Energy Impact of Ventilation and Air Infiltration
14th AIVC Conference, Copenhagen, Denmark
21-23 September 1993

Potential Energy Savings from Modified Ventilation of Dwellings

N C Bergsøe

**Danish Building Research Institute, Postboks 119,
DK-2970 Hørsholm, Denmark**

Synopsis
A total of 177 measurements have been performed in apartments in multi-story buildings without mechanical ventilation. The buildings comprised renovated and non-renovated buildings built between 1930 and 1960. Measurements of air change rate and relative humidity have been performed using passive measurement techniques including a passive multiple tracer gas technique, the so-called PFT-technique. In each apartment the main bedroom has been investigated separately. In addition, the occupants completed a questionnaire concerning their use of the dwelling.

The objects of the measurements have been to determine the level of the average ventilation in naturally ventilated apartments in existing buildings and to evaluate whether the ventilation is adequate.

The measurements were performed during two heating periods and statistical tests have shown that in addition to dividing the measurement results into two groups, being renovated and non-renovated buildings respectively, each group had to be divided additionally according to the time of year the measurements were performed.

Results have shown that in a winter period with typical outdoor temperatures there is no statistical difference in the average air change rate in apartments in renovated and non-renovated buildings, respectively. The average air change rate was about 0.4 h^{-1}. During a winter period with extraordinary mild outdoor conditions the average air change rate was somewhat higher, about 0.5 h^{-1}, in apartments in renovated buildings and more than 0.6 h^{-1}, in apartments in non-renovated buildings.

The results of the measurements of relative humidity show that on average the relative humidity is on an acceptable level. However, indications are given that some apartments may be suspected of having condensation problems.

1. Introduction

Since 1982 the Danish building code has provided the use of mechanical exhaust ventilation in apartments in multi-story buildings. The code also provides that a dwelling must be ventilated corresponding to an air change rate of 0.5 h^{-1} and specific provisions are stated regarding ventilation of kitchens and bathrooms. Previous large scale field investigations of ventilation in residential buildings built after 1982 (1) have shown an average air change rate of just under 0.6 h^{-1} in apartments in multi-story buildings equipped with mechanical exhaust ventilation.

The energy consumption for ventilation of dwellings will become increasingly important, as the energy consumption for coverage of transmission heat loss is reduced, due to overall improvements of the standard of insulation of buildings. Prospects for further reduction of the energy consumption will depend increasingly on the possibilities of reducing the energy consumption in the field of ventilation. It is of vital importance to the valuation to establish whether ventilation is adequate in existing buildings.

Renovation of multi-story buildings usually comprises replacement of the windows with new double-glazed sealed windows and improvement of the joints. This will enhance the overall air tightness of the building envelope resulting in a reduction in the uncontrolled part of air infiltration in dwellings. This in turn may have a negative effect on the indoor climate and increase the risk of causing damage to building components due to elevated humidity levels in the apartments.

This investigation concerns naturally ventilated apartments in existing buildings. An important issue is the influence from the occupants' use of their apartment on the average air change rate and the relative humidity. The matter includes the occupants' use of outdoor air inlets and window openings. This has been examined through this investigation as long-term passive sampling techniques has been used in connection with a questionnaire.

2. Procedures and measurement techniques

Through contact with numerous co-operative housing societies, a number of multi-story buildings built between 1930 and 1960 were selected. Among the buildings, which comprised renovated and non-renovated buildings, approximately 200 apartments were selected at random. The renovated buildings were primarily characterized by having had new double-glazed sealed windows installed. In each apartment the room air temperature was measured and passive measurements of outdoor air supply and relative humidity were performed. The duration of each of the passive measurements was approximately 2 weeks. In addition, the occupants completed a questionnaire concerning their use of the dwelling. The measurements were performed during the heating periods 1990/91 and 1991/92.

177 measurements turned out successfully. An overview of the apartments investigated is shown in table 1.

Table 1. Overview of the apartments investigated.

	Apartments in renovated buildings	Apartments in non-renovated buildings
Number of apartments investigated	113	64
Average living area, m^2	58.9	60.3
Average area of the main bedroom, m^2	11.8	12.5
Average number of occupants per apartment	1.9	2.0
Average living area per occupant, m^2/person	36.2	35.3

Measurements of outdoor air supply were performed using the PFT-technique, a passive sampling, multiple tracer gas technique. Tracer gas is emitted passively and continuously at a known rate from a small source. Following mixing with the room air, tracer gas is collected in passive adsorption tubes. The tubes are analysed in the laboratory by thermal desorption and gaschromatography. The outdoor air supply is taken to be equal to the reciprocal of the time averaged tracer gas concentration multiplied by the emission rate. Up to three different tracer gas types can be used simultaneously, making it possible to investigate up to three different rooms or zones in a building individually and simultaneously. In this investigation the main bedroom was examined as a separate zone. Consequently, the results presented below, comprise results covering both the apartment as a whole and the bedroom separately. A comprehensive description of the PFT-technique is given in (2).

Measurements of relative humidity were performed using calibrated, wooden blocks made from beechwood. The method is based on the fact that wood exposed to room air will attain a moisture content almost in equilibrium with the relative humidity of the room air. The moisture content is determined by weighing out the wooden blocks. As the curves for absorption and desorption of wood are dissimilar and as the curve for desorption is more invariable, the blocks were conditioned at 0.80 RH before they were placed in the apartments. Thus, desorption always occurred. The technique is described in (3).

The passive tracer gas sources, the passive adsorption tubes and the wooden blocks were placed in the apartments by qualified personnel. Measurements of room air temperatures were performed in the living-room and in the main bedroom and also the volume of the dwelling was measured. About 2 weeks later stamped and addressed envelopes and a questionnaire were sent to the occupants, asking them to return the equipment together with the completed questionnaire.

3. Results

Measurements have been performed in 177 apartments. Each apartment was investigated once, however, a complete set of results for each apartment does not exist. Individual erroneous results have been excluded. In the following result tables, the number of results being used as the basis for the average given, are shown. From statistical tests it is recognized that the results obtained are influenced by the time the measurements were performed. Therefore, in addition to dividing the results into two groups comprising results from measurements in renovated and non-renovated buildings respectively, each group were divided according to the heating period in which the measurements were performed.

Results of the measured quantities are shown in table 2. Table 3 is showing the climatic conditions during the measurement periods.

Table 2. Summary of results of measurements, mean ± standard error.

	Apartments in renovated buildings		Apartments in non-renovated buildings	
	1990/91	1991/92	1990/91	1991/92
Number of results, living-room	60 - 63	43 - 47	24 - 26	30 - 37
Number of results, bedroom	45 - 63	31 - 46	20 - 26	24 - 36
Temperature, living-room, °C	20.0 ± 0.1	21.2 ± 0.2	20.2 ± 0.2	21.2 ± 0.2
Temperature, bedroom, °C	19.7 ± 0.2	20.1 ± 0.3	19.5 ± 0.4	20.4 ± 0.3
Outdoor air supply, l/s	15.4 ± 0.8	19.2 ± 1.0	14.3 ± 1.5	25.5 ± 1.3
Outdoor air supply, l/s per m^2	0.27 ± 0.01	0.32 ± 0.02	0.24 ± 0.02	0.42 ± 0.02
Outdoor air supply, l/s per person	8.5 ± 0.6	13.2 ± 1.3	8.3 ± 1.0	16.5 ± 1.5
Average air change rate, h^{-1}	0.42 ± 0.02	0.49 ± 0.03	0.36 ± 0.03	0.65 ± 0.03
Outdoor air supply, bedr., l/s	4.4 ± 0.5	5.0 ± 0.6	4.1 ± 0.8	6.1 ± 0.7
Outdoor air supply, bedr., l/s pr. m^2	0.44 ± 0.04	0.39 ± 0.05	0.38 ± 0.07	0.49 ± 0.06
Relative humidity, living-room	0.35 ± 0.01	0.44 ± 0.01	0.39 ± 0.01	0.39 ± 0.01
Relative humidity, bedroom	0.38 ± 0.01	0.46 ± 0.01	0.42 ± 0.01	0.43 ± 0.01

Table 3. Outdoor air temperature and average water content in the outdoor air, mean ± standard error.

	Heating period 1990/91	Heating period 1991/92
Average outdoor air temperature, °C	-0.1 ± 0.3	6.8 ± 0.3
Average water content in the outdoor air, g H_2O/kg	3.2 ± 0.1	4.6 ± 0.1

From measurements of temperatures and relative humidities in the indoor air and in the outdoor air, the difference in the absolute water content in the indoor air and outdoor air is calculated. Cumulative, relative frequency plots are shown in figure 1.

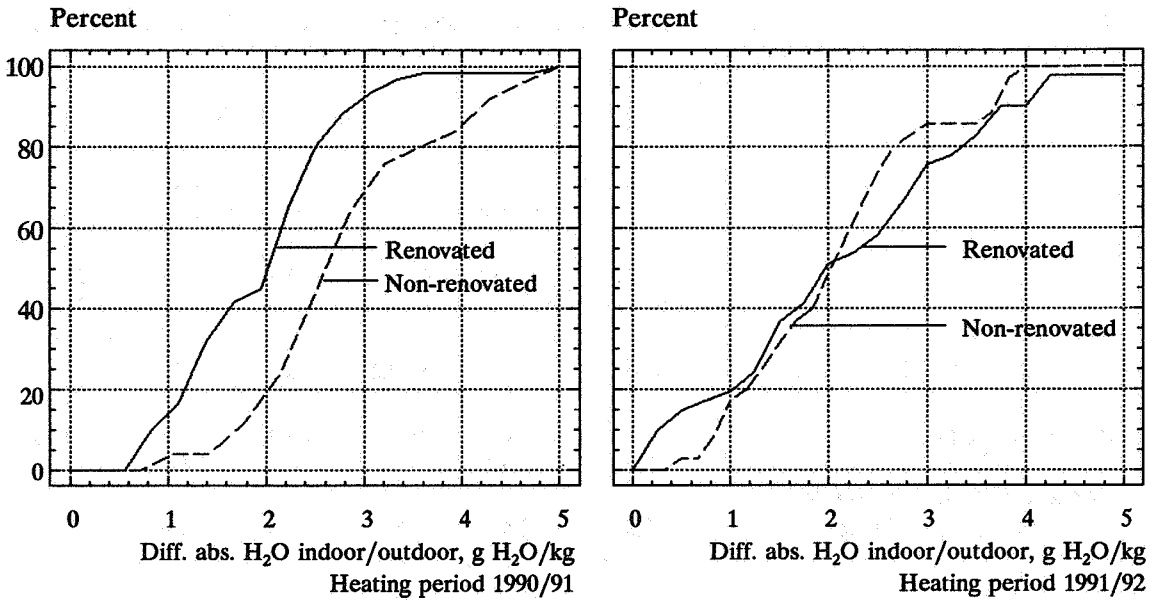

Figure 1. Cumulative, relative frequency plots of the difference in absolute water content in indoor air and outdoor air, g H_2O/kg

In addition to the measurements performed, the occupants completed a questionnaire. In appendix A tables and figures are showing the answers given by the occupants to some of the questions. Of particular interest for this investigation is whether outdoor air inlets have a significant influence on the outdoor air supply. From table A1 in appendix A it can be seen that 49 apartments in renovated buildings and 24 apartments in non-renovated were equipped with outdoor air inlets. According to the occupants the inlets were normally open in 32 apartments (~65%) in renovated buildings. In non-renovated buildings 8 apartments (~33%) had open inlets in wintertime. Table 4 and table 5 show the results of measurements, categorized according to position of the outdoor air inlets, as stated by the occupants. For clarity reasons only the mean is given in the tables.

Table 4. Heating period 1990/91. Results of measurements according to position of outdoor air inlets as stated by the occupants, mean.

	Heating period 1990/91					
	Apartments in renovated buildings			Apartments in non-renovated buildings		
	Open Inlets	Closed Inlets	No Inlets	Open Inlets	Closed Inlets	No Inlets
Number of results, living-room	5	4	47 - 51	3	4	17 - 18
Outdoor air supply, l/s	15.3	12.3	15.8	11.7	13.5	15.0
Relative humidity, living-room	0.36	0.39	0.35	0.40	0.35	0.40
Difference H_2O indoor/outdoor Living-room, g H_2O/kg	1.7	1.8	2.0	3.8	2.9	2.5

Table 5. Heating period 1991/92. Results of measurements according to position of outdoor air inlets as stated by the occupants, mean.

	Heating period 1991/92					
	Apartments in renovated buildings			Apartments in non-renovated buildings		
	Open Inlets	Closed Inlets	No Inlets	Open Inlets	Closed Inlets	No Inlets
Number of results, living-room	20 - 25	7 - 10	9 - 12	5	11	13 - 19
Outdoor air supply, l/s	21.3	14.0	19.7	29.5	20.4	29.0
Relative humidity, living-room	0.44	0.47	0.45	0.38	0.43	0.36
Difference H_2O indoor/outdoor Living-room, g H_2O/kg	2.0	3.4	1.5	1.8	2.7	1.7

Also, questions were asked concerning the reason why the occupants considered airing required in various rooms and the way in which the airing was performed. Figure A1 and figure A2 in appendix A are showing the answers given by occupants in renovated and non-renovated buildings, respectively, regarding their airing habits.

From the figures it can be seen that the principal procedure for airing the main bedroom is through constantly keeping a window ajar. Table 6 and table 7 show results categorized according to the way airing was performed. For clarity reasons only the mean is given in the tables.

Table 6. Heating period 1990/91. Main bedroom. Measurement results according to way of airing.

	Heating period 1990/91			
	Apartments in renovated buildings		Apartments in non-renovated buildings	
	Constantly a window ajar	Periodic airing	Constantly a window ajar	Periodic airing
Number of results, bedroom	16 - 22	27 - 38	7 - 8	12 - 17
Outdoor air supply, bedroom, l/s	6.1	3.4	4.9	3.7
Relative humidity, bedroom	0.39	0.38	0.42	0.42
Difference H_2O indoor/outdoor bedroom, g H_2O/kg	2.0	2.3	3.2	2.8

Table 7. Heating period 1991/92. Main bedroom. Measurement results according to way of airing.

	Heating period 1991/92			
	Apartments in renovated buildings		Apartments in non-renovated buildings	
	Constantly a window ajar	Periodic airing	Constantly a window ajar	Periodic airing
Number of results, bedroom	13 - 25	8 - 21	9 - 10	15 - 24
Outdoor air supply, bedroom, l/s	6.5	3.0	8.0	5.0
Relative humidity, bedroom	0.45	0.48	0.45	0.43
Difference H_2O indoor/outdoor bedroom, g H_2O/kg	1.8	2.4	2.6	2.4

4. Discussion

Statistical analyses and tests have been conducted to determine whether statistically significant trends occurred in the material. The correlation coefficients in the regression analyses were generally low, however, looking at both heating periods as a whole, the following findings are significant: In apartments in both renovated and non-renovated buildings the average air change rate is positively correlated to the outdoor temperature. In apartments in renovated buildings the relative humidity in both living-room and bedroom is positively correlated to the outdoor temperature and negatively correlated to the outdoor relative humidity. In apartments in non-renovated buildings the relative humidity in the bedroom is positively correlated to the outdoor temperature. No significant correlation was found for the living-room in apartments in non-renovated buildings.

For both renovated and non-renovated buildings, statistical tests have shown, that the measurement results of the average air change rate, obtained through measurements performed in heating period 1990/91, are significantly different from the results obtained through measurements performed in heating period 1991/92. In addition, tests have shown, that the average air change rate, measured in apartments in non-renovated buildings, is significantly higher in heating period 1991/92 than in heating period 1990/91. These findings are unanticipated as the outdoor temperature on average was higher in heating period 1991/92. In naturally ventilated buildings the ventilation rate is expected to be negatively correlated to the outdoor temperature. Further analysis of the results is necessary in order to explain the matter. For apartments in renovated buildings the average air change rate is found to be 0.42 h^{-1} in heating period 1990/91 and 0.49 h^{-1} in heating period 1991/92. For apartments in non-renovated buildings the results are 0.36 h^{-1} and 0.65 h^{-1}, respectively. Compared to the present Danish building code it can be seen that these provisions are met in non-renovated buildings in heating period 1991/92 and almost also in renovated buildings. However, in both renovated and non-renovated buildings the provisions are not met in heating period 1990/91. If the outdoor air supply is expressed in liters per second, l/s, the results obtained through measurements in renovated buildings show 15 l/s in heating period 1990/91 and 19 l/s in heating period 1991/92. The results from measurements in apartments in non-renovated buildings show 14 l/s (1990/91) and 26 l/s (1991/92). Specific provisions are in the Danish building code regarding extraction of air from kitchens and bathrooms. For the type and size of apartments investigated here the passive

exhaust ducts must provide extraction of 20 l/s from kitchens and 15 l/s from bathrooms, equalling a total of 35 l/s for the apartment. These provisions are definitely not met.

The results of the measurements of the relative humidity show that in both building types the humidity is higher in the bedroom than in the living-room. In non-renovated buildings there is no statistical difference between the periods 1990/91 and 1991/92.

Interesting results are seen from the calculations of the difference in absolute water content in the indoor air and outdoor air. In heating period 1990/91 the difference is higher in the non-renovated than in the renovated buildings.

Recommendations for maximum acceptable humidity in the indoor air can be given on two different viewpoints. One is that in winter condensation on the windows must be prevented. A difference in absolute water content in the indoor air and the outdoor air of 2.5 g H_2O/kg is normally considered sufficient to avoid condensation. Differences of 3 - 4 g H_2O/kg may cause problems in dwellings with double glazing when room temperature is lowered and curtains are drawn. If 3.5 g H_2O/kg is taken as the limit it can be seen from figure 1 that in heating period 1990/91 approximately 20 percent of the apartments in the non-renovated buildings may be suspected of having condensation problems. In heating period 1991/92 10-20 percent of the apartments, both in renovated and non-renovated buildings, may be suspected of having problems with condensation, however the heating period was not typical. The other viewpoint is that the number of house dust mites per gram house dust must be kept low. This means a maximum acceptable humidity in the indoor air of 7.0 g H_2O/kg corresponding to a relative humidity of about 0.45 at 20-22 °C, in typical climatic winter conditions in Denmark. Focusing on heating period 1990/91 - heating period 1991/92 was extraordinary warm - it can be seen from table 2 that some of the apartments investigated, particularly the bedrooms, may be suspected of having an increased number of house dust mites.

5. References

(1) Bergsoe, Niels C.
"Investigations on Air Change and Air Quality in Dwellings"
International CIB W67 Symposium on Energy, Moisture and Climate in Buildings. 3-6 September 1990. Rotterdam. The Netherlands.

(2) Säteri, Jorma O. (Ed.)
"The Development of the PFT-Method in the Nordic Countries"
D9:1991. Swedish Council for Building Research, Stockholm, Sweden.

(3) Nielsen, Ove
Luftfugtighed i renoverede højhuse med tre ventilationsløsninger (The humidity conditions in renovated high-rise buildings with three ventilation solutions. In Danish).
Danish Building Research Institute. SBI-report 198. Hørsholm, 1989.

Appendix A

- Table A1. Number of answers given by the occupants to some of the questions in the questionnaire.

- Figure A1. Apartments in renovated buildings. Answers given to the question: In what way do you usually air?
- Figure A2. Apartments in non-renovated buildings. Answers given to the question: In what way do you usually air?
- Figure A3. Apartments in renovated buildings. Answers given to the question: Do you consider it necessary to air daily through opening doors or windows?
- Figure A4. Apartments in non-renovated buildings. Answers given to the question: Do you consider it necessary to air daily through opening doors or windows?

Table A1. Number of answers given by the occupants to some of the questions in the questionnaire.

	Number of answers given to the questions 1-8			
	Apartments in renovated buildings		Apartments in non-renovated buildings	
	Yes	No	Yes	No
1) Is there a natural/passive exhaust duct in the kitchen?	85	19	41	11
2) Do you have a manually controlled exhaust ventilator in the kitchen?	35	76	20	43
3) Is there a natural/passive exhaust duct in the bathroom?	96	14	20	40
4) Do you have a manually controlled exhaust ventilator in the bathroom?	3	104	2	57
5) Are there outdoor air inlets in a majority of the living-rooms?	49	64	24	40
6) If 'yes' to question 5: Are the air inlets normally open in wintertime?	32	15	8	15
7) Does tobacco smoking take place daily in the apartment?	70	41	32	27
8) Does condensation occur on the windows when the outdoor temperature is around 0 °C and blinds are **not** drawn?	20	92	22	38

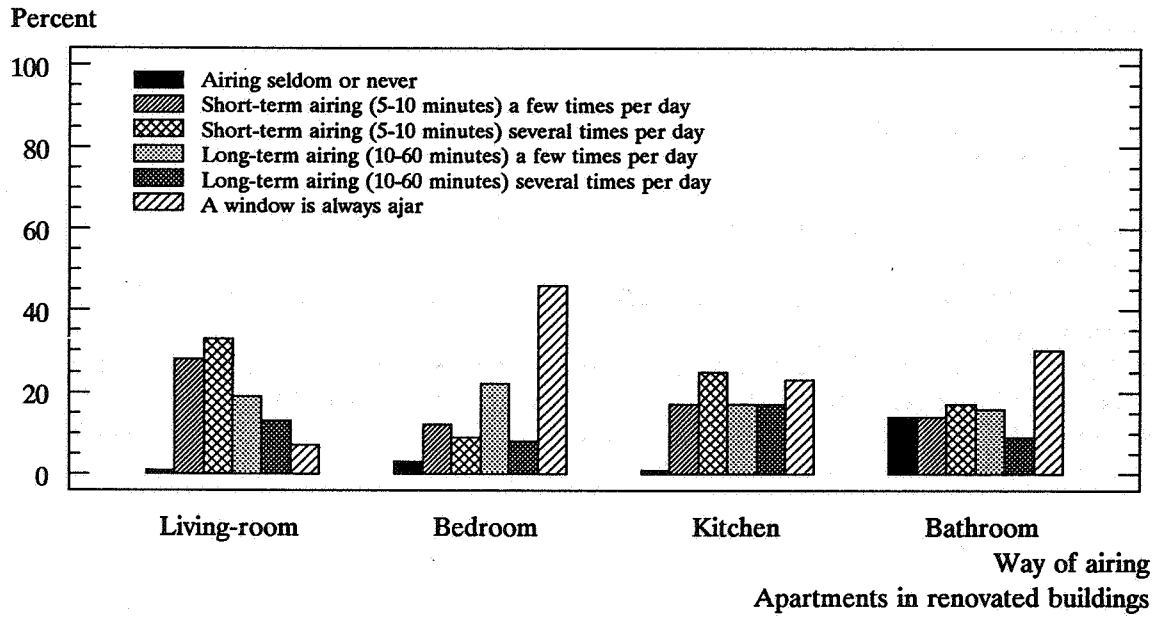

Figure A1. Apartments in renovated buildings. Answers given to the question: In what way do you usually air?

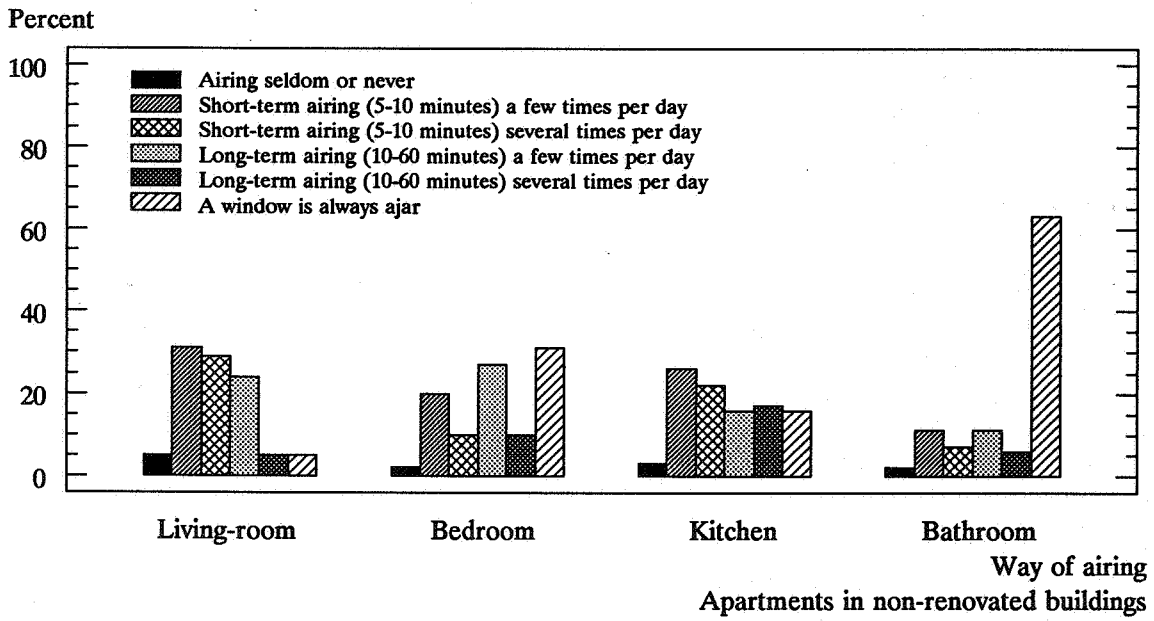

Figure A2. Apartments in non-renovated buildings. Answers given to the question: In what way do you usually air?

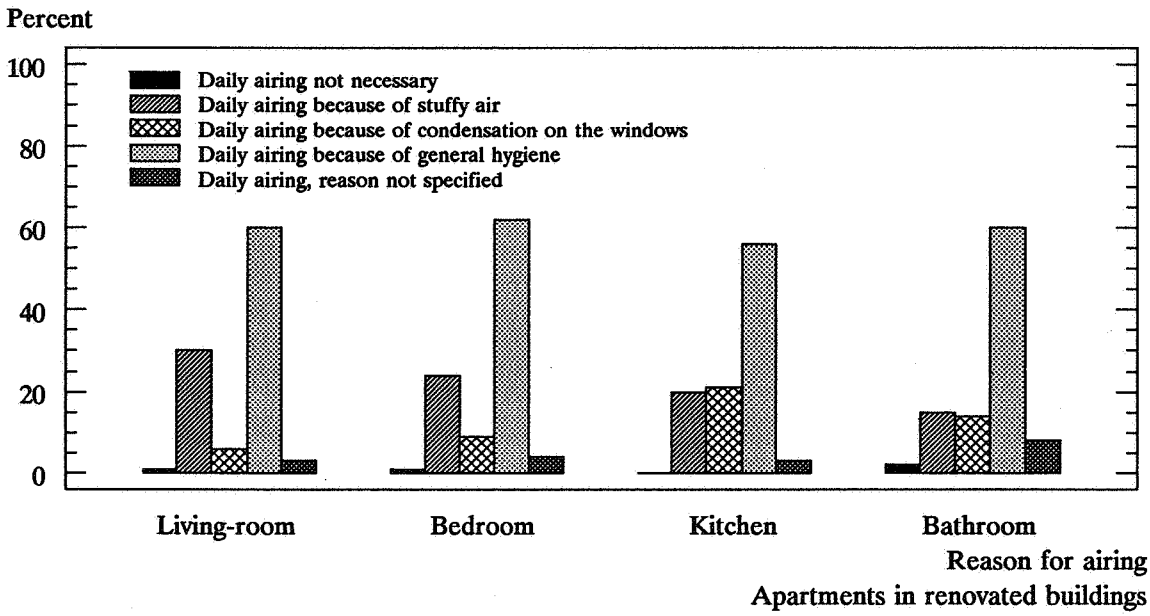

Figure A3. Apartments in renovated buildings. Answers given to the question: Do you consider it necessary to air daily through opening doors or windows?

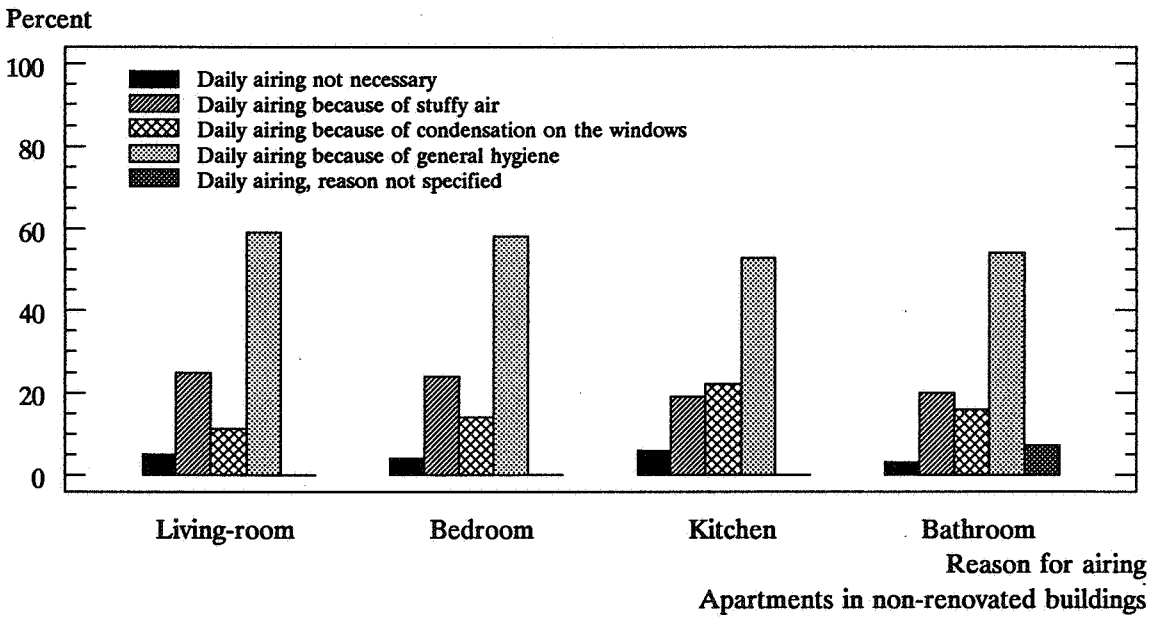

Figure A4. Apartments in non-renovated buildings. Answers given to the question: Do you consider it necessary to air daily through opening doors or windows?