Designing for good air quality in ventilated buildings

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Het ontwerpen van een goede luchtkwaliteit in geventileerde gebouwen

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Summary

Existing standards do not quarantee good air quality in ventilated buildings. New principles for design are therefore proposed. In contrast to existing standards, all pollution sources are acknowledged. The required ventilation is calculated on the basis of the total degree of indoor pollution, the available outdoor air quality and the desired level of indoor air quality. The aim is to design for air quality, not just for air quantity. An important point is to avoid pollution sources in the ventilation system. This article discusses potential pollution sources and future modifications of ventilation systems to minimize such sources.

Samenvatting

Bestaande standaarden zijn geen garantie voor een goede luchtkwaliteit in gebouwen.
Daarom stelt de auteur nieuwe ontwerpprincipes voor. In tegenstelling tot de bestaande standaardvoorschriften worden alle vervuilingsbronnen in acht genomen.
De vereiste ventilatie wordt berekend op basis van de totale vervuilingsgraad in de ruimte, de beschikbare buitenluchtkwaliteit en het niveau van de gewenste binnenluchtkwaliteit.
Het doel is om te ontwerpen naar luchtkwaliteit, niet naar kwantiteit.
Het is belangrijk om vervuilingsbronnen in het ventilatiesysteem te voorkomen.
Dit artikel behandelt de mogelijke vervuilingsbronnen en de wijzigingen in het ventilatiesysteem om deze bronnen zoveel mogelijk uit te bannen.

Introduction

The aim of ventilation and air conditioning is usually to provide thermal comfort and good air quality for occupants of a space. In quite many cases this aim is not fulfilled. Complaints of poor air quality have been documented in numerous field studies [1-4]. The complaints include the perception of stale and stuffy air, irritation of mucous membranes, headaches, lethargy etc. These complaints are sometimes called the 'sick building syndrome' [5]. The complaints are not confined to a few special buildings for they occur in most indoor spaces. There are, however, large differences in the percentage of occupants who are affected.

Ventilation systems are normally designed according to existing ventilation standards. Unfortunately, these standards have serious shortcomings. They prescribe a certain quantity of outdoor air to be supplied per person in a space. But this does not quarantee good air quality. The same supply of air may provide acceptable air in some buildings, mediocre in many others and catastrophic air quality in a few buildings.

There are reasons why the present standards do not work. Most important is that they assume the occupants to be major or exclusive polluters. But recent studies have documented that the building itself, including furnishing, carpeting and even the ventilation system in itself often may be a more important polluter than the occupants [6-8]. Another shortcoming is that the supplied air quantity is the same whether the outdoor air has a high or a low quality. A third shortcoming of many existing standards is that the indoor air quality aimed at is poorly defined. The standards prescribe air **quantity** rather than air **quality.**

The *thermal* design of air-conditioning systems takes place in a much more rational way. The cooling load is determined by adding all heat sources, the outdoor design temperature and humidity are considered and the space is designed for thermal comfort, i.e. a certain operative temperature. If thermal design was as rudimentary as present ventilation standards, a constant cooling power would be prescribed per occupant independent of the outdoor temperature, all heat sources except the occupants would be ignored and nobody would care what the temperature in the space happened to be.

It is time that we upgrade the design of ventilation and indoor quality to the same level of rationality that we have used for years in the thermal design of airconditioning systems. This article presents such rational principles for a future ventilation standard. It is specified how to design for good indoor air quality in ventilated buildings. An important point is to avoid unnecessary pollution sources in the building and the ventilation system. The paper discusses potential pollution sources in ventilation systems, and future modifications of systems to minimize such sources.

Indoor Air Quality

The occupants in a space have two requirements to the air quality in a space. First the air should be perceived fresh and comfortable rather than stale, stuffy and irritating. Furthermore, the health risk of breathing the air should be negligible.

There are large individual differences in the human requirements. Some persons are very sensitive and have high requirements to the air they are breathing. Other persons are rather insensitive and have low requirements to the air. The quality of the indoor air may be expressed as the extent to which human requirements are met.The air quality is high if there are few

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dissatisfied and a negligible health risk. In this document the ventilation required to obtain a certain perceived air quality will be discussed separately from the ventilation required for a negligible health risk.

Perceived Air Quality

Humans perceive the air by two senses. The olfactory sense is situated in the nasal cavity and is sensitive to several hundred thousand odorants in the air. The general chemical sense is situated all over the mucous membranes in the nose and the eyes and is sensitive to a similarly large number of irritants in the air. It is the combined response of these two senses that determines whether the air is perceived fresh and pleasant or stale, stuffy and irritating. Perceived air quality may be expressed in decipol [9]. One decipol is the perceived air quality in a space with a pollution source strength of one olf, ventilated by 10 l/s of clean air, i.e. 1 decipol = 0,1 Olf/(l.s). One olf is defined as the pollution from a standard person [9]. Any pollution source can be expressed in olfs, i.e. the number of standard persons required to make the air as annoying as the actual pollution source. Fig. 1 shows the percentage of dissatisfied, i.e. those persons who perceive the air to be unacceptable just after entering a space, as a function of the ventilation rate per olf. Fig. 2 shows the corresponding relation between perceived air quality in decipol and the percentage of dissatisfied.

To determine the required ventilation it is essential to consider the level of indoor air quality to be desired. In some spaces it may be sufficient to provide a **minimum** air quality. In many spaces a **standard** air quality would be required, while in other spaces a **high** air quality may be desired. These three levels of perceived air quality are given in Table 1 as percent dissatisfied and in decipol. The decision on the desired level of air quality in a space depends mainly on economical considerations and on the application of the space.

The perceived air quality in Table 1 refers to peoples' initial judgement when entering a space. The first impression is essential, i.e. it is important that the air immediately is perceived acceptable. However, some adaption does take place during the first 15 minutes of occupancy. Considerable adaption takes place in air polluted by human bioeffluents, some adaptation occurs in tobacco smoke (at moderate levels), while little adaption usually takes place in air polluted by a mixture of building materials etc. [12].

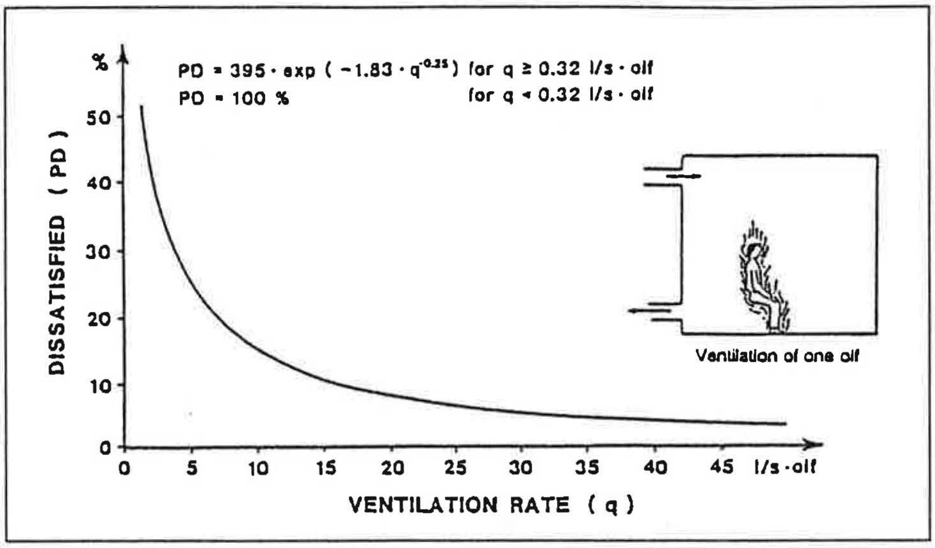

Figure 1. Dissatisfaction caused by one olf at different ventilation rates. The curve is based on European studies where 168 subjects judged air polluted by bioeffluents from more than one thousand sedentary men and women [9] Similar studies in North America [11] and Japan [10] show close agreement with the present European data.

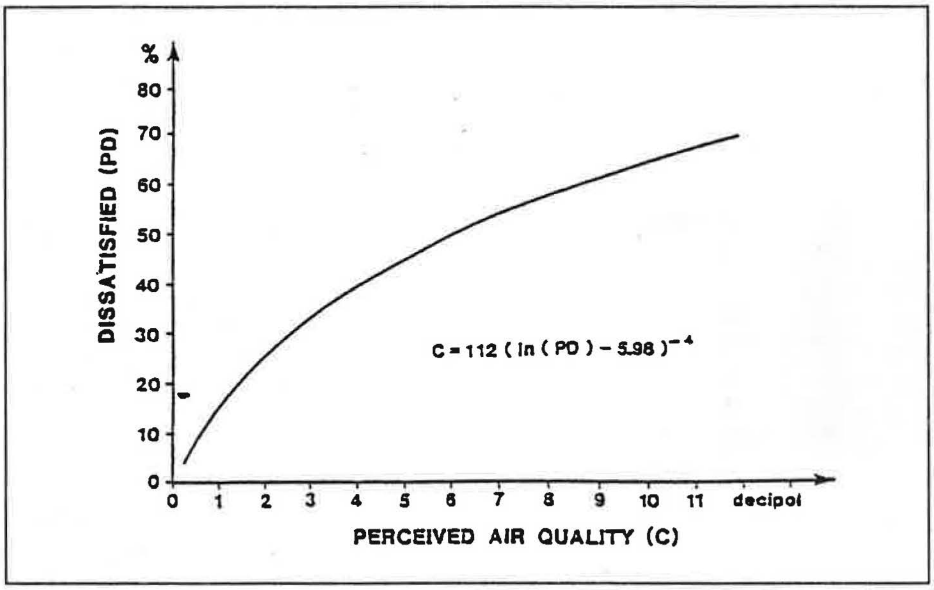

Figure 2. Perceived air quality in decipol as a function of the percentage of dissatisfied [9].

Carbon dioxide

Humans produce carbon dioxide (CO_2) proportional to their metabolic rate. By quantity it is by far the most important human bioeffluent. It is harmless and it is not perceived by humans at the low concentrations occurring indoors. Still it is a good indicator of the concentration of the other human bioeffluents being perceived as a nuisance. As an indicator of human bioeffluents carbon dioxide has been applied quite successfully for more than a century. The concentration of carbon dioxide outdoors is

	% dissatisfied	*perceived air quality decipol*	*required ventilation rate* l/(s·olf)*
High indoor air quality	~10	0,6	16
Standard indoor air quality	20	1,4	7
Minimum indoor air quality	30	2,5	4

* Assuming clean outdoor air and a ventilation effectiveness of one

Table 1. Three Levels of Perceived Air Quality

typically around 350 ppm. A one-decipol increment of perceived air pollution caused by bioeffluents correspondents to an indoor CO_2, increase of 470 ppm (for sedentary persons). Although the carbon dioxide is a good indicator of pollution caused by sedentary human beings, it is often a poor general indicator of perceived air quality, since it does not acknowledge the many pollution sources not producing CO_2.

Health Risk

Exposure to pollutants in the air may provide a certain health risk. To limit this risk to an insignificant level, it would be useful to establish an extensive list maximum allowable concentrations and corresponding exposure times for individual chemicals in the air.

For industrial premises Treshold Limit Values (TLV) exist. They apply to work places where chemicals are used routinely in the production process. In offices and similar work places there is no industrial justification for air pollution and lower limits should therefore be aimed at. The World Health Organization has recently published Air Quality Guidelines [13]. In this publication the health effect of certain air pollutants have been evaluated and guideline values for more than 20 chemicals are listed. They are elaborated for both outdoor air and indoor air. The guideline values in this brief list may be used as limits for individual chemicals in indoor air.

The metabolic processes of the occupants in a space require oxygen and produce carbondioxide. It is recommended that the oxygen concentration be higher than 220g/m_3 (80% of normal sea level concentration) and that the carbondioxide concentration be lower than 5g/m^3 (2500 ppm). The ventilation rate required to maintain these safe levels is very low. This means that oxygen and carbondioxide per se, very seldom will be a health problem in real buildings.

Air pollution Sources

The pollution sources include the occupants and their possible smoking and activities. Furthermore, materials in the building, including furnishing, carpets and even the ventilation system may contribute significantly to the pollution. Some materials pollute a lot, some a little, but they may all contribute to the degradation of the indoor air quality. It is recommended to select low-polluting materials for use in buildings. It is especially important to reduce potential pollution sources in the ventilation system.

Many pollution sources emit hundreds or thousands of chemicals but usually in small quantities. The source strength can either be expressed by the olf unit which integrates the effect of the many chemicals as perceived by human beings. Or it can be expressed as the emission of individual chemicals from the sources. The source strength may also be given as the total emission of a group of chemicals, e.g. volatile organic compounds.

The strength of some pollution sources is not constant. The source strength may change with temperature, humidity, age and pollution level in the space.

Pollution Load

The total pollution load in a space is found by adding all olf values of the different pollution sources in the space. The pollution sources usually comprise the occupants and the building, including furnishing, carpeting and air-conditioning system.

The occupants emit bioeffluents and some produce tobacco smoke. A standard sedentary person produces 1 olf, while an average smoker produces 6 olf [11]. Table 2 lists the pollution load from occupants at different activities with no smoking and with different percentages of smokers among the occupants. Table 3 lists examples of occupancy per m^2 floor in typical spaces.

	olf/occupant
*Sedentary, 1-1,2 met**	
0% smokers	1
20% smokers**	2
40% smokers**	3
100% smokers**	6
Physical Exercise	
Low level, 3 met	4
Medium level, 6 met	10
High level (athletes), 10 met	20
Children	
Kindergarten, 3-6 years, 2,7 met	1,2
School, 14-16 years, 1-1,2 met	1,3

* 1 met is the metabolic rate of a resting sedentary person (1 met = 58W/m^2 skin area, i.e. approx. 100 W for an average person).

** average smoking rate 1,2 cigarettes/hour per smoker

Table 2. Pollution load caused by the occupants

	occupants/ (m^2 floor)
Offices	0,07
Conference rooms	0,5
Assembly halls, theatres, auditoria	1,5
Schools (class rooms)	0,5
Dwellings	0,05

Table 3. Examples of occupancy in spaces

The source strength of the building may be found by adding the olf values of all materials present. But information on olf per m^2 is available for only a few materials at present. A more feasible approach is now to estimate the pollution load per m^2 floor caused by the building, including furnishing, carpeting and ventilation system. Such data have been measured in some existing buildings [6-8]. Table 4 comprises data from the measured pollution loads in different types of existing buildings. The pollution load caused by the building is often high and varies widely from building to building. It is essential that new buildings be designed as low-polluting buildings. The pollution loads listed in Table 4 for low-polluting buildings are target values for the design. They require a systematic selection of low-polluting materials for the building including furnishing, carpets and ventilation system. Many existing buildings need to be redecorated to reduce the pollution load.

The present design guidelines provide a strong encouragement to design low-polluting buildings. The award is a decreased ventilation requirement, a

	pollution load olf/(m^2·floor)	
	mean	*range*
Existing Buildings		
Offices*	0,3	0,02-0,95
Schools (class rooms)**	0,3	0,12-0,54
Kindergartens***	0,4	0,20-0,74
Assembly halls****	0,5	0,13-1,32
Low-polluting Buildings		
Target values	0,05-0,1	

* Data for 24 office buildings [6,7]

** Data for 6 schools [8]

*** Data for 9 kindergartens [19]

**** Data for 5 assembly halls [6]

Table 4. Pollution load caused by the building, including furnishing, carpets and ventilation system

smaller ventilation system and a lower energy consumption than in a high-polluting building.
It is recommended to calculate the total pollution load in a space by simple addition of the olf values of the individual pollution sources in a space. This has been shown to provide a reasonable first approximate method of combining many pollution sources [14]. But simple addition is not a prerequisite for the present method. Future studies may show that some materials, when occurring in the same space, provide a stronger or weaker total source strength than predicted by simple addition of the individual olf values.

Chemical Load
The source strength of a material may also be expressed as the emission rate of individual chemicals in $\mu g/(m^2 \cdot s)$. The total load in the space of each individual chemical can then be estimated by addition of the sources and expressed in $\mu g/s$. Unfortunately little information is available on the emission rate from the many materials used in practice. And it may be rather impractical to account for the source strength of each of the hundreds or thousands of chemicals occurring in indoor air. But in some cases where an individual chemical is suspected of being an important pollutant with respect to its toxic potential, an estimate of the total load of that particular chemical in a space may be possible.

Outdoor Air Quality
The required ventilation depends also on the quality of the outdoor air. Table 5 lists characteristic levels of outdoor perceived air quality. The World Health Organization has published Air Quality Guidelines [13], where guideline values for certain substances in the outdoor (and indoor) air are given. The outdoor air quality can be much worse than shown in Table 5 or given in the Air Quality Guidelines. In such cases it may be required to clean the air before it is suitable for ventilation.
It is the quality of the outdoor air at the air intake that counts. Proper location of the air intake is therefore essential.

	decipol
In mountains, at sea	0
In towns, excellent air quality	>0,1
In towns, fair air quality	0,2

Table 5. Typical outdoor levels of perceived air quality

Ventilation Effectiveness
The air quality may not be the same throughout a ventilated space. What really counts for the occupants is the air quality in the breathing zone. Such an inhomogeneity of the air quality in a space has an impact on the ventilation requirement. This is expressed by the ventilation effectiveness (ε_v) defined as the relation between the pollution concentration in the exhaust air (C_e) and in the breathing zone (C_i)

$$\varepsilon_v = \frac{C_e}{C_i}$$

The ventilation effectiveness depends on the air distribution and the location of the pollution sources in the space. If there is complete mixing of air and pollutants, the ventilation effectiveness is one. If the air quality in the breathing zone is better than in the exhaust, the ventilation effectiveness is higher than one and less ventilation is required. If the air in the breathing zone is poorer than in the exhaust air, the ventilation effectiveness is lower than one and more ventilation is required. The effectiveness depends on the ventilation principle for the air distribution and on the location of the pollution sources in the space [16]. For properly designed systems the ventilation effectiveness is often around 1 for mixing ventilation and around 1,2-1,4 for displacement ventilation.

Required Ventilation
The required ventilation rate to obtain the perceived air quality desired indoors is calculated from this equation [15]:

$$Q_c = 10 \cdot \frac{G}{C_i - C_o} \cdot \frac{1}{\varepsilon_v} \qquad (1)$$

where:

Q_c = ventilation rate required for comfort (l/s)
G = total pollution load (olf)
C_i = perceived indoor air quality, desired (decipol)
C_o = perceived outdoor air quality at air intake (decipol)
ε_v = ventilation effectiveness

The ventilation rates required to provide comfort will automatically decrease the concentrations of chemicals in the indoor air. In a low-polluting building with a careful selection of building materials this will in most cases lead to concentrations of chemicals causing no adverse health effects. In special cases, the ventilation required to control the air quality from a health point of view may be calculated. The ventilation required to maintain the most critical individual chemical below the alowable concentration may be calculated by this equation:

$$Q_h = 10 \cdot \frac{G}{C_i - C_o} \cdot \frac{1}{\varepsilon_v} \qquad (2)$$

where:

Q_h = ventilation rate required for health (l/s)
G = total pollution load of chemical ($\mu g/s$)
C_i = allowable concentration of chemical ($\mu g/l$)
C_o = outdoor concentration of chemical at air intake ($\mu g/l$)
ε_v = ventilation effectiveness

The ventilation rates required to control comfort and health are calculated seperately from Eqs. (1) and (2) and the highest value is used for design. Eqs. (1) and (2) apply to steady-state conditions. Adsorption and desorption of air pollutants at surfaces in the space may prolong significantly the period it takes to obtain steady-state air quality. Chemical reactions of pollutants in the space may also modify Eqs. (1) and (2).

Procedure to determine the Required Ventilation
The following procedure should be followed to determine the ventilation requirements in a building. First a decision should be taken on the desired indoor air quality in the ventilated space. Table 1 offers three levels of air quality corresponding to 10, 20 or 30% dissatisfied. Then the perceived outdoor air quality available should be estimated (Table 5).
The next step is to estimate the strength of the pollution sources in the building, i.e. to estimate the olf load. The olf load per occupant is given in Table 2, depending on physical activity and the tobacco smoking behaviour of the occupants. Examples of occupancy, i.e. the number of people per m² floor is given for different spaces in Table 3. The pollution caused by the building including furnishing, carpets and ventilation system can be estimated from Table 4. The total olf load is found by adding the loads from the occupants and the building. Depending on the principle of ventilation used in the space, the ventilation effectiveness may be estimated.
The ventilation required to handle the

total olf load and obtain the desired perceived indoor air quality is found Eq. (1).
An analogous calculation of the ventilation required to avoid health problems caused by the most critical individual chemical may be found from Eq. (2). The highest of the two ventilation rates is then used for design.
For several reasons it may still be difficult to use Eq. (2) in practice. First the emission rates from the pollution sources (the chemical load) are usually not available. Furthermore, there are guideline values available for only a small number of the many chemicals occurring in non-industrial buildings. Field studies in many buildings indicate, however, that for spaces ventilated for comfort, the concentration of chemicals will usually be very low, i.e. lower than the guidelines and typically several orders of magnitude lower than the TLV values. Still, there may occur pollution sources of concern from the point of view of health. Rather than diluting the pollutants from such sources by ventilation, it is recommended to avoid or control such sources and apply low-polluting materials in the building.

Examples
New office building, situated in a town with excellent outdoor air quality $C_o = 0$ decipol (Table 5). Standard indoor air quality is desired, i.e. $C_i = 1{,}4$ decipol (Table l). No smoking, i.e. 1 olf/occupant (Table 2). The occupancy is 0,07 occupants/(m².floor) (table 3). Systematic use of low olf materials in the building, i.e. 0,1 olf/(m².floor) (Table 2). Displacement ventilation is applied with an estimated ventilation effectiveness of 1,3.

Occupants 1 × 0,07 =	0,07 olf/(m².floor)
Building	0,1 olf/(m².floor)
Total pollution load	0,17 olf/(m².floor)

Required ventilation rate

$$Q_c = 10 \cdot \frac{0{,}17}{1{,}4-0} \cdot \frac{1}{1{,}3} = \underline{0{,}9 \text{ l/s (m}^2\text{.floor)}}$$

If instead a minimum indoor air quality is sufficient, the required ventilation is

$$Q_c = 10 \cdot \frac{0{,}17}{2{,}5-0} \cdot \frac{1}{1{,}3} = 0{,}5 \text{ l/s (m}^2\text{.floor)}$$

If, on the other hand, a high indoor air quality is prescribed, the required ventilation is

$$Q_c = 10 \cdot \frac{0{,}17}{0{,}6-0} \cdot \frac{1}{1{,}3} = 2{,}2 \text{ l/s (m}^2\text{.floor)}$$

Existing office building, situated in a town with fair outdoor air quality $C_o = 0{,}2$ decipol (Table 5). Minimum indoor air quality is desired, i.e. $C_i = 2{,}5$ decipol (Table 1).
Smoking is allowed and 40% are estimated to be smokers, i.e. 3 olf/occupant (Table 3).
The occupancy is 0,07 occupants/(m² floor). Standard materials are used in the building, i.e. 0,3 olf/(m² floor) (Table 2). Displacement ventilation is applied with an estimated ventilation effectiveness of 1,3.

Occupants 3 × 0,07 =	0,2 olf/(m².floor)
Building	0,3 olf/(m².floor)
Total pollution load	0,5 olf/(m².floor)

Required ventilation rate

$$Q_c = 10 \cdot \frac{0{,}5}{2{,}5-0{,}2} \cdot \frac{1}{1{,}3} = \underline{1{,}7 \text{ l/s (m}^2\text{.floor)}}$$

Pollution in Ventilation Systems
Ventilation and airconditioning systems are constructed to deliver a certain quantity of air which may be heated or cooled, humidified or dehumidified and filtered for particles. This should take place at a low noise level. The many dozens of materials typically occurring in the systems are applied to fulfill these needs. Nobody considered what happened to the quality of the air while passing the ventilation system. It was implicitly assumed that, if anything, the quality of the air was improved by passing through the system.
Unfortunately this is not the case. Field studies in 15 ventilated or air-conditioned buildings in Copenhagen [6] have shown that quite high pollution sources do occur in some systems (see Figure 3). On average 40% of the total pollution sources in the buildings were situated in the system but this average

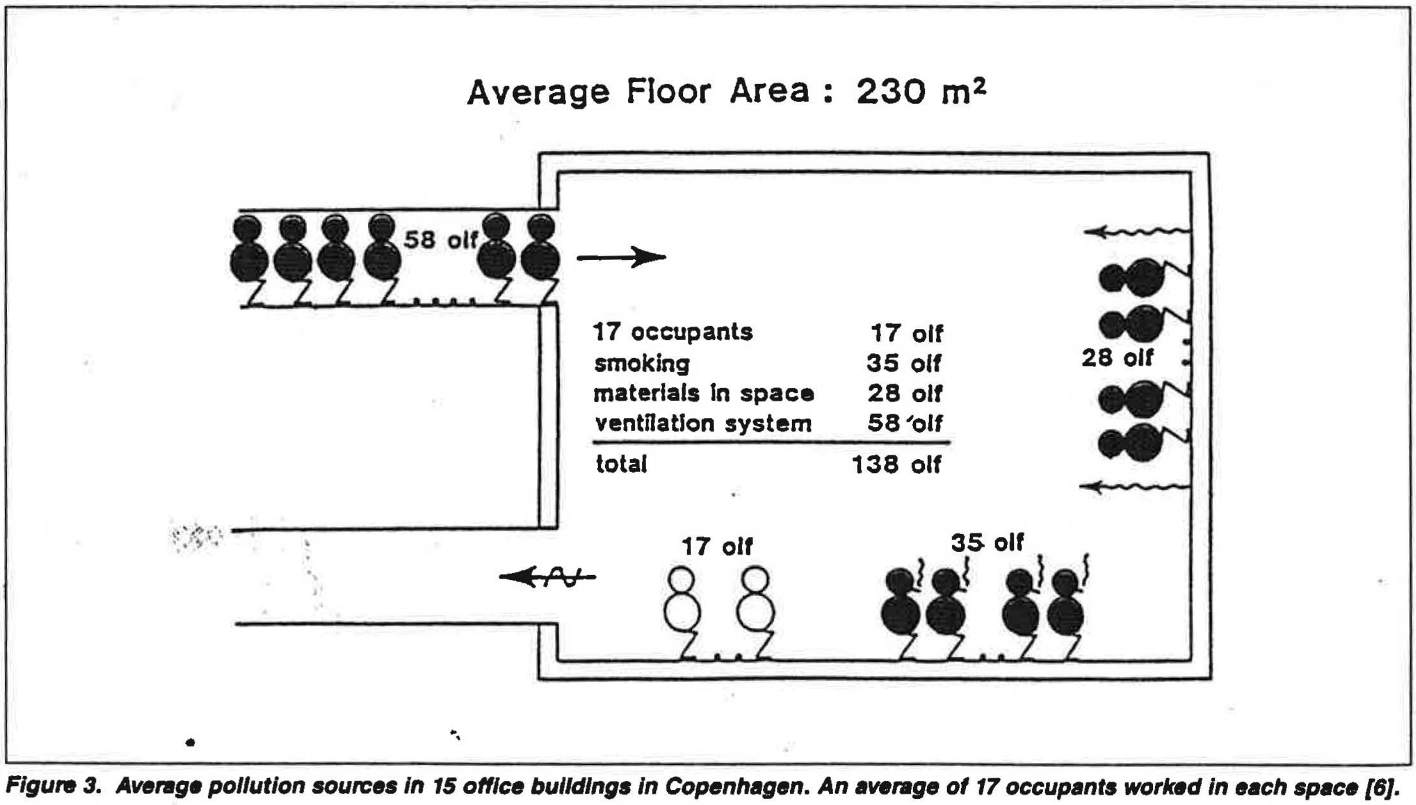

Figure 3. Average pollution sources in 15 office buildings in Copenhagen. An average of 17 occupants worked in each space [6].

covered large differences. One third of the systems were virtually clean while some high-polluting systems brought the average up.
Another field investigation on eight ventilation or air-conditioning systems [17] showed that the perceived air quality on an average changed 0,8 decipol by passing through the system, again with large differences from one system to the other. The air quality was assessed before and after each component to identify where the pollution sources were situated. Filters and rotary heat exchangers provided significant contributions.
Poorly maintained humidifiers may also pollute the air. On the other hand, spray humidifiers and sorbent filters may improve the perceived air quality.
Further studies are obviously needed. It is likely that alternatives to well-known components and processes in ventilation and air-conditioning systems need to be developed. Right now it is essential to screen the dozens of materials used in our systems and avoid high polluters. We should consider how a proper low-polluting system be designed so that it is easy to maintain during the service life of the system. We may blame the architect for pollution caused by building materials, carpeting and furnishing, but it is the exclusive reponsibility of the HVAC engineer that the ventilation system be designed and maintained without significant pollution sources. Fresh air spoils easily. It therefore deserves cautions and careful treatment in our ventilation and air-conditioning systems.

Conclusions

- Ventilation systems should be designed to provide indoor air quality, not just air quantity.
- Rational new design principles to provide a desired indoor air quality are presented.
- The building, including furnishing and ventilation system, should be acknowledged as a pollution source in line with the occupants.
- All materials and processes applied in ventilation and air-conditioning systems should be surveyed to identify and avoid pollution sources.

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