Chapter

Building for Sustainable Ventilation and Air Quality

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Abstract

Most legislations concerning ventilation are based on perceived air quality criteria, but ventilation is also important for the health of the occupants. The perceived air quality criteria can be viewed as a pragmatic tool to achieve an adequate ventilation for precautionary health measures. From a comfort and health perspective, the ventilation rate and an efficient air distribution are both important for achieving a healthy and comfortable indoor environment. Yet, most legislative requirements focus on the ventilation rate. This is not enough, and it is recommended that legislation also address the air distribution with the same zeal. In particular, the efficient distribution of fresh air to the occupied zones or lowering the concentrations of pollutants in the occupied zones. Because there are clear links between ventilation and health, it is extremely worrying that the "energy efficiency first" principle advocated in the Energy Performance of Buildings Directive (EPBD) has led to decreasing ventilation requirements in the European Union legislations, at the same time as the objective is to aggressively tighten the envelopes of the building stock. A second consequence of EPBD is probably that many naturally ventilated buildings will be retrofitted with mechanical ventilation systems. It is not clear that this would be the more sustainable solution in the long run.

Keywords: ventilation requirements, ventilation rates, air distribution, air change rate, local mean age of air, air change efficiency, indoor air quality, EPBD, natural ventilation

1. Introduction

The purpose of buildings is to protect the occupants from a harsh outdoor climate, but also to provide a comfortable and healthy indoor environment. The latter two objectives are intimately related to building ventilation, i.e. the exchange of indoor air with outdoor air. However, 40% of the total consumption of energy resources in the European Union (EU) can be traced to building use. [1] A large part of the consumption is due to the need to condition the indoor air for the thermal comfort of the occupants, i.e. heating or cooling depending on the outdoor climate. In these situations, exchanging the conditioned indoor air for unconditioned outdoor air obviously raises the energy consumption. On the other hand, striving for more energy efficient buildings without a clear strategy for adequate ventilation is likely to lead to more toxic and hazardous indoor environments. In a wider perspective, the relative projected societal costs for the occupants of a building, compared to the energy use in that building, are probably nine to one. [2] Compromising public health in the name of "energy efficiency" can therefore lead to a considerable economic backlash for society. In a larger perspective, many indoor sources of pollutants in the world have been identified as major causes of premature mortality, e.g. combustion of biomass fuels for cooking, burning incense or mosquito coils and parental smoking. [3, 4] In addition, if the occupants perceive the indoor environment to be unhealthy or uncomfortable, they are likely to take actions (e.g. use air cleaners or increase ventilation flows) that will increase the energy use in buildings. [5]

After the energy crisis in 1973, new and renovated buildings have been built with increasingly tighter envelopes to stop uncontrolled air exchanges through cracks and leaks in the construction and to improve energy efficiency. In 1974, the "Passivhaus"-concept combined three energy-saving measures: adequate thermal insulation, a tight envelope, and heat recovery into the idea of a building requiring no, or very little, energy use after it was built. [6] After a few serious backlashes in the early days, the building technologies used to achieve energy efficiency in nearly zero energy (NZE) buildings are currently more mature, but the efficiency of the corresponding ventilation strategies have not been given the same attention. There are several examples of inadequate ventilation in NZE buildings. [7] After the EU Energy Performance in Buildings Directive (EPBD) in 2010, [1] stipulating that all new building should meet the NZE requirements, a majority of EU ventilation experts were worried that EPBD would lead to a worse indoor air quality as compared to the current state. [8]

The EPBD is an integral part of the European Green Deal: an action plan to reach a "climate neutral" EU economy. [9] The European Green Deal outlines a more sustainable path for economic and societal development to "transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy". [9] The European Green Deal addresses many issues: a toxic-free environment; preserving and restoring ecosystems and biodiversity; circular economy; a fair, healthy and environmentally friendly food system; but much focus is devoted to an energy transition to reach zero net emissions of greenhouse gases in the EU by 2050 at the latest. [9] Zero net emissions means that there should be a balance, between the actual emissions of greenhouse gases and the absorption of greenhouse gases by nature (or other processes), in some bookkeeping system like the Emission Trading System. [9, 11] This goal of net zero emissions by 2050 will be legally binding for the member states if the proposal for an EU Climate Law is ratified. [10] Renewable energy sources as well as moving to more energy efficient and sustainable solutions play essential roles in the European Green Deal. [9] The EPBD is the result of the European Commission's resolve to "rigorously enforce legislation related to the energy performance of buildings". [9]

Another issue addressed in EPBD (and its amendments as well as in the European Green Deal) is that 85% of the present building stock in the EU is built before 2001, and most of those buildings are not considered energy efficient. [12, 13] More importantly, at the current rate of renewal (1%), 85–95% of the buildings that will be standing in 2050 are already built. [9, 12, 13] Increasing the rate of renovation of the existing building stock to NZE standard should therefore be strongly encouraged in order to reach "climate neutrality". [12] Recently, the European Commission also proposed to triple the building renewal rate to 3% coupled with an even more aggressive renovation strategy to kick-start the EU economy after Covid-19. [14]

Adapting existing buildings to NZE are much more complex tasks than to build a NZE-building from scratch. It requires a considerable knowledge-base of old building techniques, old installations, and the consequences that may arise when NZE technologies are retrofitted to these older structures. In addition, 25% of the existing buildings are historic and will require respect for aesthetics, conservations principles and architectural craftsmanship. [15] In fact, the craftsmanship in many older buildings, although non-historic, deserve the same respect. However, the guiding principle of EPBD: "Energy efficiency first", clearly states that the energy aspect will be given a high weight in a decision conflict. [14] Even though the EPBD states that indoor environments should be healthy or that cultural heritage should be safeguarded and preserved, it is obvious that these incentives will be pushed towards the minimum legal requirements when they are in conflict with the efforts to achieve energy efficiency. [12]

In the decision conflict between energy efficiency in buildings and adequate ventilation, EPBD has put an increasing pressure on governmental agencies in the member states to lower the standards for ventilation and air quality in existing building codes and ventilation regulations (see discussion in Section 2.3). [12] From a ventilation perspective, the standards for air quality should rather become more stringent when the buildings become tighter. There is a balance between the existing ventilation regulations in a country and the air leakages in its building stock because these air leakages contribute to the indoor ventilation, albeit uncontrollably. Legislative regulations on the performance of ventilation systems are also important counter balances to the quest for energy efficiency in buildings. The pressing question is *what* must, or should, be regulated to ensure an adequate indoor environment that is comfortable and healthy for the occupants. The aim of Section 2 of this chapter is to investigate possible answers to this question and put them in a wider perspective.

Another effect, of the coming EPBD renovation wave, is probably that the number of buildings with natural ventilation systems will decrease. [8] Many of the older buildings have some kind of natural ventilation system, whereas most new buildings have mechanical ventilation systems. Because heat recovery is such an important ingredient in NZE buildings, mechanical ventilation systems will be chosen more frequently in spite of the fact that some of the energy recovered will be offset by the energy used by the fans. In a milder climate, a balanced mechanical ventilation system with heat recovery will probably save very little energy and would be costly from a life cycle perspective. [16] Fully functional older buildings with natural ventilation systems will perhaps be retrofitted with mechanical ventilation systems and lose some of their aesthetical or cultural heritage values. On the other side of the spectrum, if such a building cannot satisfy the building code regulations, it may be declared unfit for use and demolished. [17] It would naively appear that natural ventilation, where natural driving forces for air flows are used to ventilate the building, is a more sustainable solution than mechanical ventilation, where electrical energy is used to power fans that generate air flows with high pressures. While even the older natural ventilation systems have many advantages regarding occupant satisfaction, they have some difficulties to compete with the mechanical systems when it comes to predictability, controllability, and heat recovery. [16, 18] Nevertheless, natural ventilation systems are considered the more sustainable options in many research initiatives. [19–22]

From this perspective, a revival of the use of natural ventilation systems, rather than the projected decline outlined above, would be desired. There are a number of new promising innovations and old, forgotten, know-how is rediscovered, e.g. wind towers, evaporative cooling, solar chimneys and box windows to name a few. [23] The thermal performances of many ancient buildings, with natural ventilation systems, are far superior to many modern buildings, with mechanical ventilation systems. The list could probably be made very long, but some selected examples are: the "baadgir" in the Dolatabaad garden in Yazd, Iran, that uses several of the mentioned techniques [24]; the Villas at Costozza, Italy, use cool air from nearby caves; the Palazzo Pitti in Florence, Italy, use the cooler air from the Boboli gardens and further cool it underground; the cloister Palazzo Marchese in Palermo, Italy, cool the air underground and augment the effect using underground rivers. [23] Natural ventilation systems thus display many good properties, but their drawbacks will prevent them from fulfilling all ventilation needs. The future of sustainable ventilation will probably be centered on optimal combinations of natural and mechanical ventilation techniques instead, i.e. hybrid ventilation systems.

While there are many good modern examples of buildings with natural and hybrid ventilation systems, [21] there are at least three important hurdles to cross. One hurdle is that the local building codes and the ventilation regulations in many instances are written with mechanical ventilation systems in mind, which makes it difficult for natural ventilation systems to comply. The second hurdle is that architects and builders may consider natural ventilation systems as a more risky option than mechanical ventilation systems. Describing the low pressure systems of natural ventilation is inherently more difficult than to describe the high pressure systems of mechanical ventilation. The most diligent Computational Fluid Dynamics (CFD) description of natural ventilation can be completely transformed when occupants are moving or closing doors. To cross this hurdle, better tools for design of larger buildings with natural or hybrid ventilation are needed. [16, 25] The third hurdle is urbanization. Many effects of urbanization: pollution, "heat islands", and wind obstruction, favor the use of mechanical ventilation systems. [20] Ventilation requires the outdoor air to be healthy, otherwise it must be cleaned at a considerable cost of energy. There are many issues concerning natural ventilation to discuss, but in this chapter, there is only a brief discussion (at the end of Section 2) on the hurdles for natural ventilation systems in the local building codes and ventilation regulations.

2. Requirements for ventilation

The purpose of building ventilation is to provide a healthy and comfortable environment for the occupants. However, the human perception of the conditions that constitute a healthy and comfortable environment depends on many factors. [26, 27] The section starts with a historical perspective on the evolution of different ideas concerning the relationship between ventilation and human health and comfort. This is followed by a theoretical treatment of ventilation that hopefully will give the reader some insights into how a good ventilation system performance may be specified. The section finishes with a critical examination of how legislative regulations of ventilation are specified and some suggestions on how it may be modified to facilitate the use of natural and hybrid ventilation systems.

2.1 A short history of ventilation and health effects

The notion that "bad air" leads to health problems has a long history. The name for the disease malaria is derived from the Italian *mala aria* that literally means "bad air". The origin of the word, used in the sense that the surrounding air in wet, and swampy locations is a cause of disease, can be traced back as far as the ancient Greeks and Romans. Another word for "bad air", first used in 1655, is "miasma" that is derived from the Greek *minainein* "to pollute". In the advent of urbanization in the late eighteen hundreds, medical doctors observed that diseases were more common in the poorer areas of cities. These areas were often overcrowded and situated in unsuitable damp areas. Two battling theories were put forth: the *miasma*-theory preached that diseases were caused by locally generated emissions (or antropotoxins); the *contagium*-theory preached that diseases were caused by poisonous particles that were transferred between humans. The father of ventilation science, Max von Pettenkofer, was a front figure for the *miasma*-theory and suggested increased air flows into the dwellings to remove the locally generated emissions. [28] A leader of the *contagium*-theory (from Latin *contagio* "contact"), i.e. the father of clinical microbiology Robert Koch, instead suggested measures to limit the spread of the supposed *contagium*: isolation, quarantine, and border control [29]. The scientific battle was infected by political undertones. The latter measures were unpopular among the trade-friendly industrialists that were politically opposed to the more isolation-friendly local land owners at this time. [30] It was a heated battle, where von Pettenkofer scored some political points when he in 1892 drank a cocktail of cholera bacteria without catching the disease. [31] He was probably immune. [30] By 1900, bacteria were firmly established as the *contagium*-vehicle. It was a landslide victory to the point where most of von Pettenkofers academic contributions were practically erased. He continued to maintain that *miasma* ought to be an aiding factor in the spread of diseases, until he killed himself with a pistol head shot in 1901. [30]

Today this issue may not be altogether black or white. Ventilation and overcrowding have been shown to indirectly influence the spread of diseases. [32] It becomes difficult to conduct good scientific work when political polarization and strong emotions enter the scientific discussion. The historical lessons are not so easy to adopt, as evidenced by more recent heated scientific battles such as global warming or the present Covid-19 battles (see for example [33]).

A remaining *miasma*-related question concerned the rising sense of discomfort experienced by humans in overcrowded rooms. It was well known at the time that enclosing people in a room with very little ventilation lead to symptoms like headache, nausea and dizziness. In severe cases it could even lead to unconsciousness and death. The father of chemistry, Antoine Lavoisier, in cooperation with Laplace had demonstrated in 1783 that the cause of death could not be attributed to lack of oxygen molecules, but probably to an excess of carbon dioxide [34]. Exhaled air of humans contain approximately 44 000 ppm of metabolic CO_2. [35] This means that the excess CO_2 in the blood cannot be expelled at exposures to CO_2 concentrations above that. Accumulation of CO_2 in the blood cause the pH to progressively decrease, and in turn this leads to a series of bodily malfunctions. Death by drowning is caused by the increasing acidity of the blood (acidosis) as the CO_2 concentration accumulates and not by too few oxygen molecules in the lungs. Exposure to 20 000 ppm CO_2 leads to headache and shortness of breath after a few hours. Exposure to 70 000–100 000 ppm CO_2 leads to unconsciousness after a few minutes. Exposure to >170 000 ppm CO_2 causes death in humans within one minute from first inhalation. [36] To illustrate how high these concentrations are: a human hermetically enclosed in a 2.5 m^3 box would probably still be barely conscious after 24 hours, assuming an exhalation rate equivalent to 0.018 $m^3\ h^{-1}$ pure CO_2. [35] Pettenkofer had dismissed CO_2 as the cause of diseases, but had developed simple methods to measure it and suggested that the concentration of CO_2 could be used as a proxy for the supposed antropotoxins. While investigating public venues in Munich, he had found values as high as 7100 ppm CO_2. [31] Pettenkofer noticed that human odours were clearly perceptible around 1000 ppm CO_2 (now known as the Pettenkofer number) and proposed this as a "safe" target to strive for.

The final blow to the *miasma*-theories was dealt by Carl Flügge in 1905. [37] He devised a series of experiments enclosing humans in glass boxes. The air supply to the breathing zone and to the rest of the box could be controlled separately, as well as other parameters such as temperature and relative humidity. Among other parameters, Flügge varied the odors in the air supply, e.g. air from sewage etc. He found that only the appetite of the subjects was adversely affected, otherwise the subjects adapted to the foul smells. The only "contaminant" that had any adverse effect on the comfort of the subjects was temperature. [38] These experiments totally obliterated the contemporary ventilation philosophy and turned it on its head. There appeared to be no evidence for regulating ventilation from a chemical perspective, as long as the physical parameters (like temperature and relative humidity) were within acceptable comfort-limits. The purpose of a window quickly changed from letting fresh air in to letting heat out. However, some practitioners argued (on the basis of proven experience) that it might be wise to retain some ventilation flows into buildings. [30] It took several years before new ventilation standards were proposed. [38]

The need for ventilation, and the chemical perspective, slowly crept back via odor-control. The human nose is in fact very sensitive to certain indoor odors. From an evolutionary perspective, it appears to have been advantageous for humans to judge a dwelling by its smell. While the human nose may adapt, people were not comfortable with entering a room with foul smells. This angle provided an incentive for new and fruitful experiments on ventilation requirements. In 1936, Yaglou et al. [40] extended some experiments performed by Lehmberg et al. [41] the year before. They conducted a series of experiments on a group of people to determine their subjective acceptance of the perceived air quality upon entering a test chamber. By varying a number of parameters in the test chamber, Yaglou et al. demonstrated a correlation between the degree of acceptance, the pollution load, and the ventilation air flow into the test chamber. Their results were immediately, but cautiously, adopted by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). [38]

Figure 1 (inspired by Awbi [35]) shows a compilation of the ventilation requirements historically recommended by ASHRAE, including its predecessors. [38] The news of Flügge's experiments hit like a bomb when it was presented at the ASHRAE 1911-meeting. [30] All previously accepted ventilation requirements were for all practical purposes under reevaluation until 1936. [37] (The reason why the old high ventilation requirements were maintained for some time (as shown in **Figure 1**) had to do with the fact that the previous requirements were included in many state laws. [37]) Yaglou also studied the ventilation requirements in relation to environmental tobacco smoke (ETS). [42] As non-smokers are very sensitive to any remaining smoke odor, he found that very high ventilation rates were required

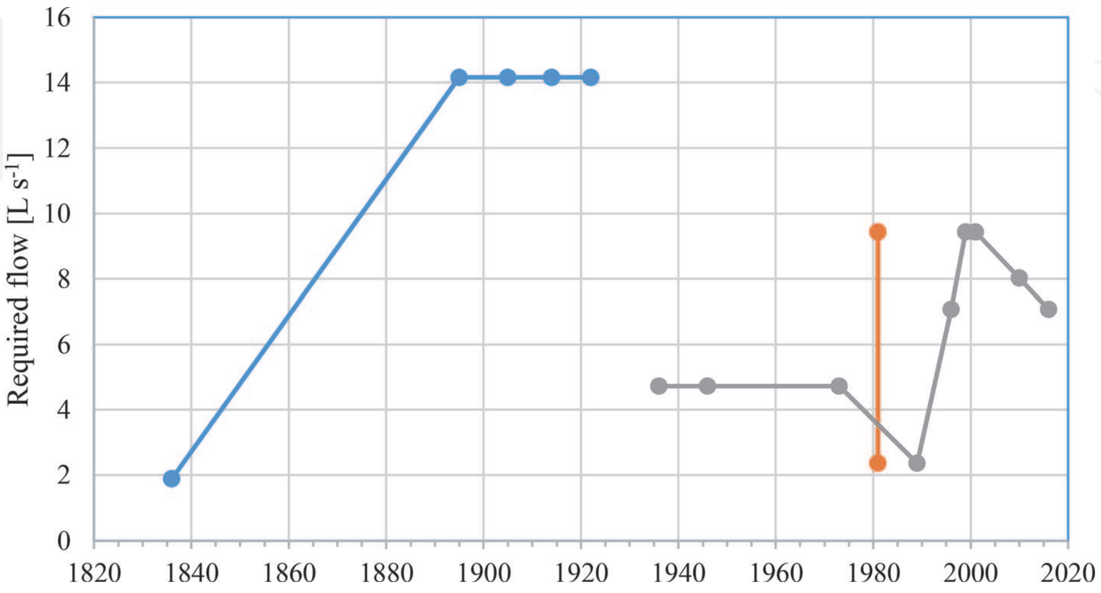

Figure 1.
Ventilation requirements recommended by ASHRAE and predecessors. From 1936 and forward (grey) the required flow per person in a standard office is shown. The earlier values (blue) are per room. The red shows the unadopted ASHRAE 62 (1981).

to reach acceptance (from them). Smoking was very common at the time. In 1965, 43% of U.S. adults were regular smokers. [43] As health concerns in U.S.A. regarding smoking and indoor ETS were starting to be officially recognized from 1964 and onwards, the question of ventilation requirements started to become a hot topic again. [43] In the ASHRAE Standard 62 (1981), two ventilation requirements for offices were proposed (shown in red in **Figure 1**). The lower one applied to offices without smokers and the higher one to offices where smoking was allowed. This was immediately perceived as a business threat by the tobacco industry. A memorandum circulated at Philip Morris concludes that adopting and enforcing this standard would at least double the maintenance costs for a workplace that allow smoking. [44] In the end, neither the American National Standards Institute (ANSI), nor the Building and Official Code Administrators adopted the 1981 standard as it was considered "controversial". Therefore, the standard was never enforced. In the next "revised" standard that was accepted by ANSI, i.e. ASHRAE 62 (1989), the lower ventilation requirement was retained and moderate smoking was allowed. [44] The tobacco industry succeeded to block the enforcement of new ASHRAE standards until 2000. [44] The recent decreases in the recommended ventilation requirements, shown in **Figure 1**, can probably also be interpreted as energy-saving measures.

Note that the lower limit proposed in ASHRAE Standard 62 (1981) (red in **Figure 1**) essentially is a revocation to the lowest ventilation requirements proposed in 1836. The guidelines for ventilation requirements are in fact influenced by a number societal parameters. By this time a fair amount of the newer buildings were mechanically ventilated. In Sweden, mechanical ventilation was primarily used in industrial buildings before 1947, but the invention of the less noisy radial fans opened the market for ventilating other buildings. [30] When the energy crisis hit in 1973, the energy used for ventilating buildings suddenly became a liability. The lowered ventilation requirements in the standard of 1981 can therefore be understood in terms of the corresponding decrease in the energy use for the fans in mechanical ventilation and for heating (or cooling) the air supplied. The air supplied into dwellings was further reduced by efforts to reduce air leakages through the building envelope, particularly in the Nordic countries. After a while, reports of occupant discomfort started pouring in. It appeared that up to 30% of the newly built office buildings had an unusually high amount of complaints. In some cases, causal relations to ill-health could be found: e.g. in the use of new materials, moisture damage, or improperly performed building techniques. [39, 45] A large group of diffuse symptoms such as headache, fatigue, lack of concentration and irritation of the skin and mucous membranes remained unexplained. In 1984 the WHO Regional Office for Europe collectively referred to these symptoms as a new medical diagnosis: Sick Building Syndrome (SBS). [46] The onset of constructing tighter building envelopes seemed to be a likely cause. This sparked a renewed research interest in finding the optimal ventilation requirements.

Fanger and coworkers repeated the Yaglou experiments, but with a much larger sample size in the 1980s. [47] In addition, Fanger attempted to quantify the perceived emissions from the human body and suggested a new subjective, relative unit: *olf*, the emission rate of air pollutants (bio-effluents) from a standard person (from Latin *olfactus* "smelling"). The idea of relative units related to standard people came from previous studies of thermal comfort. Fanger's standard person was characterized as a sedentary white-collar worker (or student) aged 18–30 with a hygienic standard corresponding to 0.7 baths/day and changing underwear daily. Deodorants were used by 80% and some were smokers, but the proportion is not specified. By varying the test chamber ventilation rate (q) in a cohort study of 1000 people judged by 168 "judges" (probably from the same cohort), Fanger found the following correlation ($r^2 = 0.79$ and valid for $q \geq 0.32$ L s^{-1} per person, or *olf*):

$$PD = 395 \cdot exp\left(-1.83 \cdot q^{0.25}\right) \tag{1}$$

where PD is the percent dissatisfied "judges", q is the ventilation rate (L s^{-1}) per person, L is liters [dm^3] and s is seconds. **Figure 2** shows the correlation curve given by Eq. (1). These results corresponded well with contemporary measurements. [48] In field studies in 15 office buildings, using a similar experimental method, Fanger et al. found that the sources of disagreeable indoor air pollutants were definitely not limited to human bio-effluents. The olf-equivalents attributed to other indoor sources were: indoor materials, 1–2 *olf*;: the mechanical ventilation system itself, 3 *olf*;: tobacco smoking, 2 *olf*. [49] These and other studies highlighted the necessity to control all indoor air pollution sources in order to reach an acceptable indoor environment in terms of perceived air quality. In a large study of school workers by Smedje et al. [27], it was also shown that their perceptions of the air quality at work were confounded by personal, psychosocial and domestic factors. In short, studying human perception is complicated by many factors and pose some challenges on experimental design.

No single factor causing SBS has yet found any consensus. Sometime after its last official document on SBS in 1995, WHO discontinued the use of SBS as a medical diagnose. A contemporary search on the homepage of WHO yields zero hits. However, that a correlation seem to exist between SBS-related issues and some ventilation parameters receives some consensus in the multidisciplinary field concerned with healthy buildings. In 2001 [50], Jan Sundell managed to convene several European principal researchers in the field to search for consensus on the connection between ventilation and health. There are few well-designed studies that adequately account for all the multiple factors that are encountered when assessing indoor environments. Out of the selected 105 scientific papers in peer-reviewed journals only 30 were deemed conclusive for the question at hand. The consensus statement include the conclusions that there is:

"*a strong association between ventilation and comfort (as indicated by perceived air quality) and health (as indicated by SBS symptoms, inflammation, infections, asthma, allergy, short- term sick leave). … also indicates that there is an association between ventilation rate and productivity (as indicated by performance of office work).*" [50].

A similar exercise, with a larger geographical spread of the researchers, was initiated by Jan Sundell and Hal Levin in 2010. Many conclusions were similar, but it should be noted that the panel members were divided as to whether the association between ventilation and health outcomes (excluding SBS) was strong or simply suggestive. [51] Both studies conclude that air change rates (see Section 2.2) below

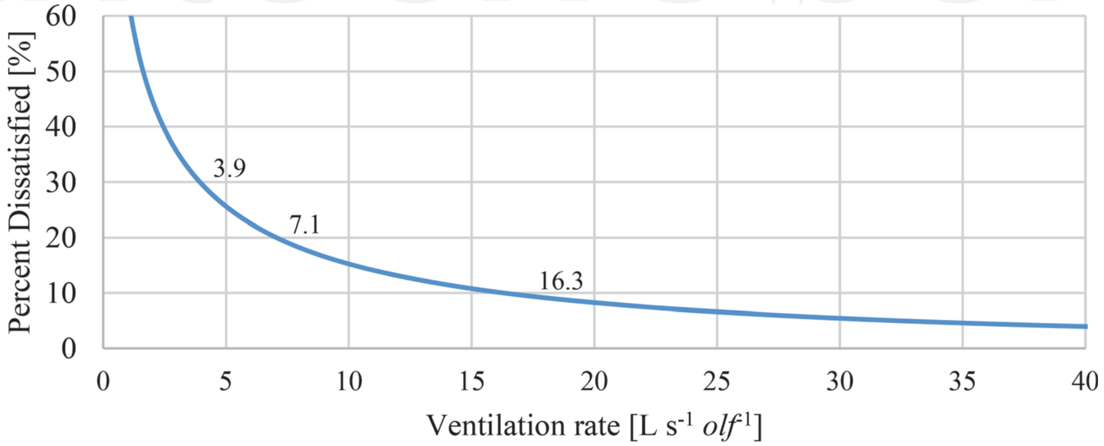

Figure 2.

Fanger's correlation between the required ventilation rate per person (or olf) and the percent dissatisfied judges upon entering the test chamber. The numbers in the figure correspond to the required ventilation rates for the 10%, 20%, and 30% levels of the percent dissatisfied judges.

0.5 h^{-1} leads to increased infestations of house dust mites in the Nordic countries. The latter was deemed important, since there is a plausible link between exposures to the feces of house dust mites and the prevalence of asthma and allergic rhinitis. [52]

This concludes the selective short history of ventilation. The idea that ventilation promotes health by removing harmful substances has been a lingering and recurring theme. The effects of indoor exposure to harmful substances are typically studied as dose–response assessments. [39] The relevant exposure dose is the *concentration* of the harmful substance in the indoor air and the responses are the measureable effects on humans. When adverse health effects are established, the exposures of those harmful substances are usually regulated or their use simply forbidden. [39] This also means that, in principle, there should be no *known* harmful substances to be removed by ventilation in the indoor environment. As will be evident in Section 2.3, most guidelines for ventilation requirements are based on perceived indoor air quality, and not health, criteria.

Nevertheless, there is a case for using ventilation as a precautionary measure to prevent adverse health effects caused by the indoor environment. There has been a significant increase in the number of chemicals never before encountered in the indoor environment, particularly in the last fifty years. [43] Today, literally thousands of chemicals are present in the indoor air (see for example [53]). Since most studies of dose–response assessments focus on one single substance at the time, the effects of mixtures of substances are largely unknown. [54] In addition, a majority of these new indoor chemicals have not been studied for health effects. When a harmful substance is forbidden, it is often substituted for new substances with (as yet) unknown health effects. In light of these *known unknowns*, it may be prudent to specify some minimum ventilation requirements as a precautionary health measure.

2.2 Some insights from the theory of ventilation

Before critically examining the existing guidelines for ventilation requirements a few theoretical explanations of the salient points are needed. Consider first the One-zone model as shown in **Figure 3a**. The flows of air supply to, and air exhaust from, the zone are equal. An air pollutant is emitted at a constant rate into the zone. The assumption for now is that the zone is fully mixed, i.e. the concentration of air pollutant is exactly the same everywhere in the zone. The validity of this assumption, and other assumptions, will be discussed below.

Assuming that the initial concentration of air pollutant is zero and no air pollutant enters via the air supply ($c_0 = c_{ext} = 0$), the mass balance equation for the air pollutant in the zone is

$$V\frac{dc_t}{dt} = \dot{m} - c_t Q \qquad (2)$$

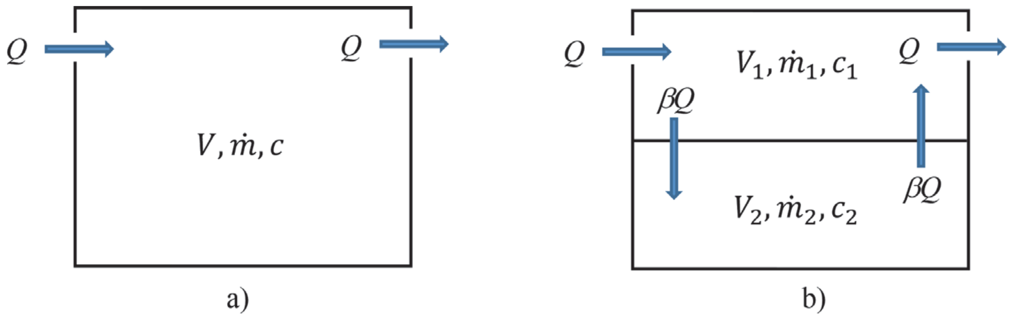

Figure 3.
Simple zone models. (a) One-zone model. (b) Two-zone model.

where V [m^3] is the volume of the zone, $\dot{m}$ [kg h^{-1}] is the constant emission rate of air pollutant, c_t [kg m^{-3}] is the concentration c of air pollutant in the zone at time t [h], and Q [m^3 h^{-1}] is the rate of air flow into and out of the zone. (The conversion factor between Q [m^3 h^{-1}] and q [L s^{-1}] is $Q = 3.6q$). The steady state solution of Eq. (2) is obtained when a constant equilibrium concentration is established in the fully mixed zone. Setting the left hand side to zero gives

$$c_\infty = \frac{\dot{m}}{Q} \tag{3}$$

where c_∞ is the constant equilibrium concentration at $t = \infty$. This is an important result. It appears that, given a constant emission rate of an air pollutant, it is the ventilation rate that determines the final concentration of air pollutant in the zone (i.e. the exposure to the air pollutant). However, this conclusion is only valid *provided that* the zone is completely mixed at all times.

For the case of a hermetically closed zone, i.e. when $Q = 0$ in Eq. (2), it can be solved by integration to yield

$$c_t = \frac{\dot{m}}{V}t. \tag{4}$$

Eq. (4) shows that the air pollutant concentration will increase linearly with time in a hermetically closed zone. Note that the volume of the zone (V) buffers the rate of concentration increase in the zone. The larger the volume, the slower the rate of increase of the air pollutant concentration in the zone.

Another illustrative one-zone case is obtained by allowing an initial concentration c_0 of the pollutant in the zone at $t = 0$ and assuming that $\dot{m} = c_{ext} = 0$. Solving for the concentration gives

$$c_t = c_0 e^{-(Q/V)t} = c_0 e^{-Nt} \tag{5}$$

where the hourly air change rate (ACH) for a completely mixed zone is defined as $N = Q/V$. Eq. (5) means that for any temporary emission of air pollutant in the zone, its concentration will decay exponentially with time. The rate of decay is gauged by the air change rate N. A higher air change rate means a faster decay.

The simple One-zone model of ventilation presented above has two main problems: (i) Emission sources are not evenly distributed in the zone volume. They are local and confined to surfaces, objects or humans. (ii) Complete mixing of a zone is difficult to achieve. Both points can be illustrated with a simple Two-zone model, originally proposed by Etheridge and Sandberg [55], as shown in **Figure 3b**. In the Two-zone model, emission sources are allowed to be slightly more local and the required mixing air flows are made slightly more explicit in terms of the inter-zonal air flows. Inter-zonal air flows are given as βQ, so when $\beta = 1$ the inter zonal air flows have the same magnitudes as the supply and extract air flows. For simplicity, complete mixing of both zones are assumed. The mass balance equations in each zone for the case $c_{ext} = c_{10} = c_{20} = \dot{m}_1 = 0$ becomes

$$\begin{aligned} V\frac{dc_1}{dt} &= \beta Q c_{2t} - (1+\beta)Q c_{1t} \\ V\frac{dc_2}{dt} &= \dot{m}_2 + \beta Q c_{1t} - \beta Q c_{2t} \end{aligned} \tag{6}$$

The steady state solutions for the concentrations in each zone are then

$$c_{1\infty} = \frac{\dot{m}_2}{Q}$$
$$c_{2\infty} = \frac{(1+\beta)\dot{m}_2}{\beta Q} \tag{7}$$

Note that the steady state result for c_1 in Eq. (7) is the same as for the completely mixed One-zone model in Eq. (3). If nothing is known about the distribution of concentrations within the zone, the proper interpretation of steady state in Eqs. (2) and (3) is that the emitted amount equals the exhausted amount and that the accumulation of air pollutant in the zone has stopped. The interpretation that the concentration is constant in the zone is not correct. Unless, of course, complete mixing is established by other measurements. In general the concentrations are not equal, as is evident in **Figure 4** where the dimensionless quotient c_2/c_1 of the steady state concentrations from Eq. (7) are plotted against β. Note that c_2 approaches c_1 very slowly as β increases in **Figure 4**. In order to reach complete mixing the interzonal air flows must be much larger than the supply and extract flows. In experiments where complete mixing of the whole zone is important, e.g. using the decay in Eq. (5) to measure the air change rate using tracer gases, several extra fans are employed to come as close as possible to the ideal case of complete mixing. It is also clear from **Figure 4** that the concentration of air pollutant in the lower zone rises very quickly as β decreases below unity. From an exposure point of view, it is problematic that concentrations of air pollutants may differ considerably within a room when mixing is incomplete.

The special case when the fresh air from the supply flow never enters the lower zone and directly exits by the extract is called ventilation short-circuiting. In this case, β is zero and the lower zone essentially behaves as a hermetically closed zone (Eq. (4)) and the concentrations of all air pollutants emitted in the lower zone rise without bounds. To be fair, ventilation systems are designed to deliver fresh air to occupants and complete short-circuiting is rare. However, poorly designed systems do exist. One example is shown in **Figure 5**. Typical situations when short-circuiting may occur are: if inlet and exhaust devices are close to each other; if there are obstacles in the flow path of a mechanical ventilation air inlet; if the air supplied is warmer than the air in the room and the extract is near the roof.

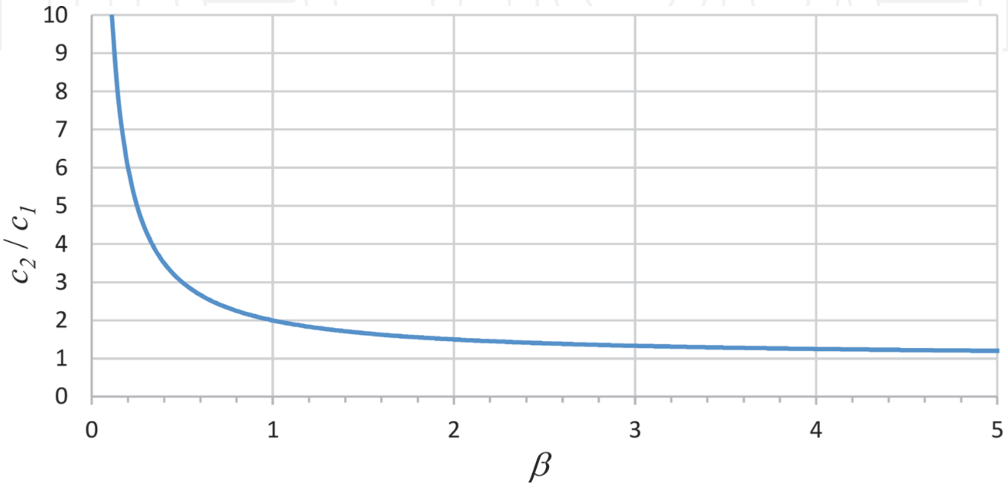

Figure 4.
Increase in the relative concentration in the lower zone (2) as a function of the interzonal flows. When β = 1 the interzonal flows are equal to the air supply.

Figure 5.
Retrofit of cooling beam (with attached light fixture) leading to a high degree of ventilation short-circuiting. Air supply device to the left and air exhaust to the right.

In a more general theoretical approach, allowing for non-homogeneous concentration distributions in the zone, all possible paths of a very small package of air from the inlet to the outlet are considered (see Etheridge and Sandberg [55] for a complete treatment). A long and tortuous path for the package or air will result in a long residence time for the package within the zone, whereas a short path corresponding to a ventilation short-circuit would lead to a very short residence time. At the outlet, packages of air escaping the zone in every instance of time will represent many different residence times. At steady state, in a similar manner as in Eqs. (3) and (7), the distribution of residence times will converge to a constant average residence time $\langle\tau_r\rangle$ for the air packages. The average residence time can also be interpreted as an average age of the air packages exiting the zone, if the age of an air package is set to zero as it enters into the zone through the inlet. This concept of ages of air packages is useful when examining the interior of the zone.

The simple process of plug (or piston) flow illustrates the age concept well. It is the most efficient method to ventilate and is used in so called "clean rooms". The idea is to achieve a laminar flow by supplying slightly colder air from the roof and letting it fall vertically to the floor where it is extracted. Ideally, all air packages entering from the whole area of the roof fall at the same speed and reach the floor simultaneously. This means that all air packages have exactly the same residence time in the zone. It is easy to show that the residence time only depends on Q and V, regardless of the shape of the zone, and is given by

$$\langle\tau_r\rangle_{plugflow} = \frac{V}{Q} \equiv \tau_n \tag{8}$$

where the nominal time constant of the ventilation system τ_n is defined. For plug flow the average residence time is equal to the nominal time constant. Since the air packages follow the shortest route from the roof to the floor in plug flow, the nominal time constant can be interpreted as the shortest possible residence time. It is also easy to determine the local age of the air packages in the interior of the zone.

It must increase linearly from age zero at the roof to an age equal to the residence time at the floor. Consider an arbitrarily small volume element within the zone. It will contain many air packages with ages that vary linearly with height. The local mean age of air $\bar{\tau}$ is defined as the average age of the air packages within the small volume element. The local mean age of air can be interpreted in terms of how well the ventilation system delivers fresh air to the volume element. As the packages of air enters the zone, they start to equilibrate by diffusion with the concentrations of contaminants in the local environment and start to become less fresh. The older the air, the less fresh it is. Now let the volume element be as small as one package of air. The average local mean age of air with respect to the entire zone must then be equal to the local mean age at half the height. Think of a process where all volume elements with a low age above the middle height can be paired with volume elements with a high age below the middle height so that their average is exactly the local mean age of air at half height giving

$$\langle \bar{\tau} \rangle_{plugflow} = \frac{\tau_n}{2} \tag{9}$$

This result can be generalized since the residence time and the local mean age of air of an arbitrary path of the air packages are related by

$$\tau_i + \tau_{rl} = \tau_r \tag{10}$$

where τ_r is the residence time of the path, τ_i is the time already spent in the interior of the zone (i.e. the local mean age of air of the air package) and τ_{rl} is the residual life time until the air package exit the zone. This is obviously valid for all paths and all air packages will eventually complete their paths to the exit. It will therefore always be possible to pair air packages (with the same residence time), so that their average local mean age is exactly half the residence time. Taking the average of all possible paths, a generally valid relation is given by

$$\langle \bar{\tau} \rangle = \frac{\langle \tau_r \rangle}{2}. \tag{11}$$

Note that the averages of the local mean age of air over all paths or over the zone space give the same results.

Since no other ventilation process can be more efficient than plug flow, the average local mean age of air for other ventilation processes cannot be lower than that for plug flow. It therefore seems natural to assign a 100% air change efficiency to plug flow and consequently define the general air change efficiency in a zone as

$$\langle \varepsilon_a \rangle = \frac{\tau_n}{2\langle \bar{\tau} \rangle} \cdot 100\%. \tag{12}$$

For the case of complete mixing, the paths of all air packages should reach any volume element within the zone with the same probability. Complete mixing may also be viewed as a process where all volume elements in the zone are instantaneously considered identical at all times. All volume elements have identical characteristics, such as the same concentrations of molecules and the same local mean age of air. Air entering through the inlet will therefore, in theory, simultaneously enter all volume elements. Within each volume element, air packages with increasing ages will continue to accumulate until the steady state is reached and the local mean age of air stays constant. In analogy, the mass balance given in Eq. (2), describes how a contaminant is accumulated in each volume element until a steady state concentration is reached. Since the mixing conditions are the same, the accumulation of ages and of concentration, respectively, follow the same time evolution. Solving for c_t in Eq. (2) gives

$$c_t = c_\infty \left(1 - e^{\frac{-Qt}{V}}\right) = c_\infty \left(1 - e^{\frac{-t}{\tau_n}}\right) \tag{13}$$

where Eqs.(3) and (8) were used. In the field of statistics, c_t/c_∞ is an example of a cumulative distribution function. By analogy, it is also the cumulative distribution function for the ages of the air packages. A probability distribution function is obtained by taking the time derivative of the cumulative distribution function. Thus, it is evident that, for a completely mixed zone, the ages of the individual air packages accumulated within a volume element at steady state are exponentially distributed according to

$$f_{\tau_i}(t) = \frac{1}{\tau_n} e^{\frac{-t}{\tau_n}} \tag{14}$$

Now the average local mean age of air for a volume element (and for the whole zone) can be evaluated to τ_n. This gives the following relations for a completely mixed system

$$\begin{aligned} \langle \bar{\tau} \rangle_{mixed} &= \tau_n, \\ \langle \tau_r \rangle_{mixed} &= 2\tau_n, \\ \langle \varepsilon_a \rangle_{mixed} &= 50\%. \end{aligned} \tag{15}$$

The average air change efficiency of a mixing ventilation system is at best 50% as compared to plug flow. In analogy with the nominal air change rate N (or ACH) being given as the inverse of the nominal time constant τ_n as

$$N = \frac{Q}{V} = \frac{1}{\tau_n}, \tag{16}$$

An effective local air exchange rate of the zone can be defined as

$$N_{eff} = \frac{1}{\langle \bar{\tau} \rangle} \tag{17}$$

where N_{eff} is the effective air exchange rate and note that the local mean age of air average is spatial and taken over the zone. It can be interpreted as the local ability of the ventilation system to dilute contaminants with fresh outdoor air in the point p. This an important property from an exposure viewpoint.

The aim of the above theoretical exercises for two mixing models is mainly to introduce the concept of local mean age of air and its properties. The fact that it is a local property that can be determined experimentally by tracer gas techniques [55] means that interior points of any ventilated zone can be characterized by it. In particular, in means that the distribution of fresh air to the occupied volumes of a zone can be tested.

The insights from this subsection can now be summarized. It has been shown that requiring a specific ventilation rate is not a guarantee for good performance of a ventilation system. The supplied air must also be distributed efficiently and this capacity should be evaluated. Possibilities for ventilation short-circuiting should be eliminated. Finally, a large zone volume can be a strategy to prevent build-up of concentrations from transient sources of air pollutants.

2.3 A critical examination of guidelines for ventilation requirements

Most of the contemporary legislative guidelines for ventilation requirements are based on criteria for perceived air quality, as concluded in Section 2.1. For more than 20 years, the basic guidelines in the U.S.A. (and also in Europe) have been based on the recommendation that no more than 20% of the occupants should be dissatisfied with the perceived indoor air quality. [56] Nevertheless, the adaptation of the human nose adds a dimension and there is a difference between the philosophy in Europe and the U.S.A on how perceived air quality should be measured. The guidelines in Europe (following Fanger et al. [49]) are based on the perceived air quality as judged by an un-adapted visitor to the room, whereas the guidelines in the U.S.A. (ASHRAE) are based on the perceived air quality by a judge that has been allowed to adapt to the room air for 15 minutes. [5] The American guidelines therefore recommend lower ventilation rates than the European guidelines at the same level of dissatisfied judges. [5]

Comparison of the work place ventilation rates required per sedentary person in **Table 1** (i.e. 7 L·s^{-1}/person) with the ventilation rates given in **Figure 2**, show that The Swedish Work Environment Authority appears to follow the European philosophy in the old, [57] as well as in the new, guidelines. [58] In line with the findings of Fanger et al. [49], many guidelines assume that all other indoor emissions of pollutants (e.g. from building materials and human activities, such as smoking, cleaning, and cooking) should be added to the emissions of bio-effluents from the occupants. All these emissions are lumped into a floor-area-based emission rate. The total required ventilation rate is then the sum of two contributions as shown in Eq. (18).

$$q_{tot} = n_p \cdot q_p + A \cdot q_A \tag{18}$$

where q_{tot} is the total required room ventilation rate [L·s^{-1}], n_p is the number of occupants, q_p is the required ventilation rate per person [L·s^{-1}/person], A is the room area [m^2], and q_A is the required ventilation rate per square meter [L·s^{-1}·m^2]. The required q_A in **Table 1** are based on a room with very low emitting materials and no smoking. The Pettenkofer number (1000 ppm CO$_2$) can also be recognized in the guidelines in **Table 1**. However, the lowest required q_p (4 L·s^{-1}/person) from The Public Health Agency of Sweden [59] can only keep the CO$_2$ concentrations below 1500 ppm in most realistic scenarios. [60] The Public Health Agency of Sweden is the only government agency recommending a specified air change rate of

	FoHMFS 2014:18	AFS 2009:2	AFS 2020:1
Air supply/person	≥ 4 L·s^{-1} ≥ 7 L·s^{-1} (schools)	≥ 7 L·s^{-1}	≥ 7 L·s^{-1}
Air supply/m^2	≥ 0.35 L·s^{-1} + 0.35 L·s^{-1} (schools)	+ 0.35 L·s^{-1}	+ 0.35 L·s^{-1}
Air change rate	≥ 0.5 h^{-1}		
CO^2 concentration	Normally < 1000 ppm	Normally < 1000 ppm	Normally < 1000 ppm
Air change efficiency		≥ 40 %	≥ 40 %

Table 1.
Values are extracted from the official Swedish guidelines for ventilation requirements and air quality. FoHMFS are the ventilation guidelines issued by The Public Health Agency of Sweden. [59] AFS are the old [57] and the new guidelines (valid from 1 January, 2021) [58] issued by The Swedish Work Environment Authority. The +-sign signifies that the required air supply per m^2 must be added to the air supply per person.

$0.5\ h^{-1}$. [59] Note that the floor area based ventilation rate $0.35\ L{\cdot}s^{-1}{\cdot}m^2$ corresponds to an air change rate (N) equal to $0.5\ h^{-1}$ if the room height is 2.5 m (a common room height in the Swedish building stock). While there are common elements between the required ventilation rates in **Table 1**, it is clear that the more generally valid recommendations from The Public Health Agency of Sweden prescribe lower ventilations rates than the recommendations from The Swedish Work Environment Authority that are valid only in nonresidential buildings.

There are mutual dependencies between the ventilation rates presently required by government agencies and the properties of the existing building stock. [8] If the building stock can be shown to cause health problems that can be traced to inadequate ventilation, then the government agencies will try to improve the situation by requiring higher ventilation rates. On the other hand, if air leakages through the building envelopes provide ample contributions to the ventilation of the building stock, in addition to the controllable ventilation rates, then the required ventilation rates need not be as stringent because the total ventilation rate will be sufficient anyway. The point here is to highlight plausible dependencies on average, even though there may be a wide spectrum of properties in the building stock. Thus, changes in the properties of the building stock will lead to changes in the ventilation requirements recommended by government agencies.

The EPBD objective to transform the building stock to NZE- buildings with tighter building envelopes should, with the above logic, lead to a more stringent requirements for ventilation rates. [8] However, as mentioned in the Introduction, the "energy efficiency first" principle in EPBD [12] pushes other incentives towards their minimum legal limits when they are in conflict with the efforts to improve the energy performance of buildings. Maintaining a good indoor air quality by ventilation is such an incentive, and therefore ventilation rates will be pushed towards their minimum legal limits. As a consequence, in the coming EPBD transformation of the building stock, the minimum legally required ventilation rates play a critical role as counterbalances to prevent a decline in indoor air quality. The required ventilation rates will probably need to be increased to maintain the present levels of indoor air quality in the building stock.

It is therefore doubly worrying that the ventilation requirements in the standards on the European level recently have been lowered as shown in **Table 2**. For example, in a standard 10 m^2 office for one person, the required ventilation rate (q_{tot}) is lowered by 43% from $10.5\ L{\cdot}s^{-1}$ in the old guideline CEN-EN15251:2006 [61] to $6\ L{\cdot}s^{-1}$ in the new guideline CEN-EN16798:2019. [62] The change corresponds to recommending 30% dissatisfied un-adapted judges in the new guidelines as compared to 20% in the old guidelines. The guidelines in the European Standards provide the "floor" upon which the legal requirements of the member countries rests. Lowering the required ventilation rates in the European Standard opens for a corresponding lowering in the legislation of the member states. While it is slightly encouraging that the Swedish legislation is unchanged at the moment, as seen in **Table 1**, it is obvious that the risk of EPBD creating unhealthy indoor environments will be augmented. The present levels of indoor air quality in the building stock risk being lowered by the combined effect of tighter building envelopes and the prospect of lower required ventilation rates.

As concluded in the previous section, simply specifying required ventilation rates cannot guarantee an adequately low exposure to indoor pollutants. [63] Legislation also need to address the air distribution. In the European Standard [62] and in the ASHRAE Standard [56], the given ventilation rates assume complete mixing in the room. Thus, they presuppose a mixing mechanical ventilation system. Other ventilation systems are accommodated by dividing with a correction factor. ASHRAE [26] proposes a correction factor called the air change effectiveness

Category	CEN EN 15251:2006		CEN EN 16278.1:2019	
	Expected Percent Dissatisfied [%]	**Airflow per person [L·s^{-1}/person]**	**Expected Percent Dissatisfied**	**Airflow per person L·s^{-1}/person**
I	10	10	10	10
II	**20**	**7**	20	7
III	30		**30**	**4**
IV	< 30	< 4	40	2.5
	Expected Percent Dissatisfied [%]	**Very low polluting building [L·s^{-1}/m^2]**	**Expected Percent Dissatisfied**	**Very low polluting building [L·s^{-1}/m^2]**
I	10	0.5	10	0.5
II	**20**	**0.35**	20	0.35
III	30		**30**	**0.2**
IV	< 30	<0.2	40	0.15

Table 2.
Values are extracted from the official European guidelines for ventilation requirements and air quality. CEN EN 15251:2006 are the old guidelines from 2006 [61] and CEN EN 16278.1:2019 are the new guidelines (valid from 8 May, 2019) [62] issued by European Committee for Standardization. The bold figures are the recommended values.

defined as $\varepsilon_I = \tau_n / \langle \bar{\tau} \rangle$ evaluated in the breathing zone. [56] For mixing ventilation this gives $\varepsilon_{I,mixed} = 1$ and for plug flow $\varepsilon_{I,plugflow} = 2$. The correction factor in the European Standard is similarly defined, but evaluated as a room average, and is called ventilation effectiveness ε_v. (The nomenclature for the correction factors is a bit confusing and may be easily mixed-up with the air change efficiency defined in Eq. (12).) If the system is not fully mixed, the correction factor is less than unity and the required ventilation rate should be correspondingly increased. If displacement or plug flow ventilation systems are used, that are more efficient than mixing ventilation, the correction factor is larger than unity and the required ventilation rates may be correspondingly decreased.

Legal ventilation requirements also address air distribution, but rephrased into requirements that newly installed ventilation should be shown to function as designed, that the ventilation rate should be sufficient, or by requiring a specified air change efficiency as in **Table 1**. I have the impression that air change efficiency is seldom tested in the field. The control of newly installed ventilation systems mostly consist of ensuring that the design ventilation flows are obtained, otherwise the ventilation system components are assumed to function with the same efficiency as in laboratory tests. However, there are a number of factors that may lower the ventilation system efficiency in a real building. Some of these factors were mentioned in connection with ventilation short-circuiting in previous section (see also **Figure 5**); ventilation systems may be very complex and design choices may have unforeseeable consequences; a ventilation designer may enter late in the planning process and may be forced to make suboptimal choices, e.g. inlets vents may end up too close to outlet vents; or occupants may tamper with the intended function of the ventilation components to minimize perceived draft. It may be prudent to verify that air is distributed with the intended efficiency in new and old ventilation installations.

The above standards clearly favor mechanical ventilation systems where ventilation rate is an easy parameter to measure. It is not that easy to measure ventilation rate for natural ventilation systems. It is more difficult to demonstrate that natural ventilation systems are in compliance with the legal requirements than it is for mechanical ventilation systems. In addition, rooms with natural ventilation systems typically have higher room heights, than rooms with mechanical ventilation systems. Naturally ventilated rooms require larger room volumes to prevent concentration build-up of transient pollution sources to offset the natural fluctuations in the ventilation rate. Historically, the introduction of mechanical ventilation systems allowed building entrepreneurs to squeeze in three floors in the same volume where previously there would be two floors in older naturally ventilated buildings. [30] Using this observation, rooms with natural ventilation are roughly estimated to be 50% larger than rooms with mechanical ventilation. If there is a legally required air change rate or a required ventilation rate per floor area (as exemplified in **Table 1**), the prescribed ventilation rates will also be 50% larger for naturally ventilated rooms, as compared to a mechanically ventilated room. This increase is probably unnecessary and it arises because the legal requirements does not consider the different ventilation strategies used in natural ventilation systems. It would be desirable that all ventilation strategies should be treated equally in the eyes of the law, with the same objective requirements for adequate indoor air quality.

If the objective of the legal regulations is to ensure that 80% of the occupants find the perceived air quality to be acceptable, as it appears to be, then it would be more fitting to simply require that less than 20% of the occupants are feeling uncomfortable. This could be tested in a questionnaire. Note that this approach is suggested in some environmental certification systems for buildings, e.g. the level GULD in Miljöbyggnad 3.1. [64] The problem with such an approach is that other factors, than the actual air quality, may affect the outcome. [27] Alternatively, the regulations should apply specifically to the occupied zone of a room. This would lead to more balanced demands on natural ventilation systems as compared to the demands on mechanical ventilation systems. To specify concentration limits in the occupied zone would be preferable because of the direct link to exposure, but the challenge is that the human nose is very sensitive so some substances and there may be difficulties to measure such low concentrations at the present time. An indirect approach would be to specify some local ventilation parameter, such as the local mean age of air, in the occupied zone.

The fact that ventilation requirements primarily targets occupant comfort, does not mean that ventilation is irrelevant for the health of the occupants. Adverse health effects caused by exposure to indoor air pollution have been estimated to cause that approximately two million disability-adjusted lifetime years (DALYs) are lost annually, based on the population in 26 European countries. In economic terms this corresponds to a societal cost exceeding €200 billion. [60] It is very likely that the combined effect of the lower ventilation requirements and tighter building envelopes due to EPBD will increase this societal cost considerably. The prospect of turning buildings into unhealthy containers for the occupants certainly tempers my enthusiasm for the projected EPBD energy savings.

3. Conclusions

Most legislations concerning ventilation are based on perceived air quality, but ventilation is also important for the health of the occupants. Perceived air quality can be viewed as a pragmatic tool to achieve an adequate ventilation for precautionary health measures. From a perceived air quality and health perspective, the ventilation rate and an efficient air distribution are both important for achieving a healthy and comfortable indoor environment. Yet, most legislative requirements focus on the ventilation rate. This is not enough, and it is recommended that legislation also address the air distribution with equal zeal. In particular, verifying the efficient distribution of fresh air to the occupied zones or the concentrations of pollutants in the occupied zones.

Because there are clear links between ventilation and health, [3, 4, 50, 51, 60], it is extremely worrying that the "energy efficiency first" principle advocated in EPBD has led to decreasing ventilation requirements in the EU legislations, at the same time as the objective is to aggressively tighten the envelopes of the building stock. A second consequence of EPBD is probably that many naturally ventilated buildings will be retrofitted with mechanical ventilation systems. It is not clear that this would be the more sustainable solution in the long run.

Every citizen's right to a healthy indoor environment has been suggested to be a basic Human Right by WHO. [65] Adequate ventilation is at the heart of the solutions to reach this commendable goal. The mantra "build tight – ventilate right" [66] is a good one, but do not forget the second part!

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Conflict of interest

The author also works as a ventilation consultant.

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