RESIDENTIAL VENTILATION SYSTEM PERFORMANCE: OUTCOMES OF A FIELD STUDY IN THE NETHERLANDS

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ABSTRACT
This paper describes the results of a Dutch national study into performance of mechanical ventilation systems and its effect on the self-reported health and perceived indoor environmental quality of occupants.
Ventilation systems with natural supply and mechanical exhaust ventilation (MEV) and balanced mechanical supply and exhaust systems with heat recovery (MVHR) were investigated. Surveys were performed in 299 homes, which included visual inspections and measurements of ventilation rates per room and installation noise levels. Furthermore, dwellers were questioned regarding perceived indoor air quality and self-reported health. Results show that shortcomings are common in many homes and for both MVHR and MEV. Shortcomings include insufficient ventilation rate, high noise levels, unclean systems and insufficient maintenance. The indoor environmental quality was perceived more positive in homes with MEV when considering air quality, dryness of air, noise and control options. There was no clear relationship between self-reported health and shortcomings of the ventilation.

KEYWORDS
Mechanical ventilation, balanced ventilation with heat recovery, self-reported health, indoor air quality, houses and homes.

INTRODUCTION
In recent years, nearly all newly built dwellings in the Netherlands are equipped with mechanical ventilation systems. The two most common systems are mechanical air supply with mechanical exhaust and heat recovery (‘balanced mechanical ventilation with heat recovery’ or ‘MVHR’) and natural air supply with mechanical exhaust (‘mechanical exhaust ventilation’ or ‘MEV’). See figure 1. MEV works with natural ventilation grilles above windows and is in use since the 1970s. MVHR is only widely used since the past 10 years in The Netherlands. All MVHR systems in The Netherlands use plate air-to-air heat exchangers.

European directive EPBD (Energy Performance of Buildings Directive, EU, 2002) is the driving-force for national regulations to reduce energy consumption in buildings. The directive “lays down requirements […] on the energy performance of buildings”. But the EPBD has a broader scope and also states that “requirements shall take account of general indoor climate conditions, in order to avoid possible negative effects *such as inadequate ventilation*” and that “... measures […] should take into account climatic and local conditions *as well as indoor climate environment* and cost-effectiveness”.

Newly built dwellings in The Netherlands are required to have a certain degree of energy-efficiency (an ‘energy performance index’), which over the past 5 years has become more and more demanding. Balanced mechanical ventilation has a significant impact on the energy performance index and can (in theory) reduce energy consumption. Therefore, many new homes in The Netherlands have been equipped with balanced mechanical ventilation over the past years.

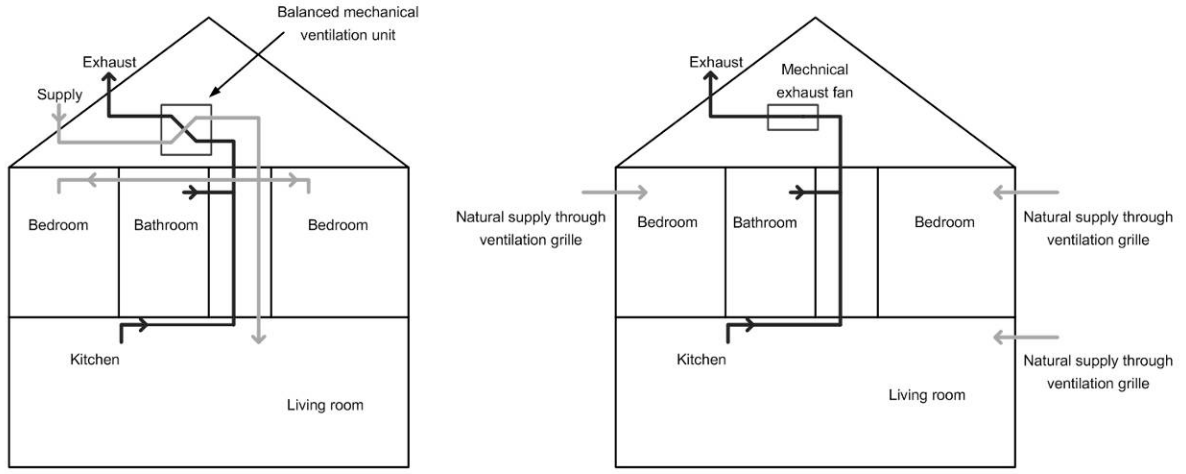

Figure 1 Left: Balanced mechanical ventilation with heat recovery; right: Natural supply with mechanical exhaust ventilation.

However, many occupants of newly built Dutch homes seem to be bothered by noise, draught, heat, poor indoor air quality and a lack of personal control caused by the ventilation system (Duijm, 2006). There has been considerable media-coverage in The Netherlands on societal concerns about the supposed relationship between health-effects and balanced mechanical ventilation in homes. This included reports on public television linking energy-efficient houses with balanced ventilation to negative health effects. A local study by the municipal health services (Duijm et al., 2007) and a nationwide study (Leidelmeijer et al., 2009) showed that health problems were indeed related to the presence of balanced ventilation systems. However, the reason why health symptoms are more prevalent in dwellings equipped with these systems could not be determined. One possible explanation is that mechanical ventilation systems, in particular balanced ventilation systems, produce relatively high levels of noise. Noise annoyance results in occupants setting the system in a low setting or turning it completely off, leading to insufficient ventilation. Other shortcomings of the ventilation systems may also play a role, but the technical performance of the systems was not determined in these studies.

The Dutch Ministry of Housing, Spatial Planning and the Environment commissioned a study into the performance of mechanical ventilation systems in Dutch homes and the relationship with perceived indoor environment and self-reported health of occupants. The overall aim was to inventory the most prevalent technical shortcomings of the two most common mechanical ventilation systems with respect to design, construction, maintenance and use. Moreover, a study was performed to explore the relationship between performance of the systems and the perceived indoor environment and self-reported health, and if occupants' report of indoor environment and health differed between the two types of ventilation systems.

The 4 research questions were as follows:
- What are the most common shortcomings of mechanical ventilation systems?
- What is the relationship between shortcomings of mechanical ventilation systems and self-reported health?

- What is the relationship between shortcomings of mechanical ventilation systems and the perceived indoor environmental quality?
- Is there a difference in self-reported health and the perceived indoor environmental quality between occupants of homes with balanced mechanical ventilation and occupants of homes with mechanical exhaust ventilation?

METHODS

The study focused on ventilation systems in single-family houses that were completed between June 2006 and January 2008. Only terraced houses, semi detached houses and detached houses were included in this study (apartment buildings and other multi-family houses were excluded). Selected dwellings were fairly equally distributed across the Netherlands. A number of 150 dwellings with balanced mechanical ventilation or (MVHR) and 149 dwellings with mechanical exhaust or (MEV) were inspected between December 2009 and June 2010.

Data acquisition consisted of two parts: (1) technical building surveys combining visual inspections and measurements and (2) questionnaires for building occupants. Part 1 aimed to determine the performance and common shortcomings of mechanical ventilation systems. In part 2, the relationship between the performance (from part 1) and perceived indoor environment and self-reported health (from the questionnaires) was explored. Results were also used to compare performance of the two different ventilation systems.

Surveys were performed in all homes, which included measurements of ventilation rates per room and installation noise levels. Mechanical ventilation rates were determined per room using a pressure-compensating air flow meter. Installation noise was determined using an integrating sound level meter. Additional technical inspections were carried out in order to qualify risk factors for the aspects indoor air quality, thermal comfort and noise. This included visual inspections of risk factors such as the hygienic condition of the ventilation unit, filters and ducts, the position of the outdoor air inlet, commissioning and the presence of a bypass on the heat recovery.

Performance of ventilation systems was compared with the requirements in the Dutch Building Code (BRIS, 2003) and the Dutch GIW/ISSO guidelines for installations in dwellings set by the Dutch Guarantee Institute for House-building (ISSO, 2008). The basic assumption in this study was that a proper ventilation system matches all requirements of both the Building Code and the GIW/ISSO guidelines.

On the day of the survey, one occupant per home completed a questionnaire on perceived indoor environment and self-reported health. The questionnaire contained mostly standardized questions on subjective health, nonspecific health symptoms, indoor environment related health symptoms and perceived indoor environment (MM-040 (Andersson, Stridh et al., 1993 & Andersson, 2010)), sleep disturbance, and perceived controllability of the ventilation system.

The indoor environment related health symptoms were not determined by the complete MM-040 scale (for which data is available) but by a selection of five items comparable to Burge's et al. (1993) Building Symptom Index (BSI 5). These were i. fatigue; ii. headache; iii. burning, itchy or irritated eyes; iv. irritated, stuffy or runny nose; v. hoarse, dry throat.

The statistical analysis was done in three steps. First, all 95 associations between technical aspects and performance of the ventilation systems and perceived health and indoor environment were tested in a univariate way. Non-parametrical tests were used, i.e., Spearman's correlation coefficient, Kruskal-Wallis, Fisher exact and Chi square tests. Second, to investigate confounding, all associations with a statistical significance level of p<0.10 were stratified according to categories of potential confounding variables such as smoking and educational level.

RESULTS

Ventilation capacity

The most common problems (where >30% of the homes did not comply with the reference level) related to the ventilation capacity are shown in Table 1. Dutch ventilation systems usually have 3 user controlled settings, where 1 is the lowest and 3 highest. The actual air supply and exhaust rates in the highest setting were insufficient in most homes. In 48% of the dwellings with balanced mechanical ventilation the total air supply rate was insufficient (< 0,7 $l/s/m^2$), while the air supply rate in 85% of dwellings was insufficient in one or more rooms in comparison with the Dutch Building Code (Figure 2). Total air exhaust rates were insufficient in 55% of the dwellings with balanced ventilation and 69% of the dwellings with mechanical exhaust. The exhaust rates in one or more rooms did not comply with the standards in 80% (MVHR) and 76% (MEV) of the dwellings (Figure 3).

Table 1 Common shortcomings related to the ventilation capacity for balanced mechanical ventilation (MVHR) and mechanical exhaust ventilation (MEV). (n/a = not applicable)

	% dwellings with shortcomings	
	MVHR	MEV
Performance		
The measured air supply rates are insufficient (Figure 2).	48%	n/a
Calculated (theoretical) air supply rate of natural ventilation grilles in bedrooms is insufficient.	n/a	36%
The measured air exhaust rates are insufficient (Figure 3).	55%	69%
Construction		
Ventilation controls settings are not properly adjusted. *The differences between the control switch steps should be >10% and >30% in total in order to provide sufficient control options.*	34%	27%
Setting of the air supply and exhaust valves is not locked or marked. *The settings of the valves should be locked or marked after commissioning in order to secure the proper settings after e.g. cleaning of the valves.*	61%	35%
Location of the air supply and exhaust valves is not marked. *The location or room of the valves should be marked after commissioning in order to secure the proper settings after e.g. cleaning of the valves.*	99%	96%
No commissioning reports about the ventilation system available.	87%	94%
Ductwork is not properly installed. *Non-smooth, bendy or tight air ducts cause extra air resistance. Leaky joints result in the loss of supply or exhaust air.*	48%	40%
The capacity of air transfer devices is insufficient. *Air transfer devices (such as a slit under a door) should be present in order to balance air supply and exhaust.*	40%	32%

Indoor Air Quality

The most common shortcomings related to the indoor air quality (where >30% of the homes did not comply with the reference level) are listed in Table 2. A surprising finding is that the air supply ducts were contaminated with dust and dirt in 77% of all homes with MVHR, while all homes were completed only several years ago. See figure 4 for a typical example of a polluted air supply duct as found during the field study. Annual maintenance is not common: 66% of homes with MVHR and 82% of homes with MEV have a longer maintenance interval. Air filters were visibly not clean (e.g. dirty enough to warrant filter replacement) in 43% of homes with MVHR, which could also negatively affect the ventilation rate. Almost all occupants (96% in both cases) do not use their ventilation system as prescribed by manufacturers.

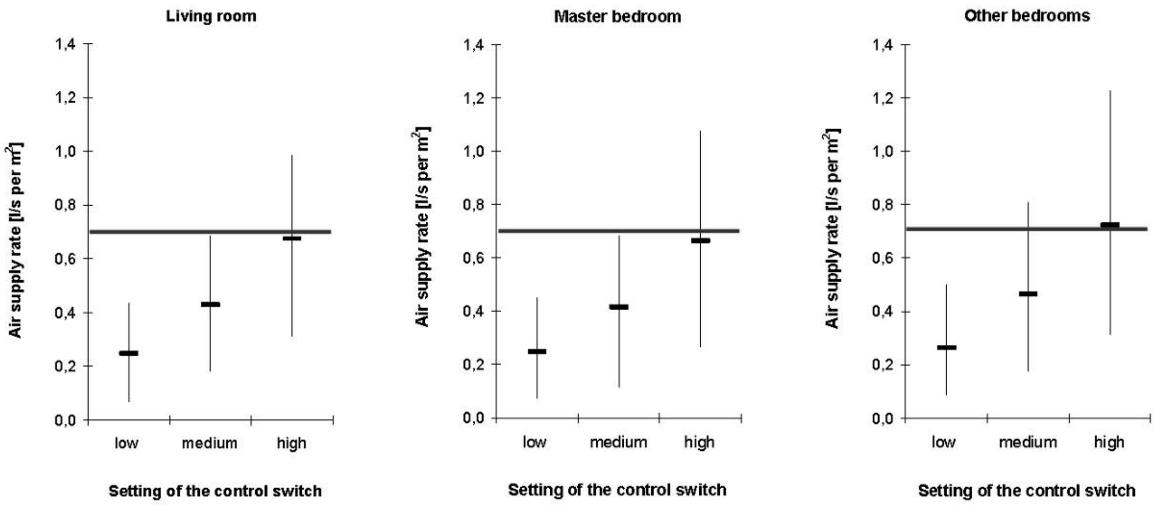

Figure 2 Air supply rates (average, P10 and P90) in the living room, master bedroom and other bedrooms in dwellings with balanced mechanical ventilation. The horizontal line gives the reference (minimum) level according to the Dutch Building Code (0,7 l/s/m^2).

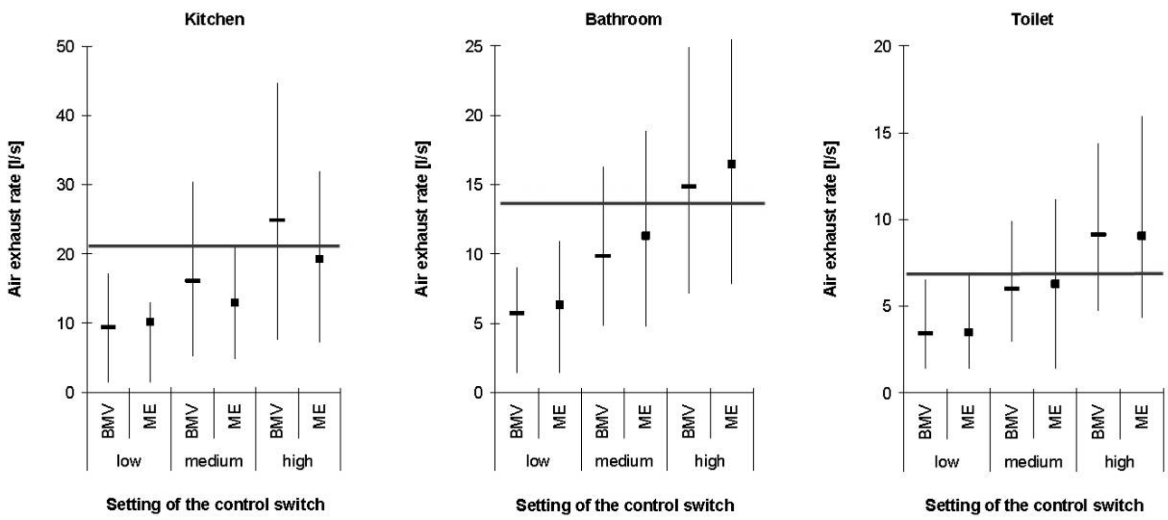

Figure 3 Air exhaust rates (average, P10 and P90) in the kitchen, bathroom and toilet in dwellings with balanced mechanical ventilation (MVHR) and mechanical exhaust (MEV). The horizontal line gives the reference (minimum) level according to the Dutch Building Code (21, 14 and 7 l/s respectively).

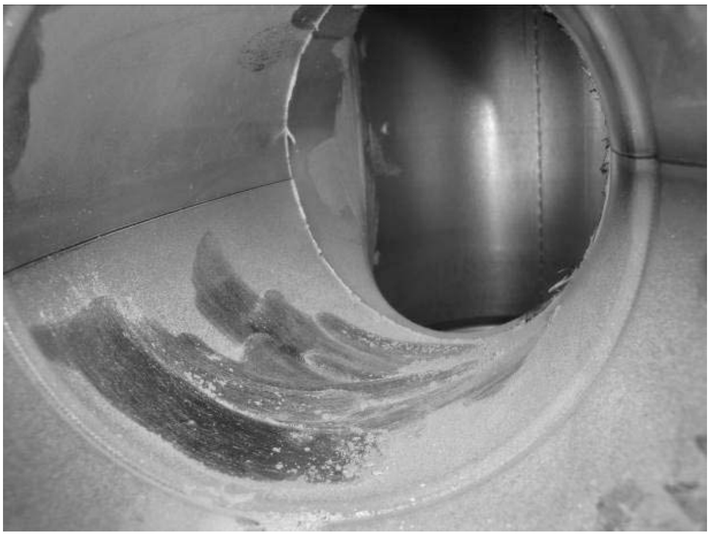

Figure 4 Example of dust accumulation in an air supply duct of a MVHR system.

Table 2 Common shortcomings related to indoor air quality for balanced mechanical ventilation (MVHR) and mechanical exhaust (MEV). (n/a = not applicable)

	% dwellings with shortcomings	
	MVHR	MEV
Design		
Insufficient control options. *A control switch should be present in the kitchen as well as the bathroom.*	81%	70%
Supply and exhaust valves in one room are situated too close together (<1 m). *As a result, parts of the room cannot be properly ventilated.*	53%	n/a
Construction		
Visible dirt in air supply ducts. *Ducts were soiled with dirt introduced during construction works, like cement or plaster.*	67%	n/a
Recirculation of exhaust air. *Qualitative experiments with smoke and particulate measurements (Balvers et al. 2011a) show that exhaust air is partly recirculated while no recirculation section is present.*	59%	n/a
Maintenance		
Filters are visibly not clean.	43%	n/a
Visible dust and dirt in air supply ducts. *Ducts were soiled with dist due to poor maintenance as well as dirt introduced during construction works, like cement or plaster.*	77%	n/a
Filters are changed less then 2x per year.	47%	n/a
No annual inspection of the overall functioning of the ventilation unit.	66%	82%
Usage		
Improper use of control switches. *The control switch is mostly used in a lower setting than recommended for proper ventilation.*	96%	96%
No oral instruction is given about the operation and functioning of the ventilation system (according to the dwellers).	42%	43%

Thermal Comfort

The most common shortcomings related to thermal comfort (where >30% of the homes did not comply with the reference level) are shown in Table 3. Heat recovery in a balanced ventilation system is unbeneficial when indoor temperatures are high (e.g. >24 °C), while the outdoor temperature is lower. This will mostly occur in summer months. A balanced system can be equipped with a bypass, which will conduct some or all air around the heat exchanger. This prevents heat from indoors being transferred to cooler outdoor air and will prevent unnecessary overheating of homes. In this study, about half of all MVHR systems were equipped with a bypass.

Table 3 Common shortcomings related to thermal comfort for balanced mechanical ventilation (MVHR) and mechanical exhaust (MEV). (n/a = not applicable)

	% dwellings with shortcomings	
	MVHR	MEV
Design		
No bypass on heat recovery.	49%	n/a
Air supply valves without air flow deflector too close to a ceiling or wall. *If supply air valves are positioned too close to a ceiling or wall (less than 30 cm) the valve should be equipped with an air flow deflector in order to deflect the air over a 180° sector instead of over 360° to avoid draughts caused by air that collides with the nearby surface and moves down.*	31%	n/a

Noise

The most common shortcomings related to high noise levels (where >30% of the homes did not comply with the reference level) are listed in Table 4. Noise levels are higher than 30 dB(A) in one or more bedrooms in 86% of homes with MVHR in the setting in which the ventilation system is providing a sufficient ventilation rate (>0,7 l/s) in many dwellings (or in the highest setting if the ventilation rate is insufficient). This was mainly a problem in dwellings with balanced mechanical ventilation. High noise levels are in part caused by incorrect placement of (flexible) ductwork, e.g. sharp bends (see Figure 5 for an example). At the moment of this study, maximum sound levels were not required by law, but a maximum level will be required in the next version of the Dutch Building Code (in effect as of January 2012). In most cases, the ventilation unit is placed on a position that will increase the chance of ventilation noise (53% of MVHR and 67% of MEV). Results from noise level measurements are shown in more detail in Figure 6. The differences between balanced mechanical ventilation and mechanical exhaust were the largest in the bedrooms.

Figure 5 | Example of incorrectly placed flexible ductwork near the ventilation unit.

Table 4 Common shortcomings related to noise of the ventilation system for balanced mechanical ventilation (MVHR) and mechanical exhaust (MEV). (n/a = not applicable)

	% dwellings with shortcomings	
	MVHR	MEV
Performance		
Measured noise levels in the living room are too high (>30 dB(A)).	72%	54%
Measured noise levels in one or more bedrooms are too high (>30 dB(A)).	86%	21%
Design		
Ventilation unit is mounted at a position that is susceptible to noise. *Ventilation units installed e.g. in a built-in cupboard in the bedroom or on light-weight walls without proper vibration control provide a high noise risk.*	53%	67%
Construction		
Silencers are not properly installed on either air supply or exhaust duct.	66%	n/a
Ductwork is not properly installed.	48%	40%

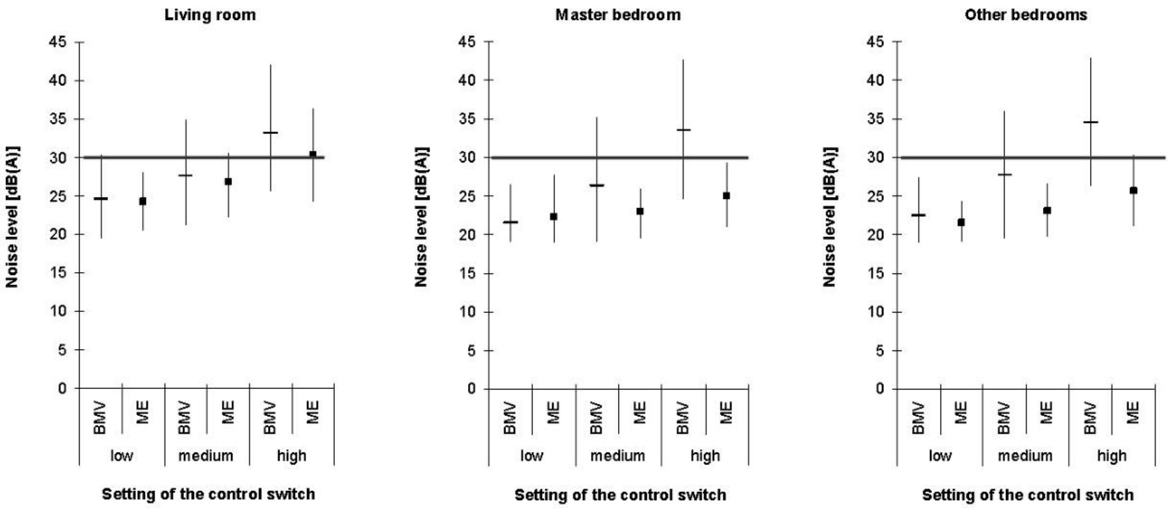

Figure 6 Measured noise levels from mechanical ventilation (average, P10 and P90) in the living room, master bedroom and other bedrooms in dwellings with balanced mechanical ventilation (MVHR) and mechanical exhaust (MEV). The horizontal line gives the reference level (30 dB(A)) (GIW/ISSO, 2008).

Perceived indoor environment and health

Results from the occupant questionnaires are presented below. Table 5 shows mean scores for the questions on self-reported health and sleep disturbance. The number of occupants with increased (i.e. unfavorable) scores was relatively low for all measures of self-reported health but somewhat higher for sleep disturbance.

Occupants of dwellings with balanced mechanical ventilation perceived the indoor environment as less favorable than occupants of dwellings with mechanical exhaust (Table 6). This was the case for perceived air quality, perceived dryness of the air, noise annoyance due to the ventilation system, and perceived personal control.

Table 5 Subjective health and sleep disturbance for occupants of dwellings with MVHR and MEV.

	Balanced mechanical ventilation	Mechanical exhaust	p-value
Nonspecific health symptoms (4-DKL sum score; range 0-32)[b]	2.7 ± 3.7	2.8 ± 4.5	0.81
Low (%)	91	92	
Moderately increased (%)	5	6	
Strongly increased (%)	1	1	
Perceived health status (VOEG-13 sum score; range 0-13)[c]	2.4 ± 2.7	2.1 ± 2.8	0.14
Increased (%)	14	12	
Indoor environment specific health symptoms (MM-040 BSI sum score; range 0-5)[d]	0.6 ± 1.1	0.5 ± 0.9	0.51
Sleep disturbance score (GSK; range 0-10)[e]	1.7 ± 2.4	1.7 ± 2.3	0.58
Increased (%)	17	18	

[a] Mean ± SD, unless otherwise specified. Higher scores are less favorable
[b] Terluin and Duijsens, 2006
[c] Sonsbeek van, 1990
[d] Andersson, Stridh et al. 1993
[e] Meijman, de Vries-Griever et al. 1988

Table 6 | Perceived indoor environment for occupants of dwellings with MVHR and MEV.

	Balanced mechanical ventilation	Mechanical exhaust	p-value
Perceived temperature			0.048[a]
Very good (%)	12	13	
Good (%)	72	68	
Acceptable (%)	15	12	
Not good (%)	1	7	
Bad (%)	0	0	
Perceived air quality			0.01[a]
Very good (%)	5	11	
Good (%)	61	68	

Acceptable (%)	24	18	
Not good (%)	10	3	
Bad (%)	1	0	
Perceived draft (% often (every week))	8	15	0.06[a]
Perceived stale air (%often (every week))	1	0	n.a.[b]
Perceived dry air (% often (every week))	20	7	0.001[a]
Perceived noise annoyance due to the ventilation system (mean ± SD; range 0-10)	1.9 ± 2,4	1.3 ± 2,1	0.003[c]
Severely annoyed by the ventilation system's noise (%)	5	2	0.34[a]
Perceived controllability (% insufficient)	32	18	0.01[a]

[a] tested with Fisher's exact or Chi^2-test
[b] not calculated because only one person complained of dry air
[c] tested with Kruskal-Wallis test

In addition, an analysis was made on the correlation between technical performance and perceived comfort and health. Three of the technical features of the ventilation systems showed a statistically significant association with perceived indoor environment or subjective health. These were:

1. A negative association between (in the case of balanced mechanical ventilation) the flow of supplied air in the most frequently used position in the bedroom during the night and nonspecific health symptoms (Spearman's r=-0.25, p=0.01);
2. A less positive perceived air quality in the case of a short-circuit between supplied fresh air and exhausted air in balanced mechanical ventilation systems (48% vs. 70% 'good' air quality, p=0.01) (Balvers et al., 2011a);
3. A positive association between the flow of exhausted air in the most frequently used position in the whole dwelling during the night and noise annoyance due to the ventilation system (in both systems; Spearman's r=0.16, p=0.01).

The statistically significant associations between performance/quality of the ventilation system and perceived health and perceived indoor environment were weak, but in line with the expectations (perception less favorable in homes with MVHR).

DISCUSSION & CONCLUSION

The overall conclusion from this study is that many things go wrong in standard Dutch housing projects with mechanical ventilation (both balanced mechanical ventilation and mechanical exhaust). The most common shortcomings are:

- Insufficient ventilation capacity. About half of all homes have at least one room with insufficient ventilation.
- Noise from ventilation systems. Noise exceeds the reference value in more than half of all homes with MVHR, especially in bedrooms.
- No operable windows available. 5% of all homes had at least one living room or bedroom without any operable windows.
- No bypass on the heat exchanger. There was no bypass on the heat exchanger in half of the homes with MVHR.
- Unclean ventilation systems. Many ventilation systems were (internally) dirty or dusty. Dust and dirt was found in the air supply ducts of about 66% of homes with MVHR. The ventilation-unit was internally dirty in a third of the homes with MVHR. Air filters were dirty in almost half of the homes with MVHR.
- Incorrect design or installation. Air ducts were not properly installed (e.g. with unnecessary bends) and air supply grilles were not placed at the optimal location in a number of homes.

- Incorrect use. Most users do not control ventilation systems as recommended. The highest setting, for example, remains mostly unused because of high noise levels. Moreover, occupants often don't know what the recommended use is, due to insufficient user information.
- Insufficient maintenance. In most cases, there was no maintenance contract for the ventilation system.
- The supply of (part of the) exhaust air. Part of the exhaust air is recirculated in more than half of all homes with MVHR. Further study is necessary to determine the exact cause and amount of recirculation.

There was no obvious relationship found between shortcomings of the ventilation systems and self-reported health. The only weak relationship found, was one between a higher nightly ventilation rate in the bedroom and a decrease in unspecific health problems.

Two shortcomings in mechanical ventilation systems were found to have a relationship with perceived indoor environmental quality. First, indoor air quality was rated less positive when recirculation of exhaust air was found in a MVHR system. Second, occupants reported more complaints about noise in situations where the ventilation system had a higher exhaust air rate at night.

No difference was found in the self-reported health of occupants with balanced ventilation or with mechanical extract ventilation. There were however some differences in perceived indoor environmental quality between homes with the two different ventilation systems:
- Occupants rate the indoor air quality higher in homes with MEV;
- Occupants rate the air less often as 'dry' in homes with MEV;
- Occupants have less complaints about noise in homes with MEV;
- Occupants rate the control options better in homes with MEV.

For more detailed information about the study and the study outcomes, see Bogers et al (2011), Balvers et al (2012) and van Dijken & Boerstra (2011) (in Dutch).

The original research reports (in Dutch) can be downloaded at http://www.binnenmilieu.nl/v2/bba/?id=141.

ACKNOWLEDGEMENTS
This study was commissioned and financed by the the Dutch Ministry of Housing, Spatial Planning and the Environment (currently: the Ministry of Infrastructure and the Environment). The authors would like to acknowledge the help and support during this study by Ellen Koudijs, Irene van Kamp, Erik Lebret, Tim Beuker en Mark Verlinde.

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