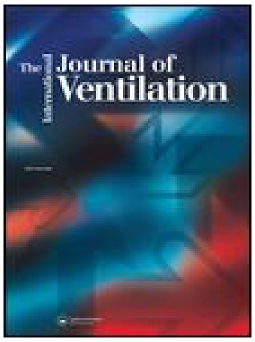

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VOC emission rates in newly built and renovated buildings, and the influence of ventilation – a review and meta-analysis

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ABSTRACT

Few field studies have evaluated ventilation strategies, such as temporarily increasing the ventilation rate, to counter the high pollutant-load from off-gassing of volatile compounds from new materials in these buildings. We reviewed longitudinal studies that measured both ventilation rate (i.e. fresh air change rate) and airborne concentration of total volatile organic compounds (TVOC). Rates of emission of TVOC follow a multi-exponential decay trend over time after completion of a building. A tri-exponential trend-was fitted by quantile regression. Although the ventilation rate is key to controlling airborne concentrations, it does not noticeably influence TVOC emission rates. Specifying low-emitting materials, or bake-out before occupancy, both have a significant impact on emission rates . The results can be used to assess and size energy-efficient practical ventilation strategies (such as demand-controlled ventilation) to keep the concentration of TVOCs within acceptable levels during hours of occupancy after completion of a new or renovated building.

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Indoor air quality; TVOC; off-gassing; emissions; new buildings; renovation; ventilation

Introduction

Ventilation for good indoor air quality (IAQ) involves removing airborne pollutants by replacing contaminated air with a sufficient supply of fresh outdoor air. The amount of ventilation necessary to maintain good air quality in a room relies predominantly on the strength of the emissions from building materials, interior objects incl. furnishings, and human activities (Liang, Wang, Yang, & Yang, 2014; Wolkoff, Wilkins, Clausen, & Nielsen, 2006). These pollution sources are either static or variable. Static sources include building materials, fittings, equipment and surface treatments, which all have highest emissions when they are new, i.e. at the start of a building's service life. Variable sources stem from occupants and occupant-related activities such as using cleaning compounds or bringing in new objects.

Due to stricter requirements for energy use, new buildings in cold climates nowadays have highly airtight building envelope to prevent uncontrolled exfiltration heat loss. These buildings need mechanical ventilation to dilute all relevant pollutants, including those emitted from materials, to provide good IAQ when the building is in use. In order to achieve good IAQ in an energy-efficient way, the ventilation rate can be varied, to account for changes in pollutant load and occupancy. For buildings such as schools and office buildings, this can be achieved

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with demand-control of ventilation (Mysen, Rydock, & Tjelflaat, 2003; Wachenfeldt, Mysen, & Schild, 2007). This requires knowledge of the rate of emission of all relevant pollutants into the indoor air.

New buildings presumably require higher ventilation rates due to off-gassing of volatile compounds from materials. These increased ventilation rates are alleged to serve two purposes: (i) to accelerate the rate of emissions from materials so as to deplete emission sources more rapidly and (ii) to reduce the resulting airborne concentrations of emitted pollutants to acceptable levels. We reason later in this paper that the rate of ventilation has no significant impact on (i) emission rates, but nevertheless is fundamental to controlling (ii) airborne concentrations.

Off-gassing from materials in a building eventually sinks to a level that is overshadowed by other pollutants that are continually introduced by occupants, at which time a ventilation strategy for the building's 'normal operating phase' becomes appropriate. The period when the emissions from new materials dominate indoor pollutant levels is denoted the building's initial 'off-gassing phase.' Extending the initial increased ventilation rates beyond this phase causes unnecessary energy use, and may not improve IAQ.

The purpose of this literature study was to collate and analyse the best available data on material emission rates from relevant studies, and that this ultimately can be applied to design practical ventilation strategies for the initial off-gassing phase. We focus on gaseous pollutants, mainly volatile organic compounds (VOCs). Very volatile and semi-volatile organic compounds (VVOCs and SVOCs) and particulate matter (fine, ultrafine) are outside the scope of this study because they are believed to have limited relevance for the initial off-gassing phase. VVOCs gas-off quicker than other VOCs, typically fading before building construction is complete. SVOC off-gassing can persist for years (Weschler & Nazaroff, 2008), so it must be handled by the ventilation strategy for the building's 'normal operating phase.' This paper attempts to answer the following research questions:

(1) What is the rate of emission of VOCs in new buildings, and how fast does it decay over time?
(2) What are the most effective measures to reduce the emission rate? i.e. what effect do low-emitting materials, bake-out, or more intensive ventilation have?
(3) Should newly built or renovated buildings have initially increased ventilation rates during the off-gassing phase, to achieve acceptable IAQ? If so, how should the ventilation rate be decided during occupied / unoccupied periods?

Methods

We used the online databases SCOPUS, Web of Science, PubMed and AIRBASE to identify relevant studies. Additional publications were identified by backward and forward snowballing (i.e. from references and citations respectively, from selected publications). Only studies that reported measurements of total volatile organic compounds (TVOCs) in newly built or renovated buildings were included. Furthermore, we focused exclusively on studies that reported ventilation rates or air change rates.

The data collated from all the longitudinal studies was analysed in a two-stage process: Firstly, the approximate volumetric emission rate of TVOC was estimated from measured TVOC concentration and ventilation rates, with Equation (1). Ideally, the emission rates should have been calculated as surface-area specific values. However, none of the studies fully documented surface areas. We therefore evaluated *volumetric* TVOC emission rates [μg/(m^{3}h)], i.e. the rate of emission per unit room volume, assuming a typical room height of 2.5 meters. This implicitly assumes that room volumes approximately correlate with exposed surface areas. In reality, the rooms have different exposed surface area-to-volume ratios (due to differences in room width, height, and furniture), which introduces variance, which is one reason why we used quantile regression in this study.

$$E''' = c \cdot ACH \tag{1}$$

where

E''' Volumetric emission rate of TVOC [μg/(m^{3}h)]
c Airborne uniform concentration of TVOC, assuming fully-mixed ventilation [μg/m^3]
ACH Ventilation air change rate, i.e. number of air changes per hour [/h]

Secondly, a multi-exponential decay curve was fitted to the measured volumetric emission rates (E'''). Quantile regression was used for this purpose as it is a robust distribution-free method, i.e. unaffected by the values of any outliers, only by the quantity of them. Preliminary analysis of the collated data indicated that the spread in emission rates in the different studied buildings is independent of time (i.e. Figure 4 shows that the 3rd quartile is approx. 2.7 times larger than the 1st quartile for all months). This fact legitimated using a constrained non-crossing solution of all three quartiles. Such simultaneous solution of multiple quartiles significantly improves the regression by adding smoothing and stability across the quantile levels (Bondell, Reich, & Wang, 2010).

Results

Table 1 provides an overview of studies, including reported ventilation air change rates and major findings. Figure 1 provides an overview of the differences found among the study parameters. These differences complicate the systematic comparison of results from the studies, but also serve as a checklist of factors to consider when designing a low-emitting building or choosing a ventilation strategy for the initial off-gassing phase. The majority of the measurements were taken in residential buildings with mechanical ventilation systems. In the absence of a ventilation system, the ventilation rate was normally determined by step-down responses using carbon dioxide (CO_2) or tracer gases. The ventilation or air change rate varied between 0.30–1.30 h^{-1} for buildings with mechanical ventilation, and 0.17–12.11 h^{-1} for buildings with natural ventilation. The results of the review are presented in separate sections below.

Initial off-gassing and concentration decay

As seen in Figure 2, the reviewed studies observed a rapid initial decline in VOC concentrations in the first few days. The study by Brown (2002) reported that the initial VOC concentration was one to two orders of magnitude higher in new and newly renovated buildings compared to in established buildings. For TVOC and formaldehyde, a bi-exponential model was a good fit for the measurements taken in a new dwelling constructed with low-emitting materials and airtight building envelope. TVOC concentration dropped 77% in the first 23 days, followed by a slower decay rate. The rate of decay of formaldehyde concentration was slower in comparison. In the same study, TVOC concentration dropped by 67% in the first six days after a dwelling extension, by 69% over seven days after installation of a carpet in a gymnasium, and by 93%–96% over 67 days after an office renovation. However, emissions from materials still affected the indoor air until about 35 weeks for the dwelling, and 8–17 weeks for the office.

In another study (Kaunelienė et al., 2016), VOC concentrations were measured in a low-energy house for five consecutive weeks after the interior was fitted. Highest initial concentrations were observed for toluene, xylenes and ethylbenzene, most likely from emission sources such as paint and varnishes. VOCs concentrations decayed following a mono-exponential trend. The concentrations of individual compounds fell by 39%–98% over the first three weeks. After four weeks, VOC concentrations reached an acceptable level according to Lithuanian guidelines.

Table 1. Overview of relevant studies with known air change rates (ACH).

Reference	Country	Building type	Ventilation type	Study period	Range of air change rates (h^{-1})	Findings
Kaunelienė et al. (2016)	Lithuania	One residential building	Mechanical	5 weeks	0.50	Toluene decreased the fastest (50% after one week).
Noguchi, Mizukoshi, Yanagisawa, and Yamasaki (2016)	Japan	Two rooms in a daycare	Mechanical	3 months	1.50 - 3.50	TVOC concentrations three months later were approx. 1/10 of the values measured just after completion, meeting the guideline value of 400 $\mu g/m^3$. Seven target VOCs were also below guidelines values.
Pei, Yin, and Liu (2016)	China	Dormitories	Natural	4 months	3.07 - 12.11	TVOC concentrations dependent on the furniture supplier. TVOC concentrations decreased by 72.8%–97.1% over a period of 3 months. Comparison with measurements done in model room test showed that the TVOC concentration decay rate is consistent with the real room; decrease of 35% within ca 20 days. In average, the formaldehyde concentration decreased by 50.8% after 3 months.
Brown (2002)	Australia	One residential building	Mechanical	35 weeks	0.35+ estimated 0.15 infiltration	Materials in the building exhibited fast initial emission decay up to 20 days, and thereafter slower (by∼20-fold) long-term decay. Baseline concentration of TVOC (200 $\mu g/m^3$) was reached after approx. 35 weeks.
Järnström, Saarela, Kalliokoski, and Pasanen (2006)	Finland	9 apartments	Mechanical	One year	0.70 - 1.50	TVOC decreased by 60%–75% six weeks after occupants moved in. In most apartments, the TVOC concentration decreased below 200 $\mu g/m^3$ in six months. No significant changes seen between 6 and 12 months.
Liang *et al.* (2015)	China	One apartment	Natural	18 months	0.17 - approx. 0.42	TVOC decreased fast during the first few months. Seasonal differences, higher during summer than winter.
Shin and Jo (2013, 2014)	South Korea	Apartments	Natural	2 years	0.34 - 0.59	Decreasing tendencies of TVOC (mean and median values) over a period of 24 months, decreased by 50% after one year.
Crump, Squire, and Yu (1997)	UK	Two test houses	Mechanical	2 years	0.30 - 0.50	The TVOC concentration declined from 9 700 $\mu g/m^3$ to about 500 $\mu g/m^3$ during the first six months after completion of the building, then a more gradual decline with some fluctuations occurred. After 16 months, the concentration was approx. 200 $\mu g/m^3$.
Tuomainen, Tuomainen, Liesivuori, and Pasanen (2003); Tuomainen, Pasanen, Tuomainen, Liesivuori, and Juvonen (2001)	Finland	12 apartments	Mechanical	3 years	0.8 - 1.7	Comparison of case and control buildings. Pre-occupancy ventilation period decreased VOC, especially aromatics and hydrocarbons (50% after 7 days). The levels of these VOCs diminished after five months.

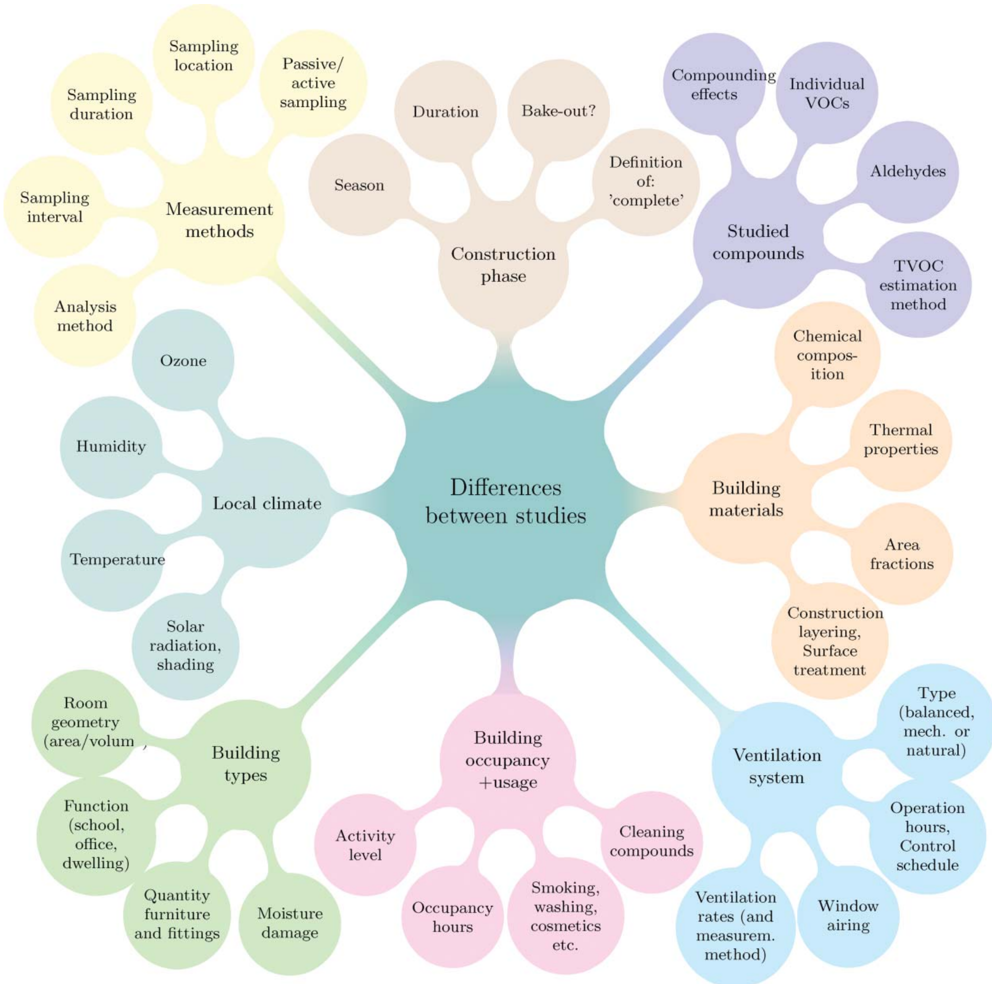

Figure 1. Mindmap overview of differences in study parameters of the reviewed studies.

Crump et al. (1997) measured VOCs in a low-energy test house in the UK, and found a rapid decline in TVOC concentrations (from 9700 to 635 μg/m^3) during the first 6 months, while it took over 16 months to reach a steady concentration of 200 μg/m^3.

Järnström et al. (2006) measured VOCs in apartments in eight buildings built with low-emitting materials and reported a rapid initial decline of TVOC concentrations, i.e. a 68% decrease of TVOC emissions within six months (Järnström, Saarela, Kalliokoski, & Pasanen, 2007, 2008). The strongest decrease in concentration of individual VOCs was observed during the first 6 months of occupancy. In one of the buildings, the TVOC concentration decreased by 60%–75% after 6 weeks of occupancy.

Tuomainen et al. (2001, 2003) measured VOCs in a similar low-emitting apartment building in Finland and found that the airborne TVOC concentration decreased by 83% after five months (incl. one week of intensive ventilation before occupancy), whilst an increased emission rate was observed for formaldehyde and acetaldehyde (presumably compounds introduced by occupancy, including furniture). In a control building, where high-emitting building and finishing materials were used, they observed the same relative decrease in TVOC concentrations, 82%, but from a much higher initial level. For both buildings, TVOC levels were further reduced after 1, 2 and 3 years of occupancy (Tuomainen et al., 2003).

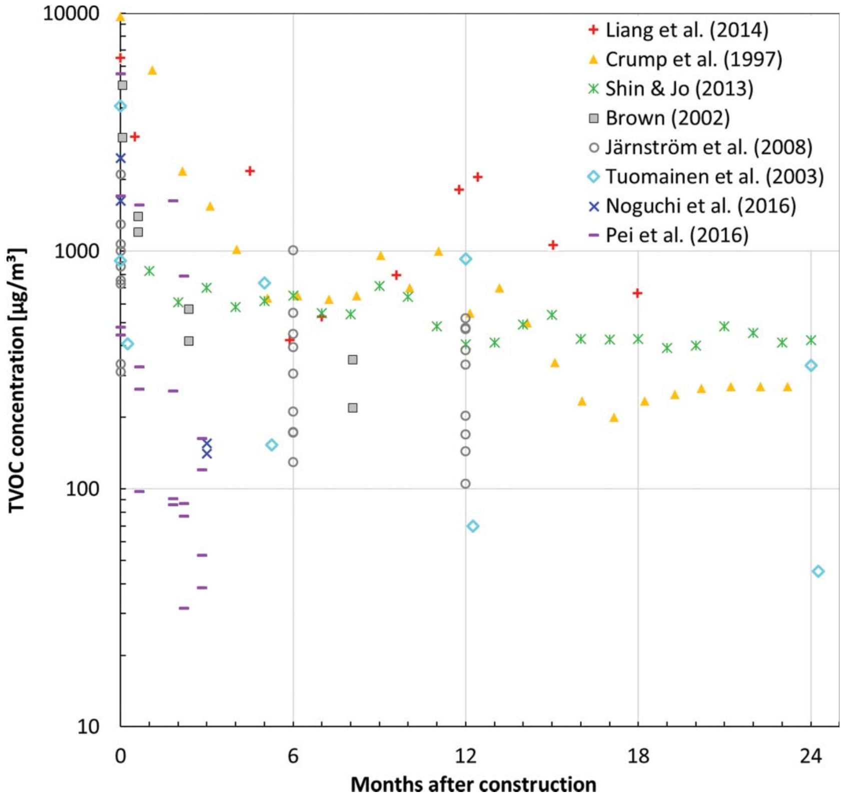

Figure 2. TVOC concentration decay from the selected longitudinal studies.

Derbez et al. (2014a, 2014b) reported, for two low-energy timber houses, the highest concentration of aldehydes (formaldehyde, hexaldehyde and benzaldehyde) and α-pinene in the pre-occupancy period compared to after the occupants moved in. Concentrations of VOC components emitted by building sources, i.e. xylenes, ethylbenzene, terpenes, styrene, declined with time as the strength of emission sources decreased. The post-occupancy concentrations of formaldehyde remained relatively stable throughout the 3-year follow-up study.

The three studies in Asia were all conducted in buildings with natural ventilation. Shin and Jo (2013) measured VOCs in apartments in South-Korea over a period of two years, and observed an initial rapid drop in concentrations during the first 12 months followed by a slower decay. Depending on the target compound, both mono- and bi-exponential models were good fits (Shin & Jo, 2014). Before the tenants moved in, highest emission rates were observed for aromatic hydrocarbons, which can be attributed to the uses of vinyl and linoleum floorings and paints (Shin & Jo, 2014). In the study by Liang, Wang et al. (2014), VOCs were measured for 18 months in a newly built occupied apartment in Beijing. They observed a rapid decay in VOC concentration during the first few months, after which the decay trends for VOCs from building materials were different from those related to human related activities. Concentrations of some alcohols and terpenes decreased rapidly in the first two weeks, while aromatics such as toluene, ethylbenzene and xylene decreased significantly over the first four months. The concentration-time behaviour for TVOC showed a fast decline during the first five months, thereafter a seasonal variation was observed. Pei et al. (2016) measured VOCs for three months in unoccupied dormitories containing furniture from four different suppliers. They found that although the furniture was all made of the same materials, the TVOC concentrations differed significantly between the different suppliers. After three months, the TVOC concentration had decreased by 97% for the highest group and 72.8% for the lowest group. Pei *et al.* fitted the 3 months of TVOC observations to single-exponential functions, but closer scrutiny of the original data indicates a bi-exponential property. The average decay rate for TVOC was estimated to be 0.0328 d^{-1}. The decay rate for TVOC was faster than for formaldehyde (2–4 times) and benzene, but slower than for alcohols and alkanes. Decay rates for terpenes and higher aldehydes were similar to TVOC. Terpenes contributed the most to the TVOC concentration.

Influence of ventilation on VOC concentrations and emission rates

Below is an analysis of the individual studies that are the basis for the emission rates shown in Figure 3:

Tuomainen et al. (2001) compared two apartment buildings: (*i*) a control building with high-emitting materials and low ventilation date, and (*ii*) a case-study building with low-emitting materials, double the ventilation rate, and with one week of intensive ventilation before occupancy. The case-study building had lower TVOC concentrations, but both buildings experienced the same *relative* reduction in TVOC concentration after 5 months compared to just after construction (82% over 5 months for the control building, and 83% over 5.25 months for the case-study building). Thus emission rates were not affected by ventilation rate, so the main key to depleting TVOC sources is time. This study illustrates the benefit of delaying occupancy — TVOC concentrations were halved during the pre-occupancy week with ventilation. The main components were aromatics and aliphatic hydrocarbons, which originate mainly from paints, glues, adhesives and building materials. However, the pre-occupancy ventilation period had no significant effect on the reduction of aldehydes.

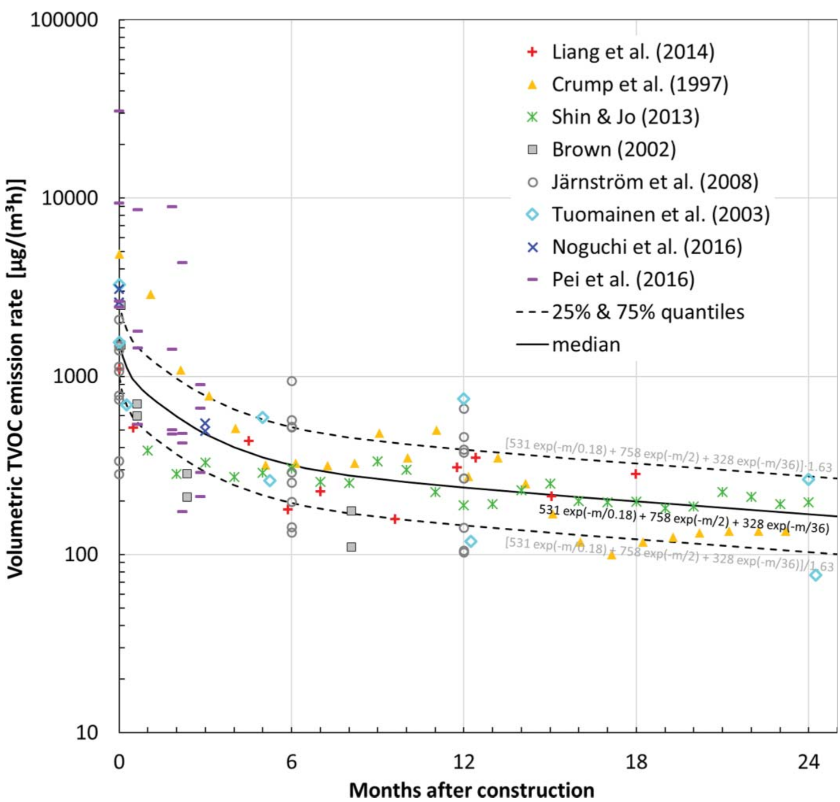

Figure 3. Approximate volumetric emission rate of TVOC from the selected studies. (median trend, 25, and 75 percentiles from quantile regression are superimposed).

Another study, Järnström et al. (2006), also analysed the effect of ventilation rates and system types. The study confirms Tuomainen's finding that pre-occupancy ventilation reduces concentrations, but not necessarily decay rates. The correlation between air change rate and VOC concentration was equivocal. The study found that buildings with balanced mechanical ventilation (supply and exhaust) had lower VOC concentrations than buildings with mechanical exhaust only, ostensibly because infiltration picks up VOCs through the facade.

Poppendieck, Ng, Persily, and Hodgson (2015) observed that when the ventilation was turned off in a house with very low infiltration rates, the indoor VOC concentration increased substantially, thus highlighting the importance of continuously maintaining minimum ventilation rates.

Noguchi et al. (2016) measured VOCs in two rooms with different ventilation rates just after completion and after 3 months. At both times, TVOC concentration was lower in the room with higher ventilation rate. After 3 months, the TVOC concentration in this room was well below half of the Japanese guideline value of 400 μg/m^3. The levels of 2-butanone, ethyl acetate and D-limonene were also much lower than Japanese guideline values. Closer scrutiny of the original data shows that both rooms experienced the same *relative* reduction over 3 months (91%–96% and 88%–95% reduction respectively) despite differences in ventilation rate.

Only one study, Hodgson, Rudd, Beal, and Chandra (2000), purports that emission rates are increased by intensive ventilation. They investigated the effect of ventilation rate on emission rates of TVOC and individual VOCs in a new site-built house in a hot humid climate. They observed that the calculated emission rate for TVOC [μg/m^{2}h^{-1}] was 30% lower when the ventilation rate decreased from 0.32 to 0.14 h^{-1}. However, the two measurements were separated by one-week only approx. one month after construction, so the observed drop in emission rates could also be explained by the inevitable exponential decay. Moreover, the apparent ratio of emission rates for the two consecutive weeks decreased with decreasing compound volatility, with only approx. 10% decrease in concentration for less volatile VOCs.

Emission rate decay regression

Figure 3 shows volumetric TVOC emission rates [μg/(m^{3}h)] calculated with Equation (1). The chart shows closer 'grouping' of the different studies than Figure 2, which has a large vertical spread of values due to differences in ventilation rates.

Figure 3 includes quantile regression curves. The interquartile range illustrates the combined effect of factors including low/high-emission materials, seasonal variations in temperature and humidity, and differences in surface area-to-volume ratio. A tri-exponential decay function was finally chosen, as it provides a significantly better fit than a mono- or bi-exponential decay. Moreover, it is physically meaningful that the decay curve is multi-exponential, for the following reasons:

1. The analytical diffusion mass transfer model though materials of finite thickness empirically fits a bi-exponential function with time (Liang et al., 2014). The elbow in the function coincides with when the diffusion gradient in the core of the material stops rising and starts falling.
2. TVOC comprises a multitude of unique VOC compounds that span a wide range of molecular sizes and volatilities (boiling points), and thus different exponential decay rates (Brown (2002)).
3. Buildings contain diverse materials with dissimilar diffusion properties (Liang et al., 2014).

In contrast, laboratory studies of the off-gassing of from thin sheet materials generally observe a mono-exponential decay characteristic for each unique VOC compound.

The 2nd quartile (median) tri-exponential regression is summarized in Equation (2b). It indicates that approx. 33% of the initial emissions have a time constant of approx. $5\frac{1}{2}$ days (high volatility), 47% of the emissions have a time-constant of approx. 2 months (intermediate volatility), and the last

20% have a time constant of approx. 3 years (low volatility). The first and third quartiles are each a factor 1.63 larger or smaller than the median.

$$E'''_{Q1} = \tilde{E}''' / 1.63 \tag{2a}$$

$$\tilde{E}''' = 531\ e^{(-m\,/\,0.183)} + 758\ e^{(-m\,/\,2.043)} + 328\ e^{(-m\,/\,35.96)} \tag{2b}$$

$$E'''_{Q3} = \tilde{E}''' \times 1.63 \tag{2c}$$

where m is the number of months after completion of construction, e.g. m = 0.23 is one week after completion.

Other relevant factors

TVOC concentrations are not only influenced by source strength and ventilation rate, but also factors such as temperature and relative humidity. It is known that increased temperature, in particular, results in increased diffusion and emission rate. In the study by Liang, Yang & Yang (2014), TVOC concentration was about four times higher in summer than in winter. For individual VOCs, such as toluene, ethylbenzene and xylene, their concentrations could be 2–10 times higher in summer than in winter. Decreased infiltration rate and increased building emission rates due to higher temperatures were considered the reasons behind the high concentrations during summer (Liang, Yang, & Yang, 2014).

Järnström et al. (2006) measured higher formaldehyde and ammonia concentrations in summer when the relative humidity was at least 50%, and larger covariance between emissions and RH than with temperature. In 6-month old buildings, lower temperature and a relative humidity below 30% resulted in lower TVOC concentrations. The buildings with balanced mechanical ventilation generally had lower temperatures. The same study observed an accelerated concentration decay rate during a pre-occupancy 'bake-out' period (space heating to 30–35 °C).

Derbez et al. (2014) observed no seasonal variation for formaldehyde concentrations, but a higher level of acetaldehyde was observed in winter than in summer which was attributed to use of a wood-burning stove.

Poppendieck et al. (2015) took monthly measurements of VOCs in a net-zero energy house during the first year of operation, and reported two temporal trends for VOC concentrations. The seasonal variation of indoor VOC (subtracted for the corresponding outdoor concentration) showed a dependency on outdoor temperature, with higher concentrations during the first summer than during the second summer. Furthermore, the concentrations of many VOCs increased during warmer sampling months and decreased during colder sampling months. In the same study, by keeping the ventilation rate constant, an 8 °C increase in temperature resulted in an average 3.8-fold increase in VOC emission rates.

The seasonal patterns seen in many studies (cf. Shin & Jo; Crump et al. in Figure 3), as well as the apparent slower decay of emission rates seen with exhaust ventilation than with balanced mechanical ventilation, may be partly explained by pollutants from materials embedded in the construction reaching the indoor air, either by bulk diffusion or by air infiltration.

Figure 4 illustrates the spread in volumetric emission rates caused by these compound factors (and all parameters illustrated in Figure 1). Figure 4 shows the empirical distribution function (EDF) for the studied buildings, at exactly 0, 1, 3, 6, and 12 months after completion. Each point in Figure 4 is taken from Figure 3. For those buildings that were not sampled at exactly 1, 3, 6, or 12 months, the points in Figure 4 are exponentially interpolated in time between the two nearest samples.

Figure 4 shows that one significant cause of spread is new furniture. All 5 curves have approximately the same gradient in the interquartile range (IQR), vindicating the use of a constant IQR-factor

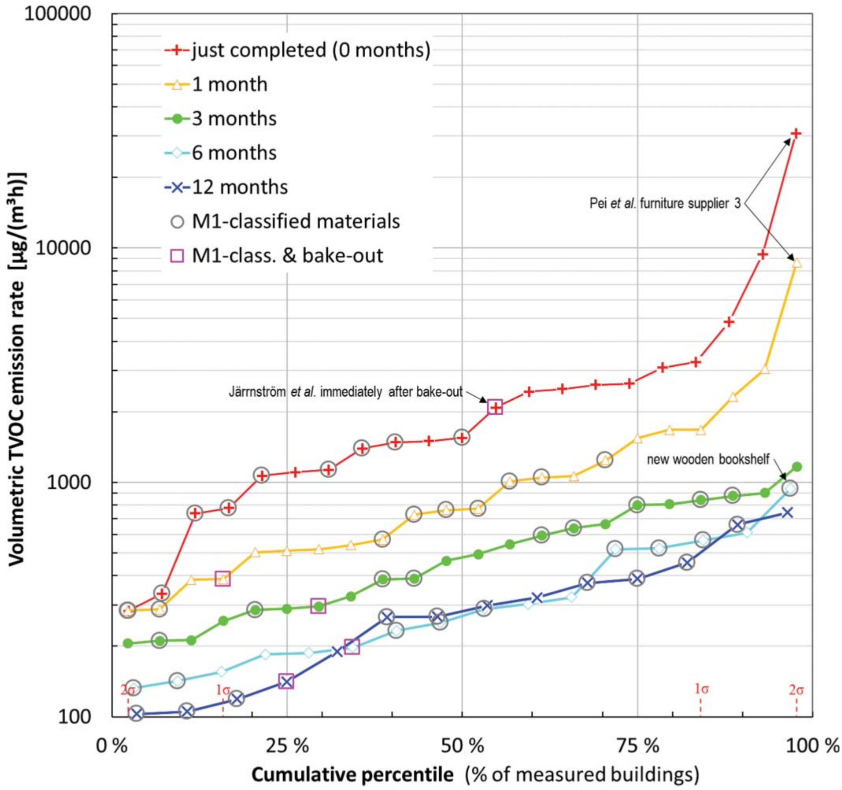

Figure 4. Empirical distribution function for volumetric emission rates at 5 points in time after completion of the buildings in the reviewed studies.

in the quantile regression. Looking in particular at the first two months (red and orange curves) the three quartiles can be assumed to represent the following building types:

- *Q3*: Buildings with unclassified materials or new furniture
- *Q2 (median)*: Buildings with M1-classified materials
- *Q1*: Buildings with M1-classified materials *and* a bake-out period before occupancy. Note that the point with bake-out at time $m = 0$ months in Figure 4 can be ignored because it was sampled during the end of the bake-out period, while bake-out was still causing high emissions.

The above classification is only suggestive; we recommend that additional longitudinal studies lasting at least 2 years be conducted to gain more confidence.

Discussion

Does intensive ventilation help to accelerate the depletion of TVOC pollutants from materials in new or renovated buildings?

Figure 3 shows that emissions of indoor air pollutants are two or more orders of magnitude higher in newly built and renovated buildings than in established buildings. The resulting TVOC concentrations should therefore be kept within health guidelines during occupied periods, by providing sufficient ventilation. Prior to this study, it was widely assumed that further increasing the ventilation rate helps to accelerate the depletion of pollutants in furniture, fittings, and building materials exposed to the room air, by virtue of increasing the difference in vapour pressure between the surfaces and the surrounding air. This effect is known to be significant in the case of surface-applied volatile compounds, such as the first hours after applying liquid products including paint (Liang et al., 2014). However, the close grouping of the data in Figure 3 indicates that increased ventilation does *not* significantly accelerate emission rates on the time scale of weeks or months. The reason for this lack of influence is explained by Brown (2002) who observed that the concentration decay rate correlates with molecular volume for individual VOCs, indicating that emissions are limited by bulk diffusivity within the materials.

Should newly built or renovated buildings have extra ventilation to achieve acceptable IAQ?

Although many studies have investigated IAQ in newly built or renovated buildings, few have assessed the ventilation requirements for newly built buildings, especially considering the necessary airflow to ventilate emissions from 'wet'-chemical building products such as paint and varnishes. Studies undertaken in laboratories to investigate the emission characteristics of various building materials indicate a heavy reduction in emissions between 3 and 28 days at a ventilation rate of 1 m^3/h per area of the test material (cf. NS-EN 717-1). The studies reviewed in this paper indicate that it is reasonable to assume a two-stage VOC emission process, starting with rapid off-gassing decay followed by slower more steady-state emissions. Building materials are initially the dominant VOC source. A ventilation strategy that is temporarily adjusted to these high emission rates would contribute to better IAQ during hours of occupancy, especially in the first days and weeks of off-gassing. However, outside occupied hours, ventilation rates can apparently be significantly reduced without affecting emission rates.

How long does the off-gassing phase last and how can it be reduced?

Generally, the airborne concentration of TVOC and many individual compounds decline quickly in new buildings, especially in the first weeks after completion. However, Figure 3 shows that the whole off-gassing phase lasts at least 2 years. The reviewed longitudinal studies mostly involved occupied buildings in which TVOC concentration stabilised after the off-gassing phase, due to continual introduction of new compounds generated by occupancy and human activities. Although TVOC concentration may rise when occupants move in (introduction of furniture and household goods), it falls again rather rapidly and stabilises after a few months (Tuomainen et al., 2003).

Some studies highlighted that delaying occupancy for one or two weeks, with the ventilation system operating, improves IAQ (Järnström et al., 2006; Noguchi et al., 2016; Tuomainen et al., 2001). All dust-generating construction work should be completed before the ventilation system is started, so as to avoid contamination of the air distribution system.

Herbarth and Matysik (2010) suggested an optimal waiting period of up to three months following home renovations. This result was based on the time it took for 26 VOCs to return to a reference load of 202.5 $\mu g/m^3$. Berglund, Johansson, and Lindvall (1982) on the other hand, recommended that newly built preschools be gassed off for at least six months with no recirculation of return air. This recommendation was based on the concentrations for 22 organic compounds.

Formaldehyde has a slower decay rate than TVOC, so if this pollutant is present in health-relevant concentrations, a different ventilation strategy might be needed. Strong seasonal variations of formaldehyde and certain volatile compounds were observed in some studies, which complicates the estimation of the duration for initial off-gassing. These seasonal variations are due to varying humidity, outdoor and indoor temperatures, or chemical reaction of compounds with ozone in supply air. Thus, seasonal variations and the contribution from outdoor air pollutions need to be considered. Nevertheless, the effect of temperature on VOC concentrations might indicate that emissions are proportional to temperature. Consequently, the bake-out procedure has been suggested as a way to speed up the off-gassing process. By increasing the room temperature to more than 30 °C, the removal efficiency of VOCs from construction materials can increase dramatically (Lv, Liu, Wei, & Wang, 2016;

Järnström et al., 2006). Non-residential buildings can be operated with elevated space temperatures during unoccupied periods (night, weekends) after the building has been taken into use, but temperatures should not even be slightly elevated during occupied periods.

Conclusions

- The findings from the reviewed studies indicate that VOC emissions in the off-gassing phase of new or renovated buildings follows a multi-exponential decay trend: i.e. a rapid decline in emissions during the first month or so, followed by a more gradual decline (with fluctuations due to seasonal changes in temperature, humidity, etc.) until approximate steady state is reached after at least two years.
- We have developed tri-exponential decay functions (Equation (2)) for volumetric TVOC emission rates. Three different functions have been developed for buildings with or without M1-certified materials, and for low-emitting buildings after bake-out, respectively. These functions can be used to determine ventilation rates required to keep TVOC concentrations at comfort levels during occupancy periods at any point in time after construction.
- The ventilation rate during occupancy should be adjusted to limit TVOC concentrations to healthy and comfortable levels (say 200 $\mu g/m^3$), but there appears to be little benefit reducing TVOC concentrations below this. Outside occupancy periods, ventilation rates can be significantly reduced, because TVOC emission rates are not noticeably accelerated by increasing the ventilation rate.

Recommendations for future work

- Further systematic studies are needed to investigate how much effect the choice of low emitting materials and bake-out have on the emission rates.
- Further analytical work is needed to develop guidelines on ventilation rates, control strategies, and the required period of extra ventilation to limit VOC concentrations.

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References

Berglund, B., Johansson, I., & Lindvall, T. (1982). A longitudinal study of air contaminants in a newly built preschool. *Environment International, 8*(1), 111–115. doi: 10.1016/0160-4120(82)90018-6

Bondell, H. D., Reich, B. J., & Wang, H. (2010). Noncrossing quantile regression curve estimation. *Biometrika, 97*(4), 825–838.

Brown, S. K. (2002). Volatile organic pollutants in new and established buildings in Melbourne, Australia. *Indoor Air, 12*(1), 55–63. doi: 10.1034/j.1600-0668.2002.120107.x

Crump, D. R., Squire, R. W., & Yu, C. W. F. (1997). Sources and concentrations of formaldehyde and other volatile organic compounds in the indoor air of four newly built unoccupied test houses. *Indoor and Built Environment, 6*(1), 45–55. doi: 10.1177/1420326X9700600106

Derbez, M., Berthineau, B., Cochet, V., Lethrosne, M., Pignon, C., Riberon, J., & Kirchner, S. (2014a). Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Building and Environment, 72*, 173–187. doi: 10.1016/j.buildenv.2013.10.017

Derbez, M., Berthineau, B., Cochet, V., Pignon, C., Ribéron, J., Wyart, G., … Kirchner, S. (2014b). A 3-year follow-up of indoor air quality and comfort in two energy-efficient houses. *Building and Environment, 82*, 288–299. doi: 10.1016/j.buildenv.2014.08.028

Herbarth, O., & Matysik, S. (2010). Decreasing concentrations of volatile organic compounds (VOC) emitted following home renovations. *Indoor Air, 20*(2), 141–146. doi: 10.1111/j.1600-0668.2009.00631.x

Hodgson, A. T., Rudd, A. F., Beal, D., & Chandra, S. (2000). Volatile organic compound concentrations and emission rates in new manufactured and site-built houses. *Indoor Air, 10*(3), 178–192. doi:10.1034/j.1600-0668.2000.010003178.x

Järnström, H., Saarela, K., Kalliokoski, P., & Pasanen, A.-L. (2006). Reference values for indoor air pollutant concentrations in new, residential buildings in Finland. *Atmospheric Environment, 40*(37), 7178–7191. doi: 10.1016/j.atmosenv.2006.06.021

Järnström, H., Saarela, K., Kalliokoski, P., & Pasanen, A.-L. (2007). Reference values for structure emissions measured on site in new residential buildings in Finland. *Atmospheric Environment, 41*(11), 2290–2302. doi: 10.1016/j.atmosenv.2006.11.033

Järnström, H., Saarela, K., Kalliokoski, P., & Pasanen, A.-L. (2008). The impact of emissions from structures on indoor air concentrations in newly finished buildings — predicted and on-site measured levels. *Indoor and Built Environment, 17*(4), 313–323. doi: 10.1177/1420326X08093948

Kaunelienė, V., Prasauskas, T., Krugly, E., Stasiulaitienė, I., Čiužas, D., Šeduikytė, L., & Martuzevičius, D. (2016). Indoor air quality in low energy residential buildings in Lithuania. *Building and Environment, 108*, 63–72. doi: 10.1016/j.buildenv.2016.08.018

Liang, W., Wang, C., Yang, C., & Yang, X. (2014). Volatile organic compounds in different interior construction stages of an apartment. *Building and Environment, 81*, 380–387. doi: 10.1016/j.buildenv.2014.07.015

Liang, W., Yang, C., & Yang, X. (2014). Long-term concentrations of volatile organic compounds in a new apartment in Beijing, China. *Building and Environment, 82*, 693–701. doi: 10.1016/j.buildenv.2014.10.016

Liang, W., Yang, S., & Yang, X. (2015). Long-Term Formaldehyde Emissions from Medium-Density Fiberboard in a Full-Scale Experimental Room: Emission Characteristics and the Effects of Temperature and Humidity. *Environmental Science and Technology*, *49*(17), 10349–10356.

Lv, Y., Liu, J., Wei, S., & Wang, H. (2016). Experimental and simulation study on bake-out with dilution ventilation technology for building materials. *Journal of the Air & Waste Management Association*, 66(11), 1098–1108. doi: 10.1080/10962247.2016.1200503

Mysen, M., Rydock, J. P., & Tjelflaat, P. O. (2003). Demand controlled ventilation for office cubicles - can it be profitable?. *Energy and Buildings*, *35*(7), 657–662.

Noguchi, M., Mizukoshi, A., Yanagisawa, Y., & Yamasaki, A. (2016). Measurements of volatile organic compounds in a newly built daycare center. *International Journal of Environmental Research and Public Health, 13*(7), 736–750. doi: 10.3390/ijerph13070736

Pei, J., Yin, Y., & Liu, J. (2016). Long-term indoor gas pollutant monitor of new dormitories with natural ventilation. *Energy and Buildings, 129*, 514–523. doi: 10.1016/j.enbuild.2016.08.033

Poppendieck, D. G., Ng, L. C., Persily, A. K., & Hodgson, A. T. (2015). Long term air quality monitoring in a net-zero energy residence designed with low emitting interior products. *Building and Environment, 94*(Part 1), 33–42. doi: 10.1016/j.buildenv.2015.07.001

Shin, S.-H., & Jo, W.-K. (2013). Longitudinal variations in indoor VOC concentrations after moving into new apartments and indoor source characterization. *Environmental Science and Pollution Research, 20*(6), 3696–3707. doi: 10.1007/s11356-012-1296-z

Shin, S.-H., & Jo, W.-K. (2014). Volatile organic compound concentrations in newly built apartment buildings during pre- and post-occupancy stages. *International Journal of Environmental Analytical Chemistry, 94*(4), 356–369. doi: 10.1080/03067319.2013.814125

Tuomainen, M., Pasanen, A.-L., Tuomainen, A., Liesivuori, J., & Juvonen, P. (2001). Usefulness of the finnish classification of indoor climate, construction and finishing materials: Comparison of indoor climate between two new blocks of flats in Finland. *Atmospheric Environment, 35*(2), 305–313. doi: 10.10166/S1352-2310(00)00157-6

Tuomainen, M., Tuomainen, A., Liesivuori, J., & Pasanen, A.-L. (2003). The 3-year follow-up study in a block of flats – experiences in the use of the Finnish indoor climate classification. *Indoor Air, 13*(2), 136–147. doi: 10.1034/j.1600-0668.2003.00171.x

Wachenfeldt, B. J., Mysen, M., & Schild, P. G.. 2007. Air flow rates and energy saving potential in schools with demand-controlled displacement ventilation. *Energy and Buildings*, 39(10), 1073–1079.

Weschler, C. J., & Nazaroff, W. W. (2008). Semivolatile organic compounds in indoor environments. Atmospheric Environment, 42(40), 9018–9040. https://doi.org/10.1016/j.atmosenv.2008.09.052

Wolkoff, P., Wilkins, C. K., Clausen, P. A., & Nielsen, G. D. (2006). Organic compounds in office environments – sensory irritation, odor, measurements and the role of reactive chemistry. *Indoor Air, 16*(1), 7–19.