial impression of the air quality at the five selected locations in the building as opposed to the occupants who gave the adapted perception of the air quality in their own office room. Furthermore, the panel concentrated only on the sensory evaluation of air, while the occupants are subject to many different sensations.

Table 6 Categories of pollution sources resulting from sensory and chemical measurements

From sensory measurements	From chemical measurements
outdoor pollution (traffic, industry) ventilation system (filters)	ventilation system
people in the office	
materials and other sources in the office (tobacco smoking, furnishing, photocopying, laserprinters, renovation works)	all sources in the room including materials, furnishing, people and tobacco smoking

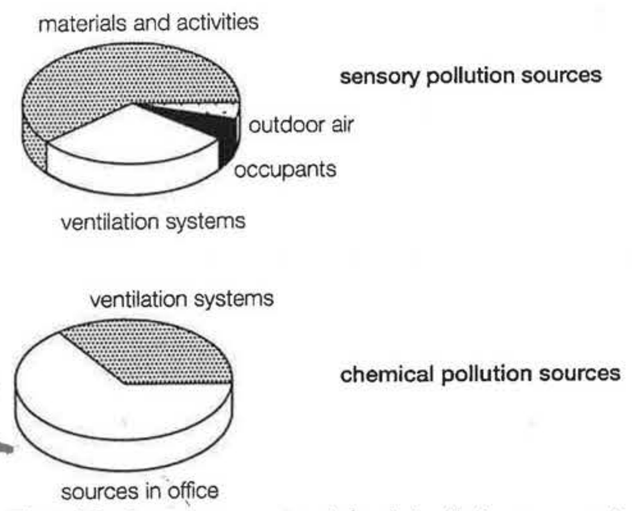

Fig. 12 Most important sensory and chemical pollution sources estimated in audited buildings.

Pollution Loads and Sources

Sensory assessments and chemical measurements of the indoor air quality, together with ventilation measurements, were part of the standard procedure. These assessments were used to calculate pollution loads of sources in chemical and sensory terms (Bluyssen et al., 1995b). From the outcome, the most important pollution sources were identified.

The mean total sensory pollution load for the offices (including building materials, ventilation systems, occupants and previous and present smoking), was 0.7 olf/m². The occupants corresponded to 0.1 olf/m² and 0.3 olf/m² came from the ventilation systems (including in some cases previous smoking through recirculation). The total mean chemical pollution load for the offices (including building materials, occupants, ventilation systems and previous and present smoking) was 0.3 µg TVOC/s·m².

The calculated pollution loads had large uncertainties. There are four main reasons for this: large uncertainties in the calculated pollution loads (due to the calculation procedure, to large uncertainties in the ventilation measurements, and minor uncertainties in measurement of specific compounds in the air); adsorption, desorption and decomposition of components in the air influencing the concentrations in the air (the calculation procedures cannot yet take this into consideration); the possible dependency of sensory evaluation on pollution level (Knudsen, 1994); and conditions which are not in equilibrium due to changes in source emissions (occupants, smoking), especially in offices with small air changes per hour. Conclusions on the importance of sources in the audited buildings are still possible, however, since the direct measurements (in decipol) provided in most cases enough information, and all measurements were performed under roughly the same conditions.

Volatile organic compounds may have an odour and irritation potential. Therefore the relation between the sensory pollution load and the chemical pollution load was investigated. The correlation between sensory and chemical pollution load was poor, as is shown in Fig. 11. Some specific components (VOCs) have a high sensory effect, others have not. Total volatile organic compounds may therefore not correlate with the sensory evaluations. Different mixtures of VOCs (with different odour and irritation potential) may, however, lead to the same TVOC-value. Furthermore, the TVOC measured with the Tenax-GC method did not include all VOCs which may have been present.

The analysis showed no correlation between the mean perceived air quality by the sensory panel and the mean TVOC concentration (in toluene equivalents), even if the outdoor level was subtracted. This result is the same as the non-correlation between the total sensory and total chemical pollution loads, since it is the same ventilation rate that is multiplied by the concentration difference in the two mass balances.

Pollution sources were identified using the calculated pollution loads in the broad categories indicated in Table 6. However, the identification was also based on professional judgements, since the large uncertainties on the pollution load calculations did not allow use of only the calculated pollution load values.

The most important sensory pollution sources are presented in Fig. 12 (276 rooms were included in the analyses). It can be seen that the materials and activities, closely followed by the ventilation systems, were likely to be identified as the most important pollution source. Among materials and activities, furnishing was identified most often as a source, as well as photocopying and building renovation. In the 50% of the situations where ventilation was identified as the most important pollution source, filters and air recirculation from other rooms were specifically identified equally often. It must furthermore be noted that the ventilation systems,

Table 7 Possible sources of most prevalent VOCs found in the audited buildings as found in a literature survey (Lagoudi et al., 1995)

No	Compound	Sources						No	Compound	Sources					
				Materials								Materials			
		O[1]	T[2]	E[3]	B[4]	F[5]	C[b]			O	T	E	B	F	C
1	$9CF_2)_n$						x	31	benzene	x	x		x	x	
2	1,1,1-trichloroethane					x	x	32	C3-alkylbenzenes	x	x		x	x	x
3	$C_2Cl_3F_3$						x	33	m-xylene	x	x		x	x	x
4	tetrachloroethylene						x	34	o-xylene	x	x		x	x	x
5	dichloromethane				x		x	35	p-xylene	x	x		x	x	x
6	dichlorobenzene						x	36	toluene	x	x		x	x	x
7	butane	x						37	naphthalene						x
8	n-hexane	x	x		x	x		38	phthalate comp.					x	
9	aliphatic $C_{fs}H_{16}$	x					x	39	1-butanol				x	x	x
10	n-heptane	x					x	40	1-ethoxy-2-propanol				x		
11	octane	x	x		x			41	2-butoxy-ethanol				x		x
12	aliph. C_9H_{20}				x	x	x	42	2-phenoxy-ethanol				x		x
13	nonane				x	x	x	43	C_5-alcohol				x		x
14	decane $C_{10}H_{22}$				x	x	x	44	ethanol					x	x
14	undecane				x	x	x	45	ethoxy-ethoxy-ethanol				x		x
16	dodecane						x	46	4-methyl-2-pentanone		x			x	
17	tetradecane						x	47	acetone					x	
18	pentadecane						x	48	cyclohexanone						x
19	2-methylbutane	x						49	benzaldehyde			x		x	x
20	2-methylpentane	x						50	nonanal			x	x		x
21	3-methylpentane	x						51	decanal			x		x	x
22	2,4-dimethylhexane	x				x		52	acetic acid butyl ester					x	
23	2-methylhexane	x				x		53	acetic acid ethyl ester					x	
24	nonane/o-xylene					x		54	butoxy-ethoxy-ethylacetate					x	
25	nonane/styrene					x		55	acetic acid				x	x	
26	dimethylcyclopentane					x	x	56	benzoic acid						x
27	methylcyclopentane					x	x	57	dodecanoic acid					x	x
28	methylcyclohexane	x				x	x	58	a-pinene					x	x
29	cyclohexane					x	x	59	l-limolene						x
30	2-methyl-1,3-butadiene					x		60	terpene comp.						x

[1] Outdoor air (O) [2] Tobacco smoke (T) [3] Office Equipment (E) [4] Building materials (B) [5] Furnishings (F) [6] Consumer products (C)

which were the most important source in 29% of all rooms, were equivalent to 32% of those mechanically ventilated.

Tobacco smoking is in general considered as the most dominating source of sensory pollution when it takes place. In this investigation the intention was to evaluate the source strength through the CO concentration. However, many of these measurements were inaccurate and the use of CO as an index of tobacco smoke may be problematic. Sensory pollution due to tobacco smoke persists after smoking stops, whereas the CO concentration decreases rapidly. This is due to desorption effects as well as to decomposition of tobacco compounds adsorbed on surfaces. The outcome is that CO concentrations underestimate sensory pollution due to smoking. Therefore, in Fig. 12 tobacco smoke as a source is included in the category materials and other sources.

The TVOC data enabled chemical pollution sources to be divided into two main categories, the ventilation systems and the office which included materials, the occupants and all their activities. Rooms without mechanical ventilation systems were excluded from this analysis, since there was only one category of source in those cases. The identified chemical sources presented in Fig. 12 are based on 211 rooms. The office, its occupants and their activities were identified as the most important source of chemical pollution in about two thirds of the rooms.

VOC Sources

The number of VOCs measured in each audited building by the Tenax-GC method was in general higher than 60. However, the 15 most abundant compounds for each building were selected and the possible sources for these compounds were noted. These sources can be divided into 6 categories:

Outdoor sources (O): traffic, industry

Tobacco smoke (T)

Materials (M):

- Building materials (B): insulation, plywood, paint, etc.
- Furnishing (F): furniture (particle board), floor/wal covering, etc.
- Consumer products (C): cleaning, hygienic, personal care products.
- Equipment (E): laserprinters and other office equipment

Table 8 Percentage of rooms complying with the recommendations of prENV 1752 (CEN, 1994). (Figures in last column assume clean outdoor air.)

Type of room	Category	Required ventilation rate		% of rooms complying with prENV draft according to	
		[L/s·m²]	[L/s·person]	Ventilation rate	Perceived IAQ
single office room	A	2.0	20	55	9
	B	1.4	14	67	12
	C	0.8	8	78	32
landscaped office (smoking)	A	2.4	34	21	9
	B	1.7	24	42	12
	C	1.0	14	67	32

Ventilation systems as a source were not included since no data are available on which VOCs originate from the ventilation systems as such.

Table 7 shows the possible sources for the most important compounds found. Most of the compounds can originate from more than one source. Therefore, it was difficult to identify the sources of individual VOCs for each building. The most important sources of VOCs for each building have been determined by using the occurrence frequency of each source and by the information supplied through the checklist (e.g. outdoor air sources, smoking, number of laserprinters in the room). Table 7 shows that the most important indoor source of VOCs was materials, especially furnishing. The dominant volatile organic compounds detected in the majority of the buildings were solvents used in floor or wall coverings and pressed wood products (carpets, PVC flooring, floor adhesives, wallpaper, particle board, etc.). However, the most important sources were not the same for all buildings. In a significant number of buildings, the most important sources were consumer products, while in some buildings, outdoor air seemed to contribute significantly to the pollution load.

It should be noted that tobacco smoke contributes many more compounds in less volatile or non-volatile fractions, so that its effect on indoor air quality could not properly be assessed by this analysis.

Comparison of these data with the ranking of sources by sensory measurements did not show a good correlation. This was expected, since the identification of VOC sources determines the most important sources that emit VOCs. Ranking based on sensory measurements included sources that emit or produce other compounds than the compounds measured with the Tenax-GC method.

It is important to note that a number of individual VOCs were highly intercorrelated (Lagoudi et al., 1995). The intercorrelation among the concentration patterns found in the buildings showed that almost all buildings had at least a weak correlation with all the other buildings. This can be explained by the fact that a number of compounds could be detected in almost all buildings, such as toluene and benzene. Moreover, very strong correlations were found among the concentration patterns of different buildings. This was mainly due to the similar dominant compounds found in the majority of the buildings. These compounds were mainly aromatic hydrocarbons, a few aliphatic compounds and acetone. Acetone is mainly produced by the occupants while the other compounds can be produced by solvent-based materials or the exhaust fumes of cars.

Ventilation Levels and Perceived Indoor Air Quality

The ventilation rates were quite high with an average of 1.9 L/s·m² or 25 L/s·person, which is well above existing ventilation standards. In spite of the generous ventilation rates, it is remarkable that nearly 30% of the occupants and 50% of the visitors (trained sensory panels) found the indoor air quality unacceptable. In 44% or 79% of the buildings studied the minimum ventilation, rate of ASHRAE Standard 62 (0.7 L/s·m²) (ASHRAE, 1989) was met. Among these buildings with an average ventilation rate of 2.1 L/s·m² there were, however, only 17 buildings (36%) that met the aim of ASHRAE 62, namely that minimum 80% of the occupants should find the air acceptable. Furthermore, only a few of these buildings met the other ASHRAE 62 aim, namely that 80% of visitors should find the air acceptable.

Meeting existing ventilation standards is obviously no guarantee for proper indoor air quality acceptable for people.

A draft European pre-standard was issued by CEN TC 156 (CEN, 1994). It proposes figures for different levels of ventilation rates in office buildings (Table 8). These figures are meant only for low-polluting building materials and furnishings, and for a ventilation effectiveness of 1. They are based on air quality as perceived by persons coming from fresh, clean air and entering a room. Category A corresponds to 15% dissatisfied only, while categories B and C correspond to 20% and 30% respectively. It is interesting to compare the recommendations of this document with the values measured in the

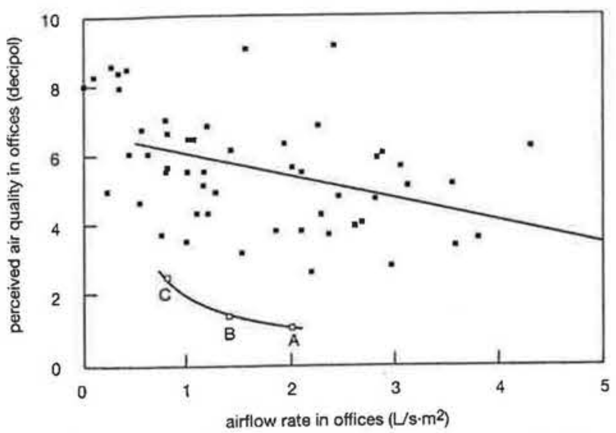

Fig. 13 Mean perceived air quality in investigated rooms per building vs. the mean outdoor air supply for the investigated rooms per building. A, B and C indicate the relationship on which CEN prENV1752 pre-standard is based.

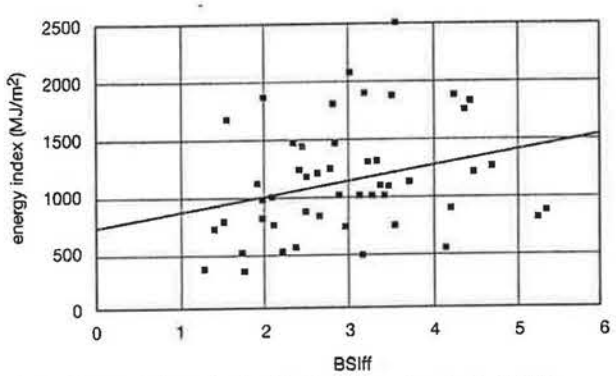

Fig. 14 Energy index related to Building Symptom Index (BSIff).

audited buildings. Therefore, Table 8 also shows the percentage of audited rooms which comply with the recommendations of prENV 1752. It can be seen that the ventilation rate in a majority of rooms is higher than the minimum requirements. However, the corresponding levels of perceived air quality were met in very few cases. No location was found below 2 decipol, and less than 3% reach category C of 2.5 decipol. Even if outdoor air were clean, only 32% of the locations would reach category C, and less than 9% would attain category A.

One of the relations that was analysed within this project is the relation between the perceived air quality and ventilation rates. Standards are based on the hypothesis that a higher ventilation rate results in better perceived air quality because of the dilution of pollutants. In this study it was found that the perceived air quality assessed by the sensory panels (in decipol) was on the average slightly better in the buildings that had a high ventilation rate, a relation that is shown in Fig. 13. The correlation between perceived air quality (in decipol) and airflow rate was statistically significant at a 5% level. The average perceived air quality (decipol) is, however, much worse than the theoretical relationship on which the prENV is based (see Fig. 13). A reason for this may be that in this comparison the quality of the supply air was not taken into consideration. Furthermore, pollution sources present in the ventilation system make a comparison difficult or even invalid.

Energy Consumption

Energy is required to heat or cool and to humidify or dry the outdoor air to ensure a comfortable indoor climate. Therefore, a relationship between the outdoor airflow rate and energy use may exist. However, such a relationship could not be found for two reasons. First, energy is used for many other purposes than ventilation, and the amount required for air conditioning is usually much less than 50% of the total. Secondly, it is not necessary to use a lot of energy to ensure a good indoor climate and proper ventilation. Ventilation is required for hygienic purposes. Heating and cooling can be provided by other means than air and a large part of the enthalpy contained in exhaust air can be recovered by convenient devices.

Average maximum and minimum energy indices were calculated for various groups of buildings, sorted by ventilation system, the presence of cooling or of heat recovery. Among the audited buildings, the eight buildings with natural ventilation, on average, had the lowest energy index. The buildings with mechanical ventilation included the largest consumers, independent of ventilation system. In each group there were buildings with a relatively low energy index. The presence of cooling or of heat recovery did not seem to have a great influence on the average energy index, except that the largest consumers were cooled buildings.

Figure 14 shows that high energy consumption did not necessarily result in better health. However, there was a significant and positive correlation between the BSI and the energy index, indicating more complaints in the most energy-consuming buildings (R^2=0.43). This may indicate that a potential exists for optimizing indoor air quality without consuming more energy (Roulet et al., 1995).

Discussion of IAQ-Audit Procedure

General

Representativeness of the audited buildings can be challenged in particular, as specific criteria were established in their selection (more than two years in operation, size large enough to accommodate 125+ workers, etc.). However, as no other region-wide consistent auditing procedure has been used up to now, these buildings represent the only choice for use.

In selecting locations to be measured, it was important to find those that were representative of each building as a whole. The sensory evaluations precluded the areas being too far apart, and in a building with many floors only a few floors could therefore be investigated. Selecting only five locations in a building with more than 100 or more offices may not be sufficient to obtain representative data for the whole building.

Measuring for only one day per building may not be sufficient to give a good indication of the pollution present, but financial limitations imposed this restriction. Repetition in the same building on multiple days could give more valid data.

Checklist and Questionnaire

The checklist used to register characteristics of the building, the ventilation system and selected locations was prepared beforehand. The information collected was used for the identification of pollution sources. On conclusion of the audit, several data were missing in the checklist and some of the information given was omitted as being irrelevant for interpretation of the results. Suggestions, together with a revised checklist, can be found in the final report (Bluyssen et al., 1995a).

Comments and possible or recommended adjustments of the questionnaire used in this project are given in the final report (Bluyssen et al., 1995a). However, a revised version of the questionnaire was not issued, firstly because this questionnaire was unique to the present study and may not apply to other studies, and secondly because no consensus on recommended adjustments was reached for all items.

Sensory Evaluation

Most of the participating countries performed the sensory evaluation by using a trained panel for the first time. A few complications arose because the process was new, but if it were to be used a second time, the necessary equipment is now available, people know how to use it and therefore are well able to train others in its use.

An alternative method is the use of an untrained panel. However, at least 50 persons are needed in such a panel to achieve the same accuracy as a trained panel of 12 to 15 persons (Gunnarsen and Bluyssen, 1994). The field procedure would therefore be more complicated.

Not all countries followed the instructions as given in the manual (Clausen et al., 1993) with respect to training equipment and procedures for selection and training. Therefore, comparison of panels is complicated, but a new approach was introduced in which three performance factors were defined (Elkhuizen et al., 1995). The Individual Performance Factor (IPF) describes the performance of a panel member with 2-propanone, the Panel Performance Factor (PPF) describes the performance of the whole panel with 2-propanone, and the Deviation Performance Factor (DPF) describes the panel performance with pollution sources other than 2-propanone. The three new performance factors IPF, PPF and DPF seem to be independent of the perceived air quality level.

In none of the selected spaces was the perceived air quality below 2 decipol. This lack of low levels in the audited buildings can be related to the method used. In general, levels below 2 decipol are hard to attain, even in the training method (some participants used a training room which did not comply with the recommendations in the manual). The reason for this can be twofold. Either it is essential to improve methods for measuring low pollution levels (<2 decipol), or the pollution levels below 2 decipol are just not as critical as we think. The latter indicates that the relation between the perceived air quality expressed in decipol with the percentage of dissatisfied visitors needs to be studied carefully, especially at the low decipol levels.

Chemical and Physical Measurements

CO_2, TVOC, temperature and relative humidity should whenever possible be measured continuously over at least 24 hours, to gain more information on the variation in time as a result of number of persons, opening/closing doors/windows. In that way the influence of the presence of researchers and panel members can also be taken into account. Continuous recording of about a week around the audit day could be useful to check whether the audit day is a special day or a standard day. CO_2, thermo-hygrograph or multigas semi-conductor sensors may be suitable for that purpose.

This project resulted in a enormous amount of information on VOCs in the 56 investigated office buildings throughout Europe. Considering the list of the most abundant compounds found in the 56 buildings, explanations for the occurrence of symptoms could not be found. With respect to future IAQ Audit programmes, it should be evaluated very carefully whether the effort involved in a (T)VOC analysis is justified in relation to the desired results.

The experience of this study suggests that in many buildings the specific task of estimating pollution source strengths was subject to an unacceptable accumulation of uncertainties due to: large uncertainties in the calculated pollution loads; adsorption, desorption and decomposition of components in the air influencing the concentrations in the air; the possible dependency of sensory evaluation on the pollution level (Knudsen, 1994); and conditions which are not in equilibrium due to changes in source emissions.

A significant source of experimental uncertainty arose from the combined use of different instrumentation in measuring ventilation rates, e.g. flowmeter used to measure air supply rate, tracer gas analyser used to determine overall ventilation rate, and CO_2 meter used to indicate occupancy. However, satisfactory results were established in cases where some degree of "control" was possible. Examples were cellular offices, with doors closed and negligible "leakage" paths to other rooms, constant air supply rate and recirculation fraction. It is therefore suggested that controlled measurements in isolated, typical, rooms could be a viable way of estimating pollution source strengths in buildings "in use".

Ventilation Measurements

Ventilation conditions were in general satisfactory for the purpose of assessing ventilation performance in terms of overall or outside air supply rates compared to design.

A more general assessment of the ventilation performance of a building, within the framework of assessing air quality, can be defined in terms of the following parameters:

- total supply rate of the ventilation system;
- total exhaust rate of the ventilation system;
- recirculation fraction of supply air;
- exfiltration and infiltration rates.

Metabolic carbon dioxide (CO_2) has been considered as a possible indicator of outside air ventilation rate, either overall or "per person". In principle, this could also enable a comparison with other buildings and against design values, and correlation checks with questionnaire data. An advantage is the ease of measurement, since CO_2 is always present in occupied buildings. In the audit procedure it has been used as an indicator of the number of occupants present, the ventilation rate being known from a separate measurement. In either case, certain minimum requirements must be met:

- steady-state conditions should be ascertained;
- number of occupants and activity levels should remain constant and must be known;
- outdoor CO_2 concentration must be monitored since it is variable over time.

An alternative approach has been proposed, using the "passive" perfluorocarbon tracer (PFT) techniques (Walker et al., 1994) and homogeneous emission.

Energy Consumption

From the experience gained during the audit, it can be concluded that in order to be able to manage and control energy consumption in office buildings, detailed information is needed on:

- electricity used for lighting and office appliances;
- electricity used for HVAC devices (pumps, fans, control systems, etc.);
- energy used for heating and for cooling, preferably in relation to internal and external temperatures and solar radiation.

Conclusions

- The ventilation rates were quite high with an average of 1.9 $L/s \cdot m^2$ or 25 $L/s \cdot$person, which is well above existing ventilation standards. Nevertheless, nearly 30% of the occupants and 50% of the visitors found the air unacceptable. Meeting existing ventilation standards is therefore no guarantee for acceptable indoor air quality.
- The ventilation rates met in general the draft European pre-standard prENV 1752. It should be noted that the figures in the draft pre-standard apply for buildings with low-pollution materials and furnishing.
- The average TVOC in $\mu g/m^3$ toluene equivalents, the mean particulate matter, the CO_2 and the CO concentrations met in general the requirements in existing national standards and European guidelines.
- Important pollution sources in the audited buildings were the materials, furnishing and activities in the offices and the ventilation system in the buildings. The occupants were less significant pollution sources.
- No relation was found between sensory and chemical pollution loads or perceived air quality and TVOC levels. Because some specific components (VOCs) have a high sensory effect, while others have not, total volatile organic compounds might not correlate with the sensory evaluations.
- Pollution sources comprised materials and furnishings in the office environment, the ventilation system, occupants, tobacco smoking and outdoor pollution. The following contributors were suggested: flooring, glues, paints, wax, office machines, cleaning agents, filters, humidifiers, heat exchangers, ducts, present and previous tobacco smoking, consumer products, outdoor traffic and industrial pollution.
- The mean perceived air quality showed significant correlation with the measured ventilation rates, implying that buildings with high ventilation rates had better perceived air quality than other buildings.
- The mean perceived air quality assessed by the sensory panels giving the unadapted impression of the air quality showed no correlation with occupants' health and their acceptability of the air quality.
- No correlation between the perceived air quality assessed by the sensory panels in the offices and the perceived air quality assessed by the sensory panels outdoors seemed to be present. Also, the perceived air quality in offices did not correlate with the perceived air quality in the ventilation supply air.
- The analysis of the questionnaire showed that responses from the retrospective part and the present-time part were correlated.
- The yearly energy consumption per gross heated floor area varied by a factor of seven from the least to the most energy-consuming building which shows a large theoretical saving potential as well as a great diversity of conditions for the different buildings within each country and for the different countries.
- Energy data were often difficult to obtain from the building management because the energy consumption was not known in detail. This indicates that energy consumption is often still of less importance to management, probably because it represents only a minor part of the operating costs of the building.
- Energy consumption in the buildings audited in the northern European countries was not higher than in the buildings audited in the other European countries, which seems to indicate that energy consumption has been adapted to national standards (which address climate conditions).
- Energy consumption varied strongly from building to building. In practice, it depends more on planning, construction, and management than on climate, building type or HVAC systems. It is thus possible to construct low-energy buildings using different architectural designs and various HVAC systems.
- No contradiction between low energy consumption and good indoor air quality was found. Hence, a potential exists for optimizing indoor air quality without consuming more energy.
- No correlation between energy consumption and outdoor airflow rate was found. This indicates that in general energy is used for other purposes than ventilation.
- No systematic regional differences were found in the 56 European office buildings as regards IAQ parameters, occupant responses or energy consumption.

Concluding Remarks

This study clearly indicates that the occupants are a less dominant pollution source and that sources of pollution in the audited European office buildings comprised mostly building materials and components in the ventilation systems. Since the source of pollution was mainly the building rather than the occupants, documented by low CO_2 concentrations, it is essential to acknowledge the building, including the ventilation system, as a pollution source. To improve indoor air quality without consuming more energy, source control should be applied. Source control should be the first priority instead of dilution of pollutants by ventilation or by cleaning the air. Source control must be applied to the materials, the systems and activities (e.g. smoking). By reducing pollution sources, e.g. by selection of low-polluting floor covering, indoor air quality may be maintained or even improved at lower ventilation rates. Manufacturers of building materials and furnishings should be encouraged to provide information on their products so that engineers and architects more easily can select low-polluting materials. Designers of systems, manufacturers of components and maintenance professionals must be aware of the importance of systems as a potential source of pollution. A reduction or elimination of environmental tobacco smoke, for instance by regulation of the smoking policy in office buildings, can improve indoor air quality or allow lower ventilation rates.

The present procedure with a one-day building audit was successfully carried out in all buildings by 9 teams, in 9 countries. The audit method, including equipment, is described in the Research Manual (Clausen et al., 1993) and thoroughly discussed in chapter 5 of the final report (Bluyssen et al., 1995a). In future building audits, elements of the method could be used and compared with the results from the present Europe-wide survey. Some improvements of the procedure could be adopted. The database with occupants' responses, measured IAQ-parameters and energy consumption is now available as a reference standard.

In this project, the use of a trained panel was demonstrated. The assessments of a trained panel are a measure of the possible dissatisfaction of visitors or the first impression of indoor air quality. Since Yaglou, existing ventilation standards (e.g. ASHRAE, CIBSE, Scandinavian) are based on the first impression of indoor air quality. Since 1981, ASHRAE 62 has prescribed a panel method to test the first impression. This first impression may be different from the adapted impression of occupants, as is clearly shown in this project. This does not mean that the first impression is not important. The first impression of indoor air quality is important in its own right, just as the first impression of any other parameter can be essential. The unadapted first impression is the basis on which ventilation systems have been designed for 60 years. The adapted impression of the occupants is gradually also being considered by design and in standards. It is also an impression in its own right and according to the present study, the two impressions need not correlate for the reasons given in this paper.

In this project, for the first time, sensory panels were trained in nine different countries, using a predescribed method. This method can be improved and development is necessary. However, the project showed that sensory panels can be used to screen buildings for combined source-ventilation problems. In this project, the sensory panels were used to gain an impression of the different sources and to describe the total sensory pollution load in olfs. Trained sensory panels are therefore yet another instrument to describe indoor air quality and sources of pollution in buildings. The future will tell us how important they are or can be.

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Sensory Pollution and Microbial Contamination of Ventilation Filters

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Abstract The sensory pollution load and microbial contamination of glass-fibre filters at high and low relative humidity were investigated in an experimental set-up in the laboratory. Dust and particles from the outdoor air were collected in two EU7 glass-fibre filters for a pre-conditioning period of 16–18 weeks during which there was a constant airflow with a velocity of 1.9 m/s through the filters. One of the filters was exposed to outdoor air of approximately 40% relative humidity and 10°C, the other to outdoor air of approximately 80% relative humidity and 5°C. The dust in ventilation filters can constitute a serious pollution source in the indoor environment, causing deterioration in the quality of the supply air even before it enters the ventilated spaces. The sensory pollution load from the used filters after the continuous operating time of 16–18 weeks was significantly higher than the sensory pollution load from new filters but the sensory load at 40% and 80% relative humidity did not differ. The microbial contamination of the supply air downstream of the filters, which on average had been exposed to outdoor air of 40% and 80% relative humidity, was negligible.

Key words Indoor air quality; Perceived air quality; Sensory pollution source; Ventilation filter; Microbial contamination; Dust

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Introduction

The aim of mechanical ventilation in office buildings is to remove and dilute emitted pollutants by supply and removal of air to the space in order to achieve an acceptable indoor air quality for the occupants of the ventilated spaces. However, during the last decade, numerous studies have reported that a significant percentage of occupants in non-industrial spaces may be exposed to indoor environmental conditions that can cause discomfort, reduced performance and even adverse health effects (Burge et al., 1987; Finnegan et al., 1984; Jaakola et al., 1991; Kröling, 1988; Robertson et al., 1985; Skov et al., 1987; Sundell et al., 1994; Turiel et al., 1983; Zweers et al., 1992). A major cause of the problems may be the mechanical ventilation or the air-conditioning system since several studies report more complaints and symptoms among occupants in mechanically ventilated or air-conditioned buildings than in naturally ventilated buildings.

Ventilation systems as a potential source of contamination in buildings have until recently been ignored in ventilation standards and guidelines (ASHRAE, 1989; NKB, 1981). The introduction of the sensory units, olf for sensory pollution source strength and decipol for perceived air quality, made it possible to quantify all pollution sources in a space (Fanger, 1988). Investigations in more than 50 buildings comprising offices (Fanger et al., 1988; Pejtersen et al., 1990), assembly halls (Fanger et al., 1988), schools (Thorstensen et al., 1990), kindergartens (Pejtersen et al., 1991) and bars (Pejtersen et al., 1988) have shown that the ventilation system often contributes a major part of the total sensory pollution load. In a more detailed study of eight ventilation systems, rotary heat exchangers, humidifiers and filters were found to be major pollution sources (Pejtersen et al., 1989). Further studies on the sensory pollution load of filters showed that the pollution load was caused by dust in the filters rather than by the filter material itself (Bluyssen, 1990; Hujanen et al., 1991) and that the pollution load increased with increasing operating time and with the amount of dust accumulated in the filters (Pasanen et al., 1994).

Ventilation systems may function as a reservoir or an amplification site for microorganisms (Morey, 1988; Ager and Tickner, 1983). Microorganisms need water and nutrients to be able to grow (Miller, 1992; Pasanen et al., 1991). Since ventilation filters are often placed close to the outdoor environment, the relative hu-

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