Proposal of an effort-benefit diagram to compare unit and room air-change rates applied to a literature review

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ABSTRACT

The main task of every ventilation system is to dilute and extract pollutants from indoor air, most importantly in occupied space. This is usually achieved by exchanging polluted indoor air with less polluted outdoor air. In the case of a mechanical ventilation system, this process requires a fan power to be provided which is approximately proportional to the power of three to the resulting airflow. Because of this, reducing the necessary airflow to be provided by the ventilation unit e.g., by 10% would lead to a reduced power supply of about 27%. Vice versa, a necessary increase of 10% of the airflow provided by the unit, would result in an increased power supply of about 33%. To determine whether a reduced unit airflow is feasible or an increase in unit airflow is required, it is important to evaluate the ventilation efficiency for the occupied zone and any other zone with certain air change rate requirements. Unfortunately, this evaluation process is time-consuming as well as labour-intensive and can't be done for every indoor zone separately yet. However, for those situations where it has been performed, a common procedure for comparing them in a comprehensible graphical way would be helpful. This paper proposes a diagram to visualize how efficiently certain ventilation systems provide their unit air change rate as a room air change rate. As characteristic physical limits and isolines the values for ideal mixed ventilation and plug flow are included as well. Furthermore, the diagram has been applied to visualize air change rates from a literature review. The overview indicates, other than often assumed, real buildings do not necessarily reach ideally mixed ventilation. Pointing out that, it must be admitted as well, that currently the available data for such a comparison is often not based on a uniform measurement and evaluation procedure. Nevertheless, the proposed diagram can be a useful tool to communicate the air exchange performance of ventilation systems.

KEYWORDS

air change rate, air change efficiency, literature review

1 INTRODUCTION

Due to the challenges we all face because of climate change, the building sector needs to contribute to energy savings by more airtight building envelopes combined with controlled ventilation systems. To keep the required power consumption of these systems as low as possible, it is essential to strive for a high ventilation or air change efficiency. However, this requires awareness in the design-phase of building of the fact that it is not sufficient to only move air, but also assure "fresh" or better younger air is provided where it is actually needed. Vice versa, a ventilation system has to efficiently extract polluted, or older air from the sources of these pollutants. Unfortunately, in practice, it is often assumed unit air change rates according to Equation (1) are equal to the air change rate present in any point within a ventilated space. This assumption is, for example, implicitly made in the German standard DIN 1946-6, which means every ventilation system reaches by default the air change efficiency of ideal mixed ventilation or $\varepsilon_j^{\mathrm{a}} = 50$ %. This is problematic because with such an assumption, there is no motivation to further improve the most relevant characteristic of a ventilation system.

$$n_j = \frac{\dot{V}_j}{V_j} = \frac{1}{\tau_j} \tag{1}$$

n_j	Nominal air change rate of a system j	$[\mathrm{h}^{-1}]$
$\dot{V}_j$	Effective volume flow for a ventilated system j to exchange the air	$[\mathrm{m}^3\ \mathrm{h}^{-1}]$
V_j	Entire volume of the system j to be ventilated	$[\mathrm{m}^3]$
τ_j	Nominal time constant of the system j as a characteristic statistical measure for the time air spends at least within that system	[h]

2 THEORY

To better understand the theoretical background of air change efficiency, it helps to imagine a simplified real room like in Figure 1. Most importantly, a real indoor space cannot be ideally mixed, rather it can be viewed as a more or less coarse or fine discretized mesh of zones filled with air of different ages which interact with each other.

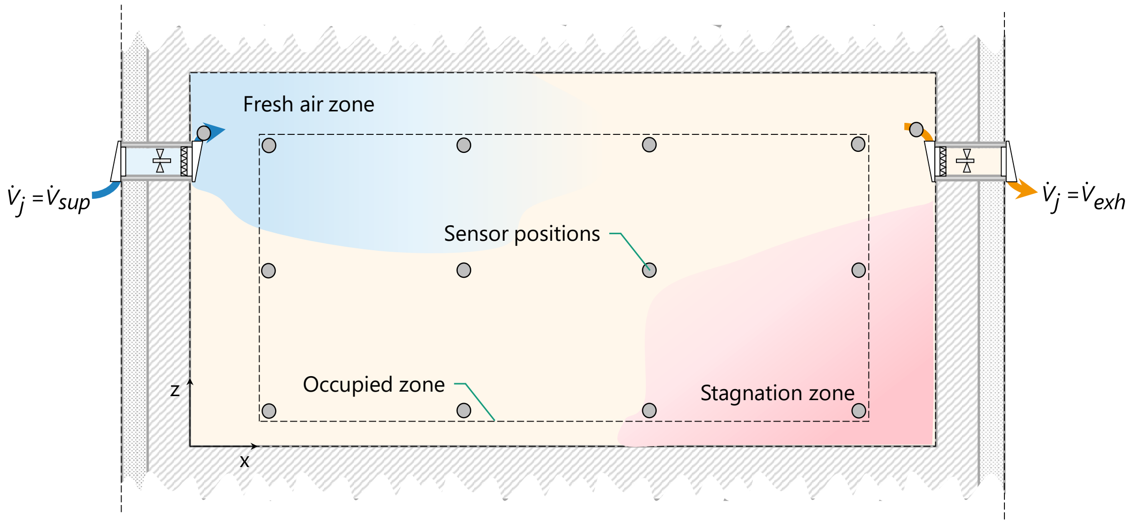

Figure 1: Simplified sketch of a ventilated room with various air ages, where the exhaust catches air of some room average air age. A fraction of older air is stagnating in few regions of the indoor space (Auerswald 2023).

The assumption of mixed ventilation means that the average air age $\langle\bar{\alpha}\rangle_j$ of all locations over the whole space equals the nominal time constant τ_j of that space. The condition of ideal mixed ventilation is a theoretical reference condition, where every location or zone $\boldsymbol{x}_i$ has that average air age $(\bar{\alpha}(\boldsymbol{x}_i) = \langle\bar{\alpha}\rangle_j = \tau_j,\ \varepsilon_j^{\mathrm{a}} = 50\ \%)$. The other two theoretical reference conditions are complete short-cut ($\varepsilon_j^{\mathrm{a}} = 0$ %), where the air age in every indoor location is infinity ($\bar{\alpha}(\boldsymbol{x}_i) = \infty$). And plug-flow ($\varepsilon_j^{\mathrm{a}} = 100$ %), where the air crosses the indoor space on the most direct path from supply to exhaust without leaving a single location unventilated. The air age $\bar{\alpha}(\boldsymbol{x}_i)$ under plug flow conditions increases linearly from 0 at the supply to τ_j at the exhaust, which means the average air age is $\langle\bar{\alpha}\rangle_j = 0{,}5 \cdot \tau_j$. With this said, the definition of the absolute air change efficiency $\varepsilon_j^{\mathrm{a}}$ follows than Equation (2) (Skåret 1986; Mundt and Mathisen 2004; Sandberg and Sjöberg 1983; Sandberg 1981).

$$\varepsilon_j^{\mathrm{a}} = \frac{\tau_j}{\langle \bar{t}_j \rangle} = \frac{1}{2}\frac{\tau_j}{\langle \bar{\alpha}_j \rangle} = \frac{1}{1 + \mu_2^{\prime *}(\tau_j)} = \frac{1}{2}\frac{\langle \bar{n}_j \rangle}{n_j} = \frac{\langle \bar{n}_{\mathrm{e},j} \rangle}{n_j} \tag{2}$$

$\varepsilon_j^{\mathrm{a}}$	Absolute air change efficiency of a system *j*	[-]
τ_j	Nominal time constant of the system *j* as a characteristic statistical measure for the time air spends at least within that system	[h]
$\langle \bar{t}_j \rangle$	Average residence time of air within the system *j* or air age in the exhaust plane of that system	[h]
$\langle \bar{\alpha}_j \rangle$	Average air age within the system *j*	[h]
$\mu_2^{\prime *}(\tau_j)$	Dimensionless second order central moment or dimensionless variance of the statistical distribution of residence times outside the system	[-]
$\langle \bar{n}_j \rangle$	Average room air change rate	[h^{-1}]
n_j	Nominal air change rate of a system *j*	[h^{-1}]
$\langle \bar{n}_{\mathrm{e},j} \rangle$	Average room air change rate in the exhaust plane of the system *j*	[h^{-1}]

However, often it is neither relevant nor practically feasible to measure or otherwise evaluate the absolute air change efficiency. One example is here air volumes, which are enclosed by furniture. Relevant for the air exchange is mostly the zone occupied by persons. In order to reduce the complex reality and to consider the relevance of various zone for the use cases of the indoor space, it is helpful to set up a model which discretizes an indoor space into subsystems. With this in mind, it is logical to define a relative air change efficiency $\langle \varepsilon_j^{\mathrm{a}} \rangle_i$ for a subsystem *i* inside the system *j*, according to Equation (3).

$$\langle \varepsilon_j^{\mathrm{a}} \rangle_i = \frac{\tau_j}{\langle \bar{t}_j \rangle_i} = \frac{1}{2}\frac{\tau_j}{\langle \bar{\alpha}_j \rangle_i} = \frac{1}{2}\frac{\langle \bar{n}_j \rangle_i}{n_j} = \frac{\langle \bar{n}_{\mathrm{e},j} \rangle_i}{n_j} \tag{3}$$

$\langle \varepsilon_j^{\mathrm{a}} \rangle_i$	Relative air change efficiency of a subsystem *i* in *j*	[-]
$\langle \bar{t}_j \rangle_i$	Average residence time of air within the subsystem *i* or air age in the exhaust plane of that subsystem	[h]
$\langle \bar{\alpha}_j \rangle_i$	Average air age within the subsystem *i* in *j*	[h]
$\langle \bar{n}_j \rangle_i$	Average room air change rate in the subsystem *i*	[h^{-1}]
$\langle \bar{n}_{\mathrm{e},j} \rangle_i$	Average room air change rate in the exhaust plane of the subsystem *i*	[h^{-1}]

Since air change efficiencies are a ratio of the achieved room air change rate to the nominal air change rate provided by the ventilation unit, it can be seen as a ratio of the benefit in relation to the necessary effort.

3 EFFORT-BENEFIT DIAGRAM FOR THE AIR CHANGE EFFICIENCY

Even though the evaluation of the air change efficiencies provides a method to quantify the performance of a ventilation system's capability to exchange indoor air, it is rarely used. The reason for this is the effort it takes to measure or simulate it. Also, because of the wide range of individual definitions for $\langle \varepsilon_j^{\mathrm{a}} \rangle_i$ and even sometimes an unclear differentiation from the absolute air change efficiency, $\varepsilon_j^{\mathrm{a}}$ makes it difficult to further optimize existing ventilation system configurations. However, for those cases where the air change efficiency has been, and more importantly, will be evaluated, the effort-benefit-diagram for ventilation systems in Figure 2 can be a graphical method to reduce the burden of comparing different ventilation systems.

Furthermore, the diagram can be used to better communicate expectations from standards and regulations for ventilation systems.

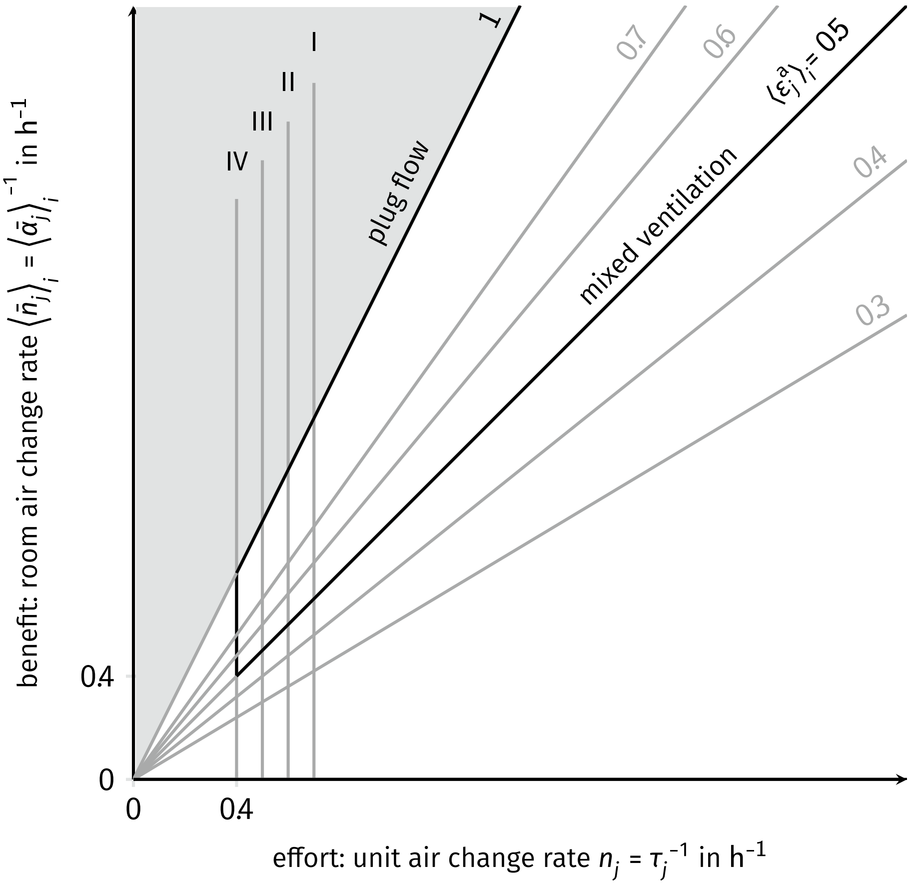

Figure 2: Effort-benefit-diagram to visualize how efficiently a ventilation system provides a certain unit air change rate to the indoor space (Auerswald 2023).

The proposed diagram shows the ratio between the provided nominal or unit air change rate n_j in relation to the achieved room air change rate $\langle \overline{n_j} \rangle_i$. As a result, the diagonal isolines correspond to the relative air change efficiency $\langle \varepsilon_j^a \rangle_i$. If $\langle \overline{n_j} \rangle_i$ covers the entire indoor space where n_j has been provided to, these lines become the isolines for ε_j^a. The two bold diagonal lines mark the values for the two reference cases, mixed ventilation and plug flow. The grey area is physically not possible to reach. If $\langle \overline{n_j} \rangle_i$ considers the requirement zone like the breathing level and Skåret's (1986) rules are considered, then efficient ventilation systems shall be designed for a relative air change efficiency $\langle \varepsilon_j^a \rangle_i$ above the 50%-level. Additionally, the four vertical lines mark, as an example, the reference air change rates for the four indoor air quality expectation categories (IEQ) for a residential indoor space according to DIN EN 16798-1 (p. 56, table B.11). Since the standard suggest assuring an IEQ well above IV and to design for II, the area framed in bold lines in the diagram represents the target range for ventilation systems.

4 REVIEW OF RESULTS FOR THE RELATIVE AIR CHANGE EFFICIENCY

The following section provides an overview of measured and simulated air change efficiencies based on a literature review of scientific publications. Besides Google-Scholar the AIVC Airbase has been used to search for publications regarding ventilation efficiency, air change efficiency and air age evaluations. From the publications found the review considers only the reported points of interest inside the evaluated space. In the case of centralized ventilation systems with a continuous unidirectional flow, this data is sometimes provided additionally to the easier accessible data in the exhaust ductwork, which leads to an absolute air change efficiency $\varepsilon_j^{\mathrm{a}}$. Especially for decentralized systems with alternating flow, the accessibility between $\varepsilon_j^{\mathrm{a}}$ and $\langle \varepsilon_j^{\mathrm{a}} \rangle_i$ is precisely the opposite, since there is no such location which continuously represents the exhaust duct only measurement data for the indoor space can be measured directly. For all presented data, it must be considered that there is no common practice how to exactly install the trace gas measurement equipment and how detailed the uncertainties of these evaluations shall be determined. Even though it shall be mentioned that there are the standards DIN EN ISO 12569 (2018) and DIN ISO 16000-8 (2008) which describe the tracer gas technique and how to calculate $\langle \overline{n}_j \rangle_i$ or $\langle \overline{\alpha}_j \rangle_i$ respectively based on the measurement data. Of these two standards the second is more detailed. Based on the procedure in DIN ISO 16000-8 (2008) Auerswald (2023) presents an improved evaluation method for the measurement data and their uncertainties.

The first results on air change efficiency were published by Lidwell (1960), Sandberg (1981), and Skåret and Mathisen (1982). They transferred the tracer measurement technique to ventilation systems and tested it in the laboratory using nominal air change rates higher than those used in common practice for most buildings nowadays. Further investigations in a laboratory environment were carried out by Tomasi et al. (2013). A comprehensive summary of field measurement results in non-residential buildings (NRB) can be found in Fisk and Faulkner (1992). Data on the air change efficiency of residential ventilation systems are published by Merzkirch (2015), Mikola et al. (2017) and FGK e. V. (ed.) (2019). The classification of the studies considered by building and system type is listed in Table 1. Figure 3 visualizes the results of these studies by the introduced effort-benefit diagram.

Table 1: References for evaluations of the nominal and room air change rate, as well the resulting relative air change efficiencies. TS = test facility or simulation, NRB = non-residential building, H = including a heat source

Reference	**Building type**			**System type**		
	TS	NRB	flat	centralized	decentralized	
					continuous	alternating
Sandberg (1981)	•			•		
Sandberg and Sjöberg (1983)	•			•		
Sandberg (1984)	•	•		•		
Fisk et al. (1985)		•		•		
Offermann and Int-Hout (1987)		•		•		
Fisk et al. (1988)		•		•		
Persily and Dols (1991)		•		•		
Fisk et al. (1991)	•			•		
Bauman et al. (1992)	•			•		
Persily et al. (1994)		•		•	•	
Manz et al. (2000)	•, H				•	•
Olesen et al. (2011)	•, H			•	•	
Tomasi et al. (2013)	•			•	•	
Merzkirch (2015)			•	•	•	•
Mikola et al. (2017)			•		•, H	•
FGK e. V. (ed.) (2019)	•			•	•	•
Auerswald (2023)			•		•	•

5 CONCLUSIONS

From this small overview it can be concluded, that ventilation systems installed in buildings tend to not achieve at least mixed ventilation and thus do not satisfy Skåret's (1986) rules. Especially for those systems in residential buildings in Germany, it seems they tend to be underdimensioned. From references found and considered here, most of the systems which satisfied the requirement $\langle \varepsilon_j^{\mathrm{a}} \rangle_i \geq 0.5$ are test facilities. This indicates that there may be a transfer gap from accepted scientific knowledge for the indoor air exchange to real-world buildings.

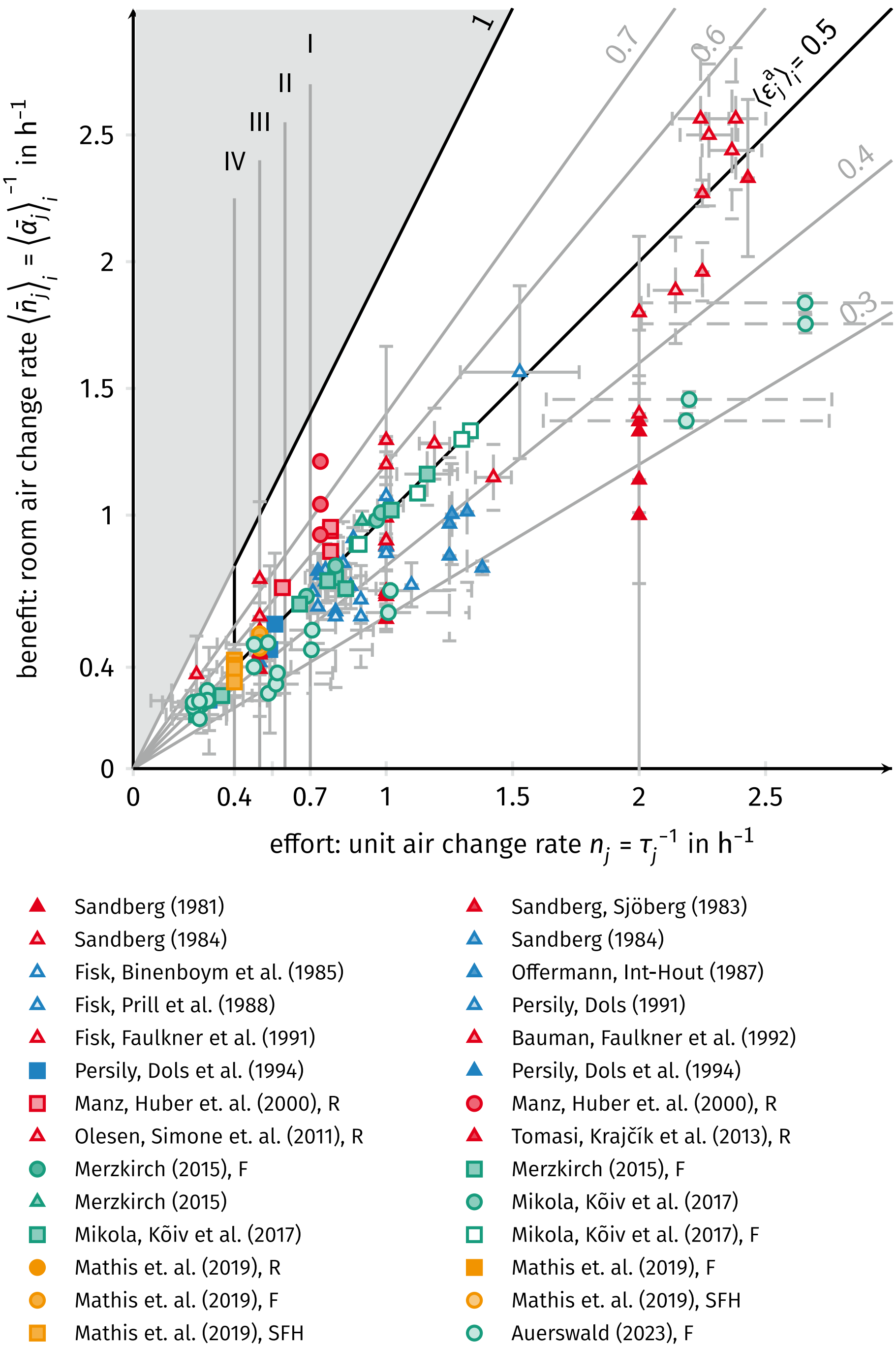

Figure 3: Effort-benefit-diagram applied to the comparison of data from a literature review about nominal air change rates to room air change rate, as well as the resulting air change efficiencies. Red = test facility, blue = non-residential building, green = residential building, orange = simulation (residential), triangle = centralized continuous system, rectangle = decentralized continuous system, circle = decentralized alternating system

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