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Evaluation and Demonstration of Domestic Ventilation Systems - State of the Art

IEA, Energy Conservation in Buildings and Community Systems Program. Annex 27

Lars-Göran Månsson (editor)

BYGGFORSKNINGSRÅDET
The Swedish Council for Building Research

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Evaluation and demonstration of domestic ventilation systems - State of the art

IEA Energy Conservation in Buildings and Community Systems Programme - Annex 27

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ABSTRACT

Within the IEA (International Energy Agency) programme on Energy Conservation in Buildings and Community Systems eight countries are co-operating in the project on Evaluation and Demonstration of Domestic Ventilation Systems. The main goal is to develop tools to make it possible to predict the consequences of installing a particular ventilation system.

This report, based on about 300 references, gives the basis for making assumptions as input in the computer models that will be used. In the report is given data on housing and the development of the number of persons per dwelling past, today, and in the future. Here is also given information on the residents' behaviour. Various pollutants indoors are discussed and both peak and average values are given.

The use of computer models are discussed in this report for predicting the indoor air quality by the use of multi zone models, energy calculations, sensitivity analysis on the thermal comfort equation, how to express ventilation efficiency, noise consequences, life cycle costing and illustrating the reliability by comparing three different ventilation systems.

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Foreword

The main aims with this report have been to point out how important the residential sector is, the variety both with respect to the living area and number of residents, the differences in habits and behaviour. However, we can also see that the general habits and do not differ that much from country to country. So in fact here is pointed out that the individual variation can be very broad but this is rather similar in the participating countries. With this as a base it is then possible to use the collected data in this State of the Art report to make the assumptions to be used in our future work with developing tools to evaluate Domestic Ventilation Systems.

The review has been a joint effort and the collection of data with reference to existing reports have been a matter of using many sources. Appointed participants have been responsible for the peer review of a chapter. Of course comments have been given also to the other chapters. There was two reasons for doing it. One was that all participants needed to have the same background material and the other was that all the participants now agree on the content of this report and that the most essential knowledge is collected from good reliable sources.

The reader of this report makes the best out of it by using it as a reference work. You can go back and find a lot of information concerning the residential sector in general and in particular factors, that is to be taken into account, when discussing the need for ventilation in dwellings. New knowledge is always gathered as it is a continuos process. But with giving as many tables and diagrams as possible it is easy for you as an active reader to compare your own new collection with this reviewed data and make your own opinion if our conclusion still is valid in your own case either it is a particular residential building or more general.

As most of the text here is written by people that do not have English as their mother tongue, there is for sure many clumsy formulations that could be made more smoothly. However, the time for doing it is less worth compared to make it possible to be read much earlier. With this foreword I would like to thank the participants for the work. To the reader I would say, enjoy the contents in small portions!

Lars-Göran Månsson
Operating Agent

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Participants, contact list of national representatives

Preface

International Energy Agency (IEA)

The International Energy Agency (IEA) was established in 1974 as an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the 22 IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources, and energy research development and demonstration (RD&D). This is achieved in part through a programme of collaborative RD&D consisting of 46 current Implementing Agreements

Energy Conservation in Buildings and Community Systems

As one element of the Energy Programme the IEA sponsors research and development in a number of areas related to energy. In one of these areas, the Implementing Agreement "Energy Conservation in Buildings and Community Systems Programme", the IEA is sponsoring various exercises to predict more accurately the energy use in buildings, comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy behaviour. Nineteen countries and the Commission of the European Communities have elected to participate and have designated contracting parties to take part in the collaborative research within this Implementing Agreement.

Belgium, Canada, CEC, Denmark, Finland, Greece, Israel (associated), Italy, Japan, The Netherlands, New Zealand, Norway, Poland (associated), Sweden, Switzerland, Turkey, The United Kingdom, The U.S.A.

The designation by governments of a number of private organisations, as well as universities and government laboratories, as contracting parties, have provided a broader range of expertise to tackle the projects in the different technology areas that would have been the case if participation was restricted to governments. The importance of associating industry with government sponsored energy research and development is recognised in the IEA, and every effort is made to encourage this trend.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new areas where collaborative effort may be beneficial. The Executive Committee ensures that all projects fit into a pre-determined strategy, without unnecessary overlap or duplication but with effective liaison and communication. The Executive Committee has initiated the following projects to date, each implemented by a subcommittee or Annex.

Annex no	**Project title**
1	*Load Energy Determination of Buildings*
2	*Ekistics & Advanced Community Energy Systems*
3	*Energy Conservation in Residential Buildings*
4	*Glasgow Commercial Building Monitoring*
5	Air Infiltration and Ventilation Centre
6	*Energy Systems & Design of Communities*
7	*Local Government Energy Planning*

8 *Inhabitant Behaviour with Regard to Ventilation*
9 *Minimum Ventilation Rates*
10 *Building HVAC Systems Simulation*
11 *Energy Auditing*
12 *Windows and Fenestration*
13 *Energy Management in Hospitals*
14 *Condensation and Energy*
15 *Energy Efficiency in Schools*
16 *BEMS 1 - Energy Management Procedures*
17 *BEMS 2 - Evaluation and Emulation Techniques*
18 *Demand Controlled Ventilating System*
19 *Low Slope Roof Systems*
20 *Air Flow Patterns within Buildings*
21 *Thermal Modelling of Buildings*
22 *Design of Energy Efficient Communities & Urban Planning*
23 Multizone Air Flow Modelling (COMIS)
24 Heat Air and Moisture Transport in New and Retrofitted Insulated Envelope Parts
25 Real Time Simulation of HVAC-systems for Building. Optimisation, Fault Detection and Diagnostics
26 Energy Efficient Ventilation in Large Enclosures
27 Evaluation and Demonstration of Domestic Ventilation Systems
28 Low Energy Cooling Systems
29 Daylight in Buildings
30 Bringing Simulation to Application
31 Environmental Impacts
32 Integral Building Envelope Performance Assessment

Completed projects in italics

Annex 27 Evaluation and Demonstration of Domestic Ventilation Systems

The idea to initiate this Annex was that there is a need to develop tools to better evaluate domestic ventilation systems in various situations. Different systems in various climates must handle situations with a large range of residential behaviour. With the use of the most complex models a large number of combined situations will enable us to develop simplified tools, that can be used of practitioners in specific cases.

This report gives the background data that enable us to make good assumptions for the case studies. Results from other Annexes (A 3, 5, 8, 14, 18, 20, and 23) have been used.

Participating countries are Canada, France, Italy, Japan, The Netherlands, Sweden, U.K., U.S.A. A contact list is provided in the Appendix.

1. Summary

The main purposes with this report on State of the Art are to give the background data for making it possible to give realistic assumptions for the case simulations and to review the models that are possible to use, maybe also imply further development.

The statistical data on housing give us both the average figure and the distribution. The construction year of dwellings give us that there are 4 different categories. Those are the countries with about 50 % of the dwelling that are more than 50 years old (B, DK, F, UK); 50 % of the dwellings 25 - 50 years old (D, S, I); 50 % of the dwellings less than 25 years old (CAN, JAP, NL, SF, USA); and finally an even distribution (CH, N). The average dwelling area varies within the range of 65 - 152 m^2. A better measure is the area per person, that varies from 27 m^2 to 61 m^2. Another very important factor to take into account is the number of person in each dwelling. Small households are more common and 2-person-household stands for 70 % of all in Sweden, 50 - 60 % in most of the European countries and North America and 40 % in Japan.

Natural ventilation is the most common way to ventilate dwellings, either by means of window opening or by the stack effect in vertical ducts or shafts. Mechanical ventilation has become more common in some of the countries during the last 20 years. The tightness of the envelope varies considerably but goes seldom below 3 h^{-1} (n50) unless new constructed. The air change rates goes from 0.2 to 0.8 h^{-1}, which together with the size of the dwelling gives a considerably great variation of the energy use.

The pollutants in the dwellings to take into account are moisture, volatile organic compounds, particles, and bioeffluents with the tracer gas CO_2. The different loads can vary within a magnitude and ventilation systems may have to deal with this. The survey of measurements indicates both normal and more severe levels, that may occur in new or just refurbished homes or just in some problem buildings or in gasfired homes or when smoking.

Residential buildings can have been built on radon emitting ground or on landfill spillage. Precaution must be taken if the dwelling is depressurized both for outside pollutants and when combustion appliances are dependent on combustion air from the dwelling.

To give realistic assumptions for the residents´ exposure in different situations a detailed review of existing reports concerning the behaviour has been done. Here is given the time spent at home, the body washing habits giving a great supply to the moisture production within a dwelling. The moving frequency indicates, that most families have established their final home before the age of 35 years. The indoor temperature varies within a great range from 21 °C to 16 °C. The window airing pattern varies but is mostly coupled to the outdoor temperature, the cloudiness, and if it is windy.

The different models for simulation of energy, multizone models for pollutant exposure (IAQ-models) and air flow rates, and thermal comfort are discussed. The conclusion is that the models are more sensitive for the input data than for the selection of computational model. The ventilation efficiency is very important and the various expressions are described. Noise reduction is very essential in densed populated areas, when dwellings are exposed to traffic noise. Special attention must be taken to the supply terminals. As one of the task is to give life cycle cost calculations for different situations a discussion of the consequences of the use of life cycle costing is given and the parameters discussed.

All the detailed components in a ventilation system must function. The reliability of a system is discussed both for the matter of fault and dust accumulation decreasing the ability to give the required air flow rate and for principally different systems to keep the required flow rate in different rooms and at what seasons of the year.

With this fundamental parts consisting of statistical data on housing, different ventilation systems, pollutant loads indoors and outdoors, residents´ behaviour, the models for energy, IAQ, thermal comfort, noise, life cycle cost, gives us the possibility to formulate assumptions for different realistic cases to apply the most elaborated models on the situations. In addition further developments will be necessary, when models are lacking or to simplified. The development of the simplified tools will make it possible for the practitioner to evaluate a dwelling in a specific situation.

2. Introduction

Author Lars-Göran Månsson, Sweden, Operating Agent

In the introductory chapter is given the background and the reasons for starting an international collaboration in the field of domestic ventilation. The objectives are given and the means to fulfil these goals are briefly described. This report is concerning the first phase, the Subtask 1 - State of the Art. In this report is briefly explained the reasons for why we are giving standard values and threshold values and measured data. The reason is that the knowledge has not fully been possible to use when codes and standards have been decided upon. But the foremost reason is to explain why it is needed, when we are setting out for our next subtasks and making the assumptions for realistic cases to be calculated.

2.1. Background, Objectives, Scope, and Subtasks of Annex 27

Annex 27 of the International Energy Agency (IEA) is working on **Evaluation and Demonstration of Domestic Ventilation Systems**. It is a part of the IEA Research and Development program on Energy Conservation in Buildings and Community Systems. The results of the first subtask are contained in this book, "State of the Art".

Background

Ventilation is of major importance for the well-being of people in their homes. The rate of outdoor air supply as well as comfort aspects associated with air distribution and the ability of the systems to remove pollutants are important factors to be considered at the design stage, during the commissioning procedure, and when using the building during its life cycle.

The two main purposes of ventilation are to obtain an acceptable indoor air quality and to avoid the degradation of building fabric e.g. rot in wood, rust on steel. The definition of "acceptable indoor air quality" is on the other hand not easy to define, especially in dwellings.

Everyone should have the right to an acceptable indoor air quality in his home. As distinct from a work place, residents can vary across a wide span from an allergic infant to a well trained sportsman, from active people spending most of the days outdoors to elderly people confined to a life indoors.

Objectives

The objectives of IEA Annex 27 are:

① Develop methods for evaluating domestic ventilation systems
② Validate the methods with data obtained from measurements,
③ Demonstrate and evaluate domestic ventilation systems for different climates, building types, and use of dwellings.

Scope

During the life expectancy of a building its residential patterns vary. This results in a varying need for supply air to obtain acceptable indoor air quality (iaq) and avoid degradation of the fabric. Emissions from building materials are also time dependent. When the building is new or recently refurbished it may be necessary to dilute the emissions by extra supply air. In standards and codes the supply air needed in a dwelling is generally based on the maximum number of persons living in the dwelling defined by the possible number of beds contained therein. Statistics from various IEA countries indicate that, in general, about 50 % (range 46 - 71 %) of the dwellings have only one or two occupants.

Dwellings represent about 25 - 30 % of energy use in the OECD-countries. Ventilation in dwellings will in the future represent up to 10 % of the total energy use. Thus even relatively small reductions in overall ventilation levels could represent significant savings in total energy use. The great potential for energy saving is of course in the existing buildings.

Today there is a vast range of different ventilation strategies in the different OECD countries. In some countries the only ventilation possible is adventitious ventilation and window airing, while in others there are natural ventilation systems more or less commonly in function. In countries with colder climate, mechanical systems, either exhaust or balanced systems, have been installed in new buildings during the last 15 - 20 years, with or without heat recovery units. The majority of dwellings, however, still have natural ventilation even in countries with colder climate (in single family houses 75 - 80 % and in flats about 50 %).

There are benefits and drawbacks with all ventilation systems. Adventitious ventilation is known to be unsatisfactory from indoor climate also from an energy point of view and should be avoided in the future. Natural ventilation systems normally lack the capability of controlling the ventilation rates, which depends greatly on the prevailing weather conditions. When chilly and windy outside the ventilation works best whilst in warmer and calm situations the ventilation rate is in most cases low. The first case leads to energy waste and the second to air quality problems and/or moisture problems.

It is possible to control the air flow rate in a mechanical ventilation system thus making it possible to achieve an acceptable indoor climate during a longer period of time than is the case with adventitious and natural ventilation systems. In mechanical ventilation systems heat recovery units can be installed thus saving energy.

Improvement of residential ventilation is of concern in both existing and future building. The functioning of the ventilation systems may deteriorate at all stages of the building process and during the lifetime of the building.

Subtasks

The means involve calculation, compilation of data, measurement, collection of data, and analysis. Three subtasks are set up with objectives means how to achieve those goals.

The work is divided into the following three subtasks:

Subtask 1. State of the Art

Objectives of the subtask

- ☐ Give an overview of system solutions
- ☐ Identify the most frequently used system solutions and the reasons behind
- ☐ Review existing evaluation methods

Means for the achievement

- ○ Describe typical and most frequently used ventilation systems in new and old domestic buildings
- ○ Reviewing the efficiency of the typical solutions in providing occupants´ required comfort and avoiding the risk of building material deterioration
- ○ Giving the background for existing ventilation systems and standards
- ○ Describing the energy consequences
- ○ Reviewing existing evaluation methods thus identifying the gaps
- ○ Describing promising ventilation system developments

Subtask 2: Development and Validation of Evaluation Methods

Objectives of the subtask

- ☐ Define evaluation parameters
- ☐ Select methods to be used in this Annex
- ☐ Develop new methods/tools where appropriate
- ☐ Validate methods

Means for the achievement

- ○ Energy use by considering the heating of supply air and heat recovery possibilities and fuel type
- ○ Life cycle cost by considering the installation investment, maintenance cost, and energy cost
- ○ Reliability of systems by considering the ability of the various systems to maintain the required air flow rate over time
- ○ Controllability by considering the methods available to the occupants to control the air flow rate
- ○ Acceptable indoor air quality and comfort by considering air flow rates and distribution
- ○ Measurement data to be used for validation

Subtask 3: Evaluation, Demonstration, and Application of Current and Innovative Ventilation Systems

Objectives of the subtask

- ☐ Use the methods/tools developed in Subtask 2 in order to evaluate ventilation systems for a set of variables
- ☐ Demonstrate good performance of principally different ventilation systems
- ☐ Demonstrate innovative systems for future buildings

Means for the achievement

- ○ Identify limited number of values of each variable
- ○ Evaluating different systems for climate types, building types, user patterns, construction types for new, renovated, and existing residential buildings
- ○ Defining the ventilation systems regarding design assumptions and methods
- ○ Demonstrating the application of the evaluation methods by calculation and field demonstration

Reports

From each of the subtasks a separate report is planned to be published. Intermediate reports on specific topics as well as overviews will be published in conferences and technical briefings in conjunction with the executive committee meetings. These reports can be received from AIVC.

Target Audience

Decisions on ventilation are made in all countries by standard bodies, policy makers, companies involved in the housing industry, and others. But these decisions have been made without a comprehensive evaluation method. Research in recent years described in IEA annexes e.g. now makes it possible to formulate such methods to evaluate domestic ventilation systems.

2.2. State of the Art

In this book is given today's knowledge on available evaluation methods and the systems most used in the participating countries. Some of those methods are here discussed more from a principle point of view than an overview of all available methods. The annex is aiming at the more principle way to deal with the evaluation thus giving possibilities to validate developed tools. If the complex models will be replaced by others it easy to compare. Most methods do not differ too much in results from each other. The essential is to give appropriate input data.

Objectives

The main objective with this report on state of the art is mainly to give a discussion how the various pieces fit together, identify the gaps, and the difficulties with the methods we have today.

Another objective with this subtask is to let the reader understand that, when the standards and codes were decided upon, it was usually a worst case that was calculated. This case lasts usually only during a short period of time of the building life cycle. An average or even low load situation was never of any concern when writing a standard. This may of course lead to a to high use of energy.

A third objective has been to give a detailed background of all the variations in the dwelling with respect to area, number of residents, time spent at home, and other residential behaviours. With all these details realistic assumptions can be made on how the dwelling is used in different situations. With the application of various systems and climatic conditions it is possible to simulate a large number of variations, calculate the life cycle costing, and see the frequency of different systems to keep required conditions.

3 Statistical Data on Housing

Author Lars-Göran Månsson, Sweden, Operating Agent

In this chapter is given statistical data of the number of dwellings in the individual countries, table 3.1, the room area per person, the construction year of the dwellings , number of residents in different sizes of dwellings defined as the number of rooms. From this data an idea of the variation in the usage of dwellings might be realised. When studying the equipment in dwellings it might be seen that the load from the appliances will vary. Here we can also realise a variation in the social structure. With this base statistical data a more varied discussion on demand related ventilation according to the residents´ need can be made in the forthcoming subtasks in the annex as well as creating realistic case studies.

Table 3.1 Dwelling area in some OECD countries (Ref. Hedman 1993, Bundesamt für Statistik, Dok. Gebäudebestand 1991, Housing survey 1988)

Country	Dwellings Millions	Useful Floor Space m^2/dwelling	Total area Million m^2
Belgium (B)	3.9	130	507
Denmark (DK)	2.4	107	257
Finland (SF)	2.2	74	163
France F)	26.7	85	2270
Germany (D)	33.9	90	3051
Italy (I)	18.7	65	1216
Japan (J)	37.4	89	3340
Netherlands (NL)	6.0	110	660
Norway (N)	1.8	85	153
Sweden (S)	4.1	87	360
Switzerland (CH)	3.2	97	310
United Kingdom (UK)	23.6	90	2124
Canada (CAN)	10.0	134	1340
U.S.A. (USA)	105.7	152	16066
Total	**279.6**	**74 - 152**	**31817**

3.1 Dwellings: Number, Area, Construction Year

We can see from figure 3.1 that in Belgium, Denmark, France, and UK quite many dwellings are in buildings older than 50 years. Four countries, Finland, Japan, The Netherlands, and the USA have about 50 % of their dwellings in houses constructed less than 25 years ago. Norway and Switzerland have an even distribution over the time of the construction of the newly built dwellings or about 1/3 less than 25 years. In all the other countries about 3/4 (69 % - 83 %) of the dwellings are more than 25 years old. The conclusion is that in countries with an old building stock, there is a greater potential for new construction, whilst in the countries with the majority of the housing stock 25 - 50 years old, there is a greater potential for refurbishment.

In most countries dwellings in single family houses are most frequent , see figure 3.2. More than 2/3 of all dwellings in North America, Japan, UK, Netherlands, Denmark, and Belgium are in single family houses. There is no correlation between an old or a new building stock and the number of single family houses, as can be seen in UK with an old stock and The Netherlands with a new stock. Both countries have many single family houses.

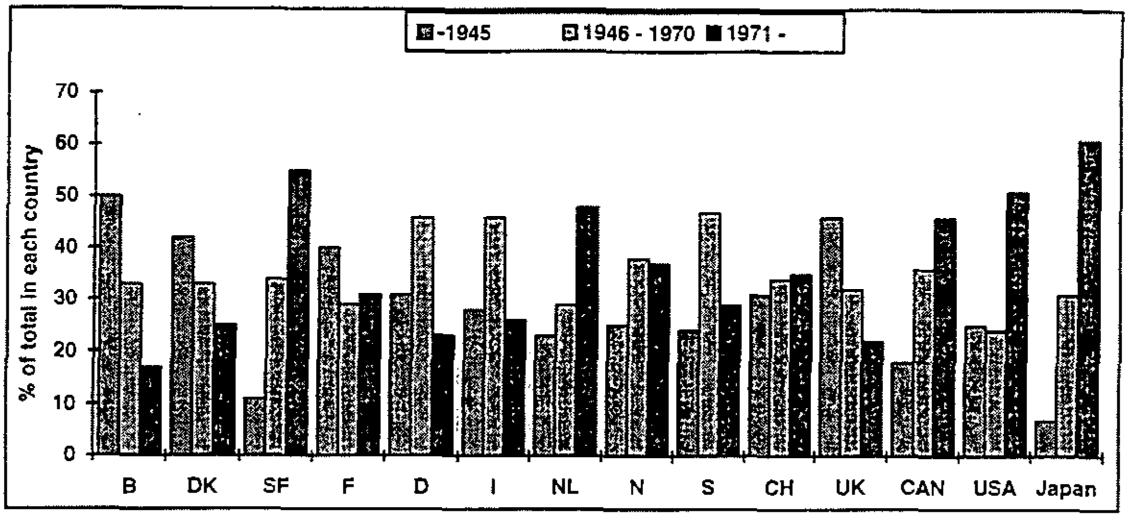

Figure 3.1 The construction years of dwellings. Percentage of total (Ref Hedman 1993, Bundesamt für Statistik, Dok. Gebäudebestand 1991, Housing survey 1988. Canada Census 1993)

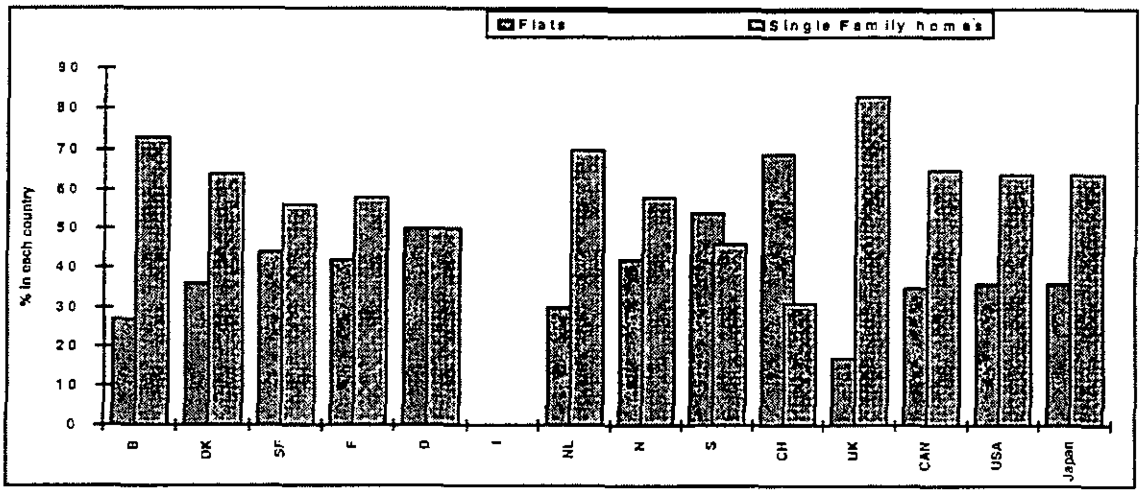

Figure 3.2 Single family homes and flats, percentage (%). (Ref: Hedman 1993, Carlsson 1989, Schipper 1984, Nordic Statistics 1992, UK G&A Home Audit, US Census data 1990, Dok. Gebäudebestand 1991, Housing survey 1988)

3.2 Demographic data

The floor area varies from 65 - 152 m^2, table 3.1, giving a volume of 150 -365 m^3 if estimating the ceiling height of 2.4 m. With one of today's standard for outdoor air change rate of 0.5 h^{-1} the flow will be 75 - 180m^3/h. If combining the volume and the number of persons/dwelling the outdoor air flow rate goes from 6.5 l/s,p to 24 l/s,p if all dwellings had mechanical ventilation adjusted to 0.5 h^{-1}.

From figure 3.3 can be seen that in 90 - 95 % of all dwellings, there is less than two persons in each bedroom. In a majority of countries, there is less than 1 person/bedroom in 1/3 or even in 1/2 of the dwellings. The trend seems to be towards even fewer residents in each dwelling. In nearly all countries 50 - 60 % of the households only consist of 1 or 2 persons and there is a trend towards even more, table 3.3. Very few of the households (less than 10 %) have 5 or more persons.

Table 3.2 ***Persons/dwellings (Ref Hedman 1993, US Census Data 1990, Bundesamt für Statistik, Housing survey 1988 Canada Census 1993)***

Country	Persons/ dwelling	Area, m^2/person
Belgium	2.7	
Denmark	2.2	49
Finland	2.5	30
France	2.7	32
Germany	2.5	35
Italy	3.2	29
Japan	3.2	28
Netherlands	2.6	
Norway	2.5	43
Sweden	2.1	47
Switzerland	2.2	39
United Kingdom	2.7	27
Canada	2.7	50
U.S.A.	2.3	61

Table 3.3 ***Number of persons/household. Percentage of all dwellings (Statistics in EC, Nordic Statistics 1992, US Census Data 1990, Housing survey 1988)***

Country	Number of persons/household (distribution %)				
	1	2	3	4	5
Belgium	26	30	18	16	9
Denmark	34	33	15	13	5
Finland	31	29	17	15	8
France	25	28	19	16	12
Germany	33	29	18	14	6
Italy	22	24	23	21	10
Japan	18	20	18	23	21
Netherlands	27	30	15	19	9
Norway	35	26	15	15	8
Sweden	40	31	12	12	5
Switzerland					
United Kingdom	24	33	17	17	9
Canada	21	30	18	19	12
U.S.A.	25	33	16	17	9

The ventilation of the bedrooms are of great concern as we spend from 8 h to 12 h there. It is of interest to study how we use this room type. It also gives us a measure on the population density in each dwelling. Sometimes this has been used to compare the habitable standard. In some countries the aim of the governmental policy of housing has been "one bedroom per person". In figure 3.3 can be seen, that in Canada, the USA, Japan, and Norway more than 50 % of the dwellings have so many rooms that there is one person per bedroom or less.

The developing of one-persons households during the last 40 years can be studied in figure 3.5. This is coupled to a growing number of elderly people living in their own dwelling. In Europe the trend towards an increasing number of one-person households is now approaching 1/3 of all households. There is a similar trend in the USA with about 1/4 and in Japan with a little less than 1/5 of all households with one person. The development has gone very fast in some countries like Japan or nearly 4 times increase since 1950, and in some European countries doubled during the same time. No country has shown a constant trend over this 40 years. The very odd figure, that the USA show 1950 compared to the following years, may be a matter of faults in some sources. The trend towards an increasing number of one person household can be forseen over the next 40 years, see figure 3.4. The number of people older than 60 years is expected to grow from about 20 % to over 30 % of the population.

There are different explanations for the trend towards fewer persons in each dwelling. The life time of the males is shorter than the females. The divorce rate has increased during the last 30 years and this trend seems to be kept for a long time. The social trends will lead to a growing number of one and two person-households.

The fertility has constantly declined since the last 30 years in the EU-countries and the Nordic countries. The population can hardly be kept up and can slowly decrease if today's situation is maintained. On the other hand this trend rapidly can be changed, if the developed countries get many refugees. The live birth today is given below per 1000 inhabitants.

Nordic Countries	13.7
EU	11.9
USA	6.7
Japan	10.0
Canada	10.9

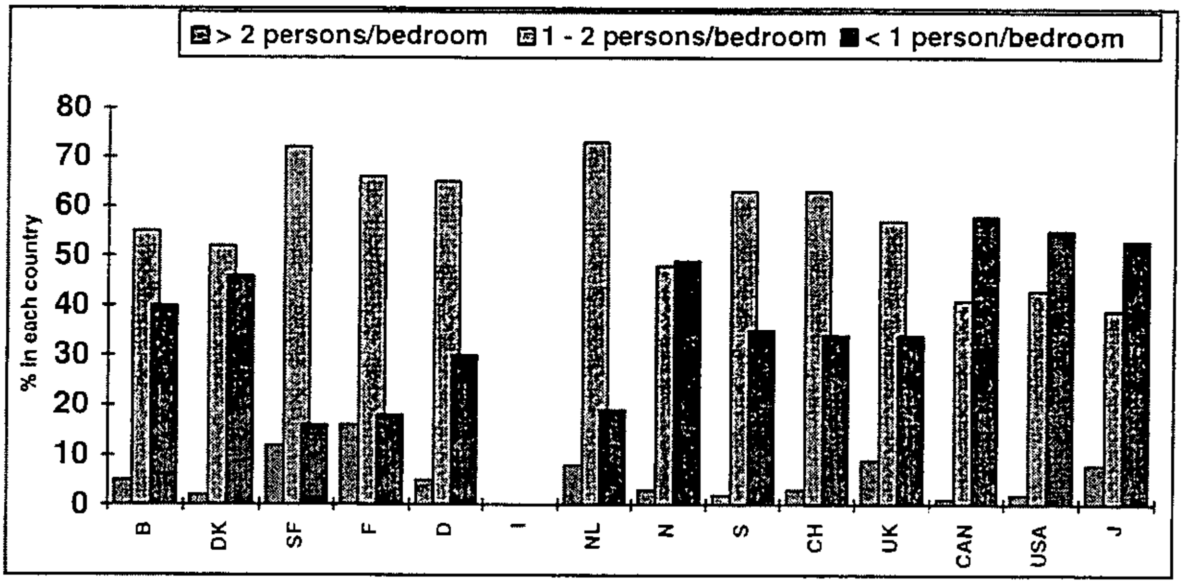

Figure 3.3 Persons per bedroom. Percentage of the dwellings (Hedman 1993, Housing survey 1988)

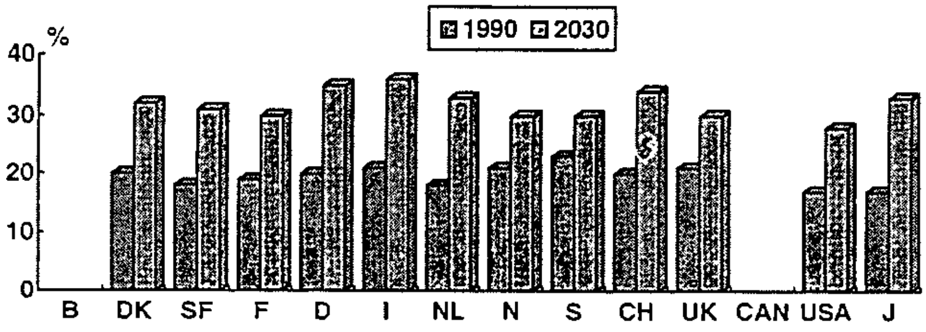

Figure 3.4 The percentage of the population older than 60 years 1990 and 2030 (World Bank)

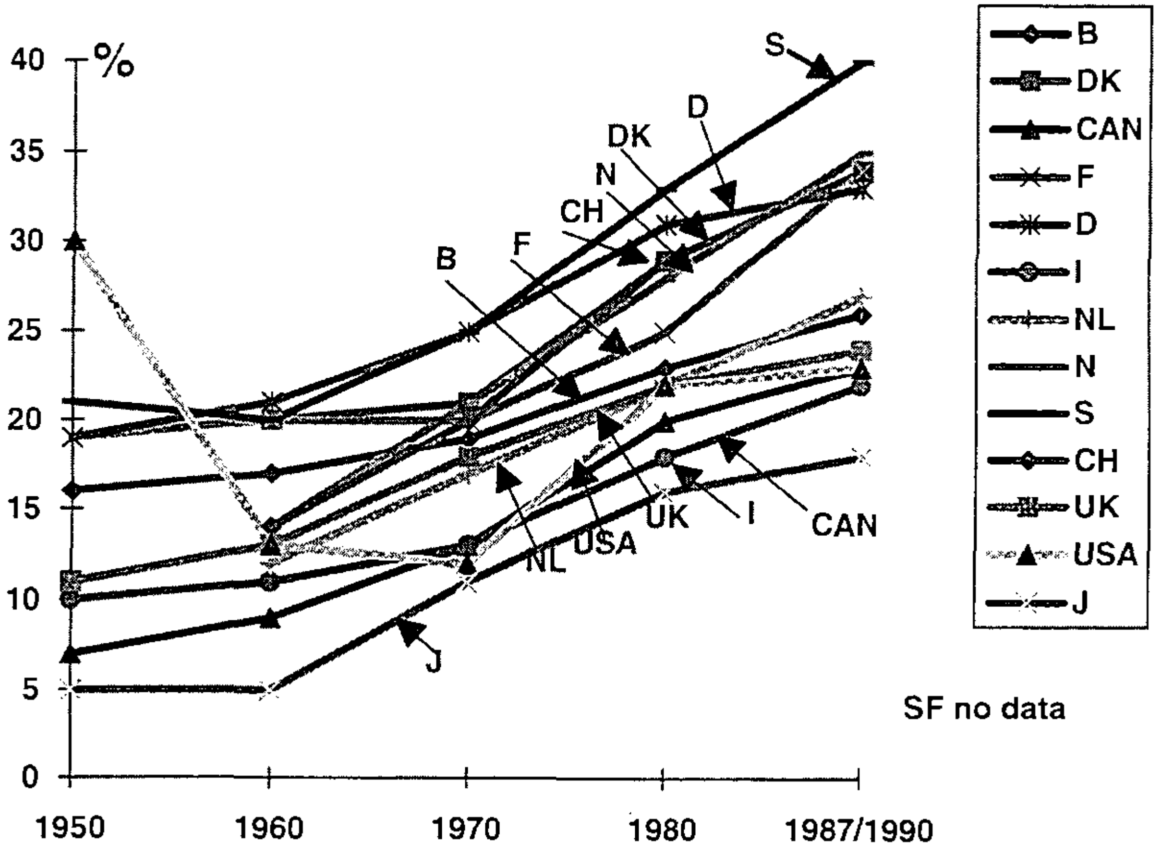

Figure 3.5 Development of one-person household. Percentage of all (Hedman 1993, Pacific North West Residential Study 1992, Japan Census data, Canada Census 1993)

3.3 Dwelling equipment

Nearly all dwellings are equipped with a shower or a bath, see table 3.5. But many baths are installed in older buildings resulting in an extra load compared to the original habits at the time of the construction of the building. Also the installation of central heating systems (hydronic or electric baseboard radiators) and the more or less sealed fireplaces have changed the original intention. The indoor environment might have been improved by stopped using the fireplace with respect to draught and smoke from the fire. However, the ventilation was before mainly provided by the chimney. Now when sealed the residents have to relay only on window airing, thus resulting in risks for higher relative humidity.

Table 3.5 ***Equipment in dwellings 1989. Percentage of dwellings with bath/shower, central heating, dishwasher, washing machine. (Hedman 1993, Housing in EC, Nordic Statistics 1992, Eurostat 1992, Pacific NW Residential Survey 1992, Housing survey 1988, National Survey 1989, Household Facilities)***

Country	Bath/ Shower	Central Heating	Dish-washer	Washing Machine
Belgium	76	51	25	90
Denmark	90	95	25	66
Finland	93	90		
France	95	75	22	81
Germany	92	75	24	83
Italy	86	57	17	87
Japan	91	3	5	100
Netherlands	99	80	7	90
Norway	96			
Sweden	99	99		
Switzerland		45		
United Kingdom	99	68	6	83
Canada	100	99	44	78
U.S.A.	99	99	66	89

The number of washing machines seems to be nearly 100%. However, we do not know if the figure is given for dwellings with access to a washing machine or if it is one machine in each dwelling. If it is the first statement that is true, there might be an increase of washing machines in flats to be foreseen. Dishwashers is still not that common. All these machines give away an extra water vapour to the dwelling, that must be properly treated and taken into consideration when designing the ventilation systems.

This brief collection of equipment data shows that the dwelling usage has change during the last decades and dramatically for buildings older than 50 years. This is closed coupled to the development of the welfare systems and the change away from dirty and heavy work.

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4. Ventilation Performance

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In order to find the range of ventilation expressed as air change rates or outdoor air supplied by leakage in a natural ventilated dwelling or supplied by mechanical ventilation a survey has been made of measured data. This is mostly to get some idea of the magnitude of the ventilation performance in today's building stock. The most frequently used systems are identified and briefly described.

4.1 Ventilation levels

Until just recently measurements have been made by expensive equipment during a few hours in dwellings. This matter has restricted the number of measured dwellings to a very few and made it impossible to exercise large surveys. With the introduction of passive tracer gas technique it is now possible to make large surveys. Dwellings measured with "active" tracer gas methods are usually special cases e.g. problem houses, research houses, new houses. Statistical selection and measuring of dwellings has been to expensive. The passive tracer gas technique gave the opportunity to reduce the cost considerably.

However, it is not always possible to compare results measured by the two methods. The passive method includes the habits of the residents, whilst for dwellings measured with the "active" methods have closed windows and doors. It must be pointed out that the two methods give the same result, when used under the same conditions. Average ventilation in a dwelling can be expressed as air change rate [h^{-1}], air flow rate per person [l/s,p], or litres per second and square metre [l/s,m^2].

Data given in table 4.1 are based on the references, that are given with reference number in the table. As can be seen the ventilation expressed as air change per volume or m^2 varies within a large range and can be said to go from close to 0 or 0.1 h^{-1} to a very high level in individual dwellings. The average very seldom exceeds 0.5 h^{-1} for single family houses and 0.6 h^{-1} for flats. If the value is given person related, [l/s,p], the value is far better as the number of residents is lower than the total number of beds the dwelling can be furnished with. Results from the Swedish survey and the Finnish study of flats in Helsinki indicate, that there is sufficient supply air, 10 - 12 l/s,p. This result gives a value comparable with offices.

4.2 Envelope tightness

Limb (1994) has summarised the codes, standards, and regulations of air tightness for whole buildings and components like windows and doors for the member countries in AIVC. Those values are, of course aimed at to be fulfilled, but only for new constructed buildings. For the existing building stock the air tightness have a great influence, when deciding upon new ventilation systems in conjunction with renovating buildings. When renovation takes place it is expected, that the air tightness is improved and particular if additional insulation has been used on the outside of the facade. However, research results have shown that this is not the case, at least for detached single family houses, even with very detailed instructions , according to Hammarsten, Pettersson (1980) and Kronvall, Månsson (1993).

Sherman and Dickerhoff (1994) show that retrofitted US dwellings cut the leakage with 25 % but were still much leakier (17 after retrofitting) than above refered houses

Table 4.1 Ventilation in dwellings

Country	No of dwell.s	Year of constr	Method p or a	Single family houses				Multi family buildings				Ref
				h^{-1}	l/s,p	$l/s,m^2$	system	h^{-1}	l/s,p	$l/s,m^2$	system	
Belgium	17	1980	a	0.5							N	5
				0.75								
Canada	40			0.2-0.6								19
Denmark	200	1930-60	p					0.4	8	0.27	N	4
	?	>1982								0.6	E	4
	150		p	0.35								18
Finland	242	-1982	p	0.40				0.62			N	3
				0.42				0.64			E	3
				0.45				0.60			SE	3
		all		0.45				0.64				
France												
Germany		all		0.8				0.8				20
Italy												
Japan	10	1984	p	0 -0.7								21
Netherlands						40 l/dw						20
Norway		<1951		0.5								20
		51-65		0.4								20
		>65		0.3								20
Sweden	≈2000	all	p	0.34	12	0.23	N	0.49	12	0.33	N	1, 2
				0.36	12	0.24	E	0.58	14	0.39	E	1, 2
				0.43	14	0.29	SE	0.60	16	0.40	SE	1, 2
Switzerland	5	mv1980s	a				N	0.5^2	11		N	6
								0.1^1				6
		all		0.7				0.7				20
UK												
USA, NY	30	?	p	0.2			?					7
Cal, L.A.	640		p^3	0.6			?					8
Georgia	22		p	0.1-6			?					9
All states	500	all	a	0.83								13
Northern states	?	all	a	<0.2								13

p=passive tracer gas method, a=active tracer gas method, 1) closed bedroom doors, 2)opened bedroom doors 3) measured in January

Within the large survey reported by Norlén, Andersson (1993) also a subsample of 50 single family houses and 30 flats were made in order to measure the air tightness with the standardised method for expressing the leakage rate at 50 Pa (average of over- and under pressure). The average value goes from 10 h^{-1} (n50) to 4.4 h^{-1} (n50) in single family houses and to 1.4 h^{-1} (n50) in multi family buildings, when comparing buildings constructed before 1940 with those after 1975 (the year when improved air tightness was introduced in the Swedish code). The standard deviation is very high for old flats but very narrow for newer. For single family houses the standard deviation gives the range of 8 - 2 h^{-1} (n50). Single measured houses in Sweden and Canada have proved, that it is possible to reach far below that level.

Values like the above have been given also in other countries. Wouters et al (1993) reported that in a multi family building constructed around 1980 the air tightness was 2.3 h^{-1} (n50).

Sherman, Matson (1993) report that less than 20 % of the houses in colder regions can meet the leakage requirement, that is about 2 h^{-1} (n50). Sherman and Dickerhoff (1994) gives the average value of 8 h^{-1} (n50 recalculated) for US dwellings built after 1980. This is based on 628 houses. The 869 houses built prior to 1980 were leakier, 17 h^{-1} (n50 recalculated). Multifamily buildings were leakier, which is quite contrary to European experiences and might be explained by different constructions.

Table 4.2 ***Air tightness in dwellings of all types.***
(Ref Orme, Liddament, Wilson 1994)

Country	Air tightness h^{-1} (n50)		Sample size	Comments
	Average	Range		
Belgium	8	2-25	57	wide distribution
Canada	5	1-20	474	most <10
Denmark				
Finland				
France	4	1-10	66	constr >1975
Germany				
Italy				
Japan				
Netherlands	10	1-30	303	a few higher, most <20
Norway	5	2-8	40	few houses even distributed
Sweden	5	1-15	144	mostly <10, a few higher
Switzerland	3	2-9	37	
UK	14	3-30	385	very many 5-25, flat freq.
USA,	11	1-30	435	highest freq 7-17

Orme, Liddament, Wilson (1994) have summarised measured air tightness in 10 countries and in table 4.2 is given the most frequent values in the building stock, the range and the number of samples the values given are based on. For three countries the air tightness in typical buildings constructed at different years are reported. It can be seen, that the improved tightness has given a cut down. However the starting level was quite different in the countries. The results for the single family houses show, that in the UK the tightness was decreased from about 20 h^{-1} (n50) to 10 h^{-1} (n50) in the Netherlands to 5 h^{-1} (n50). The higher values were for houses constructed around 1950 and the lower values are today's houses. For Sweden the results show, that old houses constructed before 1940 have an airtightness of 10 h^{-1} (n50) and the modern houses constructed after 1975 about 4 h^{-1} (n50). From table 4.2 can also be seen that the air tightness varies within a very large range. It should be noted that all types of buildings of different ages are contained in the data in table 4.2. Very few countries have splitted up the results in single family houses and flats of different construction years. The tightness in Japanese houses have been studied by H. Yoshino (1992). On Hokkaido the tightest houses were as tight as in Swedish houses from the middle of the 1970s and the leakiest as the looser houses in USA.

4.3 Frequently used ventilation systems

There are two principly different types of ventilation systems. One is the natural ventilation system (N), that has to rely on temperature difference and wind velocity. N-ventilation can be divided into a) ventilation only by window openings, called adventitious ventilation, relying on wind, b) ventilation by means of vertical shafts or ducts, also called stack ventilation.

The other type is the mechanical or fan assisted systems. The simplest is the one with an exhaust fan called exhaust ventilation system (E). This system must rely on supply air through cracks and slots (supply device usually located in the window casement or frame also called trickle ventilator). If the supply air should be more controlled, fans for supply and exhaust must be installed. This system is called supply- and exhaust ventilation system (SE). Of the principally different system types N, E, and SE, a lot of variations have been designed and also installed. The principally different ventilation systems with variants are shortly described below and with the explanatory drawings in figure 4.1.

Natural supply and exhaust (N-systems)

System 1	Natural crack ventilation (Adventitious ventilation). Supply and exhaust through cracks.
System 2	Natural window ventilation (Adventitious ventilation). Supply and exhaust through windows in one room or more.
System 3	Natural stack ventilation. Supply through cracks, windows, slots, trickle ventilators, or separate devices through the facade in habitable rooms and service rooms. Exhaust through vertical ducts (stacks) from service rooms (one or more), individual rooms, or one per dwelling

Natural supply and exhaust with local mechanical exhaust

System 4	Natural window and crack ventilation with mechanical local exhaust. Supply as in system 3. Exhaust like in systems 1 and 2 and in addition local mechanical exhaust in kitchen and/or bathroom
System 5	Natural stack ventilation with local mechanical exhaust. Like system 3 with a local exhaust fan. Usually a cooker hood

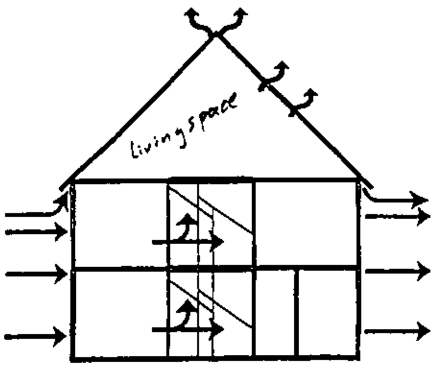
Mechanical systems (E-systems)

System 6	Natural supply and mechanical central exhaust. Supply air like in system 3. Exhaust devices in service rooms connected by ducts to a central fan.

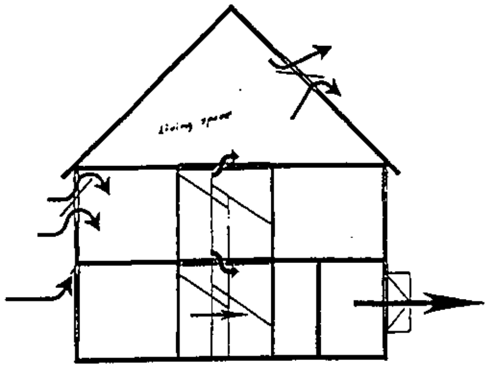
Mechanical central supply and exhaust (SE-systems)

System 7	Mechanical central supply and local exhaust. Mechanically supplied air by a fan through a ductwork and introduced in rooms. Usually for air heating systems with return air ducts. Exhaust fan(s) in the kitchen and/or bathroom(s).
System 8	Central air intake for one dwelling or building. Mechanically supplied air by a fan through a ductwork and introduced in rooms. Exhaust air like in system 6, sometimes with a separate local exhaust from the cooker hood. The system can be equipped with heat recovery, preheating or designed for air heating.

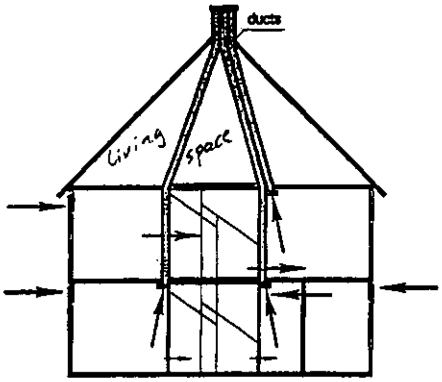
The tradition has influenced the ventilation strategy. In most dwellings constructed before the 2nd world war at least one fireplace was installed, usually more. This is especially the fact in single family houses. The chimney together with the needed combustion air gave a large air change rate in the dwelling (nothing said about the energy or thermal comfort). When central heating was introduced the fireplace or the chimney was blocked to prevent from backdraught. In new constructed buildings the traditional design continued without any vertical shaft or duct to use the stack effect thus giving at least some ventilation.



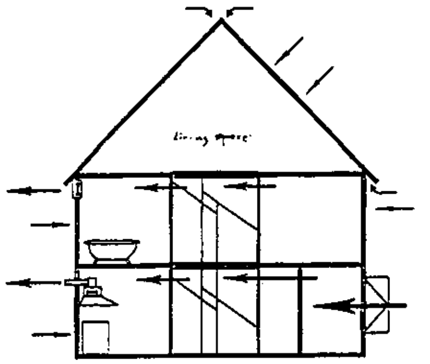
System 1: Natural crack ventilation



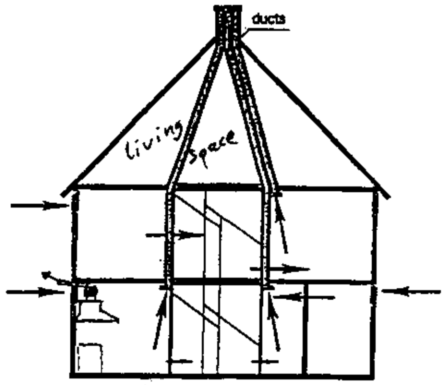
System 2: Natural window ventilation



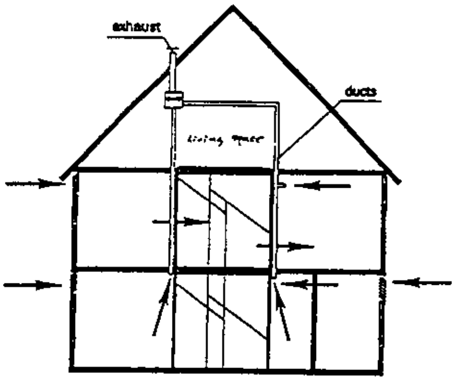
System 3: Natural stack ventilation



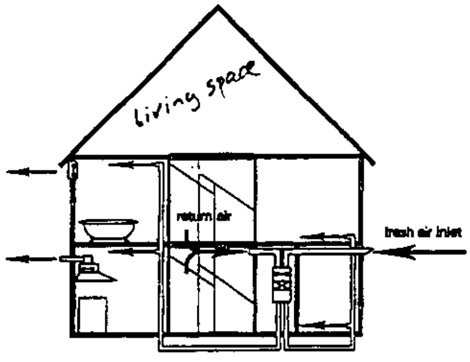
System 4 Natural supply and mechanical local exhaust



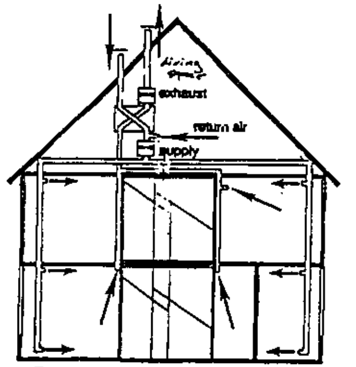
System 5 Natural stack ventilation and mechanical local exhaust



System 6 Natural supply and mechanical central exhaust



System 7 Mechanical central supply and local exhaust



System 8 Mechanical central supply and exhaust

Figure 4.1 Principle figures of the various ventilation systems

Combinations of N- and E-systems is usually the case when local exhaust fans are used for specific purposes. Such a case is the kitchen hood, which makes it possible to efficient capture the water vapour and smell from the cooking. Usually the fan is only working for an hour. Fans in bathrooms and WC connected to the light switch can also be defined as a local fan with demand control. Those ventilation strategies always need an additional ventilating system for base ventilation.

The various systems shortly described above and in figure 4.1 can be judged according to controllability of the flow rate. In table 4.3 is given the possible way of how to control both exhaust and supply rate in the systems numbered above in figure 4.1.

Table 4.3 Possible ways of controllability of the principle systems. System number, see fig 4.1

Control type	**Control of:**			
	Supply		**Exhaust**	
	Central	Local	Central	Local
No control	6	1, 4, 5	1, 2, 3, 4	1, 2
On/off	7, 8	2, 4, 5	6, 7, 8	2, 4, 7
High/low	8	2, 3, 5	6, 8	2, 4, 5, 7
Proportional	7, 8	3, 4, 5, 6	6, 8	4, 5, 7
Carbon Dioxide	7, 8		6, 8	
Air quality	7, 8		6, 8	
Humidity	7, 8	3, 4, 5, 6	6, 8	4, 5, 6, 7
Presence			6, 8	4, 5, 7
Clock			6, 8	4, 5, 7
Pressure diff	8		6, 8	5
Temperature diff	8		6, 8	

Air conditioning systems are, by definition, also combined with cooling. Another special case is forced air heating systems. The devices or purpose provided openings for the supply air can be placed in many ways. Together with how the air is transferred to the exhaust devices or openings the efficient use of air varies and hence the energy consequences at a required indoor air quality level. Many designs of the devices and openings have been seen over the years. Sometimes the new devices are tested in laboratories but some and especially the older ones are lacking any performance data. Instead of describing all the variations of the principle systems, which of course never can be complete, the aim of this Annex is to give tools to evaluate all the more or less possible variations.

An attempt has been made to estimate the proportion of the dwellings furnished with N-, E-, or SE-systems. In multi family buildings mechanical systems (E-Systems) first were introduced in countries with colder climate during the 1950s. In single family houses the E-system was introduced during the 1970s. SE-systems were introduced more broadly during the 1980s in countries with cold climate. In countries with mild or warm climate older buildings sometimes do not have any stack (vertical duct, chimney, flue), so window airing is the only measure to airing the dwelling. In table 4.4 is given the distribution of different systems in the existing residential building stock in different countries. The trends in the various countries are illustrated by table 4.5 giving the distribution of various ventilation systems in newly constructed dwellings. Multi family buildings and single family houses are treated separately.

In table 4.6 is presented a classification of different ventilation systems based on today's knowledge presented by Knoll (1992). This opinion was agreed on by specialists from the 14 AIVC countries. This classification is based on measurements, inspections, and general experiences.

Table 4.4 ***Distribution of ventilation systems in the existing dwelling stock [AIVC-workshop 1994]***

Country	**Single family houses**					**Multi family houses**				
	Natural			*Mechanical*		*Natural*			*Mechanical*	
	Adventitious	Stack (S)	Stack+ Kitchen hood	Exhaust	SE	Adventitious	Stack (S)	Stack+ Kitchen hood	Exhaust	SE
Belgium	100					95	5			
Canada		15	85							
Denmark		50 1)		48	2		50 1)		50	
Finland										
France	40	15	20	22	3	40	20	10	30	
Germany										
Italy	80		10	10		75			25	
Japan										
Netherlands		62 1)		38			37 1)		63	
Norway			80	15	5		60		30	10
Sweden		12	63	14	11		40		44	16
Switzerland	70		30			40		60		
UK		95 1)	5				100 1)			
USA,	60			40						

1) Includes all N-systems

Table 4.5 ***Distribution of ventilation systems in the new constructed dwellings [AIVC-workshop 1994]***

Country	**Single family houses**				**Multi family houses**			
	Natural		*Mechanical*		*Natural*		*Mechanical*	
	Local exhaust	S+local exh	E	SE	Local exhaust	S+local exh	E	SE
Belgium								
Canada				100				
Denmark								
Finland								
France		20	75	5	1		99	
Germany								
Italy	80		20		90		10	
Japan								
Netherlands		20	80			20	80	
Norway								
Sweden			80	20			20	80
Switzerland								
UK	100				100			
USA,	90	10			90	10		

Table 4.6 Classification of ventilation systems, Knoll (1992).
Explanation: ++ excellent, + good, o neutral, - moderate, -- bad

Ventilation System				Efficient Application of Ventilation Air			Efficient Energy Use		Specific Costs		Reliability	Comfort	
	Devices (c = controlled)			Local Applicability	Flowrate Adjustability	Airflow Pattern	Auxiliary Energy Need	Ventilation Heat Demand	Installation	Operation		User Friendliness	Supply Conditions
Type	Supply	Exhaust	Control Type										
Mechanical/ zone	local room fan (c)	local source extract (c)	humidity	+ +	+	+	+	– + + [possibility of applying alternative energy gain and heat recovery]	- -	- -	-	o	-
Mechanical/ room	local room fans (c)	local room fans (c)	humidity	+ +	+	-	+		- -	- -	-	o	-
			manual	+ +	-	-	+		- -	-	+	+	-
Mechanical	displacement grills +		odour or CO_2	-	o	+	+		-	-	o	+	– +
	ducting + fan (c) + openable windows	ducting + fan (c) + openable windows	odour or CO_2	-	o	-	+		-	-	o	+	– + + [possibility of applying air conditioner]
			humidity	-	o	-	+		-	-	-	o	
			indoor temperature	-	o	-	+		-	-	+	o	
			time	-	o	-	+		-	-	+	o	
			manual	-	-	-	o		o	o	+	o	
	ducting + fan (c)	ducting + fan (c)	manual	-	-	-	o		o	o	+	o	
Mech. supply/ Nat. exhaust	window fans (c)	grills (c)	manual	+	+	-	+	- -	-	o	+	+	-
Natural supply/ Mechanical exhaust	grills + openable windows	ducting + fan (c) + openable windows	time	-	o	-	+	– + [possibility of applying heat pump heat recovery]	-	o	+	o	-
			odours or CO_2	-	o	-	+		-	o	+	+	-
			humidity	-	o	-	+		-	o	-	o	-
			pressure difference	-	o	-	+		-	o	o	o	-
	grills (c) + openable windows	ducting + fan + openable windows	humidity	-	+	-	o		-	o	-	o	-
			pressure difference or outdoor temperature	+	+	-	o		-	o	o	+	o
			manual	-	-	-	o		o	+	+	o	-
	cracks	ducting + fan (c)	manual	-	- -	-	o		o	+	+	o	o
Natural	grills (c) + openable windows	ducting + openable windows	humidity	-	+	-	+ +	- -	o	o	-	o	-
			pressure difference or outdoor temperature	+	+	-	+ +	- -	o	o	o	+	o
			manual	-	-	-	+ +	- -	+	+	+	o	-
	grills (c) + openable windows		pressure difference	-	o	-	+ +	- -	o	o	o	o	o
			manual	- -	- -	-	+ +	- -	+	+	+	-	-
	grills (c)		manual	- -	- -	-	+ +	- -	+	+	+	-	-
	openable windows			- -	- -	-	+ +	- -	+	+ +	+	-	- -
	cracks			- -	- -	-	+ +	- -	+ +	+ +	+	- -	o

Table 1: Classification of Ventilation Systems

Code: + + excellent, + good, o neutral, - moderate, - - bad

4.4 New developments

A new system in one country might have been used in another country for decades. Never the less it will be mentioned as a new system here as the application might be under other circumstances e.g. mild or warm climate, other window constructions. Also newly introduced components and systems, that are not widely used will be mentioned here.

A general trend is to better use the outdoor air either it is forced supplied by a fan or naturally by means of trickle ventilators as supply devices. The better use of outdoor air can be a demand type controlled by humidity or pressure difference. Other devices controlled by as CO_2 or non-oxidised hydrocarbons are not very common in dwelling applications. Another trend is to develop components or parts of systems, that are aiming at keeping a more constant outdoor air flow rate.

The development are aiming at installation in new or existing dwellings. Of course it is much easier to develop systems, that are to be installed in new buildings. Often it is possible to combine and use new developed parts in systems also in the existing building stock. In this section is given trends of the development with some examples.

4.4.1 Systems

Still mechanical supply and exhaust systems are not very common in most of the countries. This type of ventilation systems can also be combined with air heating systems. Heat recovery either by heat pump or by air to air heat exchanger is used for the purpose of energy efficient systems. Additional heat is needed during a part of the heating season. The heating source can be electricity, or a gas or oil burner. In this type of multi purpose units domestic hot water can also be produced. For better use of the flue gas the heat can be recovered either separate or together with the exhaust air.

Mechanical supply and exhaust systems can also be equipped with control devices for increased outdoor air flow rate, when the pollutant rate is over a set point. But it can also be equipped with a timer directing most of the outdoor flow rate to the rooms, that are used, e.g. bedroom(s) at night-time and the living-room at daytime. By using a mechanical supply system the outdoor air can be properly filtered and also if required air conditioned (heated, cooled, humidified). If the system is used in combination with air heating new trends are also to use only outdoor air in bedrooms and allow return air only in the living-room and of cause in the service rooms.

The location of the supply devices have been a matter of studies over the years. To get the best ventilation efficiency in the room the displacement principle is used, thus giving less pollutants. However, a lower temperature than the room temperature is needed. This might result in a draught problem. A development is going on to locate the devices to the only place in the room where there is no furniture and little risk for any draught feeling. This place is on the wall where the door is opened.

Installation of heat pumps have started just recently, especially in existing houses. A development of easy installed distribution system is on the way. If a heat pump gives away all the heated air in one room the result is usually a too high room temperature and very bad distribution of the heat to other rooms. In existing multi family buildings attempts are going on to increase the indoor air quality by mechanical supply air with only one supply device.

Improvement of natural stack ventilation is going on in the direction to have the same flow rate during all seasons. This can be achieved by installing a fan unit on top of the stacks and have a control device starting and stopping or with a speed control depending on the outdoor temperature. The fan is designed to give no additional pressure drop when not running. Another development is to install an individual fan on top on each stack. If each stack is serving a separate dwelling it is also possible to have an individual fan control. This second application can also be coupled to a heat pump for efficient heat recovering. A third solution is to increase the flow rate in the stacks by induction.

Another way to give the resident's a possibility to control their ventilation need is to install a fan in each flat in multi family buildings. The air is extracted through a central duct. The fan can be located to the kitchen hood. Additional flow can be supplied automatically in the kitchen.

4.4.2 Components

With the increased use of local fans, (kitchen hood, bath room fan) there is a frequent risk for back draught in natural stack ventilated dwellings. Various components have been developed to avoid the pressure drop by installing automatic controlled devices for rapid action.

The problem with leakage between the stacks, particularly in older multi family buildings, have been a matter for development during some time. Some good measures are introduced on the market, thus enabling it to install systems that give a pressure difference between two adjacent stacks.

The development of more efficient fans has started with the increased interest to cut down the electricity use. Both small local fans and bigger units are of great interest to be developed. The knowledge how to construct electricity efficient fans has been known for a long time but just resently started to be of economical interest to produce.

The supply device (slot or trickle ventilator) for natural supply of outdoor air is the component, that has been a matter for many different solutions and locations in the window construction (frame or casement) or close to the window. Today the more sophisticated solutions are aiming at providing the dwelling with either constant outdoor air flow or keeping a constant relative humidity. The supply devices shall work automatically or as independent of the residents' behaviour. Much effort has been laid on avoiding the draught problems with the supply devices. They can be of passive or active construction. All devices that are active are motor driven in one way or another and thus electricity is needed.

In figure 4.2 is an example on a supply device, which is constructed for giving a constant flow rate independent on the temperature difference and the wind velocity. As it is going to be used also in natural stack ventilated buildings it works also at low pressure differences.

The development of an active supply device has been possible by means of measuring the air velocity and open it with a small servo motor. Thus both the wind velocity and the temperature difference is taken into account.

Humidity controlled supply or exhaust devices or combined have been known and installed during a decade but most frequent only in one country. The technique can be applied both in natural stack and mechanical exhaust ventilated dwellings. The devices can be self regulating so that the flow rate varies depending on the size of the opening. But the device can also control a fan that can be running on or off or be speed controlled. See also Månsson (1993).

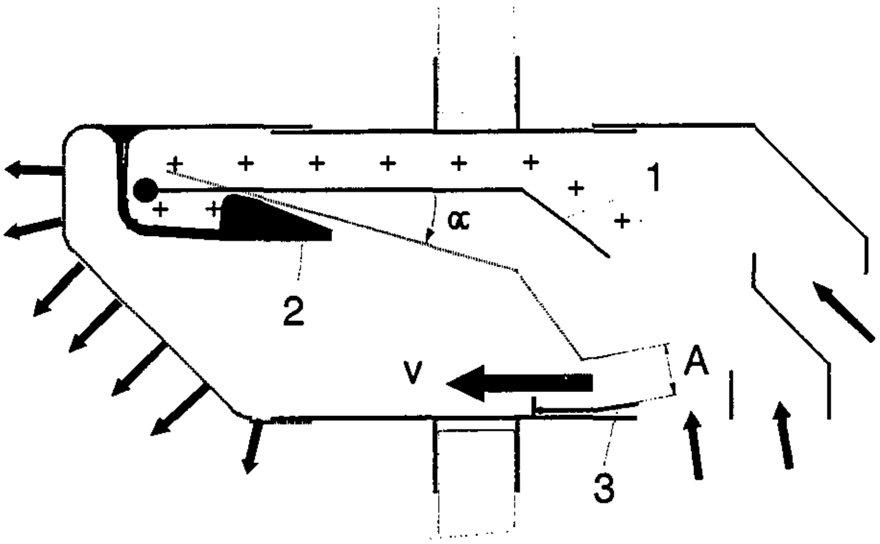


Figure 4.2 Supply device for natural ventilation giving constant flow rate

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5. Standards and Reasons Behind

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Discussions of the indoor climate have been going on since man built the first dwelling. Documents from ancient societies in Egypt (1500 BC), Greece (by Hippocrates, Aristotle), Rome (by Vitruvius, Seneca) give us some hints of how to create a good indoor climate. The first improvement for heated dwellings was the invention of a chimney to extract the smoke. During decades the population density and the personal hygiene was so bad that today's people can not imagine the magnitude of odour. To give some hints is can be said, that the clothes were kept on for a long time and ordinary people had only one set, that was used all the time. The famous king Louis XIV of France only took two baths during the life time and at both times he went ill, Englund (1991). So the conclusion was not to wash, but to use heavy perfume. Instead the good sentence of the Roman citizen Plautus should have been recalled "A woman smells best when she does not smell at all", Lord (1986).

It was first during the 18th century that scientists found, that there was a connection between odour and metabolism. The Swedish botanist, von Linné, also classified the odour in 7 groups, Linné (1756). People and domestic animals were more close and sometimes lived in the same room mostly because of the heating needed.

Theoretical studies of Leonardo da Vinci, ref. Sauer and Howell (1990), during the 15th century and Agricola 16th century described the function of a fan. During the 18th century suggestions were made to make use of fans in mines, ships, and prisons. In the middle of the 18th century the first mechanical ventilation in a hospital was introduced. The first half of the 19th century the medical profession opposed the fresh air supply of moral reason. However, it had been accepted that the oxygen and CO_2 content determined weather it was fresh or stale. With the results of von Pettenkofer also humidity and indoor temperature were discussed as parameters describing the indoor air quality. It must be remembered that also lightning (gas, kerosene) and heating were large sources for the CO_2-content, Lord (1986).

At the time of the results from von Pettenkofer the air change rate was 1.8 l/s and was now increased to 13.5 l/s. This rate was kept until 1946 when it was reduced to 4.5 l/s (10 cfm) based on the results found by Yaglou. Air quality and draught have been qualitatively expressed by some famous persons e.g. Florence Nightingale ("feel the air gently moving over the face, when still" and " the lingering smell of paint in the newly painted house is proof of want of ventilation") and Seneca that did not recommend too airtight constructions, Lord (1986).

The discussion of the ventilation rate is mostly concerning premises where mechanical ventilation can be provided and that is usually not in dwellings. But the discussion is strongly influencing the needed ventilation rate in dwellings.

Early regulations going back to the 19th century limited activities of stationary sources. An underlying philosophy was the concept of undesirable involuntary exposure and on the other hand the acceptability of voluntary exposure. From the beginning the main problems were recognised to be the outdoor air pollution. The indoor air pollutant exposure was entirely voluntary. The first air pollutant law was enacted in 1955. In the USA there are three groups of regulated air pollutants. One is the National Ambient Air Quality Standards that are regulating CO, SO_2, NO_x, O_3, and particulate matters. However, it seems like most of them are related to the outdoor environment and such linked sources except NO_x. The other two are about hazardous air pollutants and work place emissions. The indoor pollutants are categorised in two groups: 1) causing chronic effects, 2) associated with a threshold. The three most logical indicators are CO_2, particulate matters, and total hydro carbon according to Moghissi (1991). Those are indicators for human activity and the associated side effects and finally the total of hydro carbon is the sum of the emission from both activities and material. The impact of water vapour was not at all discussed.

Another way of sorting the chemical substances was to group them in gentoxic, eye and airway irritants, odorous chemicals. More than 2/3 of all threshold limit values for occupational health are made on the irritant properties of the chemicals and mostly aiming at *protecting workers. Since 50 years the ventilation requirements have been set from the odour* criterion, first to compensate for occupancy emissions only, but later to indicate ventilation performances and to be used as an early warning of indoor non-human pollutants. The odour criterion is not only a sensitive and relevant basis for decision by its own value, but also consistent with decades of practical experiences as reflected in most building codes in the world. Since most indoor air pollutants in offices and dwellings are odorous, odour control would result also in a reduction of air pollutants in general. Lindvall (1991).

Table 5.1 History of ventilation rates

Source	Year	Ventilation rate	
		l/s*p	cfm/p
Tredgold	1836	1.9	4
Billings, ASHVE req	1895	16.5	35
Flugge	1905	16.5	35
Yaglou	1936	4.7	10
ASA Standard	1946	4.7	10
ASHRAE Std 62, min rec	1973	2.4 4.7	5 10
ASHRAE Std 62, min rec. smoking	1973	2.4 4.7 9.4	5 10 20
ASHRAE Std 62 dwellings	1981	8[1] 5[1]	15 10
ASHRAE Std 62 dwellings	1989	$0.35\ h^{-1}$ >7.5[1]	15

1) Values given in the standard. The other values calculated from cfm.

McNall (1985) reports on the required flow rate for several pollutants. But here is only taken into account a single pollutant not the sum and sometimes more oriented towards the non-industrial buildings. It might also be a result of several agencies involved in the indoor air quality specialised within a more or less narrow application.

The history of the recommended and minimum ventilation rates in the USA, McNall (1988), seems mostly aiming at non-residential buildings or not specified in the paper, see table 5.1. For 1981 and 1989 the ASHRAE Standards have been quoted. Even if so, the discussion of the required ventilation rates in dwellings has been affected of this discussion in mechanical treated buildings.

When trying to summarise what have been the basis for formulating the codes and standards it must be concluded that it has been odour and pollutant removal. Moisture has never been a matter of discussion. Sometimes there is a strong impression, that the figures given in standards were more based on negotiations, than on careful reviews of the scientific results at hand. Also today's standards are mostly based on the perceived body odour and the idea, that the tracer gas is CO_2 for the indoor air quality and an indicator of an efficient ventilation. Sometimes the influence of a single pollutant, e.g. radon, was very apparent, even if the number of dwellings, that were affected of the pollutant were less than 5 % of all. The influence of the ASHRAE standard has been great since the last decades.

The present standards for dwellings in various countries have been collected by AIVC, Limb (1994) and is given in table 5.2. In the table is given values in as few units as possible, which means that the standards are not quoted directly. The units are given for **supply air** to a whole building, a living room, a bedroom; and for **exhaust air** from the kitchen, bath+WC, and WC. An exception from the SI unit has been made by dm^3/s replaced with l/s

Table 5.2 Ventilation rates. Standards, Limb (1994)

Country	**Supply air**			**Exhaust air**		
	Whole Building	**Living room**	**Bedroom**	**Kitchen**	**Bath + WC**	**WC**
Belgium NBNB 62-003	0.7-1.0 h^{-1}. 5.5 - 8 l/s,p		1.0 l/s,m^2	50-75 m^3/h	14 l/s	7 l/s
Canada (CSA F3261-M1989 ASHRAE 62-1989)	>0.3 h^{-1} 5 l/s,p			50 l/s (i) 30 l/s (c)	25 l/s (i) 15 l/s (c)	
Denmark (DS 418)		0.4 - 0.6 h^{-1}		0.7 h^{-1}	0.7 h^{-1}	
Finland (NBC-D2)		0.5 l/s,m^2	4.0 l/s,p 0.7 l/s,m^2	20 l/s	15 l/s	
France (Arrêté 24.03.82)				20-135 m^3/h	15-30 m^3/h	15-30 m^3/h
Germany (DIN 18017, DIN 1946, VDI 2088)		min 60-120 m^3/h max 60-180 m^3/h		min 40 m^3/h max 60 m^3/h	min 40 m^3/h max 60 m^3/h	min 20 m^3/h max 30 m^3/h
Italy (MD 05.07.75)	0.35-0.5 h^{-1}	4.2 l/s,p		1.0 h^{-1}	1.0-2.0 h^{-1}	
Japan						
Netherlands (NEN 1087)		1.0 l/s,m^2	1.0 l/s,m^2	21 l/s	14 l/s	7 l/s
New Zealand (ASHRAE 62-1989)	0.35 1) >7.5			50 l/s (i) 2) 12 l/s (c)	25 l/s (i) 2) 10 l/s (c)	
Norway (NBC 47-1987)		Openable area > 100 cm^2	Openable area > 100 cm^2	60 m^3/h mech or 150 cm^2 duct	60m^3/h mech or 150 cm^2 duct	40m^3/h mrch or 100 cm^2 duct
Sweden (BFS 1988:18-4:1)	>0.35 l/s,m^2	>0.35 l/s,m^2	4 l/s,p	10 l/s + cooker hood	10 l/s (c) if 2) else 10 l/s (c) and 30 l/s (i) or 15 l/s (c)	10 l/s
Switzerland (SIA 384/2, SIA 382/1)			80-120 m^3/h		30-60 m^3/h	
UK (BS 5720-1979, BS 5925-1991, Bldg reg Pt.F. CIBSE Guides A,B)	rec 12-18 l/s,p min 8-12 l/s,p	1) and tricle vents > 40 cm^2	1) and tricle vents >40 cm^2	60 l/s (i) mech 30 l/s cooker hood vents>40 cm^2	15 l/s (i)	1) or 3 h^{-1} (i)
USA (ASHRAE 62-1989)	0.35 >7.5			50 l/s (i) 12 l/s (c) or 2)	25 l/s (i)) 10 l/s (c) or 2)	

i=intermittent; c=continuous
1) openable windows required
2)or openable window

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6. Pollutant Loads

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The aims of this chapter are to give information of both normal pollutant levels in dwellings and to give the normal range of measured loads in the indoor environment. The target levels are given in case such levels are found. Together with this a brief discussion is made, to give the reasoning behind the agreed levels. In subchapter 6.6 and 6.7 is discussed the influence of the pressure difference for the case when pollutant(s) generated outside the dwelling is/are introduced/sucked into the main living area. The pollutants that can be harmful or cause problems indoors are radon, carbon monoxide (CO), landfill spillage, and moisture from crawl space. The influence of the pressure difference on the combustion is also discussed.

The pollutant loads indoors are depending on the emission from various sources. Those can be divided into:

1. Constant indoor emissions ("constant" means constant more than a few days).
2. Variable indoor emissions.
3. Emissions from sources outside the dwelling.

The emissions discussed here can give problems directly or are used as tracer gases or warning signals, that non-acceptable indoor air quality (IAQ) may be the result. To check the IAQ and thus the quality of the dwelling and of the ventilation system, it is important to identify those sources which can be controlled within the dwelling and its ventilation system.

In table 6.1 is shown a number of influencing factors on the IAQ and the possibility of influencing them by the residents or in the designing and/or construction phase. The pollutants dealt with in this chapter are moisture, volatile organic compounds (VOC), particles, bioeffluents with its tracergas CO_2, NO_x, CO, and radon.

A dwelling has a number of built in qualities influencing the IAQ that are given, when constructed or refurbished, . A number of these factors are pollutant sources. The result can be influenced by a number of factors e.g. application method of material, design of the dwelling, quality of the performance, ventilation system and components, heating systems, thermal insulation and airtightness. The most influencing factor at the design and construction phase are the material selection and the application method, and if open combustion appliances are to be used.

Residents´ behaviour can constitute a large range of emission depending on voluntary choices. There are unavoidable emissions, that are a matter of metabolism. Those are moisture, CO_2, and bioeffluents (body odour). Other emissions are connected with our well-being and high standard. The sources can be limited by the residents´ habits, but some sources are inevitably linked to the living and those are cooking, body and clothes washing, and cleaning the dwelling.

Emission sources outside the dwelling are pollutant in the ambient air from the traffic and the industry. But the sources can also be radon from the ground or landfill spillage. Of importance is also if a garage has direct access to the dwelling giving a risk for CO to seep into the living space. Most of those problems occur if there is a pressure difference.

Table 6.1 Influencing factors on the indoor air quality (IAQ)

Factor	**Influenced by**		
	Design, construction	Residents	Pollutant
"Constant" emissions			
• building materials	x		VOC (Volatile Organic Compounds)
• crawl space	x		Radon, landspill. moisture
• construction and details	x	x	Moisture, CO, NO_x
• ventilation supply	x		VOC, particles, NO_x, CO
Variable emissions			
• heating system	x	x	NO_x, CO
• unvented furnace	x	x	NO_x, CO
• domestic hot water heater 1)2)	x	x	NO_x, CO
• fireplace		x	CO, particles, VOC
• stove 1)	x	x	NO_x, particles, smell
• surface covering material	x	x	VOC
• furniture		x	VOC
• number of residents	x	x	CO_2, moisture, bioeffluent
• showering, washing etc.		x	Moisture
• animals			CO_2, moisture, bioeffluent
• hobby articles		x	VOC
• cleaning products		x	VOC, moisture
• cosmetics, perfume, deodorants	x	x	VOC
• tobacco smoke		x	Particles, VOC
1)if gas fired, 2)if vented no pollutant			

6.1 Moisture

The moisture climate indoors is discussed here assuming, that no water is introduced into the dwelling as a result of bad construction or leakage in the envelope. The water vapour content in the indoor air is described by the following sources:

- Constant emissions from pot plants. The habits are of cultural character.
- Number of residents.
- Resident´s metabolism.
- Activity related water vapour emission: showering, cooking, washing and drying clothes, dish washing, water-cleaning floors
- Water vapour content in the outdoor air supply

The water vapour gives the relative humidity (RH) that is depending on the indoor temperature. RH is the most used way to measure and report the moisture situation indoors. The survey made in Sweden, see Norlén, Andersson (1993), reports the average RH-value for single family houses is to be 38 % and for flats 32 %. Depending on location in the country, ventilation system, construction year the RH may vary. If the value is recalculated taking into account the indoor temperatures the water vapour content is 5.9 g/kg air in single family houses and 5.4 g/kg air in flats.

Depending on the construction and the climate there is a greater or smaller risk of condensation in the envelope and on the cold interior surfaces. In the long term perspective the condensation might deteriorate the construction because of mould growth and rot, thus causing oversensitive reactions and higher energy use. The oversensitive reaction can also be the case, if the water vapour content is high enough to start the growth of mould on surfaces and of house dust mites.

The comfort criteria to be meet with the purpose to firstly have good comfort and secondly acceptable comfort has been investigated by many researchers during a long time. The criteria are usually expressed as RH. Most results indicate, that the human being is not very sensitive to RH. It is the side effects and other influencing factors people are making complaints on, when feeling dryness. Such factors are high content of formaldehyde, particles, and dust. When tobacco smoking is present an extremely high particle level is generated resulting in complaints on dry air.

There are three factors to be met, when deciding the influences of the RH. Those are comfort criteria for the human being not feeling dryness, mould growth on surfaces, and the growth of house dust mites.

Metabolic generated moisture
Moisture is always generated by the residents as a function of the metabolism. The water vapour generation is depending on the indoor temperature. However, here is assumed that the resident is in comfort regulated by the clothes (clo-value). The equation is given below, see Riberon, Millet (1991).

$$\mathbf{P=16.1 \bullet (M^2+0.4M) \bullet A}$$ ①

where
P water vapour g/h
M metabolic rate in met/m^2 skin surface
A body area calculated by $A=0.202 \bullet m^{0.425} \bullet l^{0.725}$ with m mass [kg]; l length [m].
For an adult with a surface area of 1.8 m^2 the water vapour generation is

$$\mathbf{P=29 \bullet (M^2+0.4M).}$$ ②

Comfort
The comfort criteria is expressed by Leusden-Freymark, for sitting persons with normal clothing and air velocity not exceeding 0.2 m/s:
Acceptable level 20 - 90 % RH for 20 - 26 °C.
Comfort level also taking into account static electricity 35 - 70 % RH for 19 - 22 °C.

The comfort criteria expressed by DANVAK:
Comfort interval for 30 - 70 % RH

Mould growth
Mould are growing on surfaces and can start at RH below the dew point. The growth starts at colder places such as cold bridges and at 75 - 80 % RH locally measured, Annex 14 (1991). The duration of the RH is depending on the material, temperature and if the RH is exceeded frequently. Normally the mould is prevented from growing if the RH is kept below 75 % as a weekly average level.

House dust mites
House dust mites can cause oversensitive reactions and allergy amongst people. The growth have been studied and it had been found, that house dust mites can not survive when the water vapour content is below 7 g/kg air as monthly average, ref. Andersen, Korsgaard (1984). If the indoor temperature is 21 °C equal to the average in Swedish single family houses it gives a RH=45 %, and for flats with the average temperature of 22 °C a RH=42 %. A general

recommendation is to have at least one month with the water vapour content below 7 g/kg dry air. The optimum conditions is 25°C and RH of 70-80 %, ref.Biological Particles (1993), and should always be avoided

RH indoors in order to avoid comfort problems
If all the above is to be kept the RH will have to be kept within a narrow span. This can only be met by a fully air conditioned system with humidifier. A target value for the lower RH values is 30 % but in cold regions also 20 % is accepted. The higher value can be selected in order to have at least a month with a water vapour content below 7 g/kg dry air thus avoiding house dust mites growing. This can be achieved during the coldest month when it usually is slightly colder indoors also. To avoid a too high growth of house dust mites it is recommended to be well below 55 % RH.

6.2 Volatile Organic Compounds (VOC)

Pollutants that always are present in the indoor environment are the volatile organic compounds (VOC). Some of these are depending of the resident´s behaviour. Others are originating from the building fabric with the emission decreasing rapidly immediately after having been installed and after a while more slowly. The frequent use of cleaning compounds (detergents, cleaning fluid, polishing, solvent, soap, etc.) can give as a result an increased VOC level. A use of less time consuming cleaning methods may lead to a higher level, if aerosol agents will become more common. This trend can lead to the need of window airing more frequent when cleaning indoors.

The long term variation of VOC is depending of decoration of the dwelling e.g. new carpets, wallpapering, painting. The VOC-level is also increased, when the dwelling gets new furniture. Even emissions from our food can give detectable fractions. We can also very easy detect pesticides in clothes originating from the cotton. In a similar way remaining parts of the detergents can give VOC emission detectable. Water will usually also increase the emission of VOC.

A great problem is to judge whether a VOC emission is originating from an extraordinary source like decorating the walls or floors, or from frequently occurring sources. It can also be discussed how some of those frequently sources should be treated. Frequently sources are those, that may occur every day (smoking, eating, cooking) and weekly (cleaning compounds). Emissions that are less frequent can be dealt with as special cases with extra ordinary treatment.

The development of the measurement technique makes it possible to detect even fractions of a single compound. Also normal use and habits may result in peaks in case of monitoring the indoor environment. Even oranges eaten indoors gives peaks, that may be interpreted as increased emissions of the irritating compound limonen. If not eaten there might not be any peak at all. But it can also be emitted from perfume in cleaning materials. This illustrates both the measurement technique and the interpretation of the results giving that the residents´ behaviour is of great importance particularly in a very low emitting building, Jonson et al (1993). When comparing data it must be observed that errors are to be found both in the sampling technique and in the analysing methods.

Comparisons between four passive sampling methods gave that Tenax-GR and Tenax-TA showed equal values, although Tenax-GR partially caused a decomposition of β-pinene.

Carbotrap gave significant higher values than the two Tenax methods and can not be recommended as Carbotrap is completely decomposing both α- and β-pinene. The method Chromosorb 106 is impossible to use at the low levels usually at hand in dwellings, ref. Cao, Hewitt (1993).

A comparison between Tenax and Carbotrap was made by De Bortoli et al (1992) and showed, that after reconditioning the remaining compounds were twice as high in the Carbotrap samplers. However when exposed for compounds they appeared to be adequate for sampling.

Three methods for continuous monitoring VOC were compared by Bunding Lee et al (1993). The result gave only qualitative results in terms of that flame ionization detector (FID) and non-dispersive infrared (NDIR) can detect human activities and VOC-levels and variation with time. FID was the only one that could detect the complex emission from cooking. The third detector Fourier transform infrared (FTIR) was only usable when detecting single compounds and identifying unsuspected sources, but was not useful for measuring the mixture of compounds.

The two most used methods for the determination of VOC are FID and mass spectrometric (MS). Those are used both for single compounds and the total sum. After measurements in 14 locations it was found that the FID-method gave only 81 % of the values according to the MS-method. However, it should be noted that in some cases higher values were measured by the FID- than by the MS-method. The reason is that the FID-method is underestimating the heteroatoms, Cottica et al (1993). Relation close to that has also been reported by Mølhave, Nielsen (1992).

The conclusion is that it is important to use proper methods and keep to the same during monitoring periods. Comparisons of results can also be of some problems as methods are not giving equal results.

There is a continuous supply of VOC in dwellings by the use of cleaning materials on the surfaces, detergents for dishing, and clothes washing as well as VOC emitted from products for personal hygiene e.g. deodorants, hair spray, shower gel etc. When a dwelling is new or refurbished the emission from the newly installed material is high, when moving in. The decrease takes shorter or longer time depending on the selection of material with respect to emitting power, adsorption possibility, the ventilation rate, and supply from the residents. The yearly production in Japan of 27 000 t of para-dichlorobenzene is an example of how much we may use in our dwellings as this compound is used in deodorants and mothballs, ref. Matsumura et al (1993). If nothing is exported and we use the deodorant frequency given in the Swedish study, see chapter 7 figure 7.25, together with the number of dwellings in Japan, with a volume of 300 m^3/dwelling, we get that every day is supplied to the dwelling 10 mg/m^3 of para-dichlorobenzene. This level is 1/30 of the hygienic maximum level for 15 min exposition in workplaces (AFS 1990:13). The VOC pattern during a day varies also and can not be measured by a passive sampler. Studies indicate that the variation can be in the ratio 1:5, Crump and Madany (1993). If this study also is to be taken into account the level might be on the hygienic limits in work places that might have resulted in a demand for either local exhaust, increased ventilation rate or limitation of the usage.

In some countries comprehensive surveys have been made. To get an indication on frequent levels of VOC a collection of the results from such surveys is of a good guidance. Together with smaller studies with the aim of monitoring the levels in new or just refurbished dwellings a good picture of the VOC-levels, that the ventilation system has to deal with. The two modes, that are forming the base load or the needed ventilation rate during the building life cycle, are the refurbished and the average during most of the time.

In table 6.2 is given average values from surveys in Sweden, Canada, UK, Germany, and Switzerland. In the Swiss survey only new or just refurbished flats were measured, while in all the other representative dwellings were selected.

Table 6.2 Average concentration of VOC, 95 % confidence intervals μ g/m^3

Factor	**Sweden**		**Canada**	**UK**	**Germany**	**Switzerland**
	Single family houses	**Flats**	**Single family houses**	**All bldg types**	**Single family houses**	**New or refurbished flats**
References, voc #	*21, moist 4*	*21,moist 4*	*18*	*16, 17*	*19*	*20*
Number of houses	101	92	754	120	180	22
Sampling and analyse method	Tenax, MS	Tenax, MS	OVM3500 ,MS	Tenax, FID	homemade FID	
All houses	470 ± 180[1]	310 ± 40	winter 8 spring 10 summer 4 autumn 11	110	90 45 - 886	13 000 700 - 35 600
Constructed -1975	490 ± 230	320 ± 40				
1976-1988	380 ± 50	270 ± 50			before 1986	new
Ventilation Natural	500	330			x	x
Mechanical	340	280				
Particle board Present	430	320				
Absent	510	310				
Wall to wall carpeting Present	550	-				
Absent	380	290				

[1] If the high value of 5100 is excluded the average is lowered to 380

The problems with all the surveys are, that the result is given in an average way not distinguishing between factors that might influence the emission. In the Swedish study the results have been analysed with regard to some of the factors, that could have influenced the levels, but the major factors have not been possible to check or not yet analysed.

As can be seen the levels varies considerably. In Sweden the average level is in the range 300 - 500 $\mu g/m^3$ and in Germany and UK about half of that if only corrected from FID to MS. But the levels in Canada is a magnitude less or about 10 $\mu g/m^3$. The example from Switzerland shows that with a very low ventilation rate, 0.1 h-1, the decrease takes a long time. After 5 months the level in one flat had decreased from 28 500 $\mu g/m^3$ to 900 $\mu g/m^3$. Outdoor level was in average 250 $\mu g/m^3$.

Today the experts on VOC have not found proof that the total VOC measurement is a means of assessing health effects. It has been proposed by Seifert (1990) to use total VOC values with care because the methods are not comparable and also that VOC total is not a sum of the individual compounds. Restrictions are also recommended as the total VOC is not specified in terms of an analytical method, Seifert (1991). Nevertheless a level of 300 $\mu g/m^3$ is mentioned as a target level. But this is the sum of compounds including maxima for individual groups of compounds like alkanes, aromatic hydrocarbons, terpenes, halo carbons, esters, aldehydes and ketones, and all the others.

Wallace et al (1991) reported, that for several US cities, the VOC level indoors in 198 dwellings were found to have a mean value of 1000 $\mu g/m^3$ and a median value of 700 $\mu g/m^3$. It should be noted that the outdoor concentration was very high or half of the indoor value.

Some of the difficulties and questions, that occur when comparing and analysing VOC surveys and detailed measurements are given below.

- When the measurement is made we usually don't know the time since renovation and since moved in.
- Number of residents and their age.
- Short description of the interior that can adsorb VOC such as wall to wall carpets and many bookshelves full of books.
- Ventilation systems.
- Measurement of the air change rate.
- The season of the measurement.
- Some hints of the window airing pattern.
- Indoor temperatures.
- The sampling and analysing methods.
- Are measurements comparable.
- The water vapour content (some researchers can not find any correlation).
- Dwellings with smokers and non-smokers are not split up in two categories.
- Usually the result is given in total VOC (also TVOC) which is a result given in toluene equivalents. This is often a value lower than the sum of the individual compounds.

The usual definition of VOC is depending on the boiling point. In this document is used the definition that VOC is an organic matter that evaporates pollutants at any rate, Månsson, Svennberg (1993).

6.3 Particles

In modern dwellings with a leakage area like in Sweden or Canada it is not likely than more than a fraction originates from outdoors. It is less than 10 % of coarse particles and maximum 50 % of fine particles, that can reach the indoor of the dwelling as long as we keep to air change rate below 1.0 h^{-1}.

In a survey carried out in USA in the beginning of the 1980s about 3/4 of the people reported to be exposed to tobacco smoke in their homes. It was also reported that about 1/3 of the adults were smoking.

A common level in homes with only non-smokers can be estimated to be 0.02 mg/m^3 for fine particles in most cities. However, smaller studies in Europe have reported higher levels at low air change rates, but it is not always known, if the particles are respirable or total. Another difference between USA and Europe is the floor covering material. Exceptions may be the more polluted areas like greater Los Angeles, which has a doubled level. The studies # 37 and # 38, see table 6.3, indicate a lower level in colder regions. However, those studies were in more rural situated places. On the other hand the studies also indicated a slightly lower level during winter compared to the summer level.

In homes where smoking is taking place, the levels can vary within a very large range. Probably the range is indicating, that there is a lack of information of the air change rates. For homes with <10 cigs/d the reported levels are in the range from 0.03 mg/m^3 to 0.2 mg/m^3. For homes with heavy smoking habits or >10 cigs/d the level can be at 0.5 mg/m^3. Peaks above 0.7 mg/m^3 has not been noted.

Seifert (1991) summarises the particle concentration to be in the same range as above for non-smokers´ homes. Maybe he has chosen a value slightly higher because most of the studies reported have levels well below 0.020 mg/m^3. Seifert gives for suspended particles the average value of 0.020 - 0.050 mg/m^3 and peak values of 0.100 - 0.200 mg/m^3.

It must be kept in mind that even in homes without any smoker the short time peaks can be higher than the average levels here reported. These peaks can be the more severe conditions to be dealt with. For smokers´ homes the level can not be fixed because of the strong relation between the level and the number of cigarettes smoked. However Seifert has given the average level of 0.040 - 0.080 mg/m^3 and a peak value range of 0.50 - 1.00 mg/m^3. No figures on peak values are given in the references, which gives that more measurements must be done before the peak values can be fixed.

Table 6.3 is a summary of all measurements reported in table 6.4 and discussions found in the references for the particle concentrations in average homes. Some standards are also given.

Table 6.3 Particle levels in homes, average and peak values. Standards

	Average mg/m^3		Peak mg/m^3
	Normal areas	Polluted areas	
Non-smokers	0.020	0.050	0.1 - 0.2
Smokers	0.10 - 0.20	-	<1.0
Standards			
Netherlands	0.070		
USA federal	0.150		
USA California	0.050		

Biological particles that can be of interest in dwellings are: House dust mites (see moisture 6.1), Dunder from furred animals, fungi, bacteria, legionella. According to the ref. Biological Particles in Indoor Environments, these biological particles can be of significance for indoor air quality. In this annex we consider that dander from pets are treated by vaccum cleaning. Legionella is nearly not any problem connected with ventilation systems in dwellings, as humidifying very seldom is the case. Fungi and bacteria is always at hand indoors. There are also 100 000 known species of fungi. They are usually growing at temperatures between 10 and 35°C. There is a strong relationship with the RH. Measured values in homes can be from <10 CFU/m^3 to 20 000 CFU/m^3 or even higher in exceptional cases. If no mould is present in the room a usual level is below 300 CFU/m^3 and a magnitude higher when present. A level <200 CFU/m^3 is considered to be a low value. Bacteria in dwellings are generally low. The number can go from 50-20 000 bacteria/m^3. Average values seems to be about 500 even if the material is not large and there is a seasonal variation that can be a magnitude. A low value is considered to be below 500 bacteria/m^3. For fungi and bacteria see also ref. Biological Particles in Indoor Environments (1993). [CFU=Colony Forming Unit]

Table 6.4 Measured particle data in dwellings given in various references

No	Author(s)	Ref	Particle		Smoking			Comments
			mg/m^3	Numbers	Unknown	Yes	No	
1	Girman, et al	IA´81	11000			x		1 cig sidestream
2	Tosteson et al	IA´81	0.032				x	
3	Lebowitz et al	IA´81	5.7 - 55.8		x			Total suspended particles (TSP)
4	Lebowitz et al	IA´81	0 - 28.8					Respirable
5	Silverman et al	IA´81	0.070		x			
6	Hollowell et al	IA´81	0.01 - 0.05			x	x	Total. 5 houses
7	Hollowell et al	IA´81	0.006 - 0.03			x	x	Fine. 5 houses
8	Hollowell et al	IA´81	0.009/0.031				x	Fine/Total. 3 houses
9	Hollowell et al	IA´81	0.031/0.062			x		Fine/Total. 3 houses
10	Spengler	IA´81	0.063/0.131			x		smokers amongst 733 persons in 2 cities
11	Spengler	IA´81	0.04/0.026				x	non-smokers amongst 733 persons in 2 cities
12	Offerman et al	IA´84 vol 1	10 mg/cig			x		side stream emission
13	Green	IA´84 vol 5	0.04/0.15			x	x	no smoking/smoking
14	Ueno	IA´84 vol 5	0.09 - 1.14	$5*10^7$-$3*10^{10}$		x		summary from other studies
15	Ueno	IA´84 vol 5	0.02 - 0.06				x	summary from other studies
16	De Bortoli et al	IA´84 vol 4	0.080		x			respirable particles, 14 homes
17	Sextron et al	IA´84 vol 4	0.400	10^{11} - $2*10^{11}$		x		test chamber 1 cig
18	Hoffmann et al	IA´84 vol 2	4.600			x		test chamber 16 m^3 4 cigs, 6 h^{-1}
19	Krause et al	IA´87 vol 1	5.3 mg/m^2,day			x	x	2744 homes in Germany
20	Quackenboss	IA´87 vol 1	<0.03	PM2.5/PM10			x	1390 homes in USA, Arkansas
21	Quackenboss	IA´87 vol 1	0.03/0.05	PM2.5/PM10		x		1-10 cigs/d 1390 homes in USA, Arkansas
22	Quackenboss	IA´87 vol 1	0.06/0.08	PM2.5/PM10		x		11-20 cigs/d 1390 homes in USA, Arkansas
23	Quackenboss	IA´87 vol 1	>0.08	PM2.5/PM10		x		>20 cigs/d 1390 homes in USA, Arkansas
24	Kulmala et al	IA´87 vol 1	0.016		x			dwellings, offices, downtown and suburban
25	Lebret et al	IA´87 vol 1	0.0221				x	70 homes in USA, fine particles
26	Lebret et al	IA´87 vol 1	0.054			x		150 homes in USA, fine particles
27	Revsbech et al	IA´87 vol 2	0.091				x	11 homes in Denmark 0.23 h^{-1}
28	Revsbech et al	IA´87 vol 2	0.169/0.475			x		<10cigs/10 - cigs daily. 33 homes in DK 0.23 h^{-1}
29	Stolwijk	IA´87 vol 4	0.080		x			calc concl daily intake 1.080 RSP
30	Perritt et al	IA´90 vol 2	0.018				x	162 homes in USA, geo mean
31	Perritt et al	IA´90 vol 2	0.061			x		62 homes in USA, geo mean
32	Lebret et al	IA´90 vol 2	0.030				x	non-smokers
33	Lebret et al	IA´90 vol 2	0.060		x			in all 260 homes

continued Table 6.4 Measured data in dwellings given in various references

No	**Author(s)**	**Ref**	**Particle**		**Smoking**			**Comments**
			mg/m^3	Numbers	Unknown	Yes	No	
34	Leaderer et al	IA´90 vol 2	0.015				x	75 homes in USA fine particles
35	Leaderer et al	IA´90 vol 2	0.042			x		141 homes in USA fine particles
36	van der Wal	IA´90 vol 2	0.050 - 0.195			x		10 homes in Netherlands peak, mech and natural vent
37	Spengler et al	IA´90 vol 2	0.014 - 0.030				x	250 homes USA, summer & winter, PM2.5
38	Spengler et al	IA´90 vol 2	0.025 - 0.044			x		280 homes USA, summer and winter, PM2.5
39	van Dongen	IA´90 vol 4	0.030				x	7l/p,s 57 homes, NL,balanced vent
40	van Dongen	IA´90 vol 4	0.100			x		7l/p,s 57 homes, NL,balanced vent
41	Tobin	IA´93 vol 1		34*10^6	x			60 homes with allergic children, Sweden
42	Nakai et al	IA´93 vol 3	0.035/0.065			x	x	spring, summer/autumn, 200 homes in Japan
43	Özkaynak et al	IA´93 vol 3	0.095 - 0.063 0.048 - 0.036	PM10 PM2.5		x	x	day - night. 170 homes in USA, Cal. vent: 0.15-4.7 h^{-1}; mean: day 1.24h^{-1}, night 1.24h^{-1}
44	Özkaynak et al	IA´93 vol 3	0.092/0.128 0.045/0.068	PM10 PM2.5		x	x	non-smoker/smoker } leaky building, non-smoker/smoker } heavy traffic, smog
45	Reponen et al	IA´87 vol 1	0.38		x			18 dwellings
46	Rönnberg et al	IA´90 vol 2	0.01 - 0.02 mg		x			251 dwellings
47	Månsson	DCV	0.050					normal levels in homes
48	Månsson	DCV	0.150					at vacuum cleaning
49	Brunekreef	Env Health	0.026- 0.570/0.120		x			range/geometric mean, 26 homes in NL

6.4 Bioeffluents and CO_2

The definition of bioeffluents is, that it is a mixture of particles and gases originating from the metabolism of human beings. In the metabolic process food is converted into heat, CO_2, water vapour, and waste products. The waste products give most of the bioeffluents such as sweat and other skin secretions; in addition respiration, mouth, stomach, and intestine. Also included are substances such as perfumes and deodorants used to "cover" the original bioeffluents.

Often all these "products" from the metabolism is called odour. The best tracer gas for bioeffluents is CO_2. According to DANVAK (1988) the tracer gas for bioeffluents can be calculated by:

$$\mathbf{q_c = 17M = 0.162*P \ [l/h]} \qquad ③$$

where

q_c is the CO_2 production l/h

M is the metabolism in **met** at the activity level for one person

P is the metabolism in **W** at the activity level for one person

Other values are given instead of the constant 17 l/h. Riberon and Millet (1991), see 6.5 "moisture", give the factor 18 l/h and ASHRAE 19 l/h.

The heat and CO_2 expired is often measured when resting. Practical measurements have shown that children awake, at least from the age of 6 years, have an activity level that is higher than expected. The result is that the CO_2 expired may be the same for adults at office work and children awake and active. A possible level that might result in an unacceptable perceived odour level can be calculated. However, the compounds giving the bioeffluent is chemical unstable and is rapidly decomposed into less odorous compounds. This is usually the case as the odour vanish faster than a result of the dilution, Bresle (1986).

Many attempts have been made to correlate the odour annoyance with the CO_2 -level. The tests have usually been conducted at constant supply and exhaust air in order to control the situation. All those tests have been done by panels or test persons, that should judge the quality of the air. Two different situations are always at hand. Those two are:

1. Visitor(s) entering a room with occupants. Visitors are judging the air quality.
2. Occupants are judging the air quality in the room they are staying in.

In dwellings almost always the 2nd situation is at hand as the occupants are residents and are in the dwelling for a long time. If the air quality is to be acceptable for visitors, the situation might not occur every day. When the residents are outdoors nobody is present and the odour can be decreased.

It is often found that the visitors are satisfied with the air if the CO_2 -concentration is below 800 - 1000 ppm. But if the occupants are to judge the air quality there is nearly no difference if the CO_2 - concentration is 800 ppm or 1500 ppm, Berg-Munch et al (1986), Månsson and Svennberg (1993). This discussion leads to compare the situation in a dwelling with the judgement of the occupants.

I should be noted that CO_2 is a tracer gas for bioeffluents and human activity level in combination with the ventilation rate at hand. At ordinary and also achievable levels in dwellings CO_2 is totally harmless. As CO_2 is the gas that regulates the respiration frequency the wakeness might be slightly increased. Air raid shelters are constructed to allow the level of 20 000 ppm, which is the medical limit.

6.5 NO_x

The pollutant NO_x originates from all combustion processes. As a tracer usually is used NO_2. In dwellings the pollutant can originate from unvented gasheaters, stove (range), oven, and domestic hot water heater. Modern appliances usually have a pilot flame. This results in a constant NO_x emission even if it is at a low level. However, at this low level it can not be expected that a cooker hood is run.

Large monitoring and epidemiological projects have been finalised the last few years. Results are to be implemented in standards and codes and it is expected that the levels are to be brought down. In the future it is foreseen that more vented appliances are installed. Together with an increased number of installed cooker hoods, better outdoor conditions and the use of outdoor vented appliances the NO_x levels can be expected to decrease during the next decade as those appliances don't last for more than 15 - 20 years there is a need for replacement .

If we assume that the heating appliances are vented the pollutant level of NO_x can be said to follow the cooking habit if a gas stove is used. With a separate oven the NO_x can usually not be exhausted by a cooker hood thus giving an extra high level. Sensitive individuals have been observed to feel annoyance at 100 $\mu g/m^3$ NO_2. Measured values have been reported as high as 800 $\mu g/m^3$ NO_2, weekly average in kitchens. Peak values during cooking can be up at 2200 $\mu g/m^3$ NO_2 (even higher is reported during some minutes). However, it should be noted that the level originating from traffic at can be in the range of 5 - 75 $\mu g/m^3$ NO_2 measured in homes without any natural gas appliance, with mean values often at 20 $\mu g/m^3$ NO_2. As the energy used for domestic hot water can be up to 10 times the energy used for cooking the NO_2 level is consequently much higher.

As a guidance the standards in dwellings are 60 $\mu g/m^3$ in Japan, 100 $\mu g/m^3$ in USA and Canada, as annual average. In The Netherlands it is 300 $\mu g/m^3$ for 24 h average. WHO has a maximum of 400 $\mu g/m^3$ and a 24 h maximum of 150 $\mu g/m^3$

6.6 Interaction with Combustion Appliances

Combustion appliances require air in order to support combustion of fuel and with which to dilute the waste gases and stabilise the flow in the flue. This air comes either from the room or space in which the appliance is sited or direct from outside. Similarly the waste combustion gases can be expelled either into the room or to outside. These are described briefly below. This section concentrates on open-flued appliances and in particular their interaction with mechanical extract ventilation.

Unvented appliances

These appliances take their combustion air from the room and expel the combustion products back into the room. This includes gas cookers, unvented domestic hot water appliances, and some portable heaters (kerosene or gas).

Room sealed and balanced-flued appliances

The air for combustion and dilution is drawn from outside and the waste combustion products exhausted to outside again without any contact with the air in the room or space in which these appliances are sited. They should therefore have no influence on the ventilation of this room or space, nor be influenced by any ventilation measures in the room.

Open-flued combustion appliances

Open-flued appliances draw combustion and dilution air from the space in which they are sited and expel the waste gases to outside via a flue or chimney. If the supply of air is limited, then the fuel may not burn completely or the combustion products may spill from the appliance. If the space around the appliance is depressurised, then this limits the air available to the appliance and can lead to spillage. That is the combustion gases emerge into the room rather than flowing safely away up the flue.

Mechanical Extract Ventilation

Air extract fans tend to create depressurisation in the room in which they are installed and to a lesser extent in the rest of the dwelling. This can cause spillage of combustion products from open-flued appliances by restricting the amount of air available to the appliance or by reversing the flow down the flue.

Experimentation

Recent research has been carried out principally in Canada and in the UK to investigate the interaction of open-flued combustion appliances with mechanical extract ventilation. The aim being to discover the pressure differences which would cause different types of combustion appliance to spill. The possibility of domestic extract fans creating this pressure difference in the same room as a combustion appliance to spill. The possibility of domestic extract fans creating this pressure difference in the same room as a combustion appliance or in an adjacent room must also be investigated.

Pressure Difference Which Will Cause Spillage

Experimentation with open-flued natural draught gas boilers has shown that spillage can occur at levels of room depressurisation as low as 2 Pa. In calm conditions (where the wind does not aid the flow up the flue) and with a cold flue. An internal/external pressure difference of 4 or 5 Pa will commonly be enough to cause spillage. With a hot flue the internal/external pressure difference which causes spillage is in the region of 10 to 20 Pa or more depending on appliance type and size and flue dimensions.

Different types of heating appliance will spill at different levels of room depressurisation. For example some oil boilers with pressure-jet burners have an air intake fan that can withstand pressure differences in excess of 100 Pa although at high pressure differences the level of combustion efficiency is affected. In general fan-assisted open-flued appliances will be able to withstand higher levels of internal/external pressure difference than natural draught appliances.

Factors which affect the pressure difference at which spillage will occur include: wind speed; type of flue; size of combustion air supply device; and internal/external temperature difference.

The rate of air extraction, which will cause this level of room depressurisation, depends upon a number of variables: room air-tightness; combustion air supply size; room volume; whether doors and windows are open or shut.

Spillage is generally less likely to occur with:

a fan with a lower air extraction rate;
a fan assisted appliance;
a taller flue;
a straight flue with no bends or offsets;
a heat retaining internal flue wall;
a well insulated flue;
the flue terminal in low pressure zone;
a well designed flue terminal;
a higher wind speed;
a greater internal/external temperature difference;
a less air-tight room;
a larger cross sectional area of air inlet;
the air inlet placed as low as practicable.

Not all of these can be changed if there is a problem with air spillage, although there should be some scope for adaptation.

The Practicality of Spillage Tests
A spillage test can be carried out when an extract fan is installed in the same dwelling as an open-flued combustion appliance and under different weather conditions a different result may be achieved. For example if there is a strong wind, then the wind will cause extra draught up the flue decreasing the possibility of spillage. If it is windy on the day of the test the appliance and fan may therefore pass a spillage test, which they might otherwise fail on a calm day, when there was not the extra wind induced draught up the flue. This presents a problem because for safety a spillage test should not be carried out when the wind speed is above a level which will affect the flue significantly. A maximum wind speed of 4 m/s is recommended. It is impractical to expect combustion appliance and extract fan installers to only do spillage tests on relatively calm days.

Alternative Ventilation Which will Not Cause Spillage
Possible alternatives which will not create negative internal pressures liable to cause spillage include: balanced mechanical ventilation; passive stack vent; house pressurising fan.

Other Causes of Spillage
Spillage of combustion products into the living space can be caused by other factors than mechanical extract ventilation. The most common cause (more common than extract ventilation) is due to a blocked, damaged or poorly maintained flue. Other causes include: inadequate ventilation provision so that the appliance cannot draw on the required air for combustion; badly maintained or damaged appliance; poor fit between appliance and flue; badly positioned or badly designed flue terminal. In other words, ventilation systems are not the chief cause of flue spillage problems.

With reference to the Dutch standard warning flaggs have to be rized for some combinations. If central ventilation exhaust fans are installed the heding appliances must have separate flue vent with a separate fluefan.

6.7 Interaction with Radon and Landfill Spillage

The purpose of this section is to look at the implications for domestic ventilation systems of the existence of Radon. The main methods of protection and remediation are reviewed and the interaction of radon remedial measures with the ventilation of dwellings is discussed. Landfill spillage may show similar pattern as radon and can be treated in the same way.

What is Radon

Radon is a gaseous radioactive element with three naturally-occurring isotopes, radon-219, radon-220 and radon-222. Only radon-220 and radon-222 are of radiological consequence. Radon 222, commonly called radon, occurs in the uranium-238 decay series and is the more important of the two isotopes because of its longer half-life. The four immediate decay products of radon-222 have short half-lives. They are all radioactive isotopes of solid elements. The beta and gamma radiations may be ignored, since their contribution to both lung dose equivalent and effective dose equivalent are small compared to those from alpha radiation. Furthermore, the dose from the radon gas itself may be ignored, because much of the inhaled radon is exhaled and relatively few alpha particles are emitted by it within the body. Doses are therefore due predominantly to irradiation of the bronchial epithelium by alpha particles from the short-lived decay product of radon-222, the potential consequence of principal concern is the induction of lung cancer.

How Radon Enters a Dwelling

Radon is found in all soils in different amounts. Larger concentrations may occur in certain soil types and in building materials made from soils bearing high concentration. Therefore, radon will be found to a lower or higher content in all soil gases. When radon is released from the ground out of doors, it is rapidly dispersed in the atmosphere and concentrations are low. If radon enters a dwelling, either from the ground on which it is built or from the building materials, higher concentrations may occur because the dispersion is restricted; the ground, rather than building materials, is usually the dominant source. The generally higher temperature indoors and the effect of wind on a dwelling combine to reduce the pressure indoors relative to that in the ground. The pressure difference is usually small, a few pascals, but sufficient to induce a flow of soil gas containing radon into the dwelling if the ground is fairly permeable and if an easy path for flow into the dwelling exists. In dwellings with high concentrations of radon, such pressure driven flow, rather than concentration-driven diffusion, of radon is the dominant mechanism of influx. It should be stated however that the concentrations of radon are very small, of the order of 10^{-17} to 10^{-19}, and for practical purposes we are dealing with the flow of air.

6.7.1 Radon Protection and Remediation

The details of radon protection of new dwellings and remediation (mitigation) of existing dwellings differ from country to country depending on construction methods, which often differ quite substantially from one country to another.

Radon gets into a dwelling, due to the depressurisation of the dwelling. If we consider the flow of radon laden air there are a number of things which can be done.

1. The pressure gradient can be reversed by what is referred to in the US as a sub-slab depressurisation.
2. The floor may be sealed either by sealing cracks or with a membrane to reduce the flow of radon laden soil gas.

3. In the case of suspended floors the ventilation under the floor may be increased to dilute the concentration of radon entering the dwelling.
4. The pressure in the house may be increased again to reverse the pressure field across the floor.
5. Ventilation openings at ground floor level may be increased again to reduce the pressure gradient across the floor.

Sub-slab depressurisation

Where the method of construction makes it practicable this is the most effective method of radon remediation. In the UK reduction ratios of up to 175:1 (99.5 % reduction) have been achieved. Generally in both the US, the UK and Sweden depressurisation is achieved by making a small hole typically about 400 mm diameter underneath the house and connecting an exhaust fan to the hole. Other variants on this use a brick box (UK), and sub-soil drains (Sweden). The hole is known as a sump in the UK and a pit in the US. The sump is essentially a pressure device and typically pressure in the sump itself is of the order of about 200 pascals. A typical radon sump is illustrated in figure 6.1. Whilst under right circumstances sub-slab depressurisation can be highly effective, it does require a good concrete floor and permeable fill underneath for maximum effectiveness. Sub-slab depressurisation is suitable for new and existing dwellings.

Radon sumps can draw a substantial proportion of the suppiy air from the dwelling interior, indeed they are more effective the greater proportion of the air which is drawn down through the dwelling. This inevitably, however, leads to some degree of depressurisation and this can lead to the spillage of combustion products from open flued appliances, Welsh (1994) and Wiggers (1992). The solution to this problem has largely been in the use of direct combustion air from the outside. A further effect of drawing most of the air into the radon sump down through the house is to increase the air change rate of the house, typically with permeable fill or aggregate under the house the ventilation rate may be more than doubled. This may be undesirable both from a ventilation and an energy point of view. The solution may be to tighten the house.

Sealing

Sealing may consist of sealing of individual gaps and cracks in a floor or sealing a whole floor with a membrane (sealing of wooden floors in damp climates is not recommended as is can cause rotting of the timber). It is generally acknowledged that sealing is not very effective (50 % reduction ratio, although up to 90 % is claimed in the US) and it can be expensive. However, membranes are used in the UK and Sweden in new construction where the installation of a membrane is much less expensive. Sealing of large individual cracks or gaps, for example around service entries may be effective on their own or may be necessary in combination with other measures, e.g. sub-slab depressurisation.

Under floor ventilation

This method is of course only practicable with suspended floor, typically constructed of either concrete or wood. It is here that differences in construction between different countries are most apparent. The large crawl space of a US house particularly under the US Southern Building Code is very different from the under floor space, often 300 mm or less in depth, of a typical UK house. Also the ventilation requirements of, for example, the United States Southern Building Code for crawl spaces are an order of magnitude greater than those required by Building Regulation in the United Kingdom. Mechanical ventilation of under-floor spaces may be by supply or extract. Which is the most effective, probably depends on the relative air tightness of the floor but this is difficult to determine and may be a matter of trial and error. US practice seems to favour extract. Swedish practice supply. In the US both extract and supply have been used successfully. In Sweden crawl spaces have been ventilated

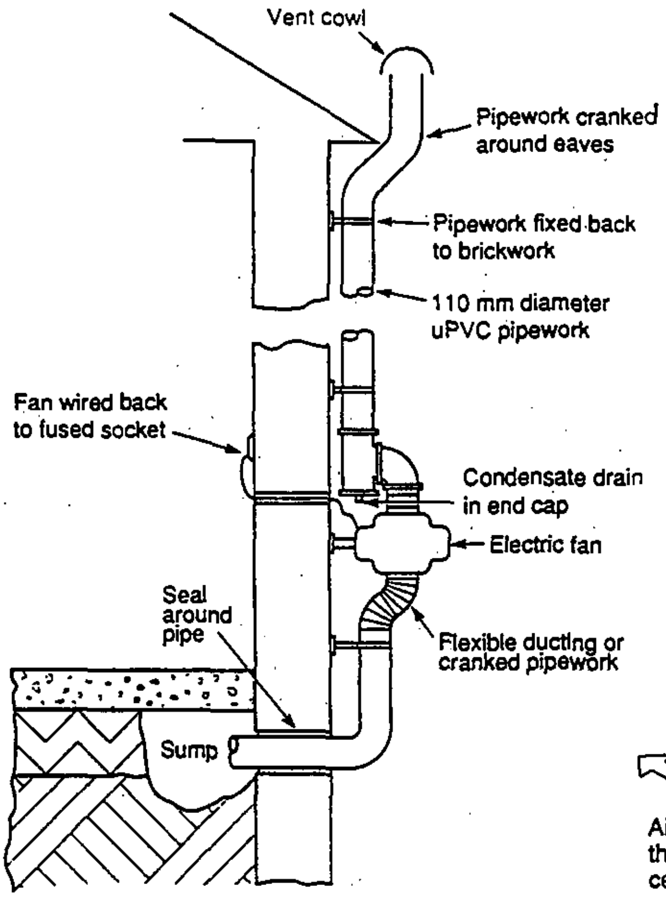

Figure 6.1 The externally excavated sump

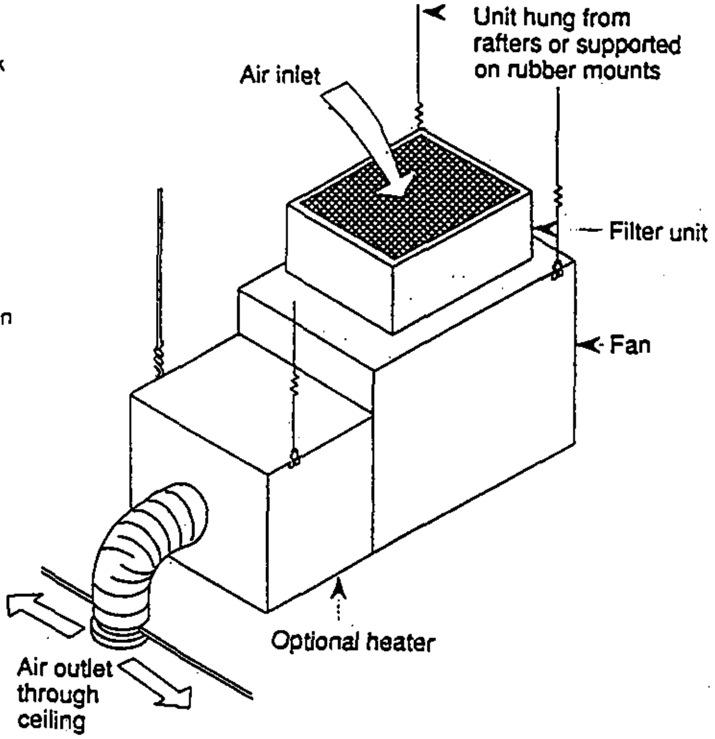

Figure 6.2 Positive pressurisation system

with indoor air together with sealing measures. The existence or otherwise of what in the UK is known as oversite concrete (a layer of concrete over the soil) is significant in the remediation of dwellings with suspended floors. Supply ventilation of the under-flow space may run a risk of pressurising that space and driving radon through leaks in the floor into the dwelling.

Positive Pressurisation

In the UK this is achieved by installing a small fan drawing air from the loft space see figure 6.2. This has the effect of slightly pressurising the house and also of increasing the ventilation rate. In the US and Sweden where mechanical ventilation systems are more common it is possible to use existing house ventilation systems, with or without additional fan(s). Essentially it is a matter of achieving balanced ventilation or a positive pressure. Sweden however does not favour the use of positive pressure because of the danger of interstitial condensation. A similar view has been taken in the UK Stephen (1994) notwithstanding the use of positive pressure fans. In the UK radon reduction ratios of about 3:1 (70 %) have been achieved. Up to 90 % for forced air is quoted in the US, Henschel (1988).

Ventilation

Increased ventilation might seem the obvious way to reduce radon concentrations, but extract ventilation increases depressurisation of the dwelling and thus increases the ingress of soil radon. In the UK mitigation at relatively low radon levels has been achieved by increasing low level natural ventilation, by the use of suitable ventilation openings (trickle vents) thus, reducing the pressure gradient across the floor. The reduction ratio has generally been less than 2:1 (50 %).

Some mention should probably be made of basements, particularly important in North America and cellars, common in certain areas of the UK. Natural ventilation has proved surprisingly effective in reducing radon levels in the rest of the house.Cavallo et al (1991)

Any mechanical extract ventilation system will increase the depressurisation of the dwelling and hence will increase the potential for radon ingress. If such a system or indeed a fan is used only intermittently this may not be too serious, but when systems are operated continuously the increase can be significant and generally will not be compensated by the increased ventilation rate. Solutions have been referred to, balanced ventilation in Sweden and positive pressure system in the US and the UK. Balanced supply and extract systems are neutral in respect of radon entry. They may have some preventive effect in that the radon concentration is reduced by dilution without depressurisation.

Radon and Flues and Chimneys

All flues and chimneys will tend to depressurise the dwelling, increasing the ingress of radon. In the UK it is recommended that unused flues and chimneys be blocked off with suitable provision made for ventilation to avoid condensation.

The Implications of Radon for the Ventilation of Dwellings in Radon-affected Areas

Any ventilation system or device which reduces pressure in a dwelling is undesirable in a radon-affected area. Thus all unbalanced extract devices, whether flues, fans, chimneys or whatever should not be used in radon-affected areas unless compensated by supply ventilation. Ventilation should be supply or balanced.

Sub-slab depressurisation, where practicable, is the most effective means of radon remediation. However, it may have the effect of depressurising the dwelling and thus causing the spillage of combustion products from open-flued appliances. A similar effect may also occur with extract from crawl spaces under suspended timber floors. In the US over 70 % of radon remediation (mitigation) is by sub-slab depressurisation. The implication is that open-flued appliances should not be used in radon-affected areas, except perhaps with a dedicated air supply or positive ventilation. It is worth nothing that in the UK it was found that no realistic opening was adequate to prevent spillage, Householders Guide (1992).

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7 The Evaluation Approach

When evaluating a ventilation system there are some parameters, that define the quality and ability of a system, fulfilling the individual resident´s demand. Those parameters involved in describing the indoor climate are briefly reviewed. In the first subchapter the ranges are given of the variations, that can occur depending on the resident´s habits. The habits are quite different and are changing with age, life style, and many other parameters.

In this chapter is discussed the use of the most developed models for simulating energy, indoor air quality and air flow rates in rooms, thermal comfort, noise, and life cycle costs. A short review is given of the various ways to describe ventilation efficiency. Finally is discussed an approach to evaluate ventilation system reliability with respect to give a pre set ventilation rate and also the reliability of the different components in a system including the ducts.

7.1. User Behaviour and Perception

Author Lars-Göran Månsson, Sweden, Operating Agent

The main aim with a ventilation system is to provide the individual resident an acceptable indoor environment. How to fulfil this task depends on the sensitivity of the resident, the individual habits, presence in the dwelling, and the activity level. The hard facts on dwelling area and number of persons/dwelling, that can be gained from statistical data given in chapter 3. Knowledge of the habits may be gained also from completely other sources than research work related to residential buildings of pure technical nature or design studies. Sometimes market studies and questionnaires on behaviour can give support to our needs.

7.1.1 Dwelling usage

The use of a dwelling varies within a wide span and with many parameters. The two principally different variations are short and long time perspective. The reason to distinguish between those two variations is given by the different kinds of variations, that a dwelling is exposed to during the life cycle of the building.

Short time variation

Daily, weekly, and seasonal variations in the need for outdoor air is depending on the activities with a constant number of residents living in the dwelling. Those variations are mostly related to what we usually call "user behaviour". Examples on short term variations are:

- Moisture production by the number of residents and their habits of cooking, washing and drying clothes, showering, window airing, use of fans.
- Odour by number of residents and their activity level.
- Volatile organic compounds (VOC) by cleaning intensity, perfume, hair spray, deodorants, ageing of the building fabric etc.

The need for outdoor air is a mix of constant flow (base flow rate) and an increase for some hours or a few minutes. When we are discussing indoor air quality we often think of the short time variations.

Long time variation

The number of occupants in each dwelling varies over the life time of the building. It is well known by planners, that the number of children is on its maximum about 10 years after completion of a new residential area. When the children grow up and move out, the number of persons living in each dwelling become fewer. This situation is illustrated in figure 7.1 with an example from Sweden.

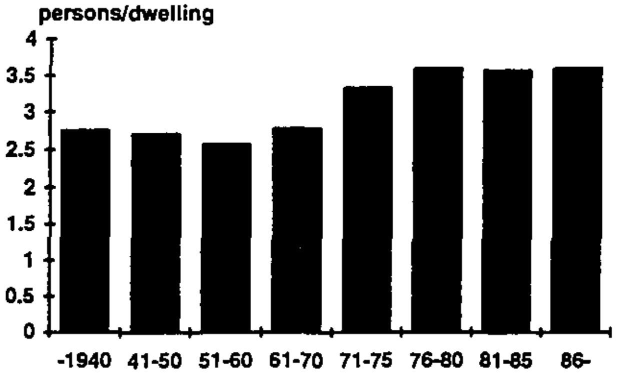


Figure 7.1. The number of persons living in single family houses with respect to the various construction years. Example from Sweden, Carlsson (1992)

From figure 3.4 we can see, that the number of one-person households have doubled in many countries during the last 40 years and are now in the range of 18-40%. If we look on the present situation of households with two persons we can see in table 3.3, that it is well over 50 % of the total (for the Nordic Countries it is over 60 % and for Japan nearly 40 %). We can expect even more households with one or two persons over the next 30 years according to figure 3.5 as the population older than 60 years is growing from 20 % to 30 % in the OECD-countries

This long time variation may also reflect a various need for outdoor air over the life time of a building . When the family is at its maximum in number of residents and activity level, a much higher outdoor air flow rate is needed, than with one or two retired persons living in the dwelling. This is also supported by studies on moving habits and household structure. First people move into flats and then into single family houses, Sanne (1985).

As expected the highest moving frequency is shown for people at the age of 18 - 35 years. Contrary to what sometimes is claimed, there is no tendency to increase the change of the dwellings, when the children have moved out or even at retirement, see figure 7.2. The frequency of various categories of households and types can be seen in table 7.1. Households with children and two parents only stands for about 1/4 of all. The three most common household types are those with:

1. A single person,
2. A couple with man and woman, and
3. A couple with children.

These household types are to be found in over 90 % of the dwellings. As we are mainly interested in the number of residents, it has been possible to use those three categories given in table 7.1. As can be seen the number households with

Table 7.1. Types of households in Sweden. Sandstedt (1991) and Thiberg (1985)

Category of household	%	%
Single person retired	13	
others	23	
Sub total		**36**
Two persons retired	12	
others	26	
Suv total		**38**
Families (including children)	26	**26**
Total	100	**100**

retired persons are quite many and are growing. However, it seems to be more households than expected compared to OECD statistics of the persons aged 65.

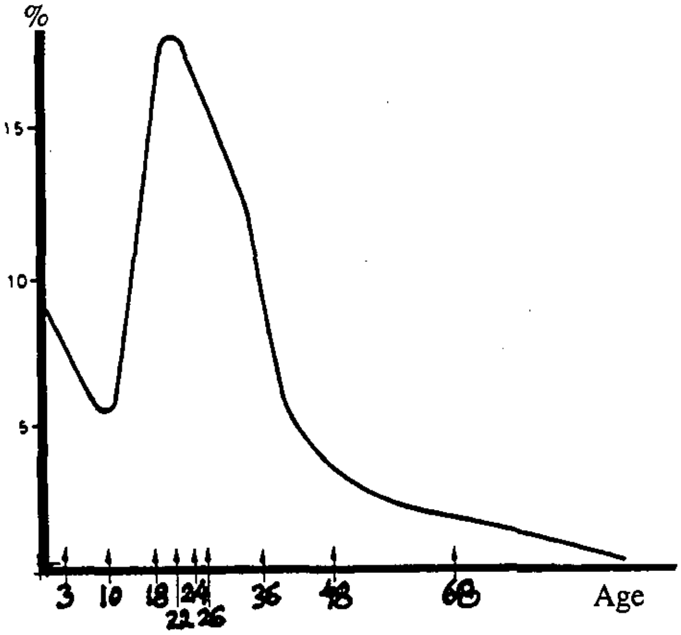


Figure 7.2 Moving frequency for different ages, in Sweden. Engström - Henecke (1989).

All the long time variations can be illustrated in what is expected during the lifetime of a building, see figure 7.3. Besides the variation of the residents in number and habits the house can undergo renovations in intervals of 10 - 30 years e.g. redecorations with paint and wallpaper every 10th year, new floor material with an interval of 20 - 30 years. Here it might be recommended to increase the outdoor air flow rate in order to dilute the pollutants rapidly.

Figure 7.3 An example of the variation of needed air flow rate during the life-time of a building

7.1.2 Trends in dwelling usage

In this section is discussed those activities that have an influence on the outdoor air flow rate needed. The future trends are also discussed.

Area and volume

The trend during the last 10 years has been towards dwellings with a slightly smaller area. But this trend might easily change in those countries with the oldest dwelling stock. In some countries (B, DK, F, UK) 40 - 50% of the dwellings are more than 50 years old. If the new communication systems with possibilities to work at home is adopted, this trend can influence partly on a trend to increase the area, when a work-space is arranged at home.

Time spent in dwellings

The time spent in dwellings varies within a great range. Old people and disabled are spending more time at home. Younger adults spend more time out of their homes.

At weekdays we expect a scheduled time spent in the dwelling but this may, of course, vary depending on the work schedule. It is also observed that in some countries people more regularly have lunch at home. In larger cities this is not possible. The figures 7.4 - 7.7 are giving information from six countries about the time spent at home. However, it should be noted that some of the studies are more than 20 years old. The newest is from Japan 10 years old and one from Sweden 5 years old. In fact it may be so that the time spent at home at lunch has gone down. The employment of women has increased slightly during the 1980s but probably the increase has been more significant during the 1970s giving a pattern more like that of the men.

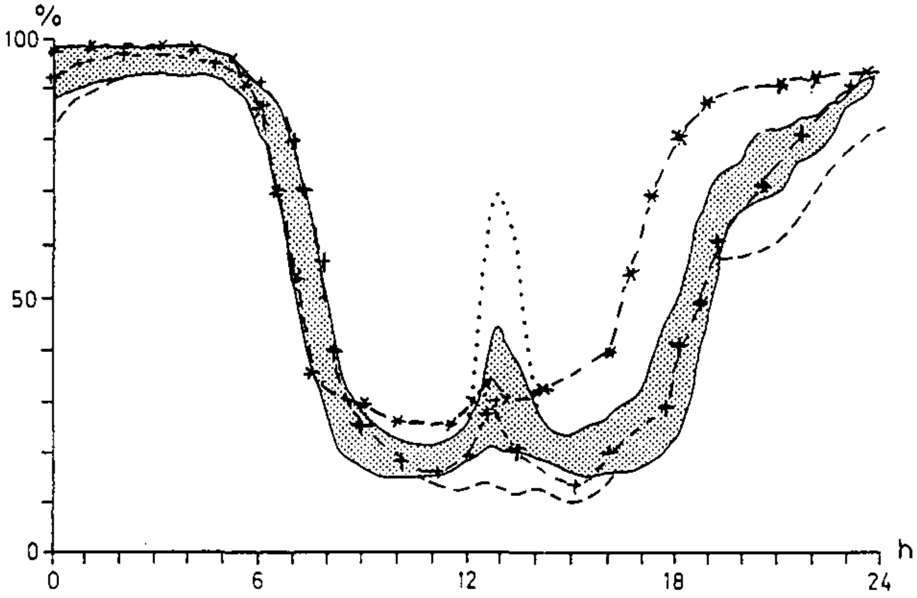


Figure 7.4 Percentage of residents being at home. Employed men weekdays in Belgium, France (dotted line), Germany (west), Japan (--+--), Sweden, USA (hatched line), and Sweden 1990/91 (---*---*). (Fracastoro & Lyberg 1983; NHK 1985, Rydenstam (1992 #80)*

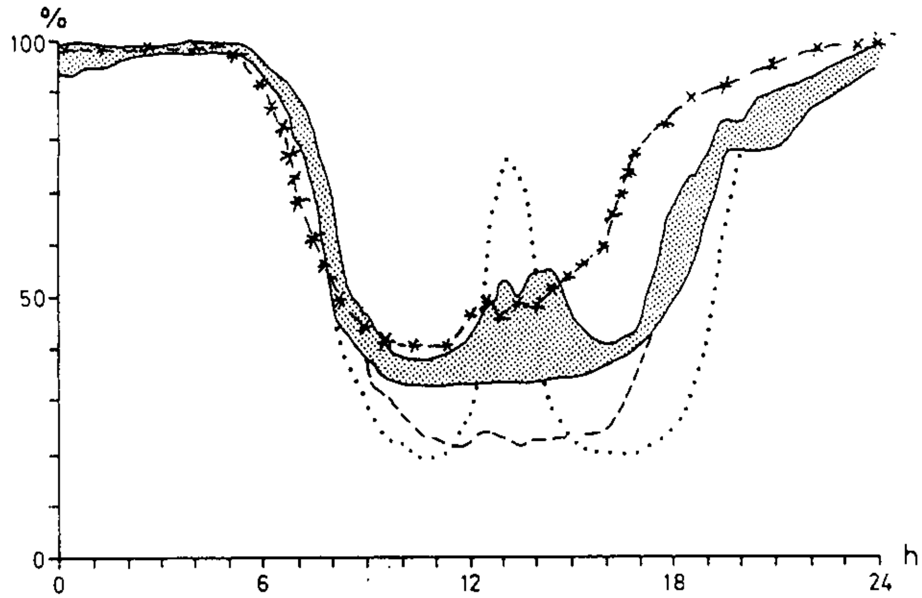


Figure 7.5 Percentage of residents being at home. Employed women weekdays in Belgium, France (dotted line), Germany (west), Sweden, USA (hatched line), and Sweden 1990/91 (--*-*). (Fracastoro, Lyberg 1983; Rydenstam,1992 #80.)*

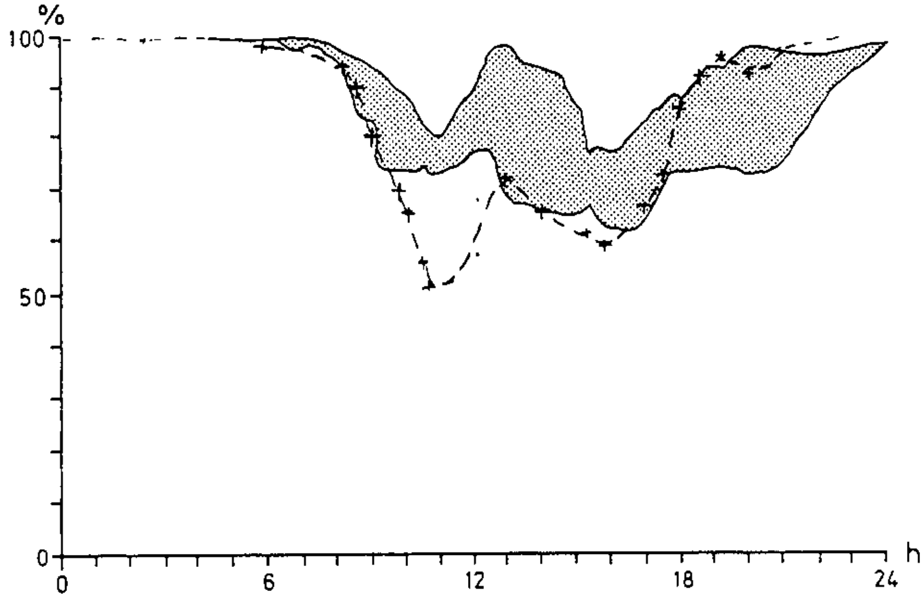
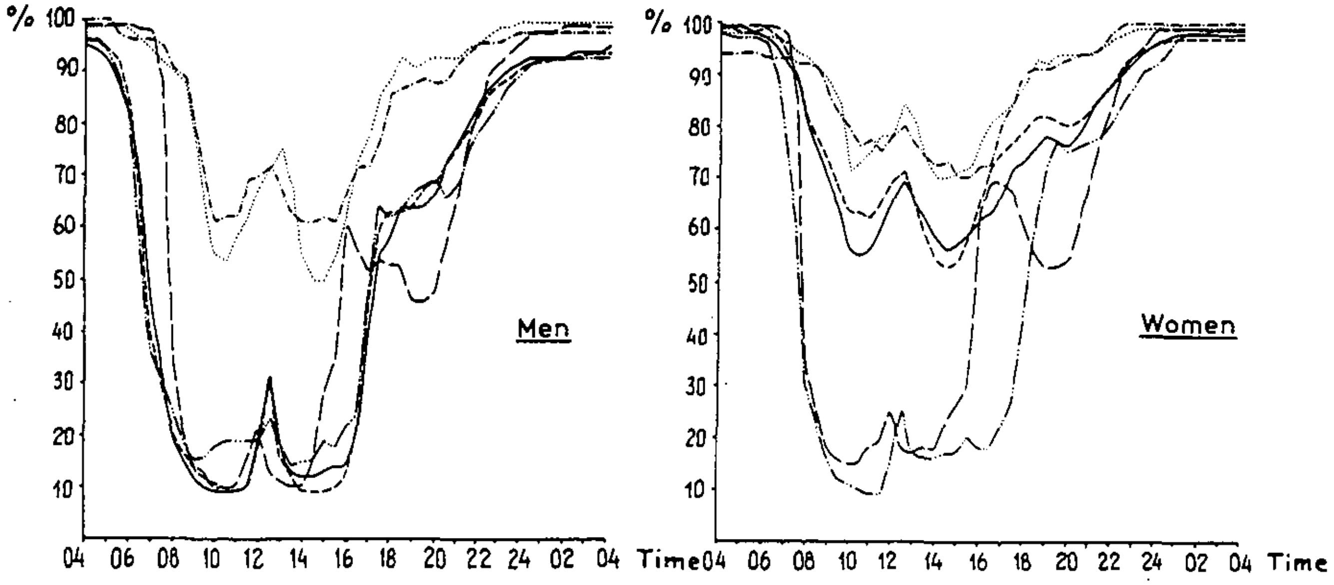


Figure 7.6 Percentage of residents being at home. Housewives weekdays in Belgium, France, Germany (west), Japan (--x--), Sweden, and USA. (Fracastoro, Lyberg 1983, NHK 1985.)



			Average time (min) Men	 Women
— — — —	Youth	age 14-15	868.0	915.9
- - - - - - -	Couples, husbands	" 22-31	791.7	1177.8
————	" "	" 35-44	788.9	1161.8
—— ·· ——	Single	" 35-44	793.8	849.2
—·—·—·	Single	" 67-75	1238.6	1280.4
············	Couple, husbands	" 67-75	1218.5	1297.4

Figure 7.7 Percentage of residents being at home at different times of the day. (Fracastoro, Lyberg 1983.)

Another parameter studied was the time spent in the kitchen preparing the meals. One result was that the time in the kitchen is proportional to the kitchen area. A cultural habit is shown in the length of the time for preparing the meals. In France the time is doubled compared to USA also for women working outside the dwelling, Fracastoro, Lyberg (1983). In Klevmarken et al (1990) is given that the household work has gone down for women during the last 25 years and increased amongst men. Comparison made by Klevmarken (1990) for Norway, USA, Sweden, Finland, and Denmark also show great differences but has gone down and 1985 indicates from 3 h to 4.5 h for household work.

Of great importance is the possibilities to give estimations of the time spent in the dwellings, how many are doing the household work and the time spent in each room. Rydenstam (1992) gives detailed information on various activities. In table 7.2 is given a summary of the study on the time spent in each room in a dwelling. The figures given are based on time budget for men and women 20 - 65 years of age. It is also an interpretation of, in which room the activities take place. Some notes must be given to table 7.2. Those are:

1 Parents' bedroom, 50 % of the preparation of clothes are made in connection to washing;
2 Children's bedroom. Here is given only the time the parents are in the room;
3 Living-room all meals are eaten here, reading, watching TV, hobbies;
4 Uniformly distributed are the activities like cleaning the dwelling, telephone calls;

If the differences between the ages of the residents are studied of course there will be trends observed. The trends for men are: at the age 35 - 49 working 1 h more each day; the time spent at work at home + sleeping + eating is the same for all; studying 0.4 h more at the age

20 - 35 years; reading and whatching TV 1 h more at the age 50 - 64. The trends for women are: At the age 35-39 working 1.30 h each day more; at the age 35-49 working at home + sleeping + eating is less than at other ages; the youngest are studying more.

Table 7.2 Average time [h] spent in different rooms, example from Sweden Rydenstam (1992 #80)

Room	**Women**		**Men**	
	Weekdays	Weekend	Weekdays	Weekend
Kitchen	1.15	1.36	0.29	0.44
Bedroom, parent	8.08	9.16	7.34	8.57
Bedroom children	0.20	0.19	0.07	0.10
Living-room	4.00	6.23	3.53	6.02
Bath/toilet	0.54	0.59	0.46	0.54
Laundry	0.13	0.15	0.03	0.05
Uniform distributed	1.16	1.26	0.48	1.15
Total	**16.06**	**20.14**	**13.40**	**18.07**

Other useful indicators for the presence in the dwelling are the employment frequency of women and how many of those who are part time emploied, see figure 7.8

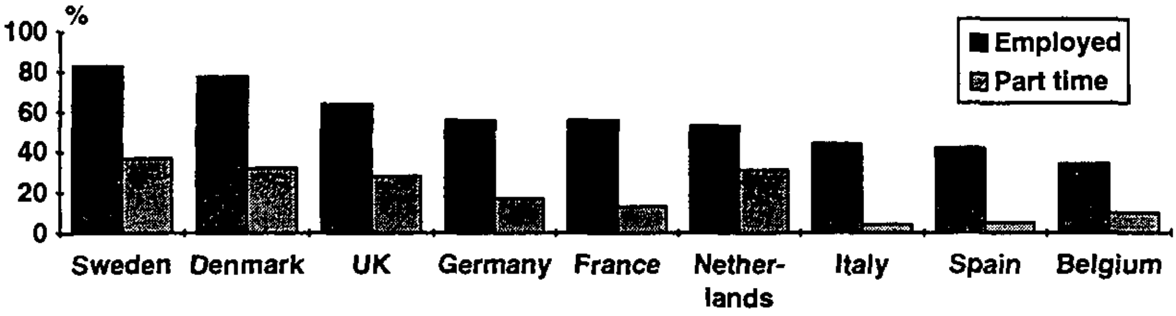


Figure 7.8 Employment frequency and part time work for women in some European countries. Percentage of total number of women (ref Eurostat)

Studies on residents' pattern giving answers on the time present in individual rooms are very rare. In figures 7.10 - 7.12 is reported a study in Japan by Sawachi and Matsuo (1989), showing in which room in the dwelling which person of the family was there and how long. The study gives a good picture how families during weekdays are living in an urbanised and industrialised society. However, even in this very detailed study in 250 dwellings we can not distinguish between kitchen and living-room. The number of hours spent in the different rooms is given in figure 7.9.

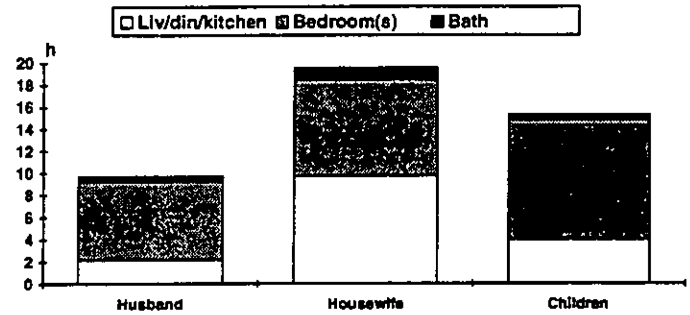


Figure 7.9 Hours spent in various rooms based on figures 7.10 - 7.12.

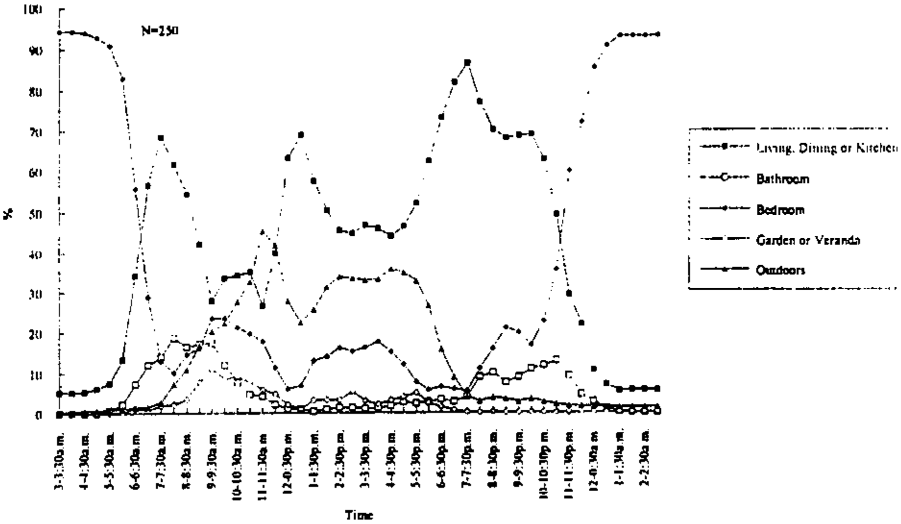


Figure 7.10 Husbands in each room at different times, Sawachi and Matsuo (1989)

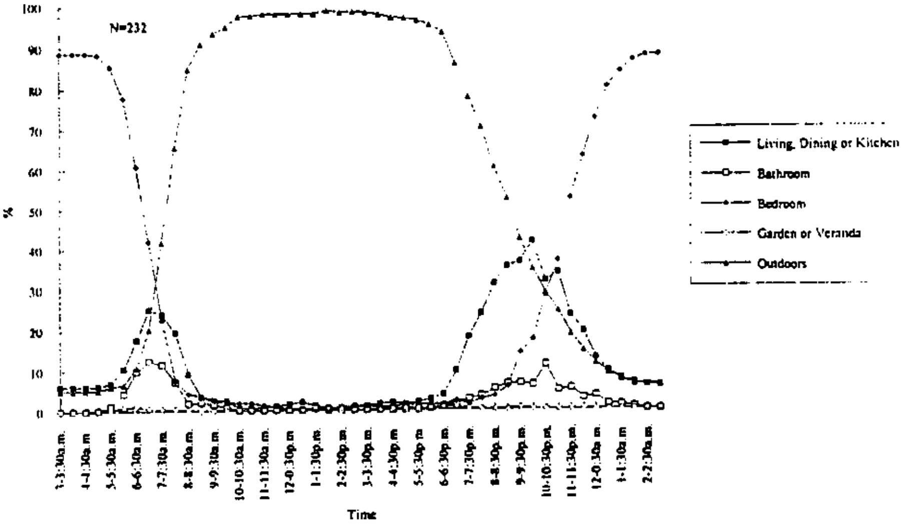


Figure 7.11 Housewives in each room at different times, Sawachi and Matsuo (1989)

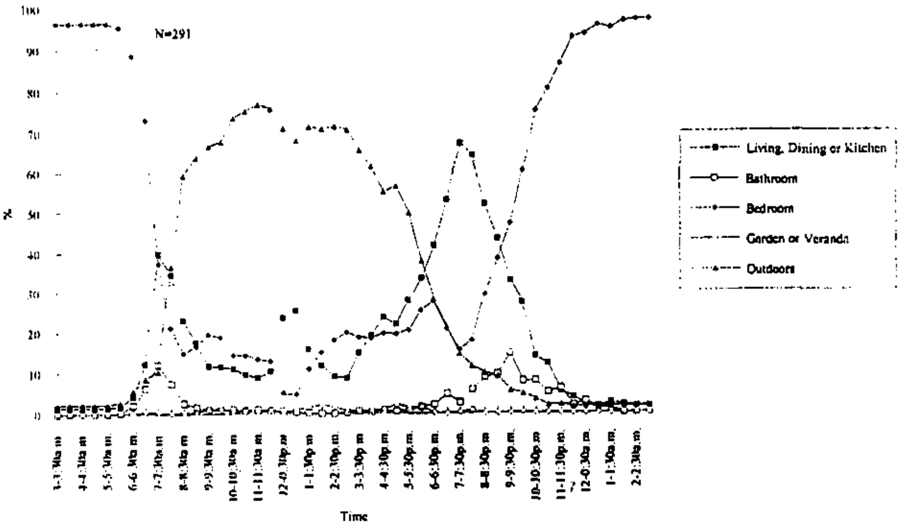


Figure 7.12 Children in each room at different times, Sawachi and Matsuo (1989)

Studies on the presence frequency were made in Sweden in the late 1970s and by questionnaires. The result has been presented as percentage of the time at home and awake. It is not directly comparable with the Japanese study and can not give the whole day distribution of the time in the individual room. The time awake is much shorter for the infants than for their parents and the time in the dwelling varies very much. However, the figure 7.13 gives indications, that are in the same direction as the Japanese study. Since the study was finished, more than one TV have become more common. In the study no information is given on the time spent outside the dwelling or the time at day nurseries or at school. In the same study is also given frequency on where different activities take place and in which room.

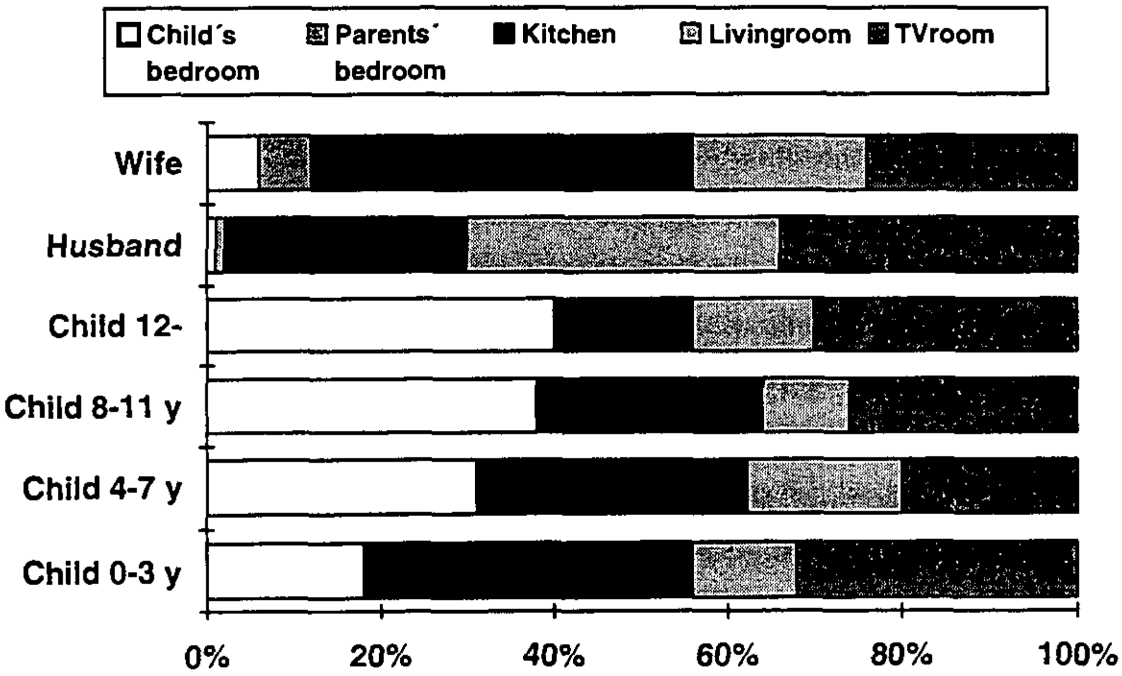


Figure 7.13 Residents' time in individual rooms when awake, ref. Lindquist, Orrbeck, Westerberg (1980)

Indoor temperature

There is a large span in the average indoor temperatures in the various countries. Even between single family houses and flats there might be a difference even in the same country. In Sweden the average temperature is 1 °C higher in flats compared to single family houses, Norlén, Andersson (1993). The deviation from the average temperature can be large and in some surveys found to be ±7 °C, Fracastoro, Lyberg (1983), but more common is ±3 °C. This might be influenced by the dressing habits and the long tradition of different indoor temperatures in various rooms.

Trends towards more even temperatures during day and night and during all seasons have been observed. It has also been observed the preference to have a similar clo-value indoors during all seasons. The adaptation of lower indoor temperatures during winter seasons seems to be less accepted amongst the younger generations. It might also reflect the urbanisation.

Low activity, high air velocities, high turbulence intensity, also influence the acceptability of the room temperature. As women has a lower metabolic rate, lower weight, and often lower clo-value compared to men, this may lead to a higher risk for unacceptable temperature and a complaint of draught. If the walls and windows have a low U-value (well insulated) the operative temperature will increase. Usually this does not lead to lowering the indoor temperature, but more often to an increased thermal comfort. After 60 years of age the metabolic rate declines. As the average living time for women is longer than for men, this means that we have more women with lower metabolic rate due to high age. Women are also the category, that represents a great portion of one-person households.

According to Norlén, Andersson (1993) the average indoor temperature in Swedish dwellings has increased with 0.4 °C within a period of 10 years. The average indoor temperature in Swedish dwellings today is 20.9 °C in single family houses and 22.2 °C in flats. In UK the indoor temperature has been reported to be about 17 °C during wintertime. The low indoor temperature can also be a result of trying to keep various indoor temperatures in different rooms. The acceptable average indoor temperature may vary from country to country or have increased as in Sweden. It can also be noted that in Sweden a temperature lower than 18°C is thought to be unhealthy and can be a matter for authority action.

If there is any variation in the indoor temperature, it might be seasonal (no variation has been found in Sweden). The long time variation is more of a reasoning and not supported by measurements. During the first years in a new single family house the economical situation usually force the owner to keep an eye on the temperature. The younger children don't know how to use the thermostats so the pre-set values can be kept. When the children grow up the temperature tends to increase and so it does with the elderly residents.

The perception of the thermal comfort is very much determined by the feeling of the feet. The habits in the individual countries of having shoes on indoors or only socks will give some hints of the perceived thermal comfort. Also the construction of the floor, the thermal resistance and the floor-covering will influence the thermal comfort. The habits may also be reflected in the average indoor temperatures. Not very much is known about the thermal comfort perception when varying many of the parameters.

Water consumption

In dwellings, where heating is necessary, the water vapour generation indoors is the most severe risk for the building because of the risk for condensation causing mould growth. Of course, the humidity can be very high also during the warmer season, specially during late summer and early autumn. But during this time of the year it is possible to use window airing without a great heat loss. How much water vapour, that is generated, is depending on the number persons and their activities and the use of water in the dwelling.

The humidity can also be increased by the cooking habits. But if there is a cooker hood of acceptable capture efficiency, it can nearly be neglected. However, all the water consumption can not give an increased humidity, as it is the heated water that gives away most of the water vapour. In table 7.3 is given the water consumption for all the functions in a dwelling in three countries based on long time monitoring by the Swedish Institute for Building Research (SIB), Botkyrka Municipality in Sweden, a collection by P. Opt d'Veld, Netherlands, and Society of Heat. etc. Japan (1989).

Table 7.3 Water consumption for various functions in dwellings [litre/(person, day)]

Function	**Sweden** Average	**Sweden** SIB, flats	**Netherlands**	**Japan**
Shower/Bath	70	60	47.5	43
Wash stand		24	3.7	17
WC	40	39	42.7	26
Clothes washing	30	20	25.7	43
Food	10			
Dish washing	40	10	9.5	39
Others	25	10	5.9	19
Total	**215**	**163**	**135.0**	**187**

The water consumption is strongly linked to the number of persons in the dwelling. As it is impossible to use the average for a dwelling, the figures are given per person, to make it possible to calculate the water vapour from the use of water. The variation is also depending on the installation e.g. the WC, which is consuming a various amount of water depending on the construction. The variation can be from 3 l/flushing to 20 l/flushing. A more aggregated comparison can be seen in figure 7.14, from which can be seen that the water consumption varies from 116 to 260 l/(p,day).

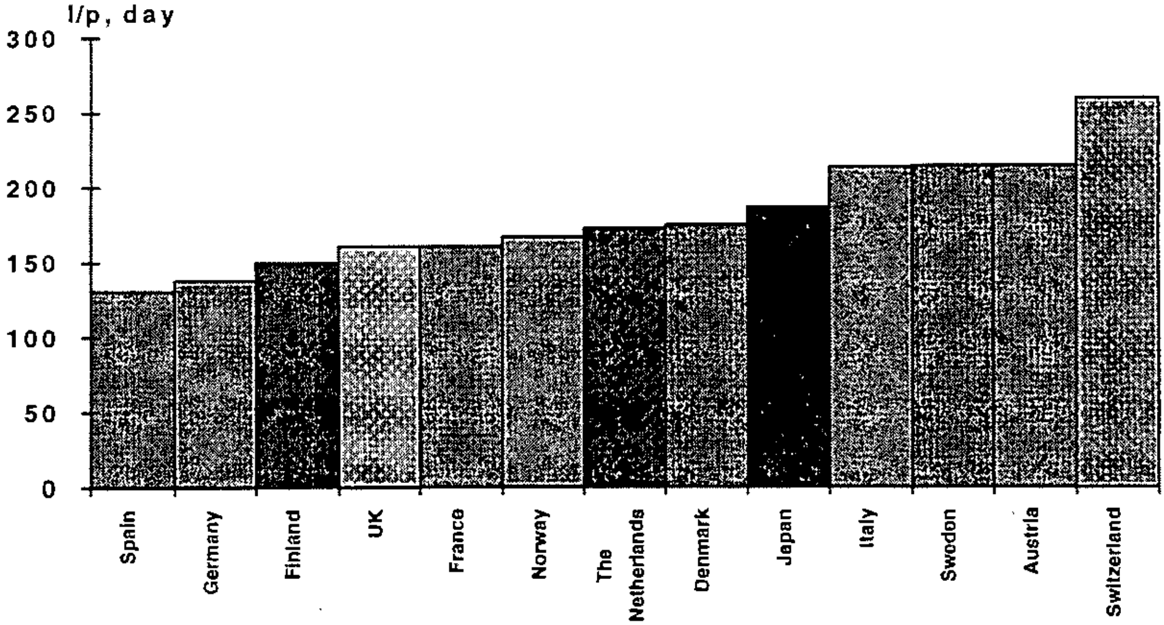


Figure 7.14 Water consumption in various countries, ref. Botkyrka Municipality in Sweden (1994), Society of Heat. etc. Japan (1989), and "Energi & Miljö" (1994).

A study made in Sweden, 1991, showed no tendency for decreasing the water consumption when the price rose 25 % (personal communication with Ö. Eriksson Swedish Water and Waste Water Works Association). On the other hand the water consumption has not increased in Sweden since 1970. The Swedish SIB-study quoted in table 7.3 aimed at detailed measurement on the water flow for dimensioning the pipes specially in multi family buildings. Still it is needed to measure, in depth, the water consumption with the purpose to find any relation between the water vapour content and the water consumption.

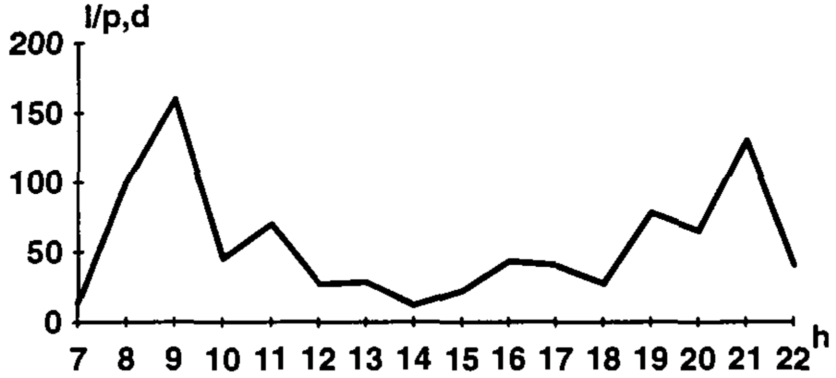


Figure 7.15 Water consumption during a day in Swedish multi family buildings, early 1970s.

The need for a demand controlled ventilation can be indicated when studying the water consumption during a day. The water consumption gives signals on presence in the dwelling and on activities. In figure 7.15 can be seen, that in the Swedish SIB-study the maximum hourly water consumption is at 8-9 h in the morning. Another peak can be seen in the evening at 21.00 h.

Cooking

The time spent on cooking can be regarded as the time when water vapour occurs. If a gas stove is used most of the NO_X is produced during the cooking, but also a constant emission is given away by the pilot flame. In the case of a gas stove there is two cases. One is when in use and the emission time is the same for water vapour and NO_X and the second as a constant source when the stove is not used.

An interesting observation is that house wives spend twice the time on cooking compared to employed women, Fracastoro, Lyberg (1983). Measurements are reported from four countries (B, F, D, USA). The time is from 2.0 - 1.6 h for housewives and about 0.1 h for men. The observations may be old and is reported from 1972 but can still be a measure of the work done at home by house wives. From Japan is reported, the White paper of welfare (1991), that housewives spend 2.7 h each day for cooking, whilst the men spend only 0.05 h on cooking, which is slightly less then reported for men in the above mentioned countries. In the study by Rydenstam (1992 #80) is reported that women spend about 1 h each day on cooking and men about 1/3 of an hour. Paid work outside the home have 63 % of all women (20 - 34 years 55 %, 35 - 49 years 74 %, 50 - 64 56 %) reported for Sweden, Rydenstam (1992 # 79).

The appliances for cooking is predicted to use less time in the future on simple water-cooking and just heating the food. Here new appliances such as separate cookers for water, potatoes, rice etc. as well as micro wave ovens rapidly can decrease the time spent on cooking and thus the moisture production will decrease. Also an induction stove can in the future decrease the water vapour as it is easier to control.

When cooking a kitchen hood often is used as a local exhaust ventilation. This installation has been more common lately in the EU countries. In Sweden most single family houses are equipped with a kitchen hood as well as many of the flats. Finland, Norway, USA, and Canada have a similar situation. Most of the hoods can capture about 70 % of the moisture. The trend is, that less time is spent on cooking because we use equipment for easy handling and pre-prepared food and. The use of a kitchen hood is increasing.

Dish washing machine

The use of a dish washing machine is increasing especially in households with many persons. The water vapour content will not be increased very much because drying is kept within the machine and most people don't use the drying function in order to save energy.

Clothes washing and drying

The access to a clothes washing machine is nearly 100 % in all the highly developed countries. But we are not quite sure, where the washing machine is standing. It may be in a separate laundry in the dwelling or a laundry with access for many dwellings in multifamily buildings. Another place can be in the kitchen or the bathroom.

The easier it is to wash the higher frequency. Even with a high efficient machine a lot of water must be dried out from the clothes, thus increasing the moisture content of the indoor air. Condensing drying machines give a high indoor temperature thus giving a higher moisture content and a need for ventilation.

The frequency of using the machines varies from daily use to a few times a month. A mean value of households with 4 persons is to use the washing machine 20 times/month, Månsson, Boman, Jonsson (1992, 1993). A study made 1972 reported, that the frequency was: Germany (west) and Belgium 9 times/month, France and USA 14 times/month, Fracastoro, Lyberg (1983). The laundry is dried outdoors, if the outdoor environment is non-polluted, the washing machine is standing in a room on the ground floor, and the outdoor temperature is appropriate. But this is the case only during the time of the year, when there is a less severe water vapour situation in dwellings.

In a resent finished study questioning 1000 persons, the frequency of clothes washing and drying show that most people use their washing machine several times a week, ref. Christensen (1993), Lindahl (1993). For people younger than 50 years about 20 % of the persons (to be interpreted as the household) wash every day. Drying in the air is the most common way. However, it is possible that the questionnaire was sent out during the summer and it is known from other studies that it is the most resent habit, that is given in the answers. As many people are drying in the air during the warmer seasons (May - August), especially people living in single family houses, the result might not be the average for the whole year. The results are given in figure 7.16 and 7.17.

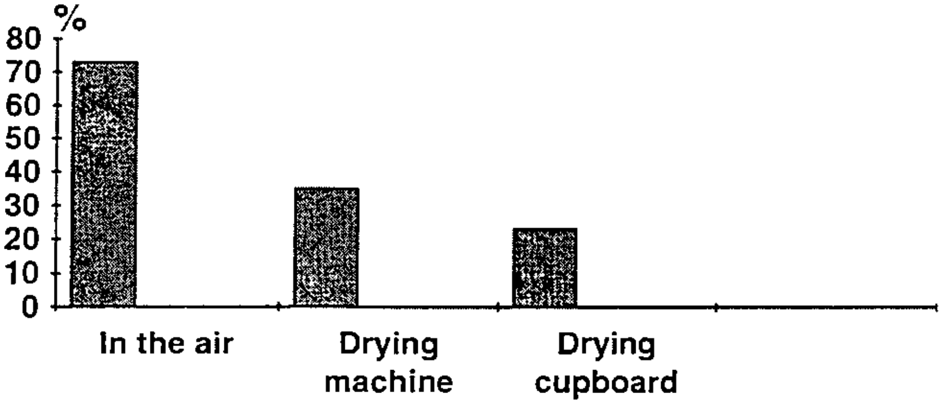


Figure 7.16 Where the clothes are dried Christensen (1993), Lindahl (1993)

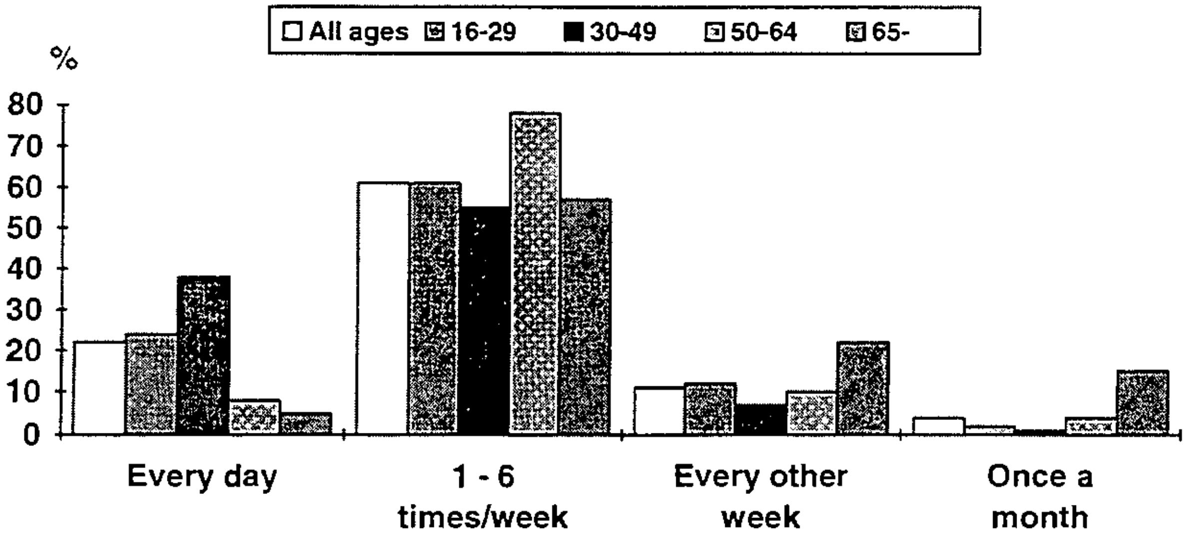


Figure 7.17 The frequency of clothes washing, Christensen (1993), Lindahl (1993)

Body washing (bath, shower)

The use of water varies much both for dwellings of the same size and number of persons. If looking on the use of domestic hot water the variation is even higher and the use corresponds mostly to the body washing habits. The variation in use of domestic hot water can be in the ratio 1:20, ref. "Samfällighet". In this case the number of persons in each dwelling is not the same. On the other hand if a comparison is made between households with the same number of persons, the use may vary at least in the proportion 1:4, Boman, Jonsson, Månsson (1993).

The water vapour production is very much depending on the habit to take a shower or a bath. In the first case, today most used, the water vapour production may be about 2600 g/h, see Annex 14 (1991). Another study, Fransson (Dec 1993), shows that even with an exhaust fan RH=100 % will be reached after only 5 minutes of showering. The water, that will remain on the floor after the shower, will not dry up linear to an increased flow rate. Here the manual way of drying up the water is most efficient. If the bathroom has a warm floor it is, of course, a good help of drying up the water left on the floor.

The removal of water vapour in bathrooms is required if mould growth shall be avoided. In rooms with windows these may be used as forced ventilation, but it might cause discomfort and a higher heat loss with window airing. The use of separate fans is increasing. In houses with central exhausted fans running all the time the exhaust flow is not always enough to immediately take away the moisture. Fransson (Dec 1993) also shows that an extra fan is more energy efficient than increasing the flow rate for the central fan during a longer period. Even if the study was small, it indicates a way to deal with bath- and shower-rooms.

In the above referred questionnaire, Christensen (1993), Lindahl (1993), was also studied the habits of taking a shower, a bath, the use of deodorants (also who is cleaning the bathroom, change of towels, tooth-brushing). The study is a common 1000 person questionnaire with the items decided, but there is no alternative answers given.

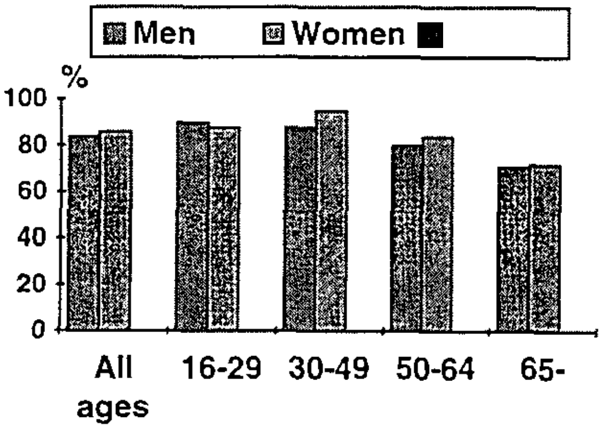


Figure 7.18 Percentage of the population that usually are showering

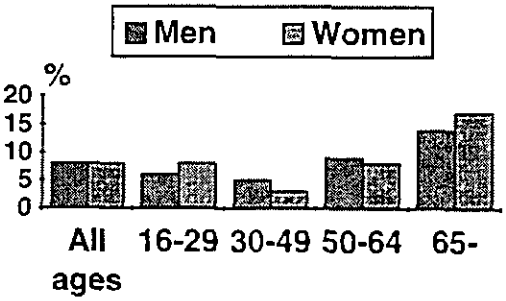


Figure 7.19 Percentage of the population that usually are bathing

The results from the study are shown in figures 7.18 - 7.21 Christensen (1993), Lundahl (1993) and the conclusions are briefly:

1. About 85 % of all are showering. Retired persons 70 %, fig. 7.18.
2. Men and women are showering in about the same proportions, fig. 7.18.
3. Once a day 65 % are taking a shower, fig. 7.20.
4. Twice a day 10 % are showering, fig. 7.20.
5. Nearly 20 % of men 16 - 29 years are showering twice a day and women 10 %, fig. 7.20.
6. Most common is a 10 min shower, fig. 7.21.
7. Women takes shorter showers than men and this is recognised especially for the busy period of the life at the age 30 - 49 with work and children .

Nearly all dwellings are today equipped with a bath/shower. We can expect that the showering will increase, when those today 16-29 years become older, because they probably will keep there habits. It means that today's habits will probably not be conserved. It is a dynamic process. Dwellings constructed before the 1960s were not planned for such a showering habit and thus the ventilation system not intended for today's water vapour production

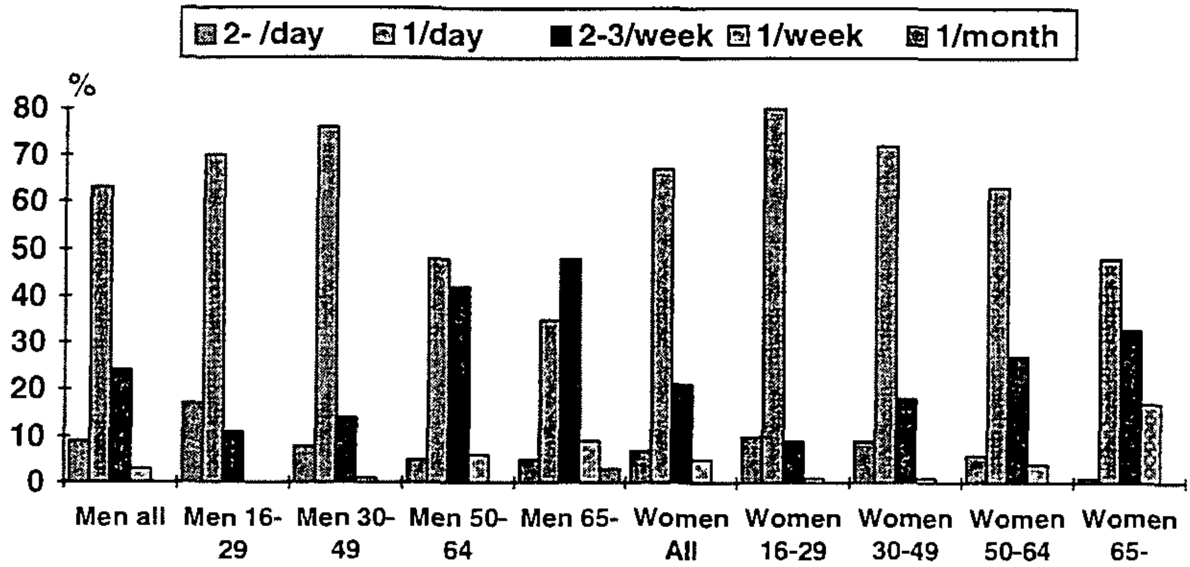


Figure 7.20 Showering frequency

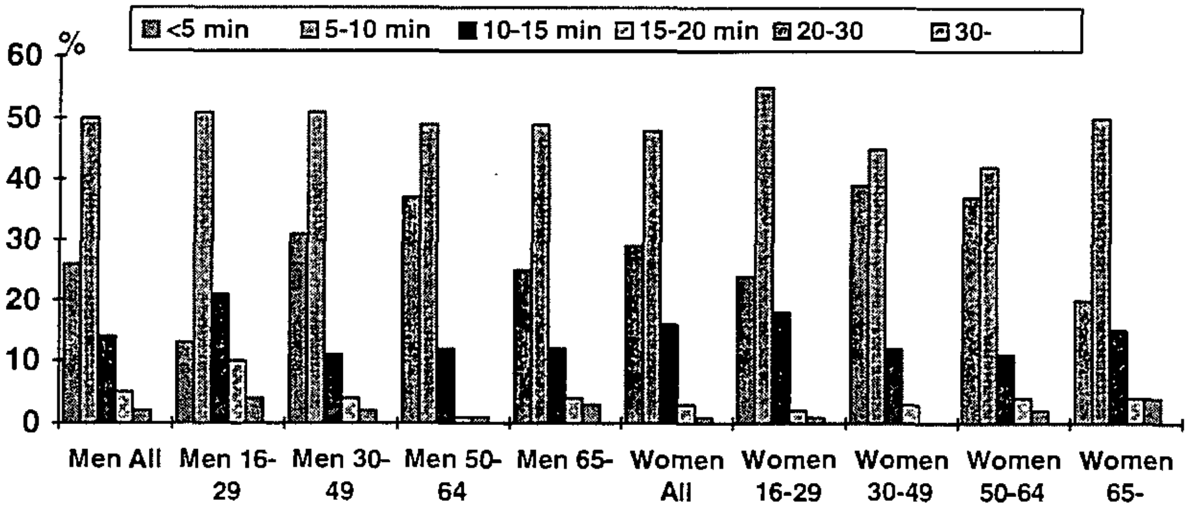


Figure 7.21 Duration of showering.

Investigation on the showering and bathing frequency in some European countries is reported by, L'Express (1995). In figure 7.22 is shown the weekly number of showers and baths. Showers might have been taken in conjunction to the baths except for Sweden. If the result for showering for other countries are increased with the number of baths, the habits are rather close to the Swedish "daily shower".

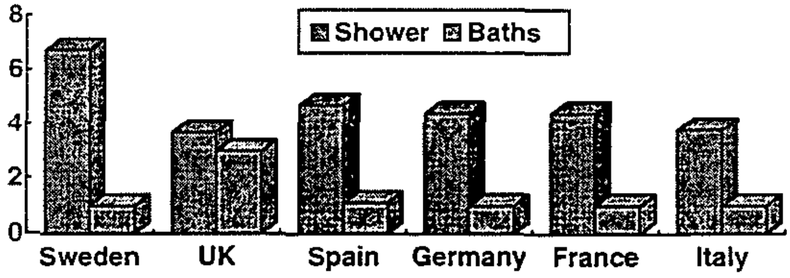


Figure 7.22 Weekly number of showers and baths in some European countries, L'Express (1995), Christensen (1993), Lindahl (1993)

Pot plants
Some hints are given in Annex 14 (1991) about the water vapour from pot plants. The result of watering the plants with the same amount according to the reference will lead to a very wet condition for the plants. Half of the volume given is a more realistic figure during wintertime.

The number of pot plants is very depending of national habits. A market research, Blomsterfrämjandet (1988), gives that Germany, The Netherlands, Switzerland, and Sweden are the countries in Europe that have most pot plants of all in their dwellings. The number given means that pot plants are placed at the whole length of all the windows. If calculating on this average figure and applied in Sweden the result is that there is 0.25 -0.30 pot plants per m^2 dwelling area. The needed air change rate to exhaust the water vapour from the pot plants is about 0.1 h^{-1}.

Window airing
The air change rate for single sided and cross ventilation has been estimated in annexes 8 and 20, Dubrul (1988), v d Maas (1992). Even if there is some uncertainty about the calculation of air flow through large openings a much bigger uncertainty will be the time when the windows are opened and the width of the opening. Other parameters are the shape and constructions of the window, indoor temperature, wind speed when the windows are opened.

The frequency of airing was found to be, Lyberg (1983), Dubrul (1988):

- The same daytime and at night
- Proportional to the outdoor temperature
- Proportional to the wind speed
- Windows are not left opened when no person is present in the dwelling.
- Doubled when tobacco smoking is allowed in the dwellings. If smoking only takes place in the living room it is only in this room the opening is doubled.
- Regulating occasionally high temperature, e.g. at parties.
- Regulating the temperature in general.
- Depending of the housewives' habits when making up the beds, and cleaning the dwelling.
- Less when higher indoor temperature was preferred.
- Less amongst elderly people.
- No socio-economic correlation
- Increased when the room has direct solar radiation
- More when sunny than cloudy

It was found by Lyberg (1983), that the number of windows multiplied with the temperature difference was constant $n \bullet \Delta T=2.2\pm0.4$ (n=fraction of windows opened; ΔT= temperature difference). This formula can be used when the temperature difference is > 7. However, the constant 2.2±0.4 was found not to be valid in another investigation carried out in 85 single family houses. Here was found that $n \bullet \Delta T=0.3\pm0.1$. The airing with fully opened windows were reported to be 5 - 10 min. (8 min according to questionnaires, 11 min according to interviews), Gaunt (1985). Conclusions from the studies might be that:

1. Fully opened only for a short time
2. Ajar mostly in multi family houses and never on ground floor for longer periods.

Many have reported, that the indoor temperature is preferred to be kept lower in bedrooms. Sometimes a difference of about 3 - 4 °C is reported. This small temperature difference is calculated to cause an air flow so that the temperature will be the same in all rooms given that the doors are opened.

In figure 7.23 is shown the percentage of opened windows at different outdoor temperatures. This gives of course the temperature difference, which is found to be the most relevant parameter today. Actually it can be a matter of over-temperature, that is more frequent when the difference is small, and the weather is sunny. In figure 7.24 is shown the relationship between different parameters influencing window airing habits.

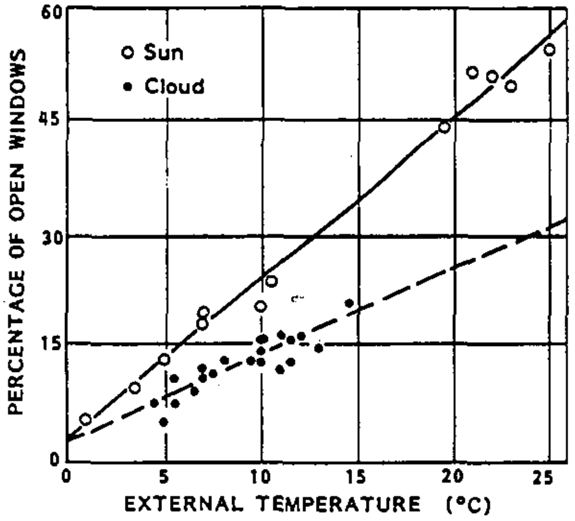


Figure 7.23 Relation between the percentage of opened windows and outdoor temperature, (Dubrul 1988)

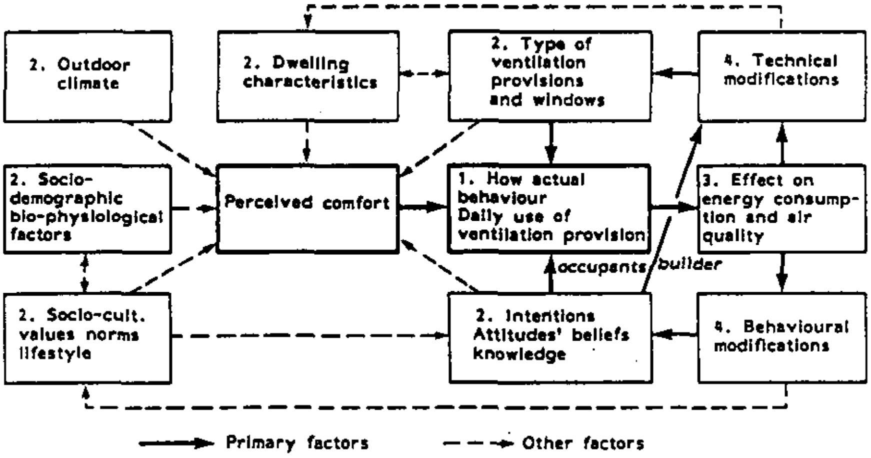


Figure 7.24 An illustration on all the various parameters influencing ventilation habits. (Dubrul 1988)

In a study by Bergsöe (1993) the frequency of window opening was studied in 113 renovated and 64 non-renovated flats with the average of 2 residents/flat. The multi family buildings were constructed from 1930 to 1960 and all have natural ventilation systems. All rooms were aired for shorter or longer periods. Windows were ajar all the time in 60 % in bathrooms of the non-renovated flats, but only 30 % in the renovated. Windows were ajar all the time in 30 % of the bedrooms in the non-renovated flats and 50 % in the renovated.

In The Netherlands it has been accepted to look upon the window airing pattern like

- 15 % of the windows opened when outdoor temp. 15 - 10 °C.
- 10 % of the windows opened when outdoor temp. 10 - 5 °C.
- 5% of the windows opened when outdoor temp. 5 - 0 °C.
- No opened window at temperatures below 0 °C.

7.1.3 Allergic and oversensitive reaction

It is a fact that some persons in our society have "inherit" the allergy and others have turned to be oversensitive. What they react on may vary within a great span. The oversensitivity may have been attained by several possible ways e.g. tobacco smoking (active or passive). A general trend is that once you have turned to be oversensitive then the threshold value is a magnitude (1:10 or 1:20 of the pollutant concentration) lower than before.

There is two different means to tackle the problem. One means is to avoid to be exposed to the pollutants (e.g. tobacco smoking). This is the long term strategy. If we do not take into account the oversensitive persons, a higher pollutant level can be kept as the threshold value. With this strategy the allergic persons that have it in their genes must be specially treated.

The other means is once a person is identified to have oversensitive reaction, that person must have a much lower pollutant concentration than before. The easiest way is to increase the outdoor air flow rate and have low emitting furniture and building fabrics. However, this may lead to an increased energy demand. In this section is discussed the "pollutants" that might contribute to oversensitive reactions either directly or indirect.

General trends

In our society the general trend is that more people are reported to be allergic and to have oversensitive reactions. Most alarming is the increase amongst children. Many very large research works have been reported on this matter. In some of these reports it is claimed that the cause of the increase is due to the building. It may be

- the building fabric
- the moisture causing mould growth
- the moisture causing house dust mite to grow
- the low outdoor air flow rate caused by tightening the house, decreasing the outdoor flow rate, and use of return air.

A general trend has been, that if you can't explain the correlation between oversensitivity and a specific pollutant it is thought to be caused by the building, the dwelling or another premises where the person regularly is. In this chapter is discussed the pollutants indoors that always are at hand indoors and direct or indirect can cause problems if not treated accordingly.

Smoking habits

The smoking habits varies both between countries and within a country. The smoking habits have also changed over the years. Today about 30 % of the population is smoking. Men and women have nearly the same smoking habits today. The trends in smoking are:

- Decreasing amongst men since 1950s from 75% to today's frequency of about 30 %.
- Women have slightly decreased since the 1960s and is now about 30 %

- Young people still starts smoking
- Smokers start well before 20 years of age.
- Passive and active smoking can cause oversensitive reaction specially amongst children and infants.
- Mothers' smoking during pregnancy may lead to oversensitivity reaction for their children.

Of course the smoking frequency is higher amongst younger people because some people grows wiser and smokers cut down their lifetime with 6 - 8 years. When problems caused by smoking occurs this may lead to stop smoking at the middle age and older. Tobacco smoking is also ranked as the greatest risk of all. In combination with other pollutants the risk will be more severe.

As there is a trend to avoid smoking indoors also in offices and hospitals and other public environments (Prohibited in Finland, Sweden, some states in USA) it might be expected that more people avoid to smoke in their dwellings. Thus we can foresee a decrease of problems caused by passive smoking, especially amongst children.

If smoking is at hand in a dwelling with children there is a need for high outdoor air flow rate. Because the society has an obligation towards the children, this problem must be considered. Adults can make a choice. On the other hand if someone wants to smoke in the dwelling it is there own choice and would not necessarily lead to an increased outdoor air flow rate.

As smoking gives a high increase of the number of particles and the smell remains in the furniture for a long time, the need for airing is much higher than in a non-smoking dwelling. There is a long list of pollutants that for each constituent can be a health risk. These pollutants will occur in the mainstream as well as in the side stream. Many of the pollutants are also coupled to the number and mass of respirable particulate matters. The particle level will be magnitudes higher, when smoking, compared to all other habits including vacuum cleaning, Månsson, Svennberg (1993)

As a family is all over the dwelling and in particular in the living room, kitchen, and bathroom the risk for being exposed to tobacco smoke is most likely to happen if a smoker is a member of the family and smoking indoors. Most of the children have a separate bedroom and spend a great part of their time awake in their room the exposure for passive smoking can be avoided a substantial time if no tobacco smoke is introduced in children's bedrooms.

Tobacco smoking causes a severe smell that is hard to get rid of by airing. This gives a need for new furnishing more frequent. The smoke also gives a yellow colour on all surfaces and this will also cause a need for painting with shorter intervals. The more frequent refurbishment that is caused by tobacco smoking will give an increased demand for outdoor air supply to dilute the pollutants from the new furnishing and redecoration. See also chapter 6.3.

NO_x

Indoors exposure to NO_x is usually defined by the choice of the dwelling. NO_x from the stove, and heating appliances can be avoided partly by the residents' choice not to install unvented furnaces, or installing a kitchen hood. If there will be an increase of NO_x is a strategic matter for decision makers involved in the strategy for energy supply systems. For heating appliances it is apparent that in countries with colder climate most dwellings have central heating and vented appliances. In countries with shorter heating seasons the trend is to include in codes and standards mandatory installation of flue gas vents (chimneys).

Volatile Organic Compounds (VOC)

The pollutant levels that are caused by the resident's behaviour e.g. cleaning habits, use of perfumes, new clothes, detergents remaining in the clothes etc. have not been studied at all. Reasons to this is that it is a practically problem to execute such a study. Minor indications have been given as side results in other projects, however, no reliable levels have been established. Moreover the mixture in all those household chemicals varies over the time.

Hints of the levels measured in dwellings are given in chapter 6. But here is a mix of constant and variable sources and over a longer or shorter time. Almost all the studies have had the aim to investigate the personal exposure or correlate annoyance to indoor concentrations. We also lack information of the day to day use, in new established families, amongst household with infants etc. etc.

The instantaneous addition to the VOC content in the indoor environment is also a matter of day to day use of various non-odour compounds. From the survey amongst 1000 persons is shown the frequent use of deodorant, Christensen (1993), Lindahl (1993). As 50 % of the men and 65 % of the women are using deodorant every day the increase of non-oxidised gases are substantial.

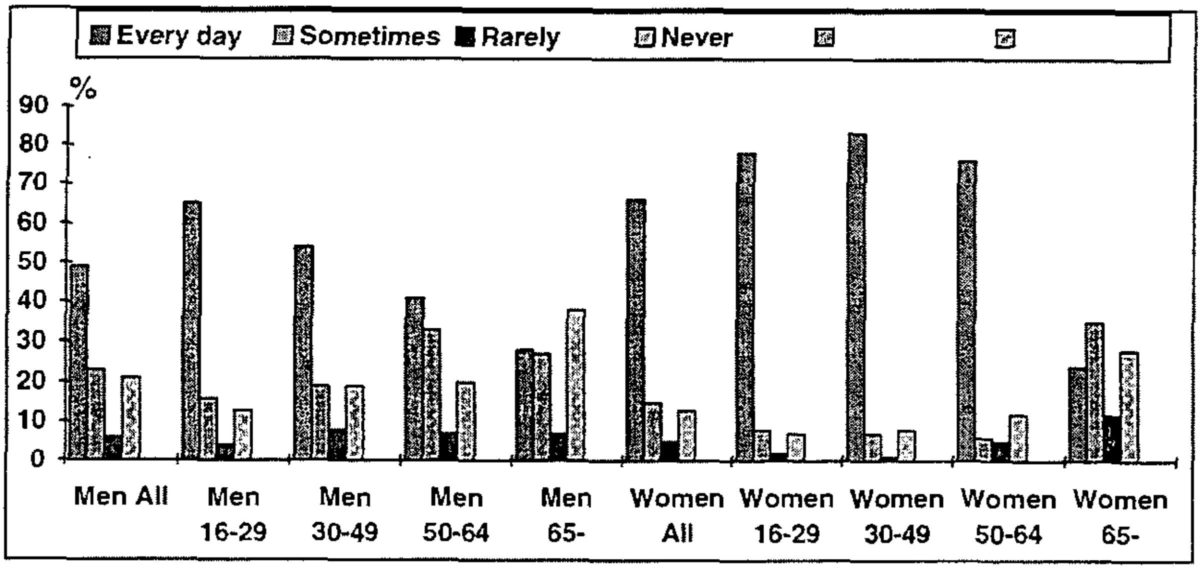


Figure 7.25 The use of deodorant.

The use of deodorant in some European countries is given in figure 7.26. It indicates, that an instant daily addition of VOC, is most common in every dwelling. Together with figure 7.25 it shows a higher frequency in households with small children.

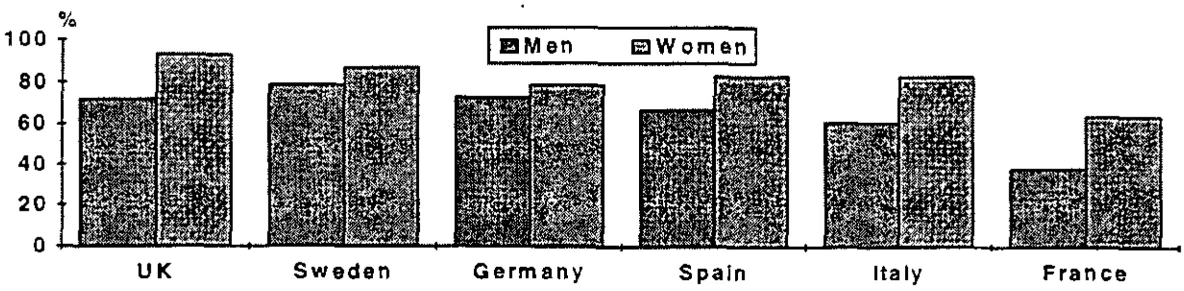


Figure 7.26 Percentage of men and women using deodorant

Sensory Effects

As there are so many different pollutant sources, hygienists claim that it is the perception of the indoor climate that is valid for judging the acceptability. In the WHO Aur Quality Guide lines for Europe is recommended that the nuisance threshold level gives dissatisfaction of 5 % of the occupants not more than 2 % of the time. The European guidelines for indoor air quality require the dissatisfaction within a range from 10 % to 30 %.

Below is quoted from WHO Air Quality Guidelines for Europe page 11:

Criteria for Endpoints other than Carcinogenicity
Criteria for consideration of sensory effects

> *Some of the substances selected for evaluation have malodorous properties at concentrations far below those at which toxic effects occur. Although odour annoyance cannot be regarded as an averse health effect in a strict sense, it affects the quality of life (7). therefore, odour threshold levels for such chemicals have been indicated where relevant and used as a basis for separate guideline values.*
>
> *For practical purposes, the following aspects and respective levels were considered in the evaluation of sensory effects:*
>
> *(a) intensity, where the detection threshold level is defined as the lower limit of the perceived intensity range (by convention the lowest concentration that can be detected in 50 % of the cases in which it is present);*
>
> *(b) quality, where the recognition threshold level is defined as the lowest concentration at which the sensory effect, e.g. odour, can be recognized correctly in 50 % of the cases;*
>
> *(c) acceptability and annoyance, where the nuisance threshold level is defined as the concentration at which not more than a small proportion of the population (less than 5 %) experiences annoyance for a small part of the time (less than 2 %); since annoyance will be influenced by a number of psychological and socioeconomic factors, a nuisance threshold level cannot be defined on basis of concentration alone.*

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7.2 Energy Models

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The energy required to condition air brought into the home either through natural leakage or international ventilation depends on the enthalpy difference between infiltrating and exfiltrating air. For heating dominated climates, sensible temperature differences typically are the primary concern.

Thermal liabilities, in the form of additional space heating load, will be incurred when air leakage and ventilation cause the internal temperature of residences to fall below a certain balance point. For poorly insulated, low mass houses, this point will be close to the thermostat set point. For most modern well insulated houses, the balance point would typically be 4 to 6°C below the thermostat set point. The balance point for each house depends on the rate of internal heat gains, the solar-optical properties of glazed fenestration, conduction, and mass. Variations in induced ventilation rate combined with natural leakage will also shift the balance point.

When ventilation rates are excessive, such as during "airing", the ventilation rate exceeds the capacity of the heating system to warm the infiltrating air to the indoor temperature. The heat capacity of the thermal mass of the house can become discharged, and thermal liabilities become very difficult to calculate.

7.2.1 Calculation Procedures

The preferred method of calculating thermal liability is to use the net air exchange rate determined by multi-zone air flow modelling as an input for a thermal simulation model which takes into account the physical parameters of the building, net heat recovery from mechanical ventilation, if any, local climate, and internal heat gains. Several such models exist, examples would include SUNDAY, SUNCODE, DOE2, BLAST, CALPAS, HOTCAN.

The total energy import resulting from ventilation will be the sum of the thermal liability of infiltration and intentional ventilation plus the fan energy, net of any heat recovery. Simple heat loss calculations Liddament (1986), may be adequate for determining thermal liabilities if an appropriate balance point is chosen, and only those hours where the external ambient temperature is less than the balance are included in the calculation.

Simplified heat loss calculations with no heat recovery gives

$$H = Q\rho \; c_p(T_{int} - T_{ext})\cdot t \qquad \text{(Wh)}$$

Where Q = air flow rate (m^3/s)

ρ = air density (kg/m^3)

c_p = specific heat of air (J/kg)

T_{int} = internal temperature (K)

T_{ext} = external temperature (K)

t = time [h]

For the portion of ventilation provided by mechanical means, fan energy must be included, and enthalpy (sensible and latent heat) recovery needs to be included if applicable to the mechanical system.

Degree-day calculations

Where applicable degree-day information exists, it is possible to replace (T_{int} - T_{ext}), averaged on a daily basis, with degree days at a specific base temperature. Caution should be exercised, as most degree-day data is at a base temperature higher than the balance point temperature, and must be adjusted. Erbs, Beckman and Klein, 1981 have developed calculation procedures for adjusting the degree day base to better represent the balance point of buildings.

Seasonal energy use calculations

The results of numerous thermal simulations performed on a variety of housing prototypes, including high and low thermal mass structures located in climates varying from cool to cold, suggest that one reasonably accurate method of determining the thermal liability is to use a limited heating season with the simple calculation. The best agreement between heating liabilities determined by thermal simulation and heating liabilities determined by simple calculation occurs when the simple calculations are limited to a seven month heating season by excluding May through September, Jackson and Kennedy, (1994). Constraining the heating season results in an average agreement within about seven percent between thermal simulations and the simple calculations.

Simplified calculations can be performed on an hourly basis, but using daily or weekly averages or binned hours for temperatures and averaged net flow rates results in only minor loss of accuracy, in the one to three percent range, relative to thermal simulation results.

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7.3 IAQ Models

Author Lars-Göran Månsson, Sweden, Operating Agent

The development of computer codes for solving mass balance equations have resulted in some program accessible for both researchers and developers during the last decade. To deal with the individual rooms in a dwelling and the ventilation system it is necessary to have a multi-zone model. Mostly those models have given results of the air flow rates in each room. Further development has resulted in modelling the emission of pollutant either as a constant source all over the dwelling or in a room or a local source or a moving source like the emission from human beings. Most important is the input data selection. It is more important than the choice of the model.

7.3.1 Introduction

As the main aim with the annex is to evaluate ventilation systems the influence of as many variables as possible must be able to be handled by the model. A model must be able to deal with dynamic process both indoors and outdoors. This means that a lot of parameters can be changed over the time. Examples of those parameters are:

1. External e.g. temperature, wind velocity, sunshine, shading.
2. Building envelope e.g. air tightness, unintentional cracks, intentional leakage paths (supply devices)
3. Internal e.g. pollutants (average over the dwelling, resident depending, local sources), ventilation system, room location, door opened or closed, room volume.

At least the above parameters must be able to be handled in a model, if a detailed evaluation shall be made. In particular dwellings with a natural ventilation system are not possible to evaluate unless all the influencing parameters are dealt with. Only very few models take into account all the parameters like wind dynamics, Feustel and Raynor-Hoosen (1990).

All the multi zone models assume complete mixing in each zone. If an individual room is to be investigated on the consequences of not having complete mixing it can be handled by the discussion of ventilation efficiency and the use of computational fluid dynamic models (CFD). In such case most often only one room is dealt with.

The models can include adsorption and emission of different gaseous pollutants as well as the treatment of water vapour. The greatest problem is to find material data specifying water vapour sorption and emission/adsorption of gaseous pollutants.

7.3.2 Model Comparison

The selection of a model is depending on how well it models the algorithms. If the models are compared the same input data must be used and the models ran by the same person in order to avoid differences in the input data. Orme (1995) shows that there is not great differences between the four models tested. The models were COMIS 1.3, CONTAM93, MZAP, BREEZE 6.0f. As the main aim was to see if the modelling of various input data were similar no comparison was made on weather the simulations could take into account a dynamic process over a day or a year.

The comparison gave identical results or less than 1 % deviation between the average of the four models and an individual one. If a very small leakage path is at hand the deviation can be about 10 %. However, the mass flow rate for the smallest flow path (~ 0.9 kg,h^{-1}) is 1/10 of the next two and the total outgoing flow rate was in average 154.6 kg,h^{-1} and the deviation from the average value is less than 0.5 %.

The conclusion is that it is not the model that is the most important but the careful selection of the input data. Of course, the model must not be too simplified, but compatible to the models compared in this study.

7.3.3 Validation

The validation of the models to measured data is very complicated, as it is both time consuming and expensive to measure all the detailed flow rates during different conditions. As full scale measurements are under the influence of many practical circumstances that can give fault in the collection of data also uncertainties will exist in measured values. Often the validation must be done by comparing shorter periods like weeks during different seasons. Such validations can also be of great value especially if extreme situations are represented as well as more normal ones.

Blomsterberg (1990) validated with the model MOVECOMP the measurements made in different single family houses. For houses equipped with mechanical ventilation good agreement was shown, but for houses with natural ventilation the agreement was much less in agreement. However, the measurement period was only a week and the characteristic of some of the flow paths were nearly impossible to measure (e.g. exfiltration). Still more detailed measurements have to be done in order to be able to validate the models.

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7.4 Thermal Comfort Model (Draught Model)

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The perceivel thermal comfort in a room is a complex situation depending on many parameters and the temperature of the supply air is a very important one. Of course the satisfaction of the thermal climate is very depending on the metabolic rate and the clothing. The traditional parameters for controlling that the thermal comfort can be achieved are:

1. Ambient room temperature
2. Relative humidity (or wet bulb temperature, water vapour pressure etc.)
3. Radiant mean temperature
4. Radiant temperature asymmetry
5. Vertical temperature difference

Those factors are also depending on the heating system, U-values in the external walls, roof, and floor, and the area of the windows. The ventilation system must be checked so that no conflict with those criteria will appear.

Ventilation directed parameters that can be perceived as parts of the thermal comfort, also called the draught sensation. The definition of draught is "*An unwanted cooling of the human body due to air movement*". The parameters are:

a. Air velocity
b. Turbulence intensity
c. Room air temperature.

An equation has been formulated by researchers at the Technical University of Denmark (DTH), Lab. of heating and air conditioning, Lyngby for the links between a, b, and c, see the equation below. As this is a result of the perceived draught by people in a panel the equation is purely an empiric equation. The perception of draught is very complicated and are also a matter of the activity level and clothing.

As many complaints on the supply of air is directed towards the draught sensation, we would like to have a design tool, to check, if the performance will fulfil that an agreed number of occupants are satisfied. The parameters can be measured in a laboratory and predictions can be made by calculations using the equation. From an engineering point of view this is required in the design stage and will make a demand for measured data reported for the components. Of course, we have to deal with the uncertainty of the measurement equipment.

The regression model of The Draught Equation is:

$$PD = (34-t_i)\times(v-0.05)^{0.62}\times(3.14+0.37\times v\times T_u)$$

where

PD	Predicted dissatisfied in percentage (%)
t_i	Indoor room temperature (°C)
v	Air velocity (m/s) (often given as the velocity directed towards the neck of a person)
T_u	Turbulence intensity in percentage (%)

The sensitivity study of the constants has been made with the air velocity from 0.1 m/s to 0.35 m/s and the indoor temperatures 19 °C, 20 °C 21 °C, 22 °C, 23 °C, 24 °C, and 25 °C at turbulence intensities 10 %, 20 %, 30 %, 40 %, 50 %, and 60 %.

Variation of the constant with the given value 34
34±1 gives only 1 %-unit deviation in the result (PD) for a fault in the given constant.
34±5 gives about 6 %-units deviation in the result (PD) for a fault in the given constant.

Variation of the constant with the given value 0.05
0.05±0.01 gives a 2 %-unit deviation in the result (PD) for a fault in the given constant.

Variation of the constant with the given value 0.62
If the constant is 0.6 a 2 %-unit deviation is given in the result.

Variation of the constant with the given value 3.14
If the constant is 3 the derivation is very small.

Variation of the constant with the given value 0.37
If the constant is 0.4 a 1 % unit deviation is given in the result.

If the constants are given a few percentage faults, the result is not very dramatic as the PD-value should be used as a guidance. It is not necessary to calculate the exact single unit. On the contrary it is easier to understand if the result is given ending with the figures 5 or 0 (5, 10, 15,... etc.).

With a fault of 3 % of the given values of the constants the results can be deviating up to 20%. For the greater faults of about 10 - 15 % the result will end up deviating up to 100 % from the result with the equation. As the original equation is based on measured air velocity, turbulence intensity and room air temperature the measurement errors must be the bases for the sensitivity in the constants.

A 10 % fault in the measurement is very common. With the discussion above the PD-value must be given with much care and with a range possibly also an upper limit. In a study on various anemometers for the measured turbulence intensity Melikov and Sawachi (1992) report that for 5 different anemometers the difference between the highest and lowest values a 10 %-unit deviation at the low value of 10 % turbulence intensity and a 30 %-unit deviation at 30 % turbulence intensity (range 10 - 40 %). With such a large range of uncertainty it may cause problems to interpret the measured values as well as the equation above as uncertainties may arise in what type of anemometer that was used when the data were collected.

If we accept a low fault in the constants of the formula we can meet the uncertainty in the measured values of the various devices by using the higher values. From practice we also know, that low turbulence is very hard to achieve. The above fault discussion can be used when giving the boundary conditions and the range that can be allowed in real cases.

Conclusion

The conclusion is that if the aim is to have the PD-value at 15 % it might also be up to 30 % with the given measured values for air velocity, turbulence intensity and room air temperature. If the target was a PD-value = 10 % the calculation with measured values and within the uncertainty within the empiric equation the PD-value could also end up to be PD=20%.

The practical way to use the equation is to compare different solutions in the selection phase. Another means can be to recommend how close to a device a person can sit or stand. We can use the equation as a quality index, especially when discussing if all the space can be used, even close to the external walls and windows.

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7.5 Ventilation efficiency

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7.5.1 Introduction

Despite of the fact that the flow rate is in accordance with the ventilation standards and the lack of thermal bridges, mould growth, i.e. in bathrooms, arises frequently. This can be caused by a short-circuit flow of ventilation air. Air that is supplied at the lower end of the door is exhausted almost immediately through an exhaust device in the ceiling, nearby the door. Moisture remains in the room and causes mould growth. The efficiency of the ventilation system with respect to the removal of the produced moisture is insufficient.

Literature study gives a limited number of criteria for ventilation effeciency. It is important to make a distinction between the replacement of "old polluted" room air with clean air and the removal of pollutants from the room to prevent them from spreading to the occupied zones. In habitable rooms, ventilation is particularly used to replace polluted room air. In service rooms, such as kitchen and bathroom, the objective is to remove produced moisture or odour rapidly.

The usefulness of the different criteria for evaluating ventilation efficiency in dwellings is marked on the basis of six qualifications, which are worked out for several types of ventilation systems.

7.5.2 Ventilation efficiency criteria for service rooms

Ventilation efficiency, $\in$

$$\in = \frac{C_e}{C_r} \qquad (0 \leq \in < \infty)$$

C_e = Concentration of pollutants in the exhaust duct (m^3/m^3)

C_r = Mean concentration of pollutants in the occupied zone (m^3/m^3)

$\in$ does not provide direct information about air quality (concentration of pollutants). C_e is not constant, but is influenced by C_r. $\in$ is specifically meant for the determination of the efficiency of a local exhaust system. When as a result of (local) natural cross-ventilation C_e decreases relatively more than C_r, ventilation efficiency will decrease, while air quality in the occupied zone increases.

By measuring the concentration of pollutants on several points, it is possible to show the mean concentration of pollutants as well as local concentration differences. Since $\in$ is measured in equilibrium condition, $\in$ does not offer insight into dynamic exhaust behaviour of the ventilation system.

Contaminant removal efficiency, η

$$\eta = \frac{C_e}{C_r + C_e} \qquad (0 \leq \eta \leq 1)$$

In principle the same remark goes for η as well as for $\in$.

Capture efficiency, S

$$S = \frac{C_e}{\frac{q}{Q}} \qquad (0 \leq S \leq 1)$$

q = Pollutants flow rate (m^3/s)
Q = Exhaust flow rate (m^3/s)

There is no relation between S and the concentration of pollution in the occupied zone. Therefore, S is an evaluation of the functioning of the ventilation system and not a validation of air quality as a result of this ventilation system. I.e., by using natural cross-ventilation air quality in the occupied zone can improve strongly, while S remains nearly constant.

Due to the fact that no concentrations are measured in the occupied zone, it is not possible tot establish concentration differences. S is measured in equilibrium condition. Dynamic effects are not taken into account.

Removal efficiency, η

$$\eta = \frac{\sum Q_e}{\sum Q_r} \qquad (0 \leq \eta \leq 1)$$

ΣQ_e = total pollutants mass exhausted (kg)
ΣQ_r = total pollutants mass supplied (kg)

During the determination of η the total pollutants mass exhausted is related to the total pollutants mass supplied. There is no direct relation between η and the airquality in the occupied zone. During natural cross-ventilation a part of the pollutants will be blown off outside of the local exhaust system. As a result ΣQ_e will decrease and air quality will improve but η will decrease.

Due to the fact that the total pollutants mass exhausted off is measured in the exhaust duct, it is not possible to determine (local) concentrations. Because the total mass of pollutants exhausted is measured from the beginning, dynamic changes are taken into account when determinating η.

Collection efficiency, CE

$$CE = 1 - \frac{C_r}{\frac{q}{Q}\left(1 - e^{\left(\frac{Q}{v} \cdot t\right)}\right)} \qquad (-\infty < CE \leq 1)$$

t = time (s)
v = room volume (m^3)

The mean concentration of pollutants in the room that occurs during the working of a local exhaust duct, will be related to the concentration that occurs by complete mixing. Therefore, inspite of the constant concentration of pollutants, *CE* changes if room volumes or flow rates will vary. *CE* gives only an indication of air quality as a result of the ventilation system.

Because there is a direct link (non-lineair) between *CE* and the concentration of pollutants in the room, the influence of natural cross-ventilation in the room will be expressed by the *CE* value.

The mean concentration of pollutants will be measured 10 minutes after starting the pollutant production by mixing the air and followed by measuring the concentration of pollutants. The mean concentration of pollutants is measured in the room, not in the living area. Concentration differences are not measured. The mean concentration in the room results from the preceding production of pollutants and the exhaust process. Therefore dynamic variations are taken into account.

Pollution index, PI

$$PI = \frac{C_r}{\frac{q}{100}(1 - e^{(-\frac{100}{v} \cdot t)})} \qquad (0 \le PI < \infty)$$

PI is in the same way defined as *CE*, except that for the exhaust flow rate the arbitrary value of 100 m^3/h is fixed.

Room Pollution Index, RPI

$$RPI = \frac{C_r}{\frac{q \cdot t}{V}}$$

The pollutant concentration in the room is related to the concentration that will occur if no pollutants would be exhausted. Therefore there is a direct (lineair) coupling between *RPI* and the concentration in the occupied zone. Because of this, it is possible to take into account the influence of natural cross-ventilation when evaluating ventilation efficiency. Comparing *RPI* from rooms with different volume has no practical meaning, because the frame of reference changes. This also fits for *CE* and *PI*.

Local differences of pollutants concentrations can be detected if the concentration will be measured at several well choosen points in the occupied zone. Dynamic behaviour of the concentration is taken into account and will be depending on the total measurement time.

7.5.3 Ventilation efficiency criteria for habitable rooms

Nominal time constant, T_n

$$T_n = \frac{V}{Q} \qquad (0 \le T_n \le \infty)$$

T_n is defined as the quotient of the room volume and the flow rate. It is reflecting the time it takes to supply the room with an amount of air as much as the volume of the room.

Air quality can be judged roughly by determing T_n, on condition that the air flow pattern in the room is not a short circuit flow. If T_n decreases the room will be faster flushed with outdoor air. Therefore air quality will improve. For short circuit flow the supply air will move directly to the exhaust point. Outdoor air is not mixed with polluted air in the room and instead of polluted air, outdoor air is exhausted.

T_n can be measured for all types and combinations of types of ventilation systems, if the flow rate is known. Concentrations of pollutants will not be measured so differences between concentration in the room can not be shown. Since T_n will be determined at equilibrium, dynamical effects can not be made visable.

Air change time, T_r $(0 \leq T_r \leq \infty)$
T_r shows the time that the air lingers in the room. $T_r = 2 \times \langle T \rangle$ where $\langle T \rangle$ is the mean age of the air in the room.

T_r gives a good indication about the air quality in the room. If air and pollutants remain shorter in the room, air quality in the room will improve. So a short T_r is desirable. The shortest possible T_r is obtained for piston flow. For local emission of pollutants T_r doesn't give a good indication of the air quality. T_r can be used for all types and combinations of types of ventilation systems. Local effects can be detected, depending on the measurement method. Dynamic effects are not taken into account.

Air change efficiency, $\in$

$$\in = \frac{T_n}{T_r} \qquad (0 \leq \in \leq 1)$$

$\in$ shows how fast air in the room is changed compared with the shortest possible lingering time of air in the room, T_n. If T_n and T_r are known $\in$ can be determined.

Air quality is improved if $\in$ increases. The best air quality will be obtained by piston flow, $\in = 1$. With complete mixing of air in the room, the value of $\in = ½$. If no air is exhausted out of the room air quality is poor (short circuit flow) and $\in = 0$. $\in$ can be determined for all types of systems and flow patten. Because the T_r can be determined by measuring concentrations of pollutants at several points in the room, local differences in concentration can be shown. Dynamic effects are not taken into account.

7.5.4 Qualifications of efficiency criteria

Practical meaning
The main aim of ventilating, airing and exhaust of pollutants is to achieve a healthy indoor air quality in the occupied zones. So it is important that this is clearly expressed by means of the used efficiency criterion. A decrease of the pollutant concentration in living spaces must lead to a more or less equivalent reduction or rise of the criterion value. It is important that the criteria relate to the same frame of reference all the time. This reference has to be unambiguous and physically justified. A reference is not valuable if it does change drawing a conclusion with regard to the functioning of the ventilation system. This also fits the case in which influence parameters (for instance the ventilation rate) are changed and effects of these changes have to be determined.

Combined effects
The main objective of a local exhaust system is to realise a healthy air quality in the living area. However, the local exhaust system is only a tool. So it is more important to evaluate the **room** ventilation efficiency instead of only the ventilation efficiency of the exhaust system. The benefit of this approach is that also the combination of ventilation systems can be evaluated. If i.e. a kitchen hood is supported by natural ventilation through cracks or

windows, the pollutant concentation in the occupied zones gives the only correct valuation of the efficiency of the combination of these ventilation systems.

Local effects
For a healthy indoor air quality in the entire occupied zone large local deviations are not acceptable. By using only an average efficiency value for the whole living zone one has to deal with loss of information and incorrect judgement concerning the functioning of ventilation systems.

Dynamical approach
Normally the concentration of pollutants in habitable rooms is in balance, which makes a stationary approach possible. This does not fit for the removal of pollutants in service rooms. During the period of i.e. preparing a meal, taking a shower or a bath the moisture or smell concentration does not always attain a stationary level. So in this case it is important that the criterion also is applicable for non stationary approach, in which the efficiency value varies in time.

Measuring method
Accordingly as the measuring method to determine the ventilation efficiency becomes simpler, the practical applicability of the criterion increases and it takes less time to measure

Measuring tools
Accordingly as the required measurement tools are simpler and less expensive the practical applicability of the criterion increases

7.5.5 Evaluation efficiency criteria

For seven distinguished ventilation systems, see chapter 4, the practical applicability of the investigated efficiency criteria is evaluated and presented in table 7.4. Thereby difference is made between habitable rooms and service rooms.

7.5.6 Conclusions and recommendations

The use of a room is determining the choise of a criterion for evaluating ventilation efficiency. Therefore, a distinction is made between habitable rooms and service rooms. For both types of rooms, efficiency criteria in which air quality or the pollutant concentration is to be expressed are the most suitable. In fact using these criteria the type of ventilation system or combination of several ventilation systems is irrelevant.

An important issue concerning the efficiency criterion is the frame of reference. Preferably, this has to be constant. This means there have to be made agreements about example measurementtime, production of pollutants etc. Also there have to be made agreements about the measurement procedure and assumptions for the simulations.

- How to simulate the pollutant sources. Odour and moisture (while preparing meals) have a different behaviour. Moisture is partually accumulated in the construction and furniture
- A life test or instantaneous measurements
- Standardised residential behaviour
- Standardised climate (temperature, wind velocity for low-rise and high-rise buildings)
- How to evaluate the measurement values. Besides the mean concentration values the local measured levels are of interest. Restrictions concerning the standard deviation of the locally measured concentrations can prevent large local differences.

Table 7.4 Ventilation efficiency criteria

Service rooms		ventilation effectiveness						
		$\epsilon = \frac{C_e}{C_R}$						
Ventilation systems		Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks
a	natural stack ventilation							
b	natural window ventilation							
c	natural supply through facades and exhaust through vertical ducts	—	0	+	—	+	+	
d	supply through facades and exhaust with fans on exhaust ducts	—	0	+	—	+	+	
e	supply via fan and ducts and exhaust fans in services rooms	—	0	+	—	+	+	
f	supply via fan and ducts and exhaust fans in services rooms	—	0	+	—	+	+	
g	supply via fan and ducts and exhaust from services rooms via ducts and fan	—	0	+	—	+	+	

Service rooms		contaminant removal efficiency						
		$\eta = \frac{C_e}{C_i\, C_r}$						
Ventilation systems		Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks
a	natural stack ventilation							
b	natural window ventilation							
c	natural supply through facades and exhaust through vertical ducts	—	0	+	— —	+	+	
d	supply through facades and exhaust with fans on exhaust ducts	—	0	+	— —	+	+	
e	supply via fan and ducts and exhaust fans in services rooms	—	0	+	— —	+	+	
f	supply via fan and ducts and exhaust fans in services rooms	—	0	+	— —	+	+	
g	supply via fan and ducts and exhaust from services rooms via ducts and fan	—	0	+	— —	+	+	

Service rooms		capture efficiency						
		$S = \frac{C_e}{\frac{q}{Q}}$						
Ventilation systems		Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks
a	natural stack ventilation							
b	natural window ventilation							
c	natural supply through facades and exhaust through vertical ducts	— —	— —	— —	—	0	—	1
d	supply through facades and exhaust with fans on exhaust ducts	— —	— —	— —	—	0	—	
e	supply via fan and ducts and exhaust fans in services rooms	— —	— —	— —	—	0	—	
f	supply via fan and ducts and exhaust fans in services rooms	— —	— —	— —	—	0	—	
g	supply via fan and ducts and exhaust from services rooms via ducts and fan	— —	— —	— —	—	0	—	

Service rooms		removal efficiency						
		$\eta = \frac{\Sigma Q_e}{\Sigma Q_i}$						
Ventilation systems		Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks
a	natural stack ventilation							
b	natural window ventilation							
c	natural supply through facades and exhaust through vertical ducts	—	— —	— —	0	—	— —	1
d	supply through facades and exhaust with fans on exhaust ducts	—	— —	— —	0	—	— —	
e	supply via fan and ducts and exhaust fans in services rooms	—	— —	— —	0	—	— —	
f	supply via fan and ducts and exhaust fans in services rooms	—	— —	— —	0	—	— —	
g	supply via fan and ducts and exhaust from services rooms via ducts and fan	—	— —	— —	0	—	— —	

Service rooms		collection efficiency						
		$CE = 1 - \frac{C_i}{\frac{q}{Q}\,(1 - e^{(-\frac{Q}{V} \cdot t)})}$						
Ventilation systems		Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks
a	natural stack ventilation	—	++	+	+	—	— —	2 3
b	natural window ventilation	—	++	+	+	—	— —	2 3
c	natural supply through facades and exhaust through vertical ducts	—	++	+	+	—	— —	1 3
d	supply through facades and exhaust with fans on exhaust ducts	—	++	— —	+	—	— —	3
e	supply via fan and ducts and exhaust fans in services rooms	—	++	— —	+	—	— —	3
f	supply via fan and ducts and exhaust fans in services rooms	—	++	— —	+	—	— —	3
g	supply via fan and ducts and exhaust from services rooms via ducts and fan	—	++	— —	+	—	— —	3

Service rooms		polution index						
		$PI = \frac{C_i}{\frac{q}{100}\,(1 - e^{(-\frac{100}{V} \cdot t)})}$						
Ventilation systems		Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks
a	natural stack ventilation	0	++	+	+	—	—	3
b	natural window ventilation	0	++	+	+	—	—	3
c	natural supply through facades and exhaust through vertical ducts	0	++	+	+	—	—	3
d	supply through facades and exhaust with fans on exhaust ducts	0	++	+	+	—	—	3
e	supply via fan and ducts and exhaust fans in services rooms	0	++	+	+	—	—	3
f	supply via fan and ducts and exhaust fans in services rooms	0	++	+	+	—	—	3
g	supply via fan and ducts and exhaust from services rooms via ducts and fan	0	++	+	+	—	—	3

Service rooms		room pollution index						
		$RPI = \frac{C_i}{\frac{q \cdot t}{V}}$						
Ventilation systems		Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks
a	natural stack ventilation	+	++	+	+	—	—	
b	natural window ventilation	+	++	+	+	—	—	
c	natural supply through facades and exhaust through vertical ducts	+	++	+	+	—	—	
d	supply through facades and exhaust with fans on exhaust ducts	+	++	+	+	—	—	
e	supply via fan and ducts and exhaust fans in services rooms	+	++	+	+	—	—	
f	supply via fan and ducts and exhaust fans in services rooms	+	++	+	+	—	—	
g	supply via fan and ducts and exhaust from services rooms via ducts and fan	+	++	+	+	—	—	

++ excellent   + good   0 neutral/not appropriate   — moderate   — — bad

1 Complementary to determine Q by means of simple measurements.

2 Complementary to determine Q by means of extended measurements, or approximate calculations.

3 On the basis of local measurements. In fact the criterium assumes that the concentration is a means value for the living zone.

Table 7.4 (cont.) Ventilation efficiency criteria

Habitable rooms		Nominal time constant							Air change time							Air change efficiency						
		T_r							$T_n = \frac{V}{Q}$							$\epsilon = \frac{T_n}{T_r}$						
Ventilation systems		Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks	Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks	Practical meaning	Combined effects	Local effects	Dynamical approach	Measurement method	Measurement tools	Remarks
a	natural stack ventilation	0	+	- -	- -	-	0	2	+	+	+	0	0	0	2 4	+	+	+	0	0	0	2 4
b	natural window ventilation	0	+	- -	- -	-	0	2	+	+	+	0	0	0	2 4	+	+	+	0	0	0	2 4
c	natural supply through facades and exhaust through vertical ducts	0	0	- -	- -	+	+	1	+	+	+	0	0	0	1 4	+	+	+	0	0	0	4
d	supply through facades and exhaust with fans on exhaust ducts	0	0	- -	- -	++	++		+	+	+	0	0	0	4	+	+	+	0	0	0	3 4
e	supply via fan and ducts and exhaust fans in services rooms	0	0	- -	- -	++	++		+	+	+	0	0	0	4	+	+	+	0	0	0	3 4
f	supply via fan and ducts and exhaust fans in services rooms	0	0	- -	- -	++	++		+	+	+	0	0	0	4	+	+	+	0	0	0	3 4
g	supply via fan and ducts and exhaust from services rooms via ducts and fan	0	0	- -	- -	++	++		+	+	+	0	0	0	4	+	+	+	0	0	0	3 4

1 Complementary to determine Q, by means of simple measurements.

2 Complementary to determine Q, by means of extended measurements, or approximate calculations.

3 Local variations of the concentration of pollution can be shown by carrying out local measurement. In fact the criterium assumes that the concentration is a means value for the living zone.

4 Local variations of the concentration of pollution can be shown by carrying out local measurement.

++ excellent

\+ good

0 neutral/not appropriate

\- moderate

\- - bad

7.6 Life Cycle Costing

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7.6.1 Introduction

Discussion of the choice of ventilation options is often restricted to purely technical criteria, ventilation effectiveness, indoor air quality and so on. Indeed in some cases criteria, particularly for example for (indoor air quality) IAQ and levels of pollutants are set with little or no reference to cost. However as will be discussed later any expenditure implies an opportunity cost; something else which might give rise to greater benefits, could be done with the money. Thus a consideration of costs is essential and technical solutions are only viable if they can be effected at an economical acceptable cost.

Costs come in many forms, capital costs or initial costs, operating costs including energy and maintenance and the costs of periodic replacement. Furthermore these costs vary greatly from country to country. Different countries have very different energy regimes and different climates affecting the balance between initial or capital costs and energy costs. Labour costs differ very greatly between different countries. Thus systems which are economically viable in one country may be totally non viable in another, but there is a need for an agreed and standardised method of comparing total costs and Life Cycle Costing has become the standard method of doing this. Life Cycle Costing (LCC) bring initial or capital costs, replacement costs and the various components of running or operating costs together.

The primary purpose of this paper is to lay down the essential parameters for carrying out a life cycle costing exercise on domestic ventilation systems. The paper will also discuss important issues such as financial risk, capital rationing and opportunity cost which are often neglected in simple LCC appraisals. Existing official guidance documents tend to be related to much larger projects and to be related to specialised areas e.g. roads, hospitals etc., There is a need to relate the basic principals of life cycle costing and investment appraisal to the particular problem of domestic ventilation. This paper will not however go into great detail about the elements of LCC and investment appraisal and of more detailed treatment of these subjects the reader is referred to the references.

7.6.2 The Essentials of Life Cycle Costing

Life cycle costing is not essentially different from investment appraisal. The basis of investment appraisal is the concept of Discounted Cash Flow (DCF). The basis of discounted cash flow is primarily that of pure time preference. If we are to be induced to save or invest our money then in receiving back our money at some later date we require to be paid interest to compensate us for the loss of use of our money in the interval. Thus a dollar today becomes worth \$ $(1 + r)$ each new year where r is the interest rate or conversely a dollar in a years time is worth $1/(1 + r)$ today or a dollar in two years time $1/(1 + r)^2$ and so on. In general a dollar in year n has a net present value of $1/(1+r)^n$. Thus a stream of expenditure over a number of years can be brought back to its value in year 0 generally know as the Net Present Value (NPV). The value r is known as the discount rate which in the public sector is a value generally lower than current interest rates and is usually fixed for public projects by Central Government. In the private sector the discount rate is the required rate of return, generally greater than the public sector discount rate. This may have a significant effect on the choice of ventilation options between public and private sector housing. The factor by which an annual sum over a number of years has to be multiplied in order to give the NPV is known as the interest time factor.

If we consider a ventilation system with an initial cost of A, an operating cost (mainly energy) of x per annum and replacement cost of B every 10 years then over the lifetime of the dwelling say 60 years the NPV will be

$$NPV = A + \sum_{1}^{60} \frac{x}{(1+r)^n} + \frac{B}{(1+r)^{10}} + \frac{B}{(1+r)^{20}} + \frac{B}{(1+r)^{30}} + \frac{B}{(1+r)^{40}} + \frac{B}{(1+r)^{50}} \qquad (7.1)$$

In practice as will be shown below the equation is somewhat more complex than this and there are other factors to consider.

Mention should be made of other methods of investment appraisal. One of the most common, which is still often used is the simple pay back method. An investment is assessed by how many years it takes to pay back the initial investment from the profits or savings. This method is wrong since it takes no account of the life of the system. Thus a cheap low quality system with a short life, which may not even exceed the payback period appears better than the system which may go on producing benefits for many years.

A method closely related to NPV is the Internal Rate of Return (IRR). In general terms the internal rate of return is the discount rate which satisfies the equation.

$$\sum_{t=0}^{n} \frac{A}{(1+r)^t} = 0 \qquad (7.2)$$

or more simply the IRR is the rate of interest which reduces the NPV to zero. In principle the IRR method is not different from the NPV method but the IRR method does not cope easily with such problems as fluctuating interest rates, thus the NPV method has become the standard method of investment appraisal.

7.6.3 Cost Components for the Evaluation of a Domestic Ventilation System

The purpose of this section is to identify in outline components of the total cost of a domestic ventilation system. Costs are listed below:

Capital or Initial Cost

Cost of Equipment
Installation Cost (labour and materials)
Cost of installation time (in the case of a domestic ventilation system this is unlikely to be significant, but in larger projects it takes account of the lost use of the building during construction).

Operating Costs

Energy
Maintenance including cleaning and breakdown costs
(consider optimum maintenance frequency)

Replacement Cost

Mechanical ventilation systems are likely to require replacement several times during the lifetime of the building. In additional to the cost of the equipment and labour an allowance should be made for the cost of disruption during replacement. This may be negligible in the case of a simple extract fan or considerable in the case of ducted systems.

7.6.4 Practical Problems in Real Investment Appraisal

In the above it has been assumed that capital expenditure is readily available at a given interest rate, that energy and other costs are fixed and predictable into the future and that the ventilation system can be considered in isolation from other aspects of the dwelling. In practice none of these are true and because they are not true this gives rise to the problems of capital rationing, financial risk, and opportunity cost which will be discussed below.

Capital Rationing

It is generally not the case that funds are readily available to fund all projects showing a positive NPV. Capital is generally restricted particularly in the public sector. Broadly there are three approaches to the assessment of investments under capital rationing, NPV ranking, benefit/cost ratio and ranking of IRR.

Ranking in terms of NPV is fairly self explanatory from section 7.6.2. Benefit cost (B/C) ratio looks at the ratio of benefits to costs and selects those projects with the highest B/C ratios up to the amount of capital available. B/C ratio and NPV will not generally give the same answer.

For example consider the following:

Project	A	B	C	D	E
Cost 000s	100	150	200	250	300
NPV 000s	10	20	15	30	35
B/C ratio	1.1	1.133	1.075	1.129	1.080

If the capital ration is 900,000 then on NPV ranking we choose E, D, B, and C because these projects have the highest NPV. On B/C ratio ranking we choose B, D, A, and E, this time in order of B/C ratio. B/C ratio always maximises total NPV because it chooses projects in terms of the greatest NPV for each unit of capital.

Projects can also be ranked on the basis of their relative internal rate of return IRR. Ranking projects on IRR however is not the same as ranking via B/C ratios. The IRR is simply an absolute % rate of return whereas what is required is a measure of project performance relative to rational investment outlay.

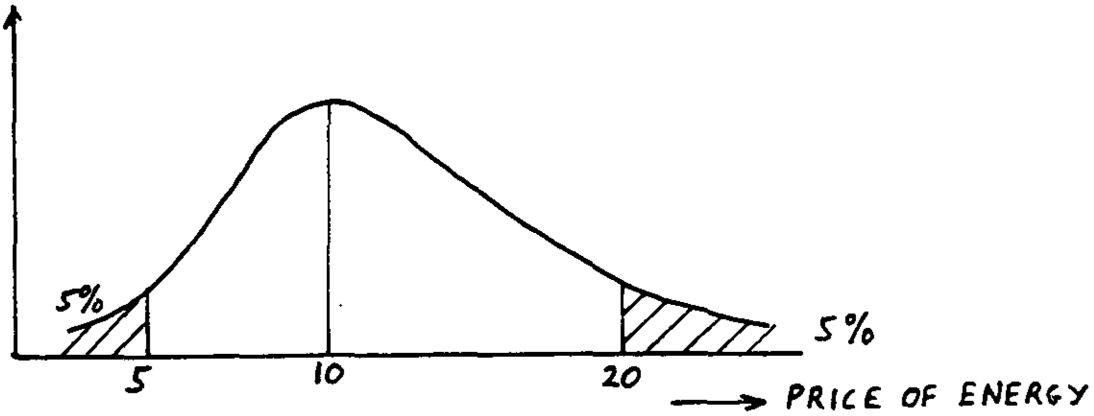
Financial risk

The question of financial risk in the selection of domestic ventilation systems arises primarily due to fluctuations in energy costs which may be considerable. Over the lifetime of a building there may also be variations in labour (maintenance) cost and in replacement costs. In the case of domestic ventilation the variance in NPV is likely to be mainly due to variations in energy prices and it will probably be adequate to consider capital, replacement and maintenance as fixed and only consider the variation in energy prices. Consider for example.

Project A High capital/Low energy
Capital cost $500
Project Life 10 years
Discount rate 10%
Interest Time factor = 6.1 (see eq (4) below
Energy use 10 units p.a. at a cost of £10 per unit
Total NPV = 500 + 6.1 x 10 x 10 = 1110

Project Life 10 years
Discount rate 10%
Interest Time Factor 6.1
Energy use 20 units p.a. at a cost of $10 per unit
Total NPV = 200 + 6.1 X 20- X 10 = 1420

Now let us assume that fuel costs have a distribution as shown below. i.e. log normal with 5% and 95% probabilities at $5 per unit and $20 per unit



At what price level will the two projects have equal NPV and what is the probability of this occurring. Let us call the price y

Then 500 + 10y • 6.1 = 200 + 20y • 6.1 therefore y = $4.9.
capital cost + project life x price interest/time factor

It can be seen that the probability of this occurring is less than 5%. This the risk of the high capital low energy project having the lower NPV is relatively small.

Opportunity cost
The choice of a domestic ventilation system is not carried out in isolation. The choice of the ventilation system is part of total building design and money spent on the ventilation system is money forgone in other areas e.g. building insulation. Thus what may appear to be the best option when simply comparing ventilation options, may not be, when considered overall. This is a complex field. A multidimensional optimisation exercise has to be carried out, involving linear programming or other optimisation methods such as hill climbing. The question is referred to in the paper by **Gustafsson** and **Karlson.**

7.6.5 Examples
The examples are based on a small house of volume $200m^3$. The ventilation rate is taken as $0.5\ h^{-1}$ and the mean heating season temperature difference typical of Southern England is taken to be 10°C. The heating season is taken as 210 days. The Building Life is taken as 60 years and the discount rate taken to be 6%.

Adventitious Ventilation

Ventilation flow rate = 0.5 h^{-1} = 100m^3/h

Therefore ventilation heat loss H $= M \cdot C_p \cdot \Delta\ T \cdot t$

$= \rho\ Q\ C_p \cdot \Delta\ T \cdot t$

Where M is the mass flow rate

ρ is the density of air

Q is the volume flow rate

C_p is the specific heat to air

Δ T is the mean inside-outside temperature difference

t is the length of the heating season

ρ = 1.2 kg/m^3; Q = 100m^3/h; C_p = 1.02 J/g°K; Δ T = 10°; t = 210 days

Thus H = 6.16 GJ

Assume gas heating with gas at £5/GJ and a boiler efficiency of 75% then the cost per annum is £41.

The annuity or interest time factor at 6% discount rate for 60 years is 16.16 so Net Present Value = £664.

Mechanical Ventilation with Heath Recovery (MVHR) Operating Cost

The airtightness of the house will be taken as having been tightened to 3 h^{-1} at 50 Pa i.e. 0.15 h^{-1} under normal conditions. By proportion from example "Adventitious Ventilation" the annual cost of the background loss is £12.3 per annum.

It is assumed that the MVHR system has an effectiveness of 0.7. The total ventilation rate is again taken as 0.5 h^{-1}. Thus 0.35 h^{-1} are supplied by the MVHR system and the heat loss is thus equivalent to an air change rate of 0.35 x 0.3 = 0.105 h^{-1}.

Thus the cost of the heat loss from the MVHR system is £8.63 per annum.

In addition there is the fan energy cost of running 2 x 40 W fans.

These use $80 \times 3600 \cdot 24 \cdot 210 = 1.45$ GJ p.a.

Electricity is taken to cost £18/GJ

Thus electricity cost is £26 p.a.

Maintenance cost is taken as £25 p.a.

Therefore the total operating cost is £71.9 p.a.

Interest/time factor for 60 years at 6% = 16.16

Therefore NPV of operating costs = £1162.

The capital cost is taken as £2000 and the life of the plant is taken as 15 years.

Thus over the lifetime of the house with a 6% discount rate the NPV of the capital cost is:

$$2000 + \frac{2000}{(106)^{15}} + \frac{2000}{(1.06)^{30}} + \frac{2000}{(1.06)^{45}} = £3328$$

Therefore Total NPV = £4490

Mechanical Extract System Intermittently Operated Operating Cost

Again assume background ventilation of 0.5 h^{-1} and mechanical extract ventilation operating for 4 hours per day providing an **additional** 100 m^3/h. This additional ventilation will be approximately half the fan flow rate.

From previous calculations the cost of the background ventilation will be £41.1 p.a. The cost of the heat loss due to the mechanical ventilation will be £6.85 p.a. The energy used by the fan assuming a 40 W fan will be:

$40 \times 3600 \times 4 \times 210 = 0.121$ GJ

Cost £18 per GJ = £2.2.

Assume maintenance cost is negligible.

Then total annual cost = £50.15 p.a.

NPV 60 years at 6% = £810

Assume capital cost of fan £50 and life 10 years.

$$\text{NPV} = 50 + \frac{50}{(1.06)^{10}} + \frac{50}{(1.06)^{20}} + \frac{50}{(1.06)^{30}} + \frac{50}{(1.06)^{40}} + \frac{50}{(1.06)^{50}} = £110$$

Therefore Total NPV = £920

System	NPV£
Adventitious Ventilation	- 664
NVHR	- 4490
Mech Extract intermittently operated	- 920

7.6.6 Sensitivity Analysis

In general terms Net Present Value may be expressed as benefits (or returns) less capital and operating costs as follows:

$$NPV=B-C-Jx \qquad (7.3)$$

Where B is the benefit

C is the capital costs

J is the interest/time factor

x is the operating cost

If we wish to compare two projects 1 and 2

Then $NPV_2 > NPV_1$

$$\text{If } B_2 - C_2 - Jx_2 > B_1 - C_1 - Jx_1 \qquad (7.4)$$

$$x_1 - x_2 > \frac{B_1 - B_2 + C_2 - C_1}{J} \qquad (7.5)$$

$$\text{The interest time factor } J = \frac{1-(1+i)^{-n}}{i} \qquad (7.6)$$

Where i is the discount rate

Where n is large $J \approx 1/i$

i and hence J may be regarded as relatively fixed. Although in economic theory the discount rate should relate to prevailing market interest rates, in practice, discount rates for investment appraisal are fixed within a percentage point or two. For a given comparison we may take B_1, B_2, C_2 and C_1 as fixed. Thus the inequality depends on $x_1 - x_2$ which in turn depend on fuel prices and the severity of the weather. If we make the comparison between system 1, adventitious ventilation, section 7.6.5 and system 2, MVHR

Then $x_1 = Wy_1$ (7.7)

Where W is a weather factor (the ratio of degree days to the standard case), and y_1 is the fuel cost in standard conditions.

$$x_2 = W(y_2 + z_2) + a_2 \qquad (7.8)$$

Where y_2 is the gas cost p.a. under standard conditions z_2 is the electricity cost p.a. under standard conditions. a_2 is the maintenance cost.

Therefore $NPV_2 > NPV_1$

If $Wy_1 - W(y_2 + z_2) + a_2 >$ Constant (7.9)

If we introduce a fuel cost factor for gas F

Then $WFy_1 - WFy_2 - Wz_2 >$ Constant, a_2 is also a constant. (7.10)

$WF(y_1 - y_2) - Wz_2 >$ Constant. (7.11)

$W(F(y_1 - y_2) - z_2 >$ Constant. (7.12)

If z_2 the cost of electricity is relatively small then MVHR will be more economic when either fuel is relatively expensive or weather relatively severe, a rather obvious conclusion. If we make eqn (7.12) into an equality and substitute the data from section 7.6.5 we have:

$y_1 = 41$, $y_2 = 20.9$, $z_2 = 26$,

$B_1 = B_2 = C_1 = 0$, $C_2 = 3328$, $J = 16.16$

$$W(20.1\,F + 26) = 181$$

If F = 1 then W = 3.9

If W = 1 then F = 7.7

The values of these factors at equality will be reduced if the benefits of MVHR are increased, the capital cost reduced or the interest time factor increased (the discount rate reduced).

since from eqn (7.5) $x_1 - x_2 \approx W \bullet (y_1 - y_2) = \frac{B_1 - B_2 + C_1 - C_2}{J}$

$$\therefore W = \frac{B_1 - B_2 + C_1 - C_2}{J \bullet (y_1 - y_2)}$$

7.6.7 References

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7.7 Noise

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7.7.1 Introduction

Controlling noise aspects, in particular reducing noise levels, is one of the most important factors that contribute to the satisfaction with a ventilation system. Noise aspects related to ventilation systems can be divided into two main classes: direct noise and indirect noise.

Direct noise is noise generated by the system itself. The system is both the source and the means of transport of the noise. Examples are noise generated by fans and by the mounting materials of air ducts (structure born noise), and noise generated by control valves and airducts and devices (aerodynamic noise).

Indirect noise includes all noise of which the source is outside the system. In this case the system merely transfers noise which originates outside the system.
Examples are traffic noise, noise from industrial plants, catering establishments and aircraft (outdoor noise), and domestic noise (internal noise sources).

7.7.2 Problem identification

In general, the following three ventilation techniques apply to dwellings:

- natural supply and exhaust;
- natural supply and mechanical exhaust;
- mechanical supply and exhaust (balanced ventilation), with or without heat recovery.

Noise related to domestic ventilation systems can be divided into three main areas:

- outdoor noise entering the dwelling through ventilation openings (cracks, slots, and air supply- and exhaust openings);
- noise generated by the ventilation system;
- sound transmission within or between dwellings by the ventilation system and/or internal ventilation provisions.

Depending on the type of ventilation system and the strategy, one or more of the three areas indicated in table 7.5 below are important.

Table 7.5 Noise importance

	Natural ventilation	**Mechanical exhaust**	**Balanced ventilation**
Outdoor noise	x	o	o
System noise	-	x	x
Sound transmission	o	o	x

- irrelevant/not applicable
o in general of minor importance
x important

7.7.3 Outdoor noise

Requirements and methods of calculation and measurement

Road traffic and other activities outside dwellings can be the cause of a noisy environment. In general, the allowable sound level in rooms is 35 dB(A) (ISO 1996). However, in some countries only 30 dB(A) is allowed (Sweden, Finland).

Dwellings with facades containing windows, unweatherstripped, and with regular glazing (single-pane 4 or 6 mm or double pane 4/6/6/ mm or 4/12/6 mm) a noise reduction of approximately 20 dB(A) is achieved. With the windows in the ventilation position (ajar), a noise reduction of approximately 15 dB(A) can be achieved. If outdoor noise levels at the facade exceed 50 to 55 dB(A), natural supply systems will require special acoustic measures, particularly with regard to the ventilation system.

The noise reduction of a facade (G_A) is the difference between the outdoor noise level (L_o) and the indoor noise level (L_i):

$$G_A = L_o - L_i \qquad \text{dB(A)}$$

The resulting noise reduction is determined by the overall sound reduction index of the facade (R_A), taking into account the noise transfer through ventilation openings, joints and cracks in the construction, and the acoustic properties of the room itself (room absorption).

$$G_A = R_A + 10\log\frac{A}{S} - 3 \qquad \text{dB(A)}$$

Where:
R_A is the overall sound reduction index of the facade in dB(A)
A is the room absorption in m^2 sabine
S is the total surface area of the facade in m^2
-3 is the correction for direct sound field to diffuse sound field.

Ventilation through the building envelope can be achieved by:

- joints and cracks around windows and doors (uncontrolled ventilation);
- ventilation openings in the facades (devices and windows);
- ducts in facades and the roof.

The way in which the contribution of the ventilation openings is taken into account depends on the way in which the sound reduction of each opening is expressed. The sound reduction index of a ventilation opening may concern i.e. the flow capacity, the cross section of the ventilation surface area, the gross surface area of the devices or a standardized room absorption, such as 10 m^2 sabine.

Noise reduction of facades

The transfer of noise across facades takes the following paths:

- closed facade areas (brickwork, panels)
- glass
- ventilation openings
- joints and cracks

If noise reduction beyond approximately 20 dB(A) is required, any joints and cracks will have to be properly sealed. Certain noise reduction standards thus prevent the possibility of ventilation by means of infiltration of air through joints and cracks in the facade. Other ventilation provisions will then be necessary, such as special - soundproofed - supply openings in windows or facades. Alternatively, the supply air can be achieved in part through noise-free facades.

To illustrate the interdependence of the acoustic properties of the different facade elements (i.e. brickwork, glass, ventilation openings and crack sealing), a mathematical comparison has been made between different facade types. The comparison is based on a room with a volume of 40 m^3. The total facade area is 10 m^2. The facade contains a window with an area of 3 m^2 and the room's reverberation time amounts to 0.5 s. The closed facade consists of brickwork and the supply air takes place by means of a soundproofed or non-soundproofed opening with a cross-section of 150 cm^2. A number of glazing alternatives have been evaluated: standard double glazing (4 mm glass - 12 mm cavity - 6 mm glass), high-quality acoustic glazing (8 mm glass - 20 mm gas-filled cavity - 10 mm layered glass) and optimal soundproofing glass (42 mm layered glass).Table 7.6 gives an overview of the maximum attainable noise reduction values pertaining to this type of facade.

Table 7.6 Maximum attainable noise reduction values (G_A) for a number of alternative facade types.

Description	Noise reduction dB(A)			
	Ventilation opening without sound-proofing	Ventilation opening with adequate sound-proofing	Ventilation opening with excellent sound-proofing	No ventilation opening
Standard glass, no weatherstripping	20.9	22.1	22.3	22.3
Standard glass, minor weatherstripping	23.1	25.2	25.7	25.8
Standard glass, good single weatherstripping	24.5	27.8	28.7	28.9
HQ ac. glass, double weatherstripping	26.2	32.8	36.4	37.6
Max. ac. glass, very good weatherstripping	26.4	34.0	40.2	44.0

Noise reduction can be as much as 40 dB(A) if ventilation openings are retained. This can only be achieved by means of proper soundproofing of the closed facade elements. In the case of a sandwich panel facade (timber thermal insulation timber), the last step towards an optimal level of provisions will not yield any improvement from C to D. Noise reduction will be restricted to approximately 32 dB(A). The reason for this is the noise contribution of the closed facade. Elaborate acoustic provisions to windows and ventilation openings can only be cost-effective if the other facade elements have good soundproofing properties.

Acoustic measures must be taken in the correct order:

- first apply adequate weatherstripping;
- then apply soundproofing to the ventilation opening;
- and finally improve the glazing.

Soundproofing of ducts

The noise reduction values of rooms with exhaust ducts for natural ventilation (i.e. ventilation stacks or "shunt" ducts) may be influenced by noise sources at the roof level e.g. from aircraft and elevated roads. If these rooms have facades without soundproofing provisions ($G_A \approx$ 20 dB(A)) such ducts will have a negligible influence on the noise reduction value (0 to 1 dB). If facades have a higher noise reduction value (i.e. 30 dB(A) to 35 dB(A)) the influence of the duct will be noticeable. Table 7.7 gives an indication of the effect of an exhaust duct with a cross-section of 200 cm^2 on the noise reduction value of a room with a volume of 40 m^3.

Table 7.7 The effect of an exhaust duct on the noise reduction value (ΔR).

G_A	ΔR [dB(A)]
20	- 1.0
25	- 2.5
30	- 5.5
35	- 9.5

Steel metal ducts in mechanical ventilation systems will have similar acoustic properties. If higher noise reduction values than the above are required, then acoustic measures are necessary to undertake such as the application of silencers or soundproofed airducts and ducts. In general, however, noise levels resulting from outdoor noise will be lower than the soundpower level L_w generated by the fan see also 7.7.4.

7.7.4 Noise generated by the ventilation system

Requirements and methods of calculation and measurement

The duct system inside dwellings is responsible for the transmission of noise generated by the fan and aerodynamic noise generated by bends, control valves and devices.

The maximum indoor noise level criteria in most of the countries with respect to noise generated by the ventilation system in rooms is 30 dB(A).
The sound power level (L_w) at the optimal operating point of the fan can be approximated by means of the following simplified formula:

$$L_W = L_{WS} + 10 \log q_v + 20 \log \Delta p \qquad \text{dB}$$

The following applies to all fan types:
L_{WS} = 1 ± 4 dB
q_v is the flow capacity in m^3/h
Δp is the total pressure difference across the fans (Pa)
In general, fans for single family dwellings have a A-weighted sound power level $L_{W(A)}$ of 60 to 65 dB(A).

For the determination of the octave band spectrum corrections must be applied. These octaveband corrections depend on the fantype and the fan speed. In dwellings centrifugal fans are commenly used. In table 7.8 an example of the corrections for this fan type is given.

Table 7.8: Example of octaveband corrections for a centrifugal fan.

Frequency	**(Hz)**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**
Correction	(dB)	-9	-6	-6	-7	-12	-15	-19

Sound reducing measures inside ducts

The noise generated by fans is propagated through the duct work system. If no special noise soundproofing measures are taken, internal noise levels of 30 to 45 dB(A) in rooms can be expected. This requires the use of soundproofing materials inside the duct work system.

Soundproofing materials in the supply system should ideally be placed immediately after the fan unit, but always before the first branching of the duct. If the system is a combined ventilation and air heating system, soundproofing materials should also be placed in the return duct just before the mixing box.

Soundproofing provisions for domestic ventilation systems usually consist of soundproofing (flexible) tubes (silencers). Alternatively, double-walled steel ducts insulated with mineral wool and with a perforated inner duct can be used.

A silencer consist of a perforated inner duct, a casing of mineral wool and an outer duct. The ducts may be plastic or metal and are often flexible to a certain extent. If plastic ducts are being used, which are often made of reinforced foil (highly flexible tubes), the noise penetration and emissions must be observed. In the case of air heating or after-heating, the maximum allowable air temperature also requires attention.

Silencers are relatively cheap and easy to integrate in an air duct system. They demand hardly any extra space. The noise attenuation of these materials is poor at low frequencies, especially if the walls provides a certain degree of sound reduction. Silencers made of thin foil provide better soundproofing at low frequencies, as a result of the fact that low-frequency noise is radiated. This can be a problem in open setups near rooms. Another disadvantage is that the soundproofing effects decrease proportionally to the increase of the internal diameter.

These silencers are therefore suitable primarily in duct work systems with diameters not exceeding 150 mm. Silencers can still be used with duct diameters of 150 mm to 250 mm but the required silencer length increases considerably. With diameters greater than 250 mm the use of a silencer is not recommended.

Table 7.9 gives an indication of the required dimensions of silencers for various capacities. Silencers must not be used as bends and must be mounted tightly, just like flexible ducts.

Table 7.9: Indication of the required dimensions of silencers for various capacities.

	Flowcapacity q_V(m^3/h)	**Diameter (mm)**		**Silencer length (mm)**
		Internal	**External**	
Ducts directly connected to rooms	$q_V < 100$	100	200	1000
	$100 < q_V < 250$	150	250	1000
Ducts directly connected to other spaces	$q_V < 100$	100	200	750
	$100 < q_V < 250$	150	250	750

Double-walled insulated ducts consist of a metal spiral seam inner and outer pipe separated by a layer of soundabsorping material with a thickness of 10 to 20 mm. Soundproofing of these ducts can be achieved by using mineral wool as an insulator and perforating the inner duct. The perforation level should be approximately 13 %. This will render the ducts eminently suitable for combined thermal and soundproofing. As a result of the thinness of the casing, the noise insulating value per linear meter is relatively low, in particular at low frequencies.

The lengths to be applied must therefore be:
- at least 2.0 m for internal diameters up to 80 mm.
- at least 4.0 m for internal diameters up to 125 mm.

Double-walled insulated ducts can also be encased within concrete floors.

Acoustic properties of terminal devices

The A-weighted sound power level of terminal devices can be approximated by:

$$L_{W(A)} = -4 + 70\log v + 30\log \xi + 10\log S$$

Where:

v is the air velocity across the terminal device in m/s
ξ is the airflow resistance factor (-).
S surface area of the terminal device in m^2.

Supply terminal devices must be selected on the basis of the nominal sound power levels to meet the required noise levels. Manufacturers have various ways of indicating the acoustic data. They usually provide a manual to help to select the terminal devices on the basis of their acoustic properties. Sound power levels of terminal devices must be measured in accordance with ISO/DP5135. Instead of listing the sound power levels (L_w) generated by the terminal devices, some manufacturers prefer to give the sound pressure levels (L_p) in an average room. In general the maximum allowable sound power levels (L_w) of terminal devices will be:

- bedrooms: approx. 35 dB(A)
- living rooms:
  - one terminal device: approx. 35 dB(A);
  - two terminal devices: approx. 32 dB(A);
  - three terminal devices: approx. 30 dB(A).

Aerodynamic noise inside ducts

The following points must be observed in order to prevent aerodynamic noise inside the ducts:

- The maximum allowable air velocity in main ducts is 4 m/s and inside branch ducts to the supply terminal devices the maximum allowable air velocity is 2 m/s.
- The use of round ducts is preferred.
- Sharp bends should be avoided and changes of cross-sectional areas of the ducts should be smooth.
- The system must be designed in such a way as to require the minimum number (preferably no) control valves. Low-noise valves such as perforated butterfly valves must be used and be positioned before the silencers.
- Air velocity inside silencers must be such that the aerodynamic noise generated is 10 dB lower than the ventilation noise immediately after the silencer. In general, the maximum allowable air velocity inside the silencer is 4 to 5 m/s.

Fan location

Fans should be placed in a vibration-insulated position on floors with a mass of less than 200 kg/m^2 in the case of single-family dwellings and on floors with a mass of 400 kg/m^2 in the case of multi-family dwellings. Vibration insulation may be achieved by placing the four corners of the unit on rubber blocks, with a vulcanized plate, and provided with studs or other mounting facility. The thickness of the rubber layer must be at least 30 mm. The total surface area of the four rubber blocks must be such that the load is 4 to 5 kg/cm^2.

It is also possible to place the fan on elastic rigid mineral wool plates (compression at least 80 kg/m^2) with a thickness of at least 50 mm, if necessary on top of a pressure compensation layer. A flexible connection piece must be used to attach the ducts to the unit. In the room in which the unit is located, metal ducts must be used with walls at least 0.5 mm thick.

7.7.5 Sound transmission in or between dwellings

Requirements and methods of calculation and measurement

With respect to the sound isolation requirements between two rooms, a distinction is made between rooms within the same dwelling on one hand and on the other hand between one dwelling and another or between a room in a dwelling and a space outside it. More stringent requirements apply to constructions which separate two adjacent dwellings. To specify the sound insulation between dwellings or between rooms it is not sufficient to use a single figure index as sound insulation is a function of frequency. Hence it should be specified over the frequency range. It is usual to specifiy the insulation as a curve or as a figure index calculated on basis of this curve. The measured insulation of a wall or floor should not come below this curve by more than a recommended amount.

There are many different ways in which the sound insulation requirements are expressed. In general for most countries the average sound reduction index R_m in the range between 125 and 2000 Hz for constructions between dwellings must be 50 to 52 dB. The sound insulation characteristic of a wall is usually expressed as the sound reduction index R. The sound reduction index R between two rooms can be evaluated from:

$$R = L_{ps} - L_{pr} + 10 \log S/A \qquad \text{dB}$$

where:

L_{ps} is the sound pressure in the source room, [dB]
L_{pr} is the sound pressure in the receiving room, [dB]
S is the surface area of the separating wall, [m^2]
A is the room absorption, [m^2 sabine].

The sound reduction index R is the result of the different sound channels from the one room to the other. This composite sound reduction index R' value is determined by:

$$R' = -10 \log \sum_{j-1}^{n} \frac{S_j}{S_{tot}} 10^{-Rj/10} \qquad \text{dB}$$

One of the sound channels may be a ventilation system. This phenomenon is also called cross-talk. Cross-talk can be defined as the effect that system components have on the integrity of the sound reduction between two rooms. Cross-talk is of particular concern in balanced ventilation systems and in collective ducts between dwellings. It can be brought about in the following ways:

- Through the duct work system.
- This can take place both between rooms within the same dwelling and between rooms in two different dwellings.
- Through the transfer devices or openings underneath doors. To facilitate the transport of air inside the dwelling, that is, from the place where air enters the rooms to the place where the air is exhausted, transfer devices are placed or the doors are shortened at the bottom. Cross-talk may occur in the case where two rooms have such openings near one another.
- Through the duct transitions in walls or floors.

Cross-talk through the duct system between dwellings

There must not be a decrease of the sound reduction between dwellings as a result of the transfer of noise through shared ducts.

Both natural and collective mechanical duct work systems usually require sound proofing provisions. Such provisions may consist of:

- a silencer on each exhaust terminal device or between exhaust terminal devices;
- a soundproofed exhaust terminal device.

The total insertion loss must at least comply with the values given in table 7.10.

Table 7.10 Minimum insertion loss for a duct between two dwellings

Octave band medium frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**
Noise reduction, duct cross section area < 0.03 m² [dB]	0	5	10	15	15
Noise reduction, duct cross section area 0.03-0.07 m² [dB]	0	5	10	15	20

Cross-talk through the duct work system within dwellings

In general, constructions which separate rooms must have an average sound reduction index [R_m] of 34 dB. In dwellings cross-talk occurs mainly in the supply duct of a balanced ventilation system if rooms are directly linked with one another. The effects of cross-talk in the system on the average sound reduction index is approximately 14 dB. In this case the overall sound reduction index value is 31 dB and additional measures are necessary. This can be a silencer in the duct between two rooms. This silencer must have a length of at least 0.5 m and a thickness of the absorption material of 25 mm. Alternatively, there are devices available equipped with sound proofing material which are capable of preventing cross-talk.

Cross-talk through transfered air provisions

When doors are shortened at the bottom to facilitate air transport inside a dwelling, the following factors should be taken into account:

- Doors must be shortened by 3 mm for each 10 m³/h of air supplied or removed from a room.
- If the doors of two adjacent rooms are directly beside one another, the sound reduction index of the separating wall must be 2 dB higher than the minimum required value in order to compensate for the transfer of noise through the gap underneath the door.

Duct transitions

Improperly constructed duct transitions may creat acoustic leaks between dwelling separating walls and slabs. Soundproof connections between the duct and the separating wall are therefore recommended. These can be achieved by using a sealing caulking or an airtight sealant.

7.8 Reliability

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7.8.1 Background

Reliability, in the context of ventilation performance can be defined as:
the probability that the ventilation system provides at least certain minimum air flow rates in each occupied part of a building during the time between scheduled maintenance occasions, under specific climatic conditions.

The minimum air flow rates may be, for example, a specified fraction of the nominal air flow rates or certain fixed values.

As the probability of failure (complete failure or malfunction) is a key issue, the result of an evaluation procedure should be expressed in such terms. In the case of natural ventilation, for example, it would be desirable to present results of ventilation rate simulations or measurements in the form of frequency diagrams.

The impact of human behaviour on ventilation reliability can be extensive. For example, the user can hazard the ventilation performance of his dwelling by obstructing the supply air terminal devices in order to avoid draughts. The draught will disappear, but the intended air flow patterns in the dwelling are changed. The performance will also deteriorate if maintenance is performed badly or neglected.

There are at least three major factors which can influence the reliability of a ventilation system:

- Outdoor weather conditions
- Dust accumulation in ducts and other components
- Malfunction of ventilation system equipment

The influence of different weather conditions on ventilation flow rates is most obvious in naturally ventilated dwellings. Mechanically exhaust ventilated dwellings experience less sensitivity to outer weather conditions than naturally ventilated ones, at least as long as the first ones are relatively airtight. This is due to the fact that the exhaust fan creates an under-pressure inside the dwelling which, for moderate wind velocities balances the suction on the leeward side of the building, thus preventing exfiltration from taking place. Poorly sealed houses with balanced ventilation behave similarly to naturally ventilated ones due to the lack of fan-induced inner negative-pressure.

It is obvious that dust accumulated in ducts and other ventilation equipment decreases the ventilation flow rates in the system. In the reliability context the most critical questions are "How large is the decrease?" and "How long will it take?" Malfunction of ventilation system equipment must be studied from the point of view of determining risks of failure of different types of equipment and the consequences of failure for the air flow rates in the building.

7.8.2 Outdoor weather conditions

Multi-zone infiltration and ventilation simulations were performed by means of the computer program "MOVECOMP PC(R)", created by Magnus Herrlin. The version run was 5.31.

The simulations were run for a 2-stories building exposed to the open environment on all sides. The lay-out of the building was according to figure 7.27. The house was orientated so, that the entrance of the house was in the north-direction.

An even distribution of leakage paths over the envelope was assumed, so that the distributed leakage over facades and roof (flat) added to the air leakage of the windows and the entrance door altogether added up to 3.0 h^{-1} at 50 Pa. The room height was assumed to be 2.5 m and the thickness of the intermediate floor 0.4 m. The internal doors were assumed to be open with the exception of the doors to the WC and the bath/WC, where appropriate leakage data were applied (a smaller gap around the door leaf and a larger gap above).

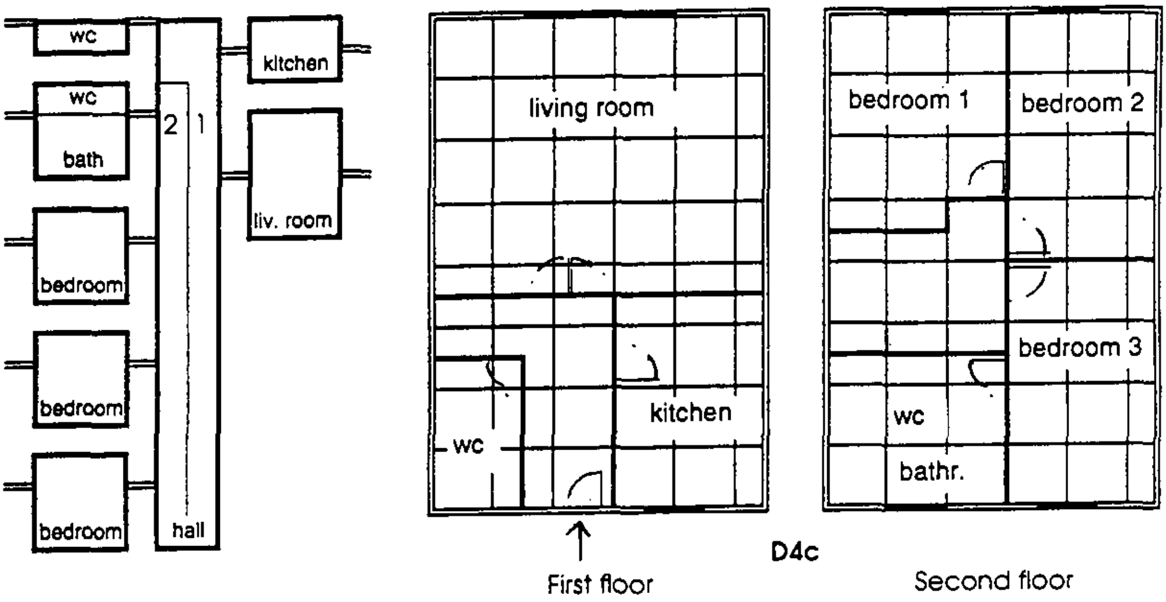


Figure 7.27 Lay-out of building simulated

The simulations were run with climatic data (outdoor temperature, wind velocity and direction) from Stockholm 1971. The period between May 8 and September 24 was excluded. The outdoor temperature was divided into the following intervals: -15, -10, -6, -2, 2, 6, 10, 14, 18, and 22 °C. The wind velocity was divided into the following intervals: 0, 0.5, 1.0, 2.25, 3.5, 5.0, 6.5, 8.0, 9.5, 11.0 and 12.5 m/s. This resulted in a condensed weather file with 84 records (combinations of outdoor temperature, wind velocity, and average wind direction). The frequency (number of hours for each combination) of each combination was finally used for the cumulative frequency diagrams.

Wind pressure coefficients according to table 3.5 (ii), AIVC Technical Note 44, were used for the simulations. The wind pressure coefficient for the top of the stack, in the case of passive stack ventilation (PSV) was chosen to be -0.3.

Three systems were simulated; a passive stack, an exhaust, and an exhaust and supply ventilation system.

Passive stack ventilation
Three individual stacks were modelled; starting in the WC and the kitchen on the ground floor and the bath/WC on the first floor and ending above roof level. The flow resistances of the stack, the air terminal device and the cowl were added up and distributed equally between the

supply and the exhaust opening of the stack, while the stack itself was modelled as a zone thus having no internal flow resistance at all.

Supply air terminal devices in the facades of the living room and the three bedrooms were modelled according to data from a manufacturer. (K=7.5 kg/h,Pa^n, n=0.5).

Exhaust ventilation
Fixed exhaust flows of 43.2 kg/h each were introduced in the WC, the kitchen and the bath/WC. Supply air terminal devices as above.

Exhaust and supply ventilation
Fixed supply flows of 32.4 kg/h each were introduced in the living room and the three bedrooms. Exhaust flows as above.

Results
The results of the simulations are summarised in cumulative frequency diagrams, figure 7.28-7.30 and table 7.11.

Table 7.11 Summarised results of the simulation

Ventilation system	**Space**				
	Whole house	Living-room	Bedroom		
			1	2	3
Passive stack					
Outdoor air ventilation rate [h^{-1}] median	0.41	0.56	0.42	0.62	0.18
Ventilation rate <0.25 h^{-1} (frequency[%])	1	0	20	8	55
Exhaust					
Outdoor air ventilation rate [h^{-1}] median	0.56	0.64	0.66	0.78	0.40
Ventilation rate <0.25 h^{-1} (frequency[%])	0	0	0	0	22
Exhaust and Supply					
Outdoor air ventilation rate [h^{-1}] medianr	0.68	0.64	1.09	1.19	1.09
Ventilation rate <0.25 h^{-1} (frequency[%])	0	0	0	0	0

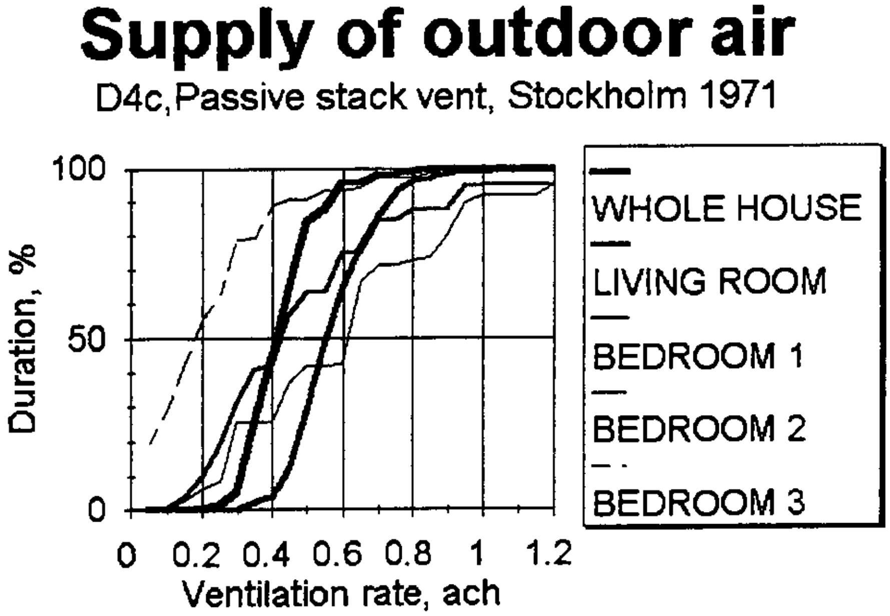


Figure 7.28 Passive stack ventilation

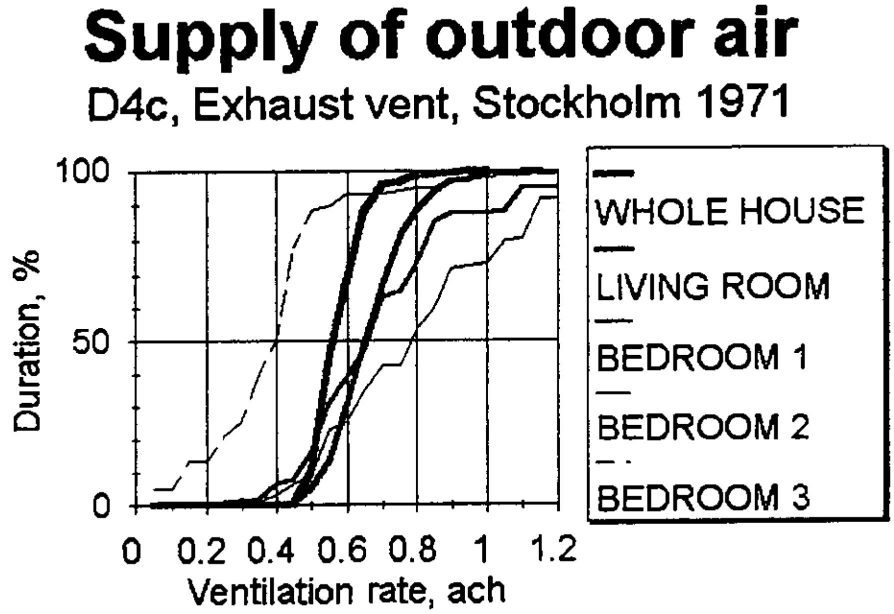


Figure 7.29 Exhaust ventilation

Passive stack ventilation
As can be seen in figure 7.28, the variations between lowest and highest ventilation rates (supply of outdoor air) are large, especially when it comes to individual rooms.

While the ventilation rate of most rooms seems to be acceptable, bedroom 3 is apparently underventilated most of the time. This room has its supply air terminal device in the north facade. The most frequent wind direction in the weather file is SW, which probably explains the low infiltration rate through the supply device in bedroom 3

Exhaust ventilation
Even in the case of exhaust ventilation, the variations are large, especially for the individual rooms.

All ventilation rates seem to be satisfactory, though still the ventilation in bedroom 3 shows the poorest performance, see figure 7.29.

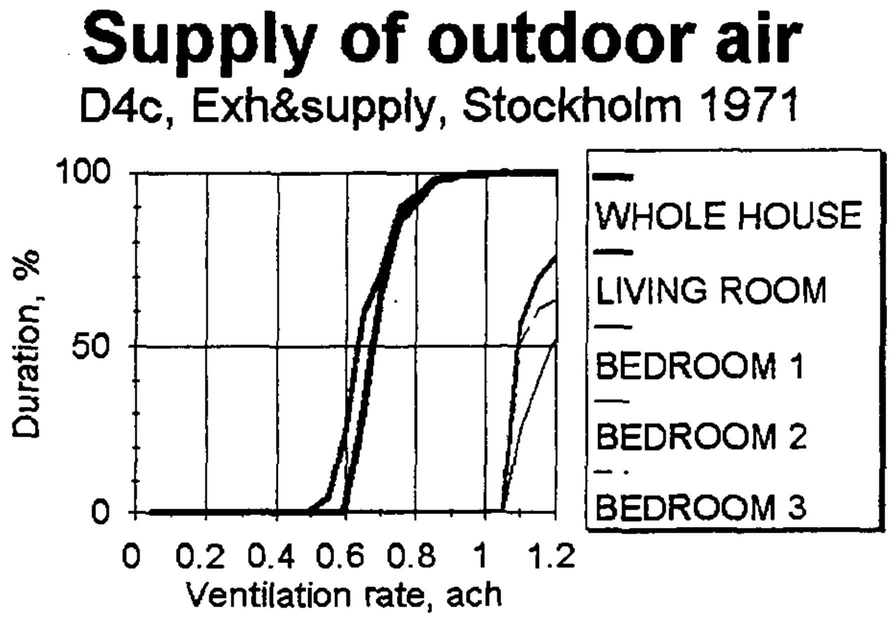


Figure 7.30 Exhaust and supply ventilation

Exhaust and supply ventilation
It is quite obvious that the minimum ventilation rates are determined by the imposed supply air flow rates. In addition to this minimum value certain proportions of infiltration are present from time to time. See figure 7.30

7.8.3 Dust accumulation in ducts and other components

Peterson (1983), reviels the present status of knowledge on dust accumulation, based on Swedish research and other experience. A summary is presented below.

How great will the decrease in ventilation flow rates be due to dust accumulation? Hööj (1970 and 1972) has shown decreases of the order of 30 % of nominal flow rates. Wallin (1978a and 1978b) has reported experiments which indicate about the same level of decrease. In a summary of the results of cleaning measures in more than ten buildings, Lindgren (1979) found still greater decreases. Thus, the decreased flow rates are serious, not only for the general air quality in e.g. a flat, but also regarding health risks and risks of mould growth. The latter is especially important.

The need for duct cleaning measures is of course of importance not only for the ducts themselves, but also for air terminal devices and fans. It is frequently found upon cleaning that the components apart from the ducts are treated harshly during the cleaning process.

The fact that accumulated dust in ventilation ducts decreases the duct diameter and may increase the duct roughness is obvious. Measurements of flow rates are also quite easy to perform and they often give clear indications of dust accumulation. See figure 7.31.

Measurements carried out by Höij (1970 and 1972) revealed serious decreases in air flow rates and he stressed the importance of regular cleaning of ventilation ducts. It was also shown that a "clean" indoor environment could result in significant changes in air flow rate. In hospitals, for example, it is not unusual that dust accumulation caused by the extensive handling of cloth (sheets etc.) creates dramatic decreases in the flow rates.

Stark (1972) presented results regarding particle concentrations in ventilation systems. His work has lead to an understanding of how particles are deposited in entire duct systems. He showed that approx. 50 % of particles introduced into the supply air ducts was accumulated in the ducts.

Wallin (1978a) found that dust accumulated in different manners in ducts of different sizes. In systems with large ducts, the influence is of course less than in small ducts (which are commonly used in modern ventilation systems). In a series of experiments in different buildings, changes in air flow rates due to cleaning of the ducts were found. In general it could be stated that cleaning led to increases in flow rates of approx. 25 %, based on the average flow rate.

A theoretical description of the influence of dust accumulation on air flow rate was drawn up by Göransson in 1978. Wallin continued this work and in 1979 presented a theory for simple system configurations. The influence of the type of fan as well as the size of the ducts was shown.

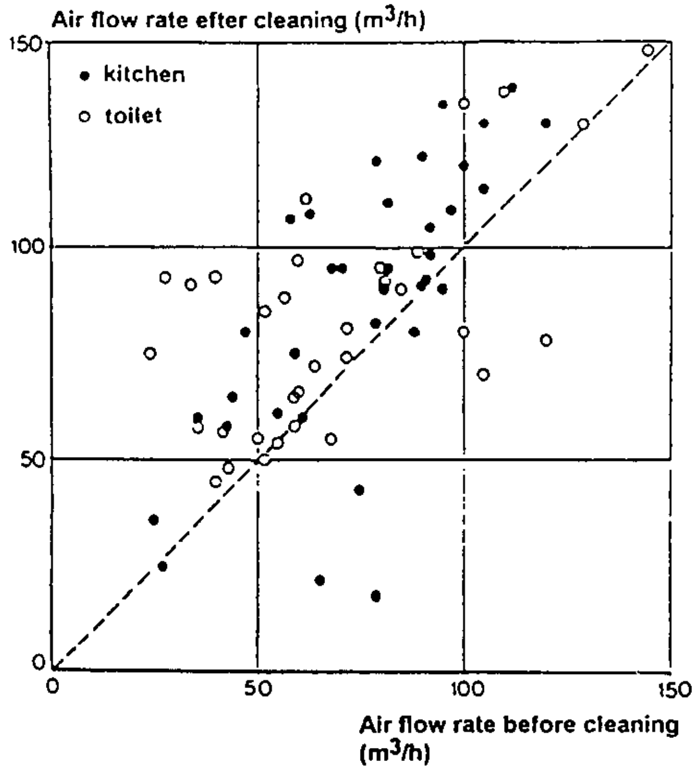


Figure 7.31. Air flow rates through exhaust air terminal devices in a multi-family building before and after cleaning

The rate of dust accumulation with time is demonstrated by a series of results from field measurements. Figure 7.32 shows how the total air flow rate gradually decreases after cleaning. An air flow rate of approximately 3 000 m3/h (after cleaning in March 1982) has, after a little more than one year, decreased to approximately 1 500 m^3/h.

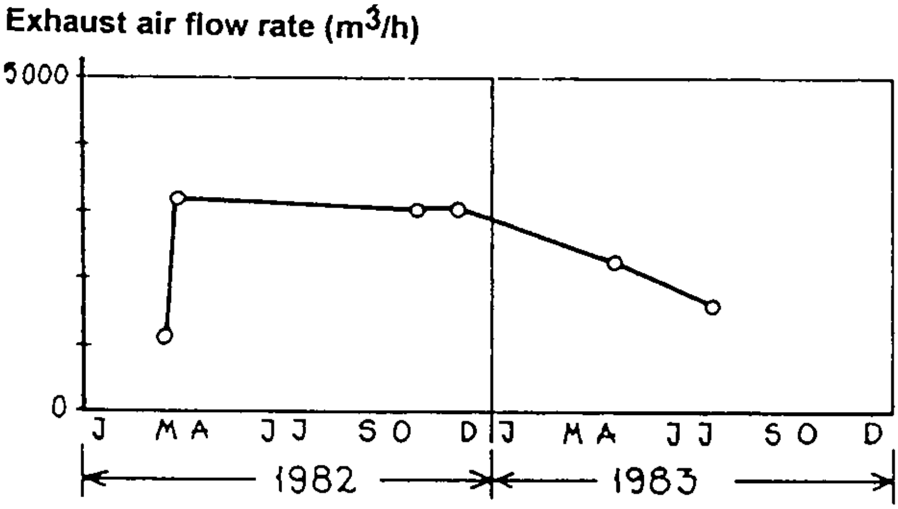


Figure 7.32

Figures 7.33-7.35 present data collected at a hospital. After cleaning in March 1982 a substantial increase in flow rates was observed for the three rooms shown in the example. With time, the air flow rates decreased - first slowly and then rapidly. After 1 1/2 years, the flow rates had decreased to just over half of the flow rates immediately after cleaning.

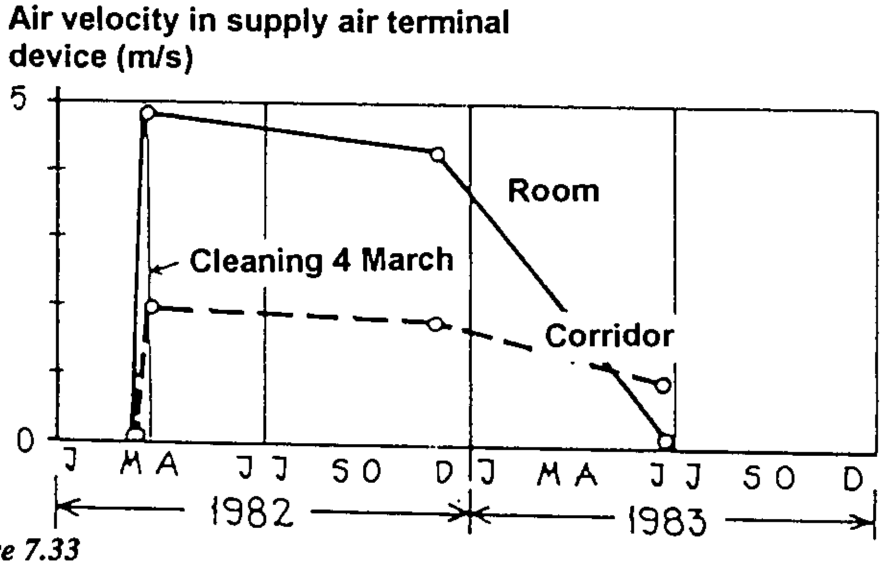


Figure 7.33

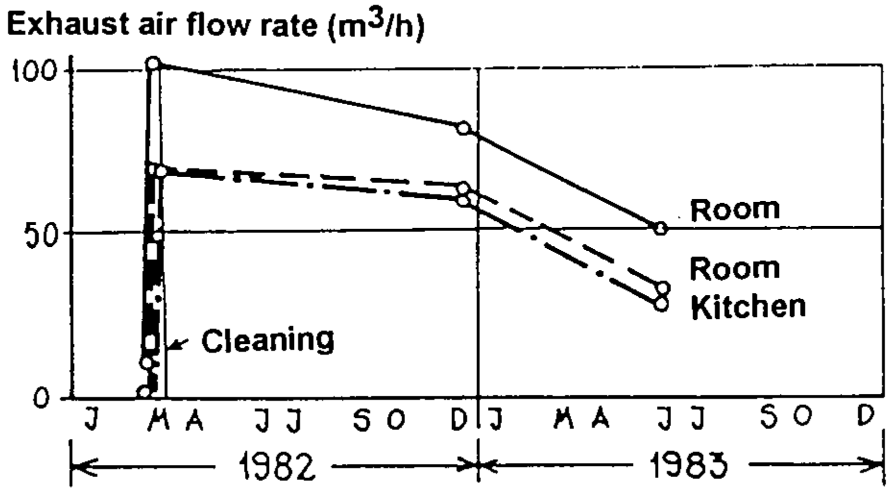


Figure 7.34

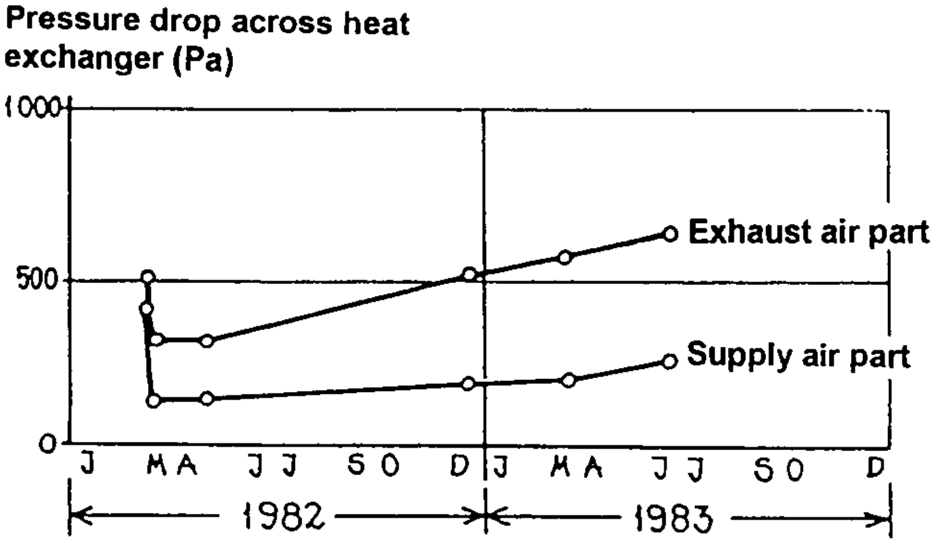
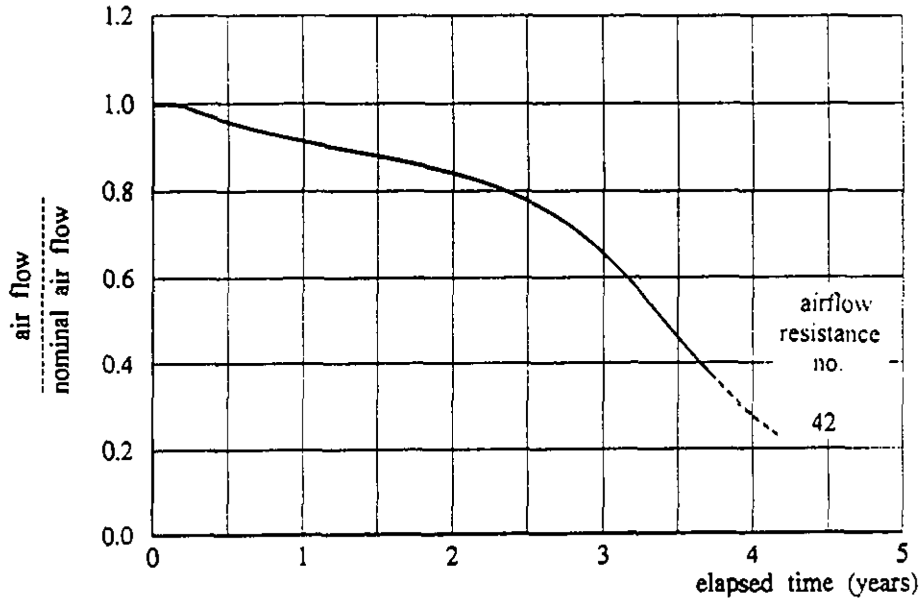


Figure 7.35

Duct cleaning is of great importance, but the cleaning of air terminal devices is also important. A couple of mm of dust in the terminal device could be equivalent to half of the effect of duct cleaning.

Cleaning of heat exchangers is also important. Dirt accumulation causes flow rate decrease and increased pressure drop across the exchanger. Exhaust devices can also become dusty and give a decreased air flow rate. The cleaning procedure is in most cases very simple - but also easy to forget! Based on measurements lab tests, and models for particle behaviour a computer model was set up by Wallin (1994). An example of the decrease of exhaust flow rate due to dust accumulation in a multi family building is shown i figure 7.36



7.36 Total flow rate for an exhaust system in a multi family building, Wallin (1994)

7.8.4 Malfunction of ventilation system equipment

The risk of failure of different types of equipment and the consequences of failure are the key points of this kind of reliability influence. There exists, to my knowledge, no comprehensive summary of these parameters in the literature. Work is underway in a research project led by Prof. S Svennberg at the Royal Institute of Technology in Sweden, Svennberg (1994). The scope of the project is to find frequency distributions for a series of faults that could occur in ventilation system equipment.

Considerable work on finding and systematizing different kind of faults has been made in the IEA annex 25 "HEVAC R.T. Simulation". For example, there is a Swiss investigation, carried out within the framework of the annex, Schiel (1992), which reports the results of a survey to 18 experts in Switzerland. Most problems were reported for the module "air conditioning" followed by "ventilation" and the main causes were reported to be "planning" and "maintenance". There is also a paper, Yoshida (1992), on typical faults of AHU systems, which gives a systematic list of such faults.

A comprehensive handbook on troubleshooting in air conditioning and refrigeration has been published in the USA, Langley (1980).

Fahlén (1993) has analysed the long-term performance of control equipment. His main findings were these. Electronic hardware rarely causes any problems. The use of national and international standards, in connection with the issue of long-term performance, is uncommon.

Table 7.11 Expected lifetime and maintenance costs for different types of installations in buildings. Månsson & Svennberg (1993). (Original source: CEN/TC 156/WG 7, Working document, June 1991.)

Component	Life span (years)	Annual Maintenance Cost, % of investment
Air conditioning units	15	4
Air heaters, water	20	2
Air heaters, steam	20	2
Air heaters, electric	15	2
Air coolers	20	2
Burners, oil and gas	10	4
Condensers	20	2
Control equipment	15	4
Cooling compressors	15	4
Dampers	20	1
Dampers with control motor	15	4
Diffusers	20	4
Dual duct boxes	15	4
Duct system	30	1
Evaporators	20	2
Exhaust air grilles	20	4
Expansion vessels,		
steel	15	2
stainless	30	1
copper	30	1
Fans	20	4
Fans with variable flow	15	6
Fan coil units	15	4
Filter frames	15	4
Filter, cleaned	10	10
exchanged	1	10
Grilles	30	1
Heat exchangers, static	15	4
rotary	10	4
Heat pumps	15	4
Humidifiers, water	10	6
steam	10	4
Motors, electric	20	1
diesel	10	4
Pipes,		
steel,open systems	15	1
steel closed systems	30	1
stainless	30	1
copper	30	1
Pumps, open system	15	2
closed system	20	2
Sound traps	30	1
Valves,		
manual control	30	4
automatic control	15	6
manual shut off	30	2
automatic shut off	15	4
V-belt drive	10	6
Wiring	30	1

The awareness of existing standards, with respect to long term performance, is poor among suppliers as well as clients. There is a need to revise some of the existing standards. A systematic approach to aspects of durability, maintenance and operation is rare. A genuine interest on the part of the client is vital for the end result.

Another way of investigating the reliability, would be to study the recommended intervals between maintenance. Schemes for determining the "best" intervals exist. These schemes ought to reflect the probable frequency of faults. Most schemes recommend visual inspection of the inner parts of all ventilation equipment installed every 3 months and cleaning every 6 months. The pressure drop across filters should be checked every 3 months and the filters cleaned or replaced once the upper critical pressure drop is reached.

Table 7.12 provides some figures on life expectancies of different parts of ventilation and air conditioning equipment, with estimated maintenance costs in relation to investment.
Some different kinds of routines for system safety analysis are shown in figure 7.37.

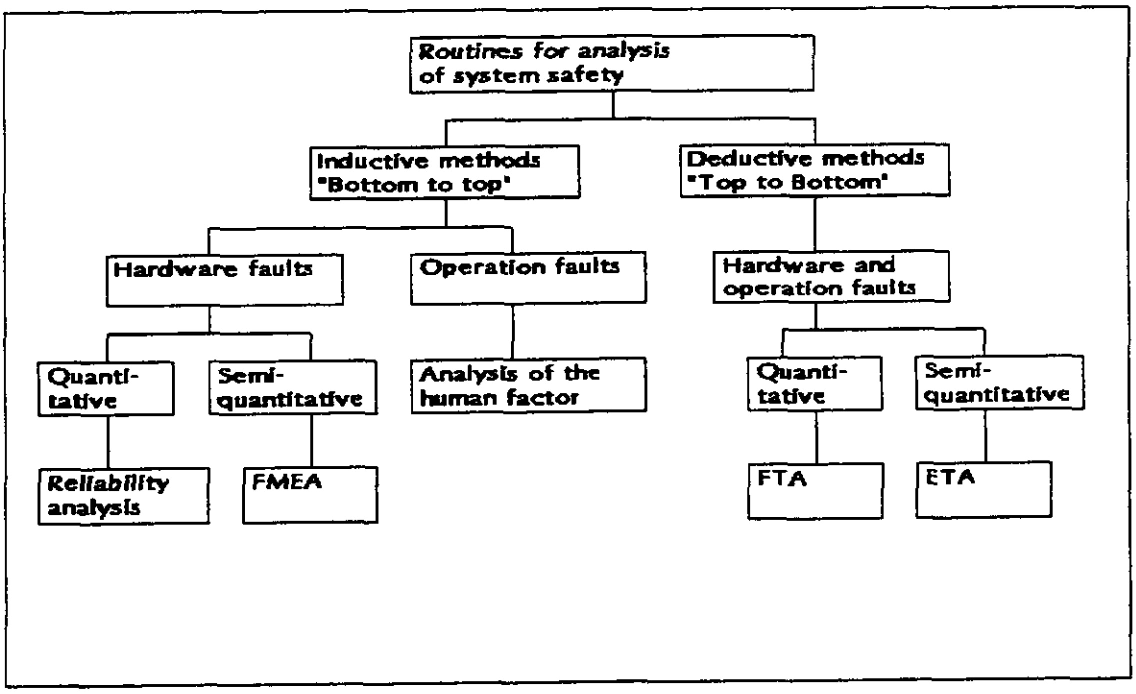


Figure 7.37 ***Different kinds of routines for system safety analysis. FMEA = Failure Modes and Effects Analysis, FTA = Fault Tree Analysis, ETA = Event Tree Analysis. From Rao (1992).***

The ***qualitative methods*** help us to understand the logical structure of different failure modes of the product, and how they interact. The quantitative methods use available data on the failure tendency of the components, estimations of times for repairing and human faults. These data can eventually be used for the calculation of the probability of a certain type of break-down of the system. The selection of a specific method depends on the complexity of the system, the amount of available statistical data and the degree of influencing human factors.

With the ***inductive methods***, the analysis work is started at components´ level by finding the failure modes of them. After that, one tries to find out what consequences there are on the system as a whole caused by a break-down on components´ level. Thus, the inductive analysis works gradually upwards from low component level up to part-system level and finally the system level. This is the way Failure Modes and Effects Analysis (FMEA) works. The military US standard US MIL-STD 1629 describes in detail how a FMEA-analysis should be worked out.

The ***deductive methods*** have a top-event as a starting point. Gradually one works downwards in the system and tries to find out the causes of the top-event. Thus, the way of working is opposite to the technique used in the inductive techniques. FTA (Fault Tree Analysis) and ETA (Event Tree Analysis) are examples of deductive methods.

FMEA is certainly the most commonly used technique for system analysis as far as product design is concerned.

ETA (Event Tree Analysis) is a graphical description of all possible events in a system. The method is based on binary logic, as events are seen in the perspective of if the have happened or not. A component is regarded as either working or non-working. Thus, it is not possible to take into account a "partially defect" state of a component. If the probabilities of each of all possible events in the tree is known, it possible to calculate the probability of (different) chains of events. The outcome of an ETA is a number of chains of events and their consequences for the system. The probability of each chain is also shown. ETA is a good technique for comparing different system configurations with each other from a perspective of operational safety. The method was initially developed for evaluating the safety of nuclear power plants.

FTA (Fault Tree Analysis) is frequently used for the analysis of complex systems. The method is extensively used within the nuclear and the aerospace industry. It is a deductive tool and as the method is highly standardised it has been used a lot. The user easily decides the degree of complexity of the system studied, as the method allows for studying separate parts of the system (so called sub-trees) one at a time. Evaluations by means of fault tree analysis was originally developed by H.A. Watson at the Bell Telephone Laboratories in 1962. The purpose was to analyse the safety concept in connection with the launching equipment for the Minuteman-missiles. After that Boeing used and developed the method further.

The purpose of FTA is to find the logical structure behind a fault event. Usually a FMEA is performed first, in which the system design, the operation of the system and the environment is analysed in order to find the causality of a fault. Thus FMEA is an important step towards the understanding of the system. Without such an understanding, it is not possible to perform a fault tree analysis.

The performance of the product is described in a flow chart in which the flows of information, signals and other relevant aspects are specified. Then the flow chart is used for identifying the different functional sequences from inside to outside. Finally a logical chart is designed, in which the functional connections has been translated to logical relations.

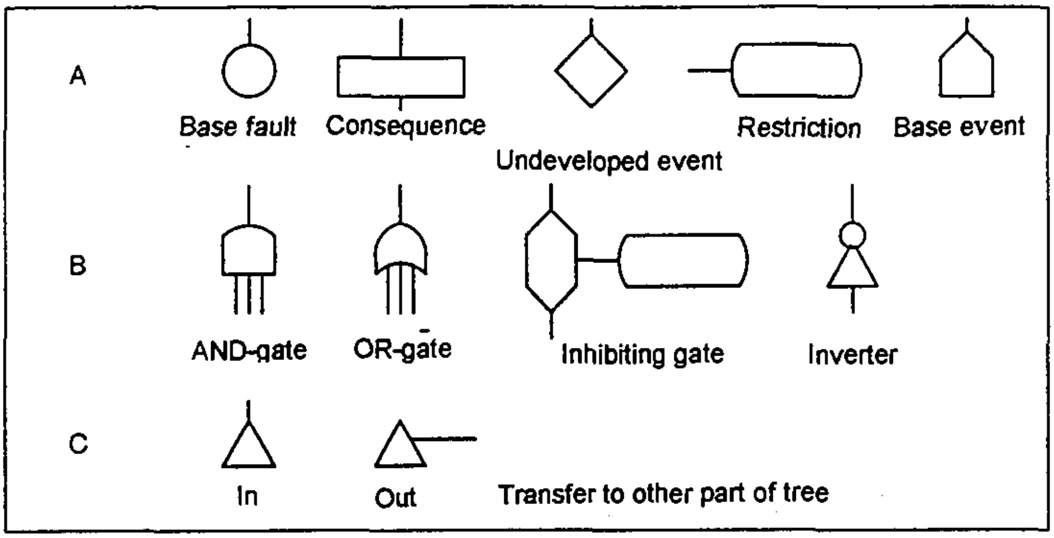
In the logical diagram different logical symbols are used, see figure 7.38.

Rau (1992) has summarised the working methodology in the following six points:

1. Define a suitable top-event.
2. Different but equivalent fault trees can be designed for the same system. Different top-events lead to different fault trees.

3. For each top-event it is investigated what events that alone or in combination can cause the top-event.
4. The primary events that directly cause the top-event and the secondary events that cause the primary events are identified. This is repeated until all levels in the system is investigated.
5. The combination of events that are needed for an event to be released at a higher level are connected to AND-gates.
6. The events that individually can cause an event at a higher level are connected to OR-gates.

An initial attempt to work out a fault tree for a mechanical exhaust ventilation system of a building is shown in figure 7.39.



- Base fault: Faults caused by a component or a part-system, for which a probability could be stated (from empirical data).
- Consequence: A fault or event caused by a combination of other events via a logical gate.
- Undeveloped event: An singular fault, i.e. a fault that cannot be split up (developed) due to lack of information or lack of meaning.
- Restriction: Condition that must be fulfilled and directing an associated gate.
- Base event: An event normally occurring when the system is working.
- AND-gate: All in-signals must be true for opening the gate.
- OR-gate: One or more in-signals must be true for opening the gate.
- Inhibiting gate: No out-signal if the associated condition is fulfilled.
- Inverter: Changes one into zero (true turns false) or vice versa.
- Transfer symbols: Indicates that the branch continues into another tree (In) or indicates the top-event in a sub-tree (Out).

Figure 7.38 Standardised symbols for fault tree analysis. From Rau (1992).

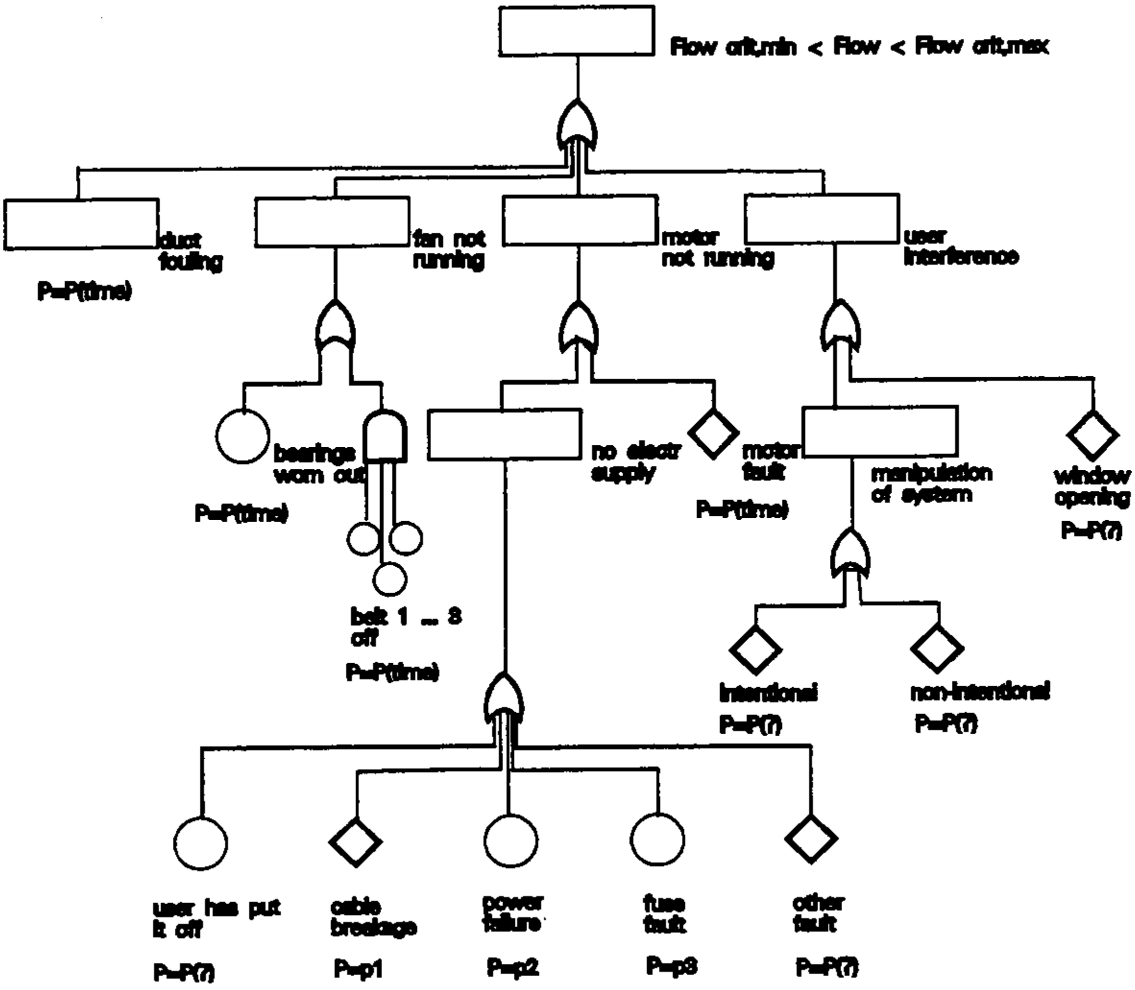


Figure 7.39 Fault tree for a mechanical exhaust ventilation system in a building.

7.8.5 References

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8. Conclusions

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There is a lot of information to collect that concerns the residents and the dwellings. However, it must always be kept in mind, that even if most of people's time is spent in dwellings and the floor area per person is much larger compared to all other non-residential area, data from non-residential studies is not easy to use. Often the situations in non-residential studies are more well defined and the range is not very large compared to the situations in dwellings. We can also see that some very well defined problem areas have been studied in depth but some that might be of larger concern for greater groups of residents have not been studied very well. Behind the scope of the work of this State of the Art Review has primarily been to clarify the following:

1. Technical status
2. Loads.
3. Available simulation programs

With this report it is possible to formulate assumptions, that are needed when realistic cases are studied. Also different climatic conditions that also are to be taken into account. Finally, the window opening pattern is strongly linked to a behavioural matter that is a part of the ventilation.

8.1 Technical status

Detailed data are available for most of the technical descriptions that are needed. Average dwelling area and the distribution of the age of the residents are well known. The airtightness and the most frequently used ventilation systems are also rather well known. However, general details for older components in ventilation systems is often lacking. We also know quite well how many possible ways architects or designers have to organize the habitable rooms and service rooms in dwelling plans.

8.2 Loads

The loads that imply the need for ventilation can be of three kinds:

1. Constant emission from internal or external sources
2. Combustion gas spillage, CO and NO_x
3. Residential behaviour e.g. odour, water vapour, VOCs, particles, tobacco smoke.

Constant emission from internal sources are usually linked to building material. However, the emission is not constant over a long time perspective of several years or a decade, but declining during the first years then emitting at a lower level. Many surveys have been conducted and a large number of results are reported. As a lot of results from many studies are at hand no further information are needed here unless it would be a large survey of the decline of emissions in newly constructed dwellings. As such survey is very expensive, we have to use the measured values in homes at various ages. It is possible to give average values and extreme values for the situation of new constructed buildings or just refurbished.

Also particle concentrations have been measured in many dwellings. However, sometimes there is a lack of information if the measurements were conducted in non-smokers' homes or not. The concentration level is of a certain mangnitude higher both for average and peak values in smokers' homes.

Radon emission is the most important external source. If there is a risk of radon emission, this case should normally be dealt with by other means than increasing the ventilation of the dwelling area. However, a warning flagg should be rised, if the dwelling is depressurised. Also landfill spillage should be treated in a similar way.

In dwellings, the use of electricity or natural gas for cooking and for local gas fired heaters must be taken into account, when evaluating the ventilation systems. The two emissions CO and NO_x are giving different side effects, the first is mortal even at low concentrations and the second might give oversensitive reactions. General surveys have been conducted and both average and peak values have been monitored in different rooms and the kitchen at different situations. If there is no direct connection to the outside the combustion air must be taken from the rooms. The risk for pollutants indoors will be increased if the dwelling is depressurised.

The study of the statistical data gives us the range of dwelling size, number of residents, how many residents per bedroom that are expected. Of course there is a difference between individual countries but there is a general trend towards fewer residents in each dwelling. It can also be expressed as a trend to have a larger area per person.

There is not too detailed information about how people behave in there dwellings. However, with the studies made we can make the conclusion that the variations are within a great range. We can also get hold of both average and more extreme figures, thus enabling us to make reliable assumptions on how most of the households are using their dwellings. It is also possible to formulate a possible use of the dwelling during the life cycle of a residential building.

Residents' behaviour is always thought to be of great variations and also of cultural differenses. It can also be observed but the variation within a country is greater than the average values from country to country. Here is also a lack of large surveys. However, the studies that are made with the same purpose show similarities in the behaviour and the results can be used as a basis for assumptions needed to be made.

The water vapour pressure is a very tricky parameter to deal with. Both behaviour and climate give a great influence. Sensitivity studies have to be done in order to find out how the various loads are resulting in risks for mould and house dust mites growths in different climates and during the seasons. The parameters that are needed to be studied here are many. Of great concern is the sorption properties of the material. We can rather well describe the pattern in an empty dwelling, but with furniture it is much worse as there is no good surveys made about the number and styles giving us any basis for making good assumptions. Even the large furniture retailers do not have any information. The dynamic of short time variations are not very well studied. The results of the minor studies, that have been reported, must be used with care, but they might give us some hints that are much better than pure guesses. To treat the water vapour in a modelling way is not an easy task.

Other behaviourally influenced water vapour pattern are the sorption pattern in combination with the presence pattern of the residents in the dwelling. Only very few studies of the presence pattern are made and some of them are about 20 years old. However, the minor studies indicates similar pattern for precense in all the participating countries. Other indications of the slow change are that today it seems that most people are showering instead of taking a bath, that was the most common way 20 - 30 years ago. The easy access of a clothes washing machine together with a dryer is indicating that the frequency has increased to use the machines.

Other uncertanties include the water vapour generation from pot plants, the time spent in the different rooms in the dwelling, and the room temperature especially in the bedrooms. Here most of the metabolic water vapour is generated. As it is in the bedrooms, that the most severe risk for house dust mites occures, it is of great interest to study the influencing parameters.

Body odour is usually linked to the CO_2 concentration level, which is a good indicator for how we expect that a visitor is going to perceive an odorous indoor environment. This is much easier to deal with compared to water vapour.

VOCs are also added to the indoor environmet by the residents' behaviour. It is a matter of cleaning habits, emission of detergents and emission from e.g. deodorants, hair spray, and other cosmetic products. As VOCs are adsorbed by other materials soon it is impossible to distinguish between original emissions and the addition from residents' behaviour.

8.3 Available simulation models

The conclusion is, that there are developed good simulation programs using the most recent knowledge on the construction of computer codes. The programs for energy, noise, and indoor air quality are very reliable even if the modelling of water vapour needs to be developed further. The modelling of draught sensation has to be used with care and only for indicating trends. It has also been shown, that the most crucial point is to find reliable data needed to run the programs.

8.4 Usage of data

Based on the State of the Art Review, in which we also have used the results in other IEA Annexes, it is now possible to give the assumptions, so that various simulations can be conducted. In table 8.1 is given the assumptions, that are needed in order to run the simulations. Then we have the possibilities to evaluate the abilities of ventilation systems with respect to various qualities.

This review has given, that it is possible to combine most varied designs with residential behaviour in dwellings. It is only the extreme cases that have not been covered. An estimation is that more than 95 % of all combinations can be formulated based on the data given in this report.

In the report is also given data for estimated trends in the future housing sector. One very important trend is, that the population is growing older. This will give us, that dwellings in the future might be even less populated than today. As a dwelling undergoes many variations during its life cycle, the requirements on a ventilation system will be within a large range and also varies during the life cycle. Usually a ventilation system is designed to serve the most severe cases, that only occurs during a few years of the life cycle. With a tool to evaluate ventilation systems a more optimum design will be possible. In table 8.1 is given the most urgent simulations to be done to give a good evaluation of how well a ventilation system might fulfil its requirements.

Table 8.1 Assumptions for the simulations

Design assumptions

1. Example dwellings
2. Ventilation systems
3. Leakage values

Residents' behaviour

4. Standard families
5. Combination of families and type plans
6. Time spent at home and the time in individual rooms
7. Window airing pattern
8. Internal door positions, indoor temperature
9. Metabolism, water vapour production
10. Criteria for house dust mites and mould growth

Simulations

- Indoor air quality
- Energy
- Thermal comfort
- Life cycle cost
- Noise
- Reliability

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