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Passive window ventilation openings in every-day use

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ABSTRACT

The integration of passive window ventilation openings (PWVO, small air inlets integrated in the window frame) with additional exhaust fans in the kitchen and bathroom(s) can ensure a user-independent basic air change rate in dwellings. The project reported on herein is focused on how well buildings with PWVO work in real life. Altogether 28 multi-family houses are investigated by site visits, a survey among the inhabitants and measurements in eight flats. The survey is conducted in the winter 2017/18 and addresses user ventilation behavior, thermal and acoustic comfort, IAQ and user satisfaction. The 270 completed questionnaires returned allow tentative inferences for future ventilation concepts. For instance, it is found that in dwellings heated with radiators, air draught caused by PWVO is reported less frequently then in dwellings with a floor heating. The measurements in the winter 2018/19 are twofold: short-term measurements with a focus on the volume flow rates, the airtightness and the relative pressures in the flats. Long-term measurements comprise CO_2 concentrations, interior and exterior air temperatures and humidities and operation modes of the extract fans. In six out of eight flats the measured outdoor air flow rate covers only 35–80 % of the amount recommended by the Swiss building standards. The airtightness of all flats varies between q_{a50}-values of 0.5 and 1.3 $m^3/(h\ m^2)$ (±10 %). CO_2 measurements show that in the sleeping rooms the mean is between 650 and 3′440 (±70–160) ppm.

1. Introduction

The air quality in an occupied building should not trouble users with unpleasant odours and, even more important, should not endanger their health [1]. These requirements are to be met with an adequate ventilation scheme. The ventilation rate may be subdivided into a basic, user independent portion for humidity control and mould protection and one for hygienic needs with present users [2]. The required air change rate for mould protection is lower and may be in the range of 0.10–0.22 h^{-1} [3]. The hygienic air change rate is higher and is meant to remove or dilute contaminants and CO_2. Literature reviews indicate that increased ventilation rates may reduce respiratory symptoms, asthma or allergy symptoms [4–6]. However, it seems difficult to deduce a threshold value below which adverse health effects occur [5]. Tentative guesses lead to values between 22 and 25 m^3/h per person [4] or 0.5 h^{-1} (for Nordic countries) [6].

The ventilation of buildings can be ensured by natural ventilation (e. g. window ventilation), hybrid ventilation (e. g. a temporarily operating mechanical extract fan with air inlets) or mechanical ventilation (e. g. supply and extract ventilation with heat recovery).

Comparisons of dwellings with mechanical ventilation and natural ventilation show, that in buildings with mechanical ventilation higher air change rates are achieved [7] and that the concentration of air pollutants is significantly lower in buildings with mechanical ventilation [8, 9]. As CO_2 is a product of the human respiratory system, it is an acknowledged indicator for indoor air quality [10]. During daytime, high concentrations are associated with a reduction of mental productivity [10], while at night high concentrations in bedrooms negatively affect sleep quality. For this relation, tentative numbers are proposed in Ref. [11]:

- "< 750 ppm undisturbed sleep quality range
- 750–1150 ppm possibly disturbed sleep quality
- 1150–2600 ppm disturbed sleep quality range
- > 2600 ppm disturbed sleep quality range with possible reduced next-day cognitive performance"

It is expected a priori and then confirmed by the literature review in

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Ref. [11], that studies which focus on mechanical ventilation report lower CO_2 levels than studies exploring natural ventilation. Average measured CO_2 concentrations in bedrooms of 62 buildings with mechanical ventilation systems and of 61 naturally ventilated buildings in Austria were found to be 1360 ppm and 1830 ppm, respectively [9].

In older, naturally ventilated buildings, the air change for mould protection is often covered by infiltration, caused by a low airtightness of the building envelope (e. g. windows). Hence, when a building is renovated, this ventilation “concept” may be adversely affected by the reconstruction. For example, in Switzerland 70 % of building refurbishments are realised in stages [12]. Quite often, only a window replacement is done and the building envelope is left uninsulated. If there is no mechanical ventilation system installed which ensures continuous air exchange, new airtight windows usually lead to a reduced infiltration air exchange and subsequently there may be moisture issues, e.g. mould damage. Especially, if surface temperatures of walls are reduced locally as a result of thermal bridges. The risk of mould damage is usually higher in dwellings than in other building types such as office buildings due to higher humidity loads (produced e.g. by cooking or washing). In dwellings, mould growth is found significantly more often in flats than in single-family homes (no data is given whether the housing is rented or owned). Within the flats, bedrooms and children’s rooms are most frequently affected by the damage (Hartmann, Reichel, & Richter, 2002). Estimations of how many dwellings are affected by a problematic mould growth vary. They range from 10 % in Germany [13] up to 45 % for Europe [14]. One study [15], accessing 50 various types of dwellings in the UK found mould in 50 % of the buildings. Mould and dampness is associated with an increase in a variety of respiratory [16] and asthma related [17] health issues for the inhabitants and especially for children. As for the building itself, moisture can lead to a deterioration in building materials [18].

Since one of the causes for mould is inadequate ventilation [14,15], a possible solution to this problem is the integration of passive window ventilation openings (PWVO), also named trickle vents. A PWVO is a ventilation device or element that is integrated into the window or is directly related to the window (Table 1). Although there can be a fan within a WVO itself, this publication deals with passive window ventilation openings only.

The PVWO themselves are part of a ventilation concept that uses them as an air inlet in combination with permanent or time-controlled extract fans in the kitchen and bathroom(s). The benefits of such a ventilation concept are that the air-change is user independent and much more reliable than the rather primitive “method” of removing existing seals in new windows, which is often adopted after moisture issues have occurred. Thus, PWVO can be an adequate means to enable a building renovation in stages without the drawbacks of building damages during intermittent use. In recent years, PWVO have increasingly been included in ventilation concepts for newly built buildings in Switzerland as well. This is reflected by the fact that the recruitment of building owners for participation in this project yielded not only existing but also newly built buildings.

As it will be seen in the next section, literature about experimental studies focusing on the application of PWVO is scarce. Specifically, studies where the air exchange is actually measured and not indirectly deduced from the ventilation mode, blower door tests or from the CO_2 concentration of the air are lacking. Moreover, the use of CO_2 as an indicator of ventilation rates may lead to unprecise results. In Ref. [20] numerous sources of error are outlined, leading to the conclusion that CO_2 concentrations are not necessarily good metrics of ventilation rates. Four out of 11 of the revised studies contain measurements of the exhaust ventilation rate, three studies use CO_2 as an indicator. Only six projects had the air tightness measured, allowing a statement on whether the air entering the building stems from the PWVO or other leakages. In several literature reviews, the need for well documented measurements is expressed [4–6]. This is supported by Ref. [21], where a critical review on the methodology of 26 field measurements stated gaps in the documentation of instruments (10 %), uncertainty (85 %), timescale or averaging (75 %). This leads to the conclusion that the present study will contribute to the existing literature of measurement projects, presenting sufficient background documentation for assessing the results. Apart from this, the issue of adequate natural or mechanical ventilation in residences is an important topic for improving indoor health conditions.

1.1. Application of PWVO in other countries (experimental studies)

Experimental studies which focus on performance measurements of PWVO in combination with an extract fan in dwellings are rare. Two recently published literature reviews support this impression. The first [22], specifically addressing trickle vents, surveyed 116 sources and mentioned three experimental studies (two schools, one office). The second review [23], dealing with hybrid ventilation, surveyed 96 sources and identified 18 measured buildings, of which three are residential buildings.

A literature review conducted for this paper focused on dwellings with air vents (not necessarily integrated into the window, but also in the wall) and extract fans in kitchen and bathrooms. Table 2 shows the main findings from ten projects. In four projects the air change rate was actually measured, in the other projects it was deduced from CO_2-measurements. The measured air change rate varies between 0.27 and 0.48 h^{-1} for the flats and between 0.3 and 0.9 h^{-1} for the single-family houses. The span might be partly attributed to different building standards and different levels of air tightness of the building envelope (one project had an ACH_{50} between 0.6 and 2.3, five measured projects had an ACH_{50} between 2.3 and 15.3 h^{-1}). For the single-family houses in two projects the air change was rated as not meeting the building code requirements, in one project the requirement by the local building standard was exceeded by 50 %. Concerning CO_2, mean values between 500 and 1′400 ppm were observed in the flats. In the bedrooms of the single-family houses, values between 800 and 3′000 ppm were recorded. The review shows that a user information might be helpful: In one study, vents were blocked on purpose [24], in two studies the habitants were not aware of the vents and had them blocked or closed out of ignorance [25,26].

The documented air tightness of the buildings shows that the bandwidth is broad. Swiss (new) buildings tend to be less leaky (in the building code [1] the limit q_{a50} for buildings with a ventilation system is 1.6 $m^3/(h\,m^2)$). Thus, the present study adds valuable knowledge, given

Table 1
Principles of PWVO depicting typical locations and pathways for the airflow. Source for principle sketches [19]:

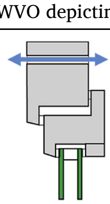
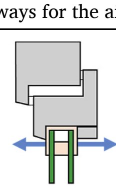
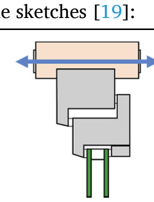
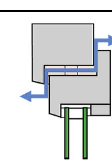
Principle				
Description	PWVO top-frame integrated into the window frame	PWVO top-frame integrated into glazing rebate	PWVO top-frame adjacent to the window frame	PWVO in the window rebate

Table 2
Summary of projects providing measurement results for ventilation rates in dwellings with vents and extract fans found in the literature. Abbreviations used: S = source, C = country, MFH = multi-family house, DH = detached house, SDH = semi-detached house, F = flat.

S	C	Building	Methodology	Ventilation system	Results
[27]	CH	MFH, 3 F	CO_2: sensor ACH: deduced from ventilator mode	Humid sensitive air inlets and extracts	CO_2: 500–850 ppm (average range F) ACH: 0.27 h^{-1}
[28]	PRT	MFH, 25 F retrofitted	CO_2: sensor ACH: calculated from CO_2	self regulating air inlets and exhaust ventilator in kitchen (continuously), bathroom (temporarily)	CO_2: not published ACH: 0.35 h^{-1}
[29, 30]	FIN/ LTU	MFH, 37 F (FIN), 15 F (LTU), retrofitted	CO_2: sensor ACH: exhaust measured	FIN: exhaust ventilation (6 h/day) LTU: occupant controlled fan in kitchen and/or exhaust fan in bathroom	FIN CO_2: 900 ppm (mean 24 h, F) ACH: 0.48 h^{-1} LTU CO_2: 1'400 ppm (mean 24 h, F) ACH: 0.39 h^{-1}
[31]	EST	MFH, 39 F built after 2000	CO_2: sensor ACH: calculated from CO_2	exhaust ventilation and air valves	CO_2: 800 ppm ACH: 0.42 h^{-1}
[24]	NL	149 DH and SDH built 2006–2008	measurements not exactly defined	Exhaust ventilation and natural air supply (grilles over windows)	ACH: insufficient in 69 % of dwellings
[32]	USA (CA)	70 DH	CO_2: sensor ACH: exhaust measured	Exhaust ventilation and vents	CO_2: 620 ppm (mean, building) ACH: in almost all buildings the airflow exceeded the code minimum requirement by 50 %
[33]	BEL	39 DH built 2007–2008	CO_2: sensor ACH: exhaust measured	exhaust ventilation and trickle ventilators above window	CO_2: 1'250 ppm (bedroom, max value of the daily mean course) ACH: the required flow rate from the building code is never reached in the kitchens, on average it is reached with the highest ventilation level in the bathrooms.
[34]	UK	1 SDH, renovated	Blower door test	Trickle vents in all windows, no extract fan	CO_2: n.a. ACH: 0.9 h^{-1} (0.8 with vents closed)
[25]	UK	28 SDH, 4 flats	CO_2: sensor ACH: exhaust measured	Extract ventilation with trickle vents	CO_2: 800 ppm (bedroom) ACH: 0.44–0.61h^{-1}
[35]	DK	1 SDH	CO_2: sensor ACH: calculated from CO_2	House: trickle vents temporarily exhaust fan	CO_2: 3'000 ppm (bedroom) ACH: 0.15 h^{-1} (0.3 h^{-1} door open)

Table 3
Analysed building types. Overview of main characteristics of the PWVO configuration, the installed product and the ID-code used throughout this paper.
Used Abbreviations: MFH = multi-family house, HH = high-rise building, N = new built, T = total refurbishment, W = window replacement, PWVO = passive window ventilation opening, EAV = external air vent, TFWF = PWVO top-frame integrated into window frame, WR = PWVO in window rebate, WF = window frame, N = no, Y = yes, (*) = two flats are measured in this building type.

ID-Code	Number, building type locality, measurement	N/T/W	# flats	PWVO/EAV	Product	Adjust-able?
ZH_1_1 to ZH_1_9	9 MFH Zürich	N	278	PWVO (TF above WF)	Anjos, L 30 S	N
WT	1 MFH Winterthur	N	10	PWVO (TFWF)	Invisivent EVO AKD, Renson	Y
ZH_2	1 MFH Zürich	W	10	PWVO (TFWF)	Trivent ZEF-S	Y
ZH_3	1 MFH Zürich (*)	N	14	PWVO (TFWF)	Sonoslot –P475, Renson	Y
ZH_4	1 MFH Zürich	W	4	PWVO (TFWF)	Aerex AL_db_450	Y
GS	2 MFH Gasel	T	22	PWVO, WR	Ego Kiefer Secco, no filter	N
SD	2 MFH Studen	T	30	PWVO, WR	Regelair "Forte"	Y
ZH_5	2 MFH Zürich (*)	N/T	26	PWVO, TF, above WF	Siegenia Aeromat VT, Typ DF2	N
BB	3 MFH Biberstein (*)	N	22	PWVO (TFWF)	ALD Aerex AL-dB-450-40	Y
DT_1	2 HH Dietikon	T	78	PWVO (TFWF)/EAV (wall)	Helios ALEFS 45/Helios ZTV-100	N/Y
DT_2	1 MFH Dietikon	T	35	PWVO (TFWF)	Helios ALEFS 45	N
DT_3	2 HH Dietikon (*)	T	32	PWVO (TFWF)	Helios ALEFS 45	N
HO	1 MFH Horw	T	12	EAV (wall)	Helios ALD ZLA 100	Y

the tendency of new regulations to make requirements for the air tightness of buildings more onerous.

1.2. Project scope

A preceding project explored the determining factors for the successful use of PWVO in dwellings in Switzerland by means of transient simulations. An accompanying market research characterised and classified typical products [3,36]. Based on this theoretical analysis, the present project focuses on realised buildings. Altogether, 13 types of dwellings (in total 28 multi-family houses) with integrated PWVO are investigated. The 13 building types are split into four newly built and eight refurbished multi-family buildings and one mix of refurbished parts and new premises (ZH_5). For six of the eight refurbished building types the refurbishment is comprehensive as it includes window replacement and insulation of the walls. For the remaining two building types (ZH_4, ZH_2) only the windows are replaced. The ventilation concepts of all buildings include PWVO and time-controlled or continuously operating ventilation via exhaust fans in the kitchen and bathroom(s). In five building types (ZH_2, ZH_4, ZH_5, DT_1 and DT_3) the evaporator of a heat pump utilises heat from the extracted air in order to increase efficiency. How PWVO perform in real life is explored by an evaluation of the planning concept, site visits, a user survey and short- and long-term measurements. The measurements are done in two flats each of four multi-family houses (marked with an * in Table 3).

2. Methodology

2.1. Recruitment of buildings

Buildings were recruited by contacting building service engineers, architects, housing cooperatives and local authorities. The burden for the inhabitants is not negligible due to the site visits, the survey and (for a small selection) the measurements. For this reason, the buildings must be considered a somewhat biased sample which favours committed building owners, property managers and tenants. Nine out of the 13 building types are owned by a housing cooperative (Table 3: #1, 3, 4, 8–13).

The buildings in which detailed measurements are carried out (marked in Table 3 with an *) are all located in central Switzerland. The buildings ZH_3, ZH_5 and DT_3 are situated in or near Zürich. The mean temperature from October 2018 to April 2019 is 5.7 °C. The coldest month with a mean temperature of 0.5 °C is January 2019. The warmest month is October 2018 with 10.6 °C. The climatic conditions in Biberstein, where the building BB is located, are similar, the mentioned temperatures are only 0.1–0.2 K higher.

Table 4
Structure of the questionnaire. Used abbreviations: OM = optional mention.

1. Housing related features	Number of rooms (OM)/Number of persons in the flat (OM)/Floor number/Years lived in the flat/Mould
2. Communication	About the PWVO and the exhaust ventilation/Ventilation habits with PWVO and exhaust ventilation
3. Level of contentment	While answering the questions/With the flat in general/With the PWVO
4. Ventilation habits in winter	incidence and type of manual ventilation/Adjustment of PWVO
5. Thermal comfort, indoor air quality and acoustic comfort in winter	Humidity/Temperature/Indoor air quality/Draught/Noise from outside and/or the exhaust ventilation

2.2. Site visits

The site visits are done between 26.02. to 26.03.2018 and include two or three flats per building type. During the site visit, the ventilation system is verified, the numbers and locations of the PWVO and/or air transfer devices are assessed and it is checked whether the PWVO are manipulated (e. g. masked) and if there is any mould in the flat. The visited flats are not necessarily the flats in which the measurements are performed.

2.3. Survey and statistical methods for evaluation

The questionnaires are distributed during the site visits as printouts to be returned anonymously within four weeks. An online version is also provided. The data is collected between 26.02. to 24.05.2018. In the buildings ZH_1_1 to ZH_1_9 the survey is an add-on to a survey organised by the property manager on a regular basis. This survey took place from 24.04. to 24.05.2018. For building ZH_2 the refurbishment was not concluded until October 2018. The questionnaire refers to wintertime experience and consists of 19 questions exploring different topics (Table 4).

Wherever a rating is asked for (Topics 2, 3 and 5) a five-point assessment is offered (Likert scale): e. g. "unsatisfied", "slightly unsatisfied", "neutral", "slightly satisfied" and "satisfied". The data is analysed using the statistical program IBM SPSS Statistics (Version 25). Depending on the level of measurement the analysis in this paper includes the calculation of the median ($\tilde{x}$), the mean ($\bar{x}$), the standard deviation (s),f and Kendall's tau-b correlation coefficient (τ_b). The correlation is assessed according to [37] as: $\tau_b > 0$ to 0.2 = very weak, $\tau_b >$ 0.2 to 0.4 = weak. The significance is indicated by an * (= significant) for a 5 % level and by ** (= highly significant) for a 1 % level. A more detailed explanation of the above-mentioned statistical methods can be

Table 5
Measurement instruments used in field tests.
Used abbreviations: s = short term measurement, l = long term measurement, d = distance from window, h = height from window, r = room, m = minutes.

Measurement	s/l	where	Time step	Product	Specifications
Air flow rate (supply and exhaust air)	s	PWVO (supply air) air intake (exhaust air)	–	FlowFinder	<20 m^3/h: ±4 m^3/h 20–50 m^3/h ±5 %, min. 2 m^3/h
airtightness	s	Flat with open/closed PWVO	–	Minneapolis BlowerDoor DuctBlaster B/DG-700	Windless < ±10 %
Extract fan induced pressure in flat	s	Flat	–	DG 700	±1 % m.v. resp. ± 0.15 Pa
Draught rate (air temperature, velocity and turbulence)	s	Living r./sleeping r. (d: 0.5 m + 1.0, h: 0.1 m, 0.6 m, 1.1 m + 1.7 m)	–	Dantec ComfortSense	±0.06 m/s/DR ± 5 %/± 0.2 °C
CO_2 concentration/air temperature/ humidity	l	Living room and bedroom	15 m	Opus	±50 ppm + 3 % m. v./± 0.3 °C (0..40 °C)/± 2 % r.h.
Interior air temperature/humidity	l	Bathroom	15 m	MSR	±0,1 °C (+5..+45 °C) ±2 % r. h. (10..85 %, 0..+40 °C)
Exterior air temperature/humidity	l	Individual	15 m	MSR	±0,2 °C (−10..+58 °C) ±2 % r. h. (10..85 %, 0..+40 °C)
Operating range of fan (for some weeks)	l	Individual or central extract fan	15 m	Clamp-on ammeter	Not specified

found in [38].

One of the central questions focused on is whether the inhabitants are satisfied with the PWVO. Because PWVO and the ventilation concept are connected, the following question is asked: "If it were up to you, would you move into a flat with exhaust ventilation system and PWVO again?" The evaluation labels this question as "PWVO satisfaction".

2.4. Measurements

2.4.1. Realisation

In four building types, short- and long-term measurements are made in two flats, each. Table 5 summarizes the apparatus used and the metrics considered. The short-term measurements focus on the volume flow rate, the airtightness of the flat (no further measures in regard to adjacent flats etc.) and the pressure difference in the flat induced by the extract fan of the ventilation system. The draught rate is also measured, but not evaluated (refer to chapter "Measurements" in the result's section). The measurements are performed in each flat for a duration of approximately 8 h in the period from October 19th through November 20th' 2018. The long-term measurements with a time step of 15 min comprise CO_2-concentration, interior and exterior air temperatures and humidities and the operation mode of the fan. The data is collected continuously from October/November 2018 to April/May 2019.

2.4.2. Assessment

During daytime, the ventilation rate per person is assumed as 30 m^3/h and as 15 m^3/h during nighttime [39]. Buildings with an extract fan generally show a negative pressure, due to the extract air volume being slightly higher than the supply air volume (with a typical negative pressure of max. 4–5 Pa in single-story flats, [40]). Infiltration must be taken into account in addition to the air entering the building by the PWVO. For dimensioning, the according extract air volume can be calculated according to the air tightness of the building envelope. For example, at q_{a50} 0.7 $m^3/(h\ m^2)$ the factor for the extract air surplus is 1.3 (negative pressure 5 Pa [40]). Thermal comfort in the building is provided with an air temperature between 20.5 °C and 25 °C [1]. Relative humidity should be in the range between 30 % and 70 %. According to Refs. [39,41] the IAQ can be classified by means of the CO_2 content. [41] defines four groups ranging from RAL 1 to RAL 4. As RAL 1 applies to laboratories, the assessment used herein ranges from RAL 2 (CO_2-level < 1'000 ppm, flow rate per person >30 m^3/h, medium IAQ) via RAL 3 (CO_2-level 1'000–1'400 ppm, flow rate per person 18–30 m^3/h, modest IAQ) to RAL 4 (CO_2-level > 1'400 ppm, flow rate per person <18 m^3/h, low IAQ). Without any special agreement for dwellings, RAL 3 is to be targeted. Measurement results are reported using the manufacturer accuracy specifications, only, thus typically underestimating measurement uncertainty somewhat. Using the standard deviation of the mean as a measure for uncertainty for the long-term measurements is not deemed correct, because the values are fluctuating per se.

3. Results

3.1. Site visits

A random sample filter check during the site visits revealed that filters in PWVO and fans are rarely changed. This implies that the users themselves are not aware of the fact that the technical equipment needs regular maintenance. However, cleaning and maintenance proves to be reliably done when the janitor is in charge, which is the case in some of the larger buildings owned by housing cooperatives included in the study. Mould problems on the wall were detected in one building type in the bathroom (DT_3).

Not every room designated for continuous occupation is equipped with a PWVO. In five out of 13 building types there are rooms without a PWVO (however, this is not the case in the measured building types).

3.2. Survey

Out of a total number of 570 distributed questionnaires, 270 were

Table 6
Ventilation habits and level of contentment with noise exposure and IAQ.
For interpretation: FWO: 0 = «never», 1 = «1-2 x/day», 2 = «3-4 x/day», 3 = «5-6 x/d ay», 4 = «> 6 x/day»; DWO: 1 = «1–5 min», 2 = «6–10 min», 3 = «10–20 min», 4 = «20–60 min », 5 = « > 1 h»; DWO30: 0 = «never», 1 = «rarely», 2 = «sometimes», 3 = «often», 4 = «always», y = yes, n = no.

		Frequency windows open (FWO)				Duration windows open (DWO)				Daytime windows open >30 min (DWO30)			
		$\tilde{x}$	$\bar{x}$	N	τ_b	$\tilde{x}$	$\bar{x}$	N	τ_b	$\tilde{x}$	$\bar{x}$	N	τ_b
Noise exposure outside	y	1.0	0.95	117	–	1.0	1.52	112	–	0.0	0.17	112	−0.188**
	n	1.0	1.1	79		1.0	1.56	77		0.0	0.4	78	
Discontent with IAQ	y	1.0	1.1	92	−0.150*	1.0	1.66	89	−0.182*	0.0	0.33	90	−0.153*
	n	1.0	0.95	115		1.0	1.39	110		0.0	0.16	111	

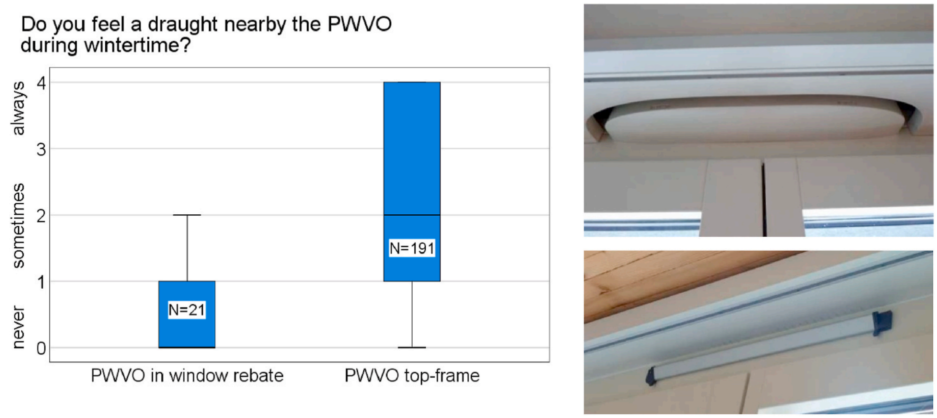


Fig. 1. Left: Boxplot satisfaction with draught corresponding to the position of the PWVO. The box indicates the range between the 25 %- and the 75 %-percentile. The horizontal line in the box indicates the median. The whiskers show the minimum and the maximum. Right: two types of PWVO top-frame.

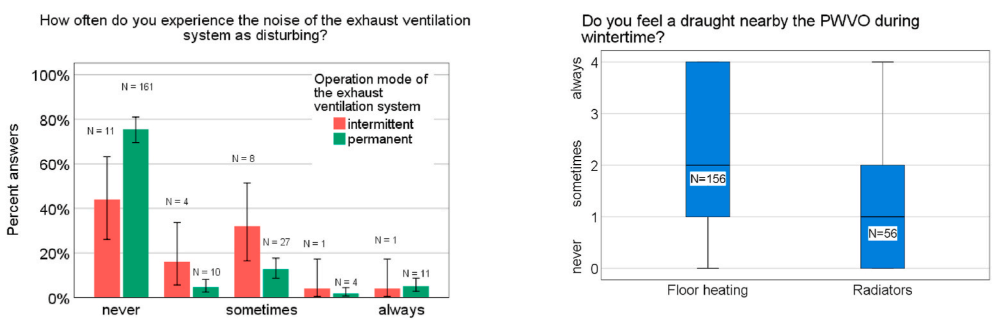


Fig. 2. Left: Disturbing noise according to the operation mode of the exhaust ventilation system. Right: Assessment of draught according to the heat distribution. Indication of error bars on 95 %-level.

Table 7
Level of contentment with thermal comfort, indoor air quality and PWVO. All building types.

		$\bar{x}$	s	N	For interpretation
Satisfaction with	Room temperature	2.79	1.19	126/217	2 = cold, 3 = agreeable
	Air humidity	3.83	0.95	114/215	3 = agreeable, 4 = dry
	IAQ	3.93	1.15	115/207	3 = mediocre, 4 = slightly satisfied, 5 = satisfied
	PWVO	1.31	0.74	251	1 = perhaps, 2 = yes

returned. The average return rate per building type is 42 %. The following two sections reflect ventilation habits and aspects of the technical building concept by means of the survey for all building types. The third section provides a short overview of the survey results, focusing on the measured buildings. A more detailed presentation of the survey can be found in Ref. [38].

3.2.1. Ventilation habits

Most of the residents open the windows during daytime between one and 5 min (60 %, N = 157/252). Less people open the window between six and 20 min (36 %). In both groups, just a few sleep with their window open (each 5 %). The IAQ shows a significant, but very weak correlation between a very intense window ventilation and the perceived air quality (Table 5). This implies that residents not satisfied with the IAQ open the windows more often and for a longer time.

Noise exposure from outside is reported by half of the respondents "sometimes" or "always". A highly significant correlation can be found between those reporting noise from outside and users opening the window >30 min (Table 6).

3.2.2. Technical building concepts with PWVO

When exploring the technical building system one topic is the mode of operation of the exhaust ventilation system. The participants are grouped into two categories, i.e., continuously and intermittently running exhaust fans. The comparison shows no difference between the groups in regard to thermal comfort, IAQ and the level of contentment. However, a very weak but highly significant correlation between the operation mode of the fan and the noise level (see Fig. 2, left) suggests that an intermittently operating fan leads to more disturbing noise (intermittent/continuous fan and disturbing noises: $\tau_b = -0.187^{**}$).

Other issues are the type and (supplementary) equipment of the PWVO. The survey results suggest that PWVO in the window rebate have fewer draught issues and therefore lead to a better thermal comfort than PWVO in the top frame (PWVO top-frame: $\bar{x} = 2.2$, $N = 191$; PWVO in widow rebate: $\bar{x} = 0.48$, $N = 21$; $\tau_b = -0.371^{**}$, see Fig. 1). This tendency is also true, when only in the group of radiators PWVO in the window rebate and PWVO in the top frame are compared (PWVO top-frame: $\bar{x} = 2.0$, $N = 35$; PWVO in widow rebate: $\bar{x} = 0.48$, $N = 21$; τ_b = -0.301**. Unfortunately, it can not be tested whether this is also true for flats with a floor heating, because the investigated building types are equipped with radiators.

Generally, a heat emission by radiators together with PWVO is more advantageous than a heat emission by floor heating, because less draught is reported by the users (draught with radiators: $\bar{x} = 1.5$, $N =$ 56; with floor heating: $\bar{x} = 2.3$, $N = 156$; $\tau_b = -0.207^{**}$; see Fig. 2).

Whether the PWVO have filters or are adjustable by the users has no significant influence on the assessment of the thermal comfort, IAQ or the level of contentment. It can, however, be shown that adjustable PWVO are not masked by unsatisfied users, which speaks in favour of

Table 8
Comparison of specified/planned and measured volume flow rates. Used abbreviations: PWVO = passive window ventilation opening, VFR = volume flow rate, F1 = Flat 1, F2 = Flat 2.

	ZH_3	ZH_5	BB	DT_3
Product PWVO	Sonoslot –P475, Renson	Siegenia Aeromat VT, Typ DF2	ALD Aerex AL-dB-450-40r	Helios ALEF 45
Specified VFR PWVO (m^3/h)	@ 2 Pa: 8.3 @4 Pa: 11.8 @ 8 Pa: 17.0 @10 Pa: 19.2	@5 Pa: 25	@4 Pa: 14.0 @ 8 Pa: 20.0 @10 Pa: 22.0	@ 2 Pa: 12 @4 Pa: 18 @ 8 Pa: 28 @10 Pa: 34
Measured VFR PWVO (m^3/h)	8 (±4 m^3) - 20 m^3/h (±4 m^3)	9 (±4 m^3) - 18 m^3/h (±4 m^3)	18 (±4 m^3) - 30 m^3/h (±2 m^3)	8 (±4 m^3) - 28 m^3/h (±2 m^3)
Planned VFR flat (m^3/h)	F1: 80, F2: 90	F1: 80	F1: 120, F2: 120	F1: 120, F2: 120
Measured VFR flat (m^3/h)	F1: 62 (±7) @ 5 (±0.15) Pa F2: 68 (±10) @ 3 (±0.15) Pa	F1: 38 (±6) @ 3–4 (±0.15) Pa	F1: 166 (±7) @ 17 (±0.17) Pa F2: 107 ± 4) @ 11 (±0.15) Pa	F1: 72 (±6) @ 9 (±0.15) Pa F2: 42 (±8) @ 2 (±0.15) Pa
Measured VFR per person (m^3/h)	F1: 62, F2: 23	F1: 38	F1: 42, F2: 54	F1: 24, F2: 8
Measured ACH (h^{-1})	F1: 0.44, F2: 0.28	F1: 0.25	F1: 0.6, F2:0.55	F1: 0.33, F2:0.22

adjustable PWVO (non-adjustable/adj. PWVO $N = 216/35$, masked non-adj./adj. PWVO, $N = 19/0$).

A correlation between user information and user satisfaction can not be found. Also, there is no significant difference between the users having received such an information and those who haven't. Only a small, but not significant difference can be seen in the habit to open the windows for longer than 30 min at a time. The informed group is represented less, however.

3.2.3. Results of measured building types

Overall, the room temperature is judged as almost agreeable (see Table 7). This exactly matches the mean vote of the inhabitants of building types BB ($N = 15$) and DT_3 ($N = 5$). The inhabitants of building types ZH_5 ($\bar{x} = 3.11$, $N = 18$) and ZH_3 ($\bar{x} = 3.17$, $N = 6$) are slightly more content with the room temperature. Air humidity is perceived as low throughout the survey. Building type ZH_5 ($\bar{x} = 3.83$, $N = 18$) closely reflects this, whereas the inhabitants in three building types (DT_3: $\bar{x} = 3.6$, $N = 5$, ZH_3 and BB: both $\bar{x} = 3.5$, $N = 6$, respectively $N = 15$) seem to be a little more satisfied. Questioned about the IAQ, inhabitants in all building types are "slightly satisfied". The building type DT_3 even exceeds this vote ($\bar{x} = 4.8$, $N = 5$). The other building types range between $\bar{x} = 3.33$ (ZH_3, $N = 6$), $\bar{x} = 3.4$ (BB, $N = 14$) and $\bar{x} = 3.67$ (ZH_5, $N = 18$). A willingness to move into a building with PWVO again, interpreted as the overall satisfaction with the PWVO, more or less exists in all buildings. The inhabitants in three of the measured buildings are more content (BB: $\bar{x} = 1.71$, $N = 14$; ZH_3: $\bar{x} = 1.67$, $N = 6$, ZH_5: $\bar{x} = 1.67$, $N = 18$), in one building the vote matches the whole sample (DT_3: $\bar{x} = 1.4$, $N = 5$). Overall, 8 % (N = 21/263) report mould problems, mostly in the bathroom. In the building type BB one (N = 14), in ZH_5 three (N = 18), in DT_3 two inhabitants (N = 5) and in ZH_3 none of the respondents (N = 6) report mould in the bathroom.

4. Measurements

4.1. Short term

Due to high exterior temperatures at the scheduled dates for the measurements the temperature difference between inside and outside is not high enough to comply with a rigorous quality check of the collected data in regard to the draught rate. Therefore, no findings can be presented.

The airtightness of the buildings (q_{a50}) lies in the range between 0.5 (BB) and 1.3 ± 10 % $m^3/(h\ m^2)$ (ZH_3). The median is 0.7 $m^3/(h\ m^2)$. According to SIA 180 [1] the limit for buildings with a ventilation system is 1.6 $m^3/(h\ m^2)$ and the target value is 0.6 $m^3/(h\ m^2)$. Four out of eight buildings meet this target value. Most of the leakages occur in the region of the window and in the installation area of the PWVO.

Table 8 compares the measured volume flow rates (VFR) with the planning data. The measurements are performed under varying outdoor conditions and resulting pressure differences, so no pressure difference for the PWVO measurement can be specified. This is also reflected in the given spread of the measured values. If the planned VFR for the supply and exhaust air differ, the higher value is relevant and thus indicated in the table. One flat (ZH_5, F2) could not be measured due to unfavorable wind conditions. The VFR per flat with closed internal doors lies between 38 (±6) and 166 (±7) m^3/h. Both the building documentation and the measurement results suggest that the design intent was to cover the hygienic air change rate as well as the air change rate for mould prevention. In six out of eight flats the measured outdoor air flow rate only covers 35–79 % of the amount recommended by SIA 2023, however. In two flats the recommended values are exceeded by 34–38 %. If the air supply is evaluated in relation to the current occupancy of the flat, the fresh air supply rate per person is found to be between 8 and 62 m^3/(h p). Given a required fresh air supply of 30 m^3/(h p), the demand is covered in four flats (building type BB, ZH_5 and ZH_3, F1). In three flats the demand is not met (building type DT_3 and ZH_3, F2). In the main bedroom, values between 8 (±4) and 58 (±3) m^3/h are measured, which corresponds to values between 3 and 29 m^3/(h p). In the flats ZH_3, F2, DT_3, F1 and F2 the measured values are significantly below the recommended 15 m^3/(h p) by the building standard. Considering the measured VFR per PWVO, it can be seen that the VFR varies between the products. In building types ZH_3 and ZH_5 the VFR per PWVO varies between 8 (±4) and 20 (±4) m^3/h, in building types BB and DT_3 the VFR can reach up to 30 (±2) m^3/h.

Specifically related to individual flats the following remarks can be made:

- ZH_3: the measured and specified VFR per PWVO are in the same region. The extract air volume for F1 is in the advisable range, for F2 it is 38 % too small. The negative pressure in both flats is in the range recommended by FprSIA 382/5 [39].
- ZH_5: the measured VFR per PWVO is lower than in the specification. However, only one flat is measured and the negative pressure in the flat falls below 5 Pa, linked to the specified VFR. In both flats the extract air volume is around 40 % too low.
- BB: the measured VFR per PWVO is higher than the specified values. The reason is that the measured negative pressure in the flats is unusually high (17 (±0.17) and 11 (±0.15) Pa). This is due to a too high extract air volume (between 130 and 200 % higher than recommended by FprSIA 382/5 [39]).
- DT_3: the measured VFR per PWVO is slightly lower that the specified values. In both flats the measured extract air volume is lower than the recommended (between 23 and 60 %). In F2, the negative pressure is too low (2 (±0.15) Pa), in F1 it is too high (9 (±0.15) Pa).

The volumes for supply and for exhaust air are measured with open and closed room doors (the room doors of all apartments have a 6–25 mm air gap allowing some air to pass underneath). No significant difference can be identified.

4.2. Long term

In most of the flats the air temperature is in the range required by SIA 382/1 2014 [41]. The $\bar{x}$ for all rooms (evaluated separately) and the whole period is in the range 20.5 °C–24.5 °C ($\tilde{x}$: 20.2–24.6 ± 0.1 °C). Which room features the highest temperatures varies between the flats:

Fig. 3. Measured CO_2-concentrations in the bed- and living room (BR, LR) in the measured flats during daytime (d) and night-time (n). The RAL-classes indicate: RAL 2 (green) = < 1'000 ppm, RAL 3 (yellow) = 1'000–1'400 ppm, RAL 4 (red) = >1'400 ppm. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In three flats it is the living room (min - max $\bar{x}$ = 21.9–23.8 °C; $\tilde{x}$ = 21.9–24.0 ± 0.1 °C), in four flats it is the bathroom (range from $\bar{x}$ = 21.6–24.5 °C; $\tilde{x}$ = 21.6–24.6 ± 0.1 °C) and in one flat the sleeping room is the warmest (range from $\bar{x}$ = 20.5–23.4 °C; $\tilde{x}$ = 20.2–23.5 ± 0.1 °C).

The relative humidity complies with the requirements of SIA 382/1 [41] (>30 % r.h.). In the living rooms, $\bar{x}$ varies between 31 and 45 % ($\tilde{x}$: 30–46 ± 2 %). In the sleeping rooms $\bar{x}$ is between 34 and 49 % ($\tilde{x}$: 32–49 ± 2 %). Unsurprisingly, the highest values are to be found in the bathroom with $\bar{x}$ 36–77 % ($\tilde{x}$: 35–82 ± 2 %). The lowest (sleeping room, F1) and highest values (bathroom, F2) for all room types are to be found in building type DT_3.

Mean CO_2-values in the living rooms are found to be between 590 ppm and 1′530 ppm ($\tilde{x}$: 560–1'500 ppm (±70–100 ppm)). In the sleeping room, $\bar{x}$ is between 650 and 3′440 ppm ($\tilde{x}$: 660–3′550 ppm (±70–160 ppm)). Fig. 2 shows the measured CO_2-concentrations in the living rooms and bedrooms. Classification of the IAQ in respect to the CO_2-level according to Ref. [41] shows that a medium IAQ is achieved for over 60 % of the time in six flats (RAL 2). In one flat (ZH_3, F2) the IAQ is modest or low (RAL 3–4) for more than 70 % of the time and in one flat (DT_3, F2) it is low (RAL 4) during 70 % of the time.

The intention behind the measurement of the operation mode of the fan is to verify the information given in the design documentation. Three building types feature a permanently operating central extract fan (ZH_3, ZH_5 (in bathroom(s)), DT_3 in bathroom and kitchen). The measurements confirm that all central extract fans operate permanently. Building type BB has one extract fan per flat. It is activated via the CO_2-content of the air, the light switch in the bathroom or a manual switch. In F1, the extract fan is switched off (manually or via CO_2-sensor) quite often, in F2 it is never switched off. This is also reflected in the CO_2-measurements (cf. Fig. 3), where F2 is in the RAL 2 class almost all the time, whereas F1 is in the RAL 3 class 20 % of the time.

5. Discussion

As stated in the introduction and the literature review, experimental studies which focus on performance measurements of PWVO in combination with an extract fan in dwellings are rare. This is especially true for the assessment of the PWVO performance in real-life conditions through user surveys and on-site measurements. In the literature, the need for carefully performed and detailed documented measurements is clearly stated. The work presented in this paper gives detailed background data and planning hints for future projects and therefore contributes important insights to the existing literature.

5.1. Survey all building types

The results of the conducted survey provide information on user behavior and allow for tentative inferences for future ventilation concepts. User acceptance is not shown to be affected by the operation mode of the fan (permanent or intermittent). Air draught caused by the PWVO is less probable by applying two planning principles: Firstly, combining PWVO with a heat emission by radiators (placed below the windows) is preferable in terms of thermal comfort to a combination with floor heating. Secondly, the air draught risk is reduced by using PWVO in the window rebates (+ radiators) instead of PWVO top-frame. PWVO with fixed openings are rated similar to adjustable PWVO. However, users do not mask the latter. Distribution of a user guide helps to prevent occupants from opening the windows for too long periods of time in winter.

5.2. Measurements

In four flats the desired fresh air supply of 30 m^3/h per person is covered. In three flats only between 35 % and 80 % of the required amount is reached. The measured outdoor air flow rate per flat lies between 38 (±6) and 166 (±7) m^3/h. This points in the same direction as [7,9,32,33,42,43] where in many cases the measured VFR fell below the required air flow rates. The literature review revealed ACH values between 0.27 and 0.48 h^{-1} for the flats (Table 2). The ACH values recorded in this paper are in good agreement and found to be between 0.22 and 0.60 h^{-1}.

The airtightness of all flats varies between q_{a50} values of 0.5 and 1.3 $m^3/(h\ m^2)$ (±10 %). Four out of eight buildings meet the target value of 0.6 $m^3/(h\ m^2)$, no building exceeds the limit value of 1.6 $m^3/(h\ m^2)$. A good airtightness indicates that the fresh air supply of the flat is mainly provided by the PWVO.

The mean air temperature found is in the permitted range for the operative temperature given by Ref. [41]. Air and operative temperatures can be compared only if the mean radiative temperature can be assumed to be close to the air temperature. This is typically the case for well insulated buildings. Therefore, the reported air temperatures are an indicator that the temperature is in an acceptable range. The measured relative humidity in living and sleeping rooms complies with the building standards. [41] allows an assessment of the IAQ in respect to CO_2 and fresh air supply. The supply air volume flow per person (calculated as measured air flow divided by the current number of inhabitants) can be rated as medium (RAL 2) in four flats, in two flats it is modest (RAL 3) and in one flat it is low (RAL 4). The CO_2-level is low (RAL 2) for over 60 % of the time in six flats, in two flats it can only be classified as modest or low (RAL 3–4) during 70 % of the time. The recorded $\bar{x}$ for CO_2 in the bedroom was between 650 and 3′440 ppm which is in good agreement with the values found in the literature review (bedrooms in single-family houses between 800 and 3′000 ppm, Table 2). Based on [11], this leads to the assumption that the conditions allow an undisturbed to possibly disturbed sleep quality in six sleeping rooms; in two rooms, only a disturbed sleep quality is achieved. The monitoring of the extract fans reveals that they operate as per design. In two flats, the CO_2-sensor based operation of the fan can be overridden by the inhabitants. In one of these flats the inhabitants make use of this possibility, which can directly be seen in higher recorded CO_2-values.

5.3. Correlating the survey and measurements

The survey reveals that the inhabitants of BB and DT_3 judge the room temperature as "agreeable" with a tendency towards "cold". In building type ZH_3 and ZH_5 the contentment is slightly higher with a bias to warm temperatures. This does not entirely match the measurement results (for all rooms), where building type ZH_3 and ZH_5 do not have the highest room temperatures. The type of heat injection (floor heating: ZH_3 and BB, radiators: ZH_5 and DT_3) does not explain the incoherence. However, the inhabitants are able to adjust the room temperature in all buildings and therefore it seems to be a topic of individual judgement. Humidity is perceived to be "agreeable" with a strong bias towards "dry" by the inhabitants of the measured buildings. The measurements do not reflect the different votes. One building type (DT_3) comprises the flat with the highest and the lowest values. In the same building type, mould was detected in one bathroom during the site visit and additionally reported in the questionnaire (N = 2/5). However, in building types BB (N = 1/14, rel. hum. in the bathroom $\bar{x}$ = 41 % and 43 %) and ZH_5 (N = 3/18, rel. hum. in the bathroom $\bar{x}$ = 43 % and 45 %) mould is reported for the bathroom as well. Only in DT_3 this is consistent with the too small fresh air supply measured. Strikingly, in DT_3, the rating of the air quality is the best of the survey. Due to the very small number of returned surveys from DT_3 this result should be treated cautiously, though. As the size and occupancy of the flats varies, one assumption could be that the fresh air supply in the other apartments is sufficient for the number of occupants. Survey votes for the four flats where the measured air supply is found to be sufficient (BB, ZH_5 and ZH_3, F1) are less satisfied than the whole sample. One explanation could be that the inhabitants' sense of smell has adapted to their own odours during a stay of several hours in the room. Without inhabitants and CO_2-emissions the air is gradually purged by means of the PWVO and the extract fans. When returning to the room the air is "fresh" again. Thus, the impression of the air quality is good which is reflected in the overall satisfaction with the PWVO. The overall satisfaction with the PWVO is high in three of the measured buildings, in DT_3 it is lower. In conclusion, the correlation between the survey and the measurements is weak in our point of view. It is not known, however, whether the inhabitants of the measured flats took the time to answer the survey. In this project the statistically correct approach was applied to de-couple the survey from the measurements. The rationale is not to influence the survey results by extensive measurements. In retrospect and for follow-up projects it is advisable to ask the inhabitants of measured flats to complete a survey. This could be a shorter follow-up survey, but it would help to link user perception and measurements more reliably.

6. Conclusions

The project results lead to the following guidelines for future project planning.

- Dimensioning: The project shows that both the building documentation and the measurement results suggest that the design intent was to cover the hygienic air change rate as well as the air change rate for mould prevention. However, the measured VFR frequently falls below the planned VFR. The successful implementation of PWVO requires a thorough planning of the desired volume flow rates. It must be clarified whether mould protection (0.10 and 0.22 h^{-1} for an exemplary flat of 190 m^3, with three inhabitants and low moisture production during heating season, depending on weekly weather data for Zuerich, further details in Refs. [1,3]) or also the hygienic air change (per room and person/sleeping room two persons: 30 m^3/h) is aimed at. Because the VFR are subject to external conditions and changing pressure differences it is advisable to keep in mind a certain safety margin to meet the required results.
- Pressure difference: In three out of eight flats, the pressure difference of 4–5 Pa recommended by Ref. [40] for single-storey flats is exceeded. Exceeding this pressure difference increases the risk that, in combination with leakages, unwanted air from adjacent flats can infiltrate. Therefore, the new SIA 382/1 2021 [39] has changed from a recommendation to a requirement of max. 4 Pa.
- Number of PWVO: Five out of 13 building types had rooms without PWVOs. Each room designated for continuous occupation (excepting extract and transfer zones) should have a PWVO.
- User influence: the building visits showed that only PVWO with a fixed air inlet were masked by the inhabitants. Thus, it can be recommended to use PWVO with an adjustable air inlet.
- Air draught: Regarding thermal comfort, PWVO in the window rebate are better rated than PWVO top-frame. This is also true for PWVO in combination with a heat emission by radiators. In order to avoid air draught, it can be advantageous to equip the room with several PWVO with a small design air flow. Heat emission by radiators is advisable.
- Noise exposure from outside: The survey showed that half of the questioned persons "sometimes" or "always" experienced noise from outside as disturbing. At noise exposed sites the use of PWVO should be critically questioned.
- Noise exposure from fan: The results of the survey suggest that a continuously running fan leads to less disturbing noise than an intermittently operating fan.
- User information: A correlation between user information and user satisfaction with PWVO is not found. However, a weak tendency to avoid permanently opened windows can be seen. Nevertheless, it seems recommendable to provide a user information. Therein it could be pointed out that additional ventilation by manual opening of windows should be based on an intermittent opening schedule, not on continuously opened windows and that a regular cleaning/changing of the filters is advisable.
- Filter: The project shows that the regular change of filters is standard practice in only five out of thirteen buildings (PWVO and extract ventilator). For hygienic reasons, PWVO should have filters. PWVO and extract ventilators are part of the technical building equipment and should be regularly maintained (change of filters, cleaning). Lack of maintenance can have a significant negative impact on the function [43].

6.1. Performance PWVO

One of the initial questions was whether PWVO can assure a user independent air change to prevent mould damage. The amount of air required is much smaller than the hygienic one for persons. The reported mould incidence rate found by the survey is in the range reported elsewhere for common dwellings [13]. This suggests that the installation of PWVO cannot assure mould protection in all cases and, by necessity therefore, the required air change per person.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

N Quantity of observations
τ_b/r Kendall's tau-b correlation coefficient/Pearson's correlation coefficient
$\overline{x} = \frac{1}{N} \cdot \sum_{i=1}^{N} X_i$ Mean
$\widetilde{x} = \frac{1}{2} \cdot (X_{\frac{N}{2}} + X_{\frac{N}{2}+1}) / \widetilde{x} = X_{\frac{N-1}{2}+1}$ Median: even number of sorted values/odd number of sorted values
$s = \sqrt{S^2}$ Standard deviation

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