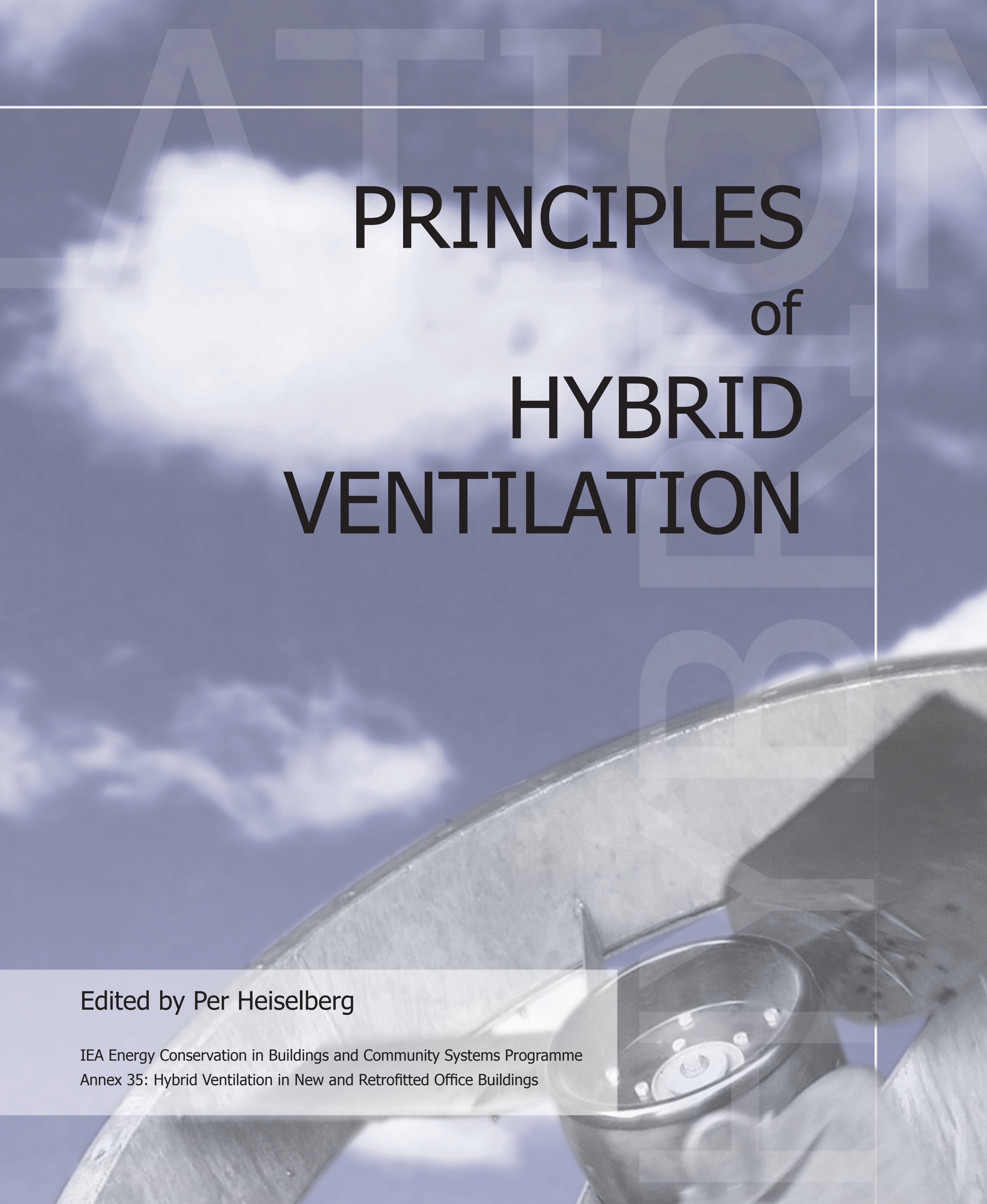

PRINCIPLES of HYBRID VENTILATION

Edited by Per Heiselberg

IEA Energy Conservation in Buildings and Community Systems Programme
Annex 35: Hybrid Ventilation in New and Retrofitted Office Buildings

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ISSN 1395-7953 R0207
Aalborg University, Aalborg, Denmark
First Published August 2002

Printed in Aalborg, Denmark by KOMMUNIK Grafiske Løsninger A/S

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PRINCIPLES of HYBRID VENTILATION

foreword

This booklet and CD-ROM summarizes the work of IEA-ECBCS Annex 35 “Hybrid Ventilation in New and Retrofitted Office Buildings” and is based on the research findings from the participating countries. The publication is an official Annex report.

With a focus on office and educational buildings, the booklet describes the principles of hybrid ventilation technologies, control strategies and algorithms, as well as analysis methods. The 13 case studies include both new-build and retrofit designs, and the booklet and information on the CD-ROM are valuable for both situations

This booklet is aimed at newcomers in the field and gives an introduction to hybrid ventilation. A secondary aim is to function as a gateway for the more detailed information that can be found on the CD-ROM.

The CD-ROM is a source of information, containing a number of technical reports and papers, etc. with detailed information about research results. Included among these are, detailed reports with measurement results and conclusions from the case studies investigated.

It is hoped, that this booklet will be helpful for both architects and engineers in their search for innovative and energy-efficient ventilation solutions. The hybrid ventilation concept is quite new, and there are still many challenges to be solved, before hybrid ventilation can be considered to be a mature and well-established ventilation concept. However, the research results found on the CD-ROM are an important step in the right direction.

Per Heiselberg
Editor

acknowledgement

The material presented in this publication has been collected and developed within an Annex of the IEA Implementing Agreement Energy Conservation in Buildings and Community Systems, Annex 35 “Hybrid Ventilation in New and Retrofitted Office Buildings”.
The booklet and CD-ROM is the result of an international joint effort conducted in 16 countries. All those who have contributed to the project are gratefully acknowledged. A list of participating institutes can be found on page 68.
Some Annex participants have taken the responsibility of collecting information and writing the chapters in this booklet. They are:

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Angelo Delsante, CSIRO, Australia is gratefully acknowledged for his careful review and English language check.

On behalf of all participants the members of the Executive Committee of IEA Energy Conservation in Buildings and Community Systems Implementing Agreement as well as the funding bodies are also gratefully acknowledged.

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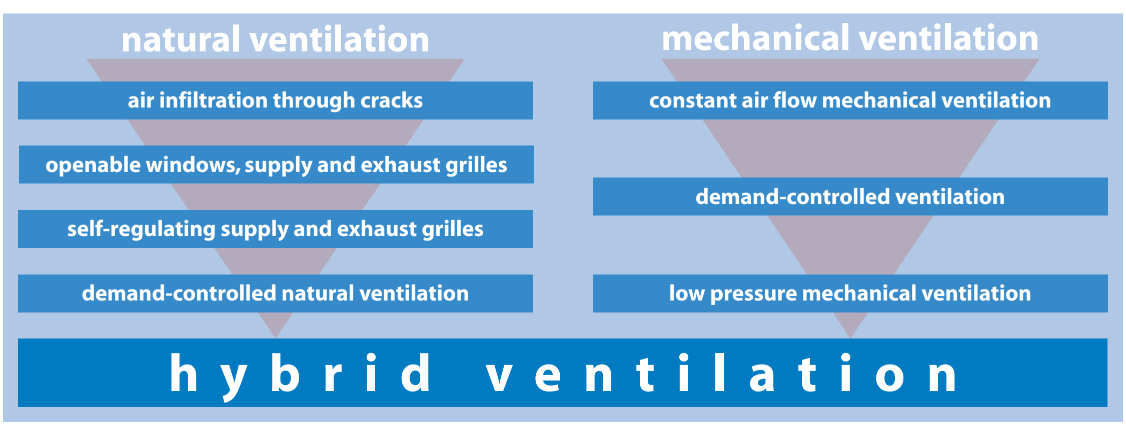
1. introduction

Today, buildings should be designed to interact with the outdoor environment. They should utilize the outdoor environment to create an acceptable indoor environment whenever it is beneficial to do so. The extent to which sustainable technologies such as passive solar gains, passive and natural cooling, daylighting and natural ventilation can be utilized depends on the outdoor climate, building use, building location and building design. Under optimum conditions sustainable technologies would be able to fulfil the demands for heat, light and fresh air. However, in most cases supplementary mechanical systems will be needed.

In thermally well insulated office buildings ventilation and cooling may account for more than 50% of the energy requirement, and a well-controlled and energy-efficient ventilation system is a prerequisite for low energy consumption. Natural ventilation and passive cooling are sustainable, energy-efficient and clean technologies, and they are well accepted by occupants (if they are optimally controlled). They should therefore be encouraged wherever possible. Unfortunately, the design of energy-efficient ventilation systems in office and educational buildings has often become a question of using either natural or mechanical ventilation. This has prevented the widespread use of sustainable technologies because with natural ventilation alone a certain level of performance cannot be guaranteed under all conditions. In fact, in the majority of cases a combination of systems would be beneficial depending on the outdoor climate, building design, building use, and the main purpose of the ventilation system.

For many years mechanical and natural ventilation systems have developed separately, see Figure 1. Mechanical ventilation has developed from constant airflow systems through systems with extensive heat recovery and demand-controlled air flows to energy-optimized low-pressure ventilation systems. Over the same period natural ventilation has developed from being considered only as a largely uncontrolled system using air infiltration through cracks and airing through windows, to a demand-controlled ventilation system with cooling capabilities. For both systems the focus in their development has been to minimize energy consumption while maintaining a comfortable and

Figure 1. Development of natural and mechanical systems. [1]



Definition of Hybrid Ventilation

The primary purpose of ventilation is to provide acceptable indoor air quality and thermal comfort. Hybrid ventilation systems can be described as systems that provide a comfortable internal environment using both natural ventilation and mechanical systems, but using different features of these systems at different times of the day or season of the year. In hybrid ventilation mechanical and natural forces are combined in a two-mode system where the operating mode varies according to the season, and within individual days. Thus the active mode reflects the external environment and takes maximum advantage of ambient conditions at any point in time. The main difference between a conventional ventilation system and a hybrid system is the fact that the latter has an intelligent control system that can switch automatically between natural and mechanical modes in order to minimize energy consumption.

Benefits of Hybrid Ventilation Systems

Hybrid ventilation has access to both ventilation modes in one system, exploits the benefits of each mode and creates new opportunities for further optimisation and improvement of the overall quality of ventilation.

Advanced hybrid ventilation technology fulfils the high requirements on indoor environmental performance and the increasing need for energy savings and sustainable development by optimising the balance between indoor air quality, thermal comfort, energy use and environmental impact.

Hybrid ventilation results in high user satisfaction because of the use of natural ventilation, the high degree of individual control of the indoor climate (including the possibility of varying the indoor climate - adaptive comfort) as well as a direct and visible response to user interventions.

Hybrid ventilation technology offers an intelligent and advanced ventilation solution for the complex building developments of today, that is user transparent and sustainable healthy indoor environment. Naturally, the next step in this process is the development of ventilation concepts that utilise and combine the best features of each system to create a new type of ventilation system – Hybrid Ventilation.

Rationale for Hybrid Ventilation

Hybrid ventilation provides opportunities for innovative solutions to the problems of mechanically or naturally ventilated buildings: solutions that simultaneously improve the indoor environment and reduce energy demand. Natural and mechanical ventilation have developed separately over many years and the potential for further improvements is limited. But the combination of natural and mechanical ventilation opens a new world of opportunities.

There are multiple motivations for the interest in hybrid ventilation: the likelihood of a positive response by occupants and a positive impact on productivity, reduced environmental impact and an increased robustness and/or increased flexibility and adaptability, and financial motivations (the prospect of lower investment costs and/or operation costs).

Naturally, expectations of hybrid ventilation performance will vary between different countries because of climate variations, energy prices and other factors. In countries with cold climates, hybrid ventilation can avoid the trend to use mechanical air conditioning in new buildings, which has occurred in response to higher occupant expectations, the requirements of codes and standards, and in some cases higher internal gains and changes in building design. In countries with warm climates, it can reduce the reliance on air conditioning and reduce the cost, energy penalty and consequential environmental effects of full year-round air conditioning.

Both natural and mechanical ventilation have advantages and disadvantages. For natural ventilation systems one of the major disadvantages is the uncertainty in performance, which results in an increased risk of draught problems in cold climates and a risk of unacceptable thermal comfort conditions during summer periods. On the other hand, air conditioning systems often lead to complaints from the occupants, especially in cases where individual control is not possible. Hybrid ventilation systems have access to both ventilation modes and therefore allow the best ventilation mode to be chosen depending on the circumstances.

The focus on the environmental impacts of energy production and consumption has provided an increased awareness of the energy used by fans, heating/cooling coils and other equipment in ventilation and air conditioning systems. An expectation of a reduction in annual energy costs has also been an important driving force for the development of hybrid ventilation strategies in many of the case study buildings. Available data from case studies are shown in Figure 2. The results show that a substantial energy saving has been achieved in a number of buildings, mainly because of a very substantial reduction in energy use for fans and a reduced energy use for cooling.

Quantification of the impact on productivity is less evident, although several studies indicate the potential for such improvements. [2]

In addition to the effect of improved thermal comfort and indoor air quality on productivity the degree of user control has an influence on the productivity - the greater the degree of user control the better the productivity. A building with openable windows and passive cooling techniques may be contributing to a greater degree of user control and therefore a better perceived productivity. Another aspect is that hybrid ventilation implies less noise (provided that there are no outdoor sources of heavy noise), which may also improve productivity. In most case study buildings the high degree of user control has been greatly appreciated by the occupants. In one of the case studies (CS1 Wilkinson Building, AU) investigations via occupant questionnaires showed that the perceived performance increased as a function of perceived indoor air quality and thermal comfort.

Estimating the initial cost of hybrid ventilation systems in buildings can be quite difficult as the installation often consists of both mechanical installations and of building elements. Part of the investment in mechanical equipment is often shifted towards a larger investment in the building itself: increased room air volume per person, a shape favourable to air movement, a more intelligent facade/window system, extract passive stacks, etc. The life cycle costs for hybrid ventilated buildings are often lower than for reference buildings, but the relationship between initial, operating and maintenance costs is different. In Annex 35 the reference cost range provided by the participants has been used to compare the initial costs of hybrid ventilation systems, and buildings with hybrid ventilation, with the initial cost of traditional systems and buildings, see "TR11 Cost of hybrid ventilation systems". In Figure 3 a comparison is made between the installation costs in buildings with hybrid ventilation systems and in buildings with conventional ventilation systems. This figure shows that the installation costs in buildings with hybrid ventilation systems may vary from less than the lower reference value (three buildings) to more than the higher reference value (one building), but typically the installation costs are at the same level as for other buildings. In Figure 4 the total building costs are compared to reference values. With two exceptions, these values are between the lower and the higher reference levels. The results from the

Figure 2. Energy use in case study buildings compared to reference buildings in the same country. Values are given for total energy use, energy use for heating, energy use for cooling, and energy use for electricity in total and for fans. For more detailed information see the case study reports for each building.

Relative Energy Use (%)	Type	Country	Total	Heating	Cooling	Electricity	
						Total	Fans
Wilkinson building	Office	AU	77	23	23		
IVEG building	Office	B					
PROBE building	Office	B					
B&O Headquarters	Office	DK		142	-	140	10
B. Brecht Gymnasium	School	D		80	-	100	10
I Guzzini Illuminazione	Office	I					
Liberty Tower of Meiji University	School	J	60		83		
Tokyo Gas Earth Port	Office	J					
Fujita Technology Center	Office	J		150	50		
Mediå School	School	N	90	90	-	90	10
Jaer School	School	N					
Tånga School	School	S	58	70	-	40	2
Waterland School	School	NL					

Figure 3. Comparison of all installation cost in buildings with hybrid ventilation systems with reference installation cost for conventional buildings.

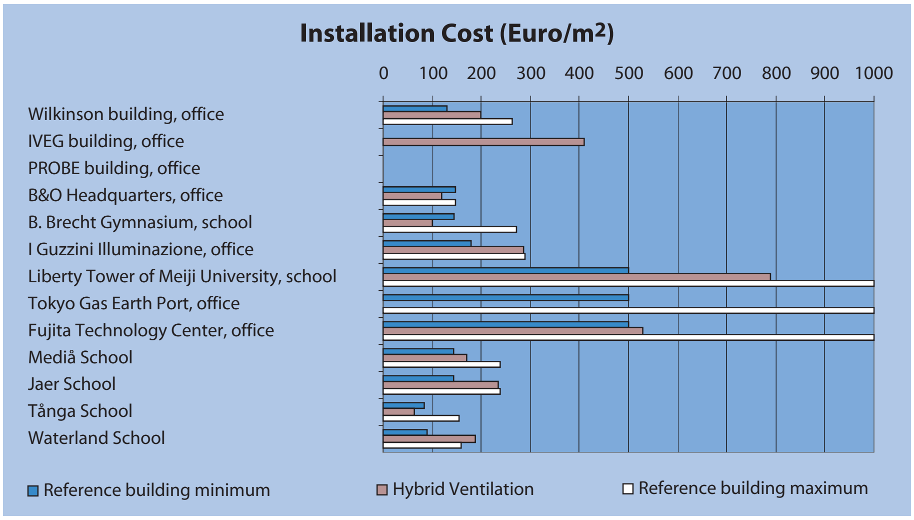
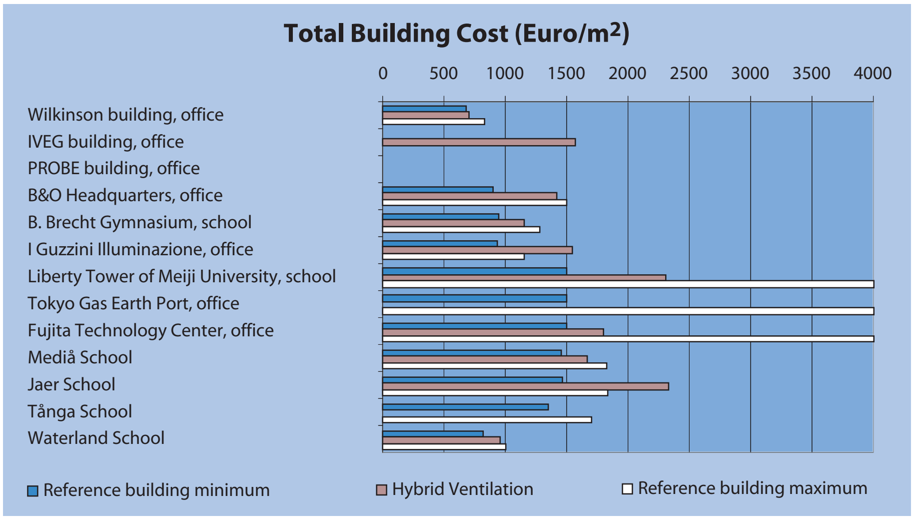


Figure 4. Comparison of total building cost for buildings with hybrid ventilation systems with total building cost for reference buildings.



case study buildings indicate a potential for cost savings, especially with regard to installation costs. The installation cost in hybrid ventilated buildings is approximately 20-25% of the total building cost.

Design Philosophy

Hybrid ventilation is based on a different design philosophy and expectations about its performance cannot be the same as for mechanical ventilation. Energy performance targets and comfort requirements must be different. Cost comparisons between hybrid and mechanical systems should be done on a life-cycle cost basis rather than simply on an initial capital cost basis, because of the different design approach, and hence the different balance between initial, running, maintenance and disposal costs.

Buildings with hybrid ventilation often include other sustainable technologies e.g. daylighting, passive and natural cooling and passive solar heating. For these buildings an energy optimization requires an integrated approach in the design of the building and its passive and mechanical systems. In an integrated approach, design teams including architects and engineers are formed and the building design is developed in an iterative process from conceptual design ideas to final detailed design. Building energy use and the sizes of mechanical equipment can be reduced implementing an effective integration of the architectural design and the design of mechanical systems.

The hybrid ventilation process is very dependent on the outdoor climate and the microclimate around the building, as well as the thermal behaviour of the building, and therefore it is essential that these factors are taken into consideration from the very beginning of the design. It is also important that issues such as night cooling potential, noise and air pollution from the surroundings, as well as fire safety and security, are taken into consideration. In the design the location and size of openings in the building as well as features to enhance the driving forces, such as solar chimneys and passive stacks, must be co-ordinated with the selected strategy for both daytime and night-time ventilation. Passive methods to heat and/or cool outdoor air might be considered as well as possibilities for heat recovery and filtration. Appropriate control strategies must be determined and decisions made regarding the level of automatic and/or manual control and user interaction. Necessary mechanical systems to fulfil comfort and energy requirements must be designed. These can range from simple mechanical exhaust fans to enhance driving forces, to balanced mechanical ventilation or full air conditioning systems. Finally, the whole system control strategy must be designed to optimize energy consumption while maintaining acceptable comfort conditions. This requires special attention and is often very challenging and difficult to implement satisfactorily.

Scope of the Booklet and CD-ROM

This booklet is aimed at newcomers in the field and gives an introduction to hybrid ventilation. A secondary aim is to function as a gateway for the more detailed information that can be found on the CD-ROM. With a focus on office and educational buildings, the booklet describes the principles of hybrid ventilation technologies, control strategies and algorithms, as well as analysis methods. Case studies include both new-build and retrofit designs and the booklet and information on the CD-ROM are valuable for both situations. Chapter 2 contains a description of the primary hybrid ventilation principles and the typical ventilation strategies used for indoor air quality and temperature control. Chapter 3 gives an introduction to the integrated design approach for hybrid ventilation systems, focusing on barriers, requirements and design targets at the conceptual design phase. Chapter 4 contains an overview of control strategies, control parameters and algorithms as well as equipment and sensors. Chapter 5 gives an overview of analysis and design tools for hybrid ventilation systems and based on the evaluated performance, the selection of appropriate methods for different stages of the design is discussed. Chapter 6 describes a method to control the quality of ventilation systems to ensure that the performance targets are achieved and Chapter 7 gives an overview of the characteristics of the case studies investigated and the lessons learned from them.

The CD-ROM is a source of information with a number of technical reports, papers, background material, etc. with much more detailed information about the research results. There are a number of references in the booklet to this information.

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[1] From "Quality in Relation to Indoor Climate and Energy Efficiency - An analysis of trends, achievements and remaining challenges", Ph.D. Thesis, Peter Wouters, UCL, 2000.

[2] Association of ventilation system type with SBS symptoms in office workers. Seppänen, O., Fisk, W.J. Indoor Air, Vol. 12, no. 2.

Ventilation and health in non-industrial indoor environments: Report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN), Wargocki et al. Indoor Air, Vol. 12, no. 2.

2. principles

There is a wide range of hybrid ventilation principles and strategies and the concepts vary widely in the level of building integration and industrialization. An integrated approach is a necessity for all hybrid ventilation systems. The integration of the building and the ventilation system is more important when natural ventilation plays a dominant role. In design of hybrid ventilation systems it is often necessary to separate ventilation design for indoor air quality control from ventilation design for natural cooling in summer. The major reason for this is the fact that devices for indoor air quality control and thermal comfort control in general are quite different, and that the potential barriers and problems to be solved, including the optimization challenge, also are fundamentally different.

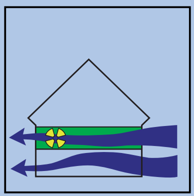
This chapter focuses on the main principles and describes how typical design challenges can be met. Three examples are selected to illustrate the different principles and possible ventilation strategies for IAQ control and natural cooling. Chapter 7 gives an overview of the principles used in all of the case study buildings in this project, while the CD-ROM contains a detailed description

Ventilation Principles

The main hybrid ventilation principles are:

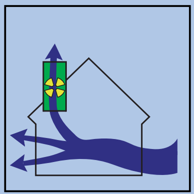
Natural and mechanical ventilation

This principle is based on two fully autonomous systems where the control strategy either switches between the two systems, or uses one system for some tasks and the other system for other tasks. It covers, for example, systems with natural ventilation in intermediate seasons and mechanical ventilation during midsummer and/or midwinter; or systems with mechanical ventilation during occupied hours and natural ventilation for night cooling.



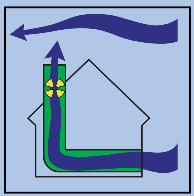
Fan-assisted natural ventilation

This principle is based on a natural ventilation system combined with an extract or supply fan. It covers natural ventilation systems that, during periods of weak natural driving forces or periods of increased demands, can enhance pressure differences by mechanical (low-pressure) fan assistance.



Stack- and wind-assisted mechanical ventilation

This principle is based on a mechanical ventilation system that makes optimal use of natural driving forces. It covers mechanical ventilation systems with very small pressure losses, where natural driving forces can account for a considerable part of the necessary pressure.



in the technical report "TR1 Hybrid ventilation and control strategies in the case studies", as well as individual case study reports with descriptions of each building, the ventilation strategy applied and the monitored performance.

Ventilation for Indoor Air Quality Control

When optimizing ventilation for indoor air quality control, the challenge is to achieve an optimal equilibrium between indoor air quality, thermal comfort, energy use and environmental impact during periods of heating and cooling demands.

First of all this includes minimising the necessary fresh air flow rate by reducing pollution sources, and by optimal demand control of air flow rates for the occupants. Secondly, it includes reducing heating and cooling demands by heat recovery, passive cooling and/or passive heating of ventilation air. Finally, it includes reducing the need for fan energy by using low-pressure duct-work and other components as well as optimising natural driving forces from stack effect and wind. During periods without heating and cooling demands there is no need to reduce air flow rates, as more fresh air will only improve the indoor air quality. The optimization challenge then becomes mainly a question of minimizing the use of fan energy. In addition to the challenges mentioned above, ventilation should of course be provided without creating comfort problems such as draught, high temperature gradients or noise.

With regard to indoor air quality control, a hybrid ventilation system based on stack- and wind-assisted mechanical ventilation, or on natural and mechanical ventilation with a seasonal changeover operation strategy, does not differ from a traditional demand-controlled mechanical ventilation system. However, for a hybrid ventilation system based on fan-assisted natural ventilation, or on natural and mechanical ventilation with a continuous changeover operation strategy, it is necessary to consider the dynamic behaviour of the air flow rate in the natural ventilation mode and the buffer effect of the building, which causes the indoor air quality to vary around an average value. The acceptable magnitude and duration of variations must be defined in order to determine when assisting fans are started or when the system switches to the mechanical mode, see Chapter 3. A strategy for switching back to the natural ventilation mode must also be defined.

Ventilation for Temperature Control

When optimizing ventilation as a natural cooling strategy, the challenge is to achieve an optimal equilibrium between cooling capacity, cooling load, thermal mass and thermal comfort.

First of all this includes reducing internal and external heat loads by using low-energy equipment, by utilizing daylight, and by effective solar shading. Secondly, it includes exploiting the thermal mass of the building, which absorbs and stores heat during occupied hours and is cooled during unoccupied hours by night ventilation. Finally, it includes reducing the need for fan energy by using low-pressure duct-work and other components, as well as optimizing natural driving forces derived from the stack effect and wind.
The major issues of concern with regard to thermal comfort are avoiding excessively low temperatures at the start of the working hours (appropriate night cooling strategy) and achieving an acceptable temperature increase during working hours (solar shading and thermal mass). The ventilation air flow rate needed for natural cooling is in general much higher than the ventilation air flow rate needed for indoor air quality control.

With regard to temperature control, it is important that a hybrid ventilation system based on stack- and wind-assisted mechanical ventilation is capable of adapting to window opening to improve occupant comfort tolerance and to reduce fan energy. As the stack effect is limited, it is also important that the ventilation system is designed for optimum use of wind effect. For a hybrid ventilation system based on natural and mechanical ventilation, the natural mode dominates for temperature control in cold climates. The size of the mechanical system (designed for indoor air quality control) is usually not enough to achieve acceptable temperature control, but in periods that lack adequate natural driving forces, it can provide a valuable supplement. In warm climates the natural mode is mainly useful for temperature control in the intermediate season, while it can give a valuable supplement to night ventilation in the summer period. For a hybrid ventilation system based on fan-assisted natural ventilation, an optimum use of the wind effect is important.

Types of Components

There are no real hybrid ventilation components as such. In nearly all cases hybrid ventilation systems consist of a combination of components, which can be used in purely natural systems or in purely mechanical systems. However, the availability of appropriate components is essential for the successful design and operation of a hybrid ventilation system. To facilitate combining natural and mechanical forces in the air distribution system, appropriate components can include:

- Low-pressure ductwork,
- Low-pressure fans with advanced control mechanisms such as frequency control, air flow control, etc…
- Low-pressure static heat exchangers and air filters,
- Wind towers, solar chimneys or atria for exhaust. Underground ducts, culverts or plenums to pre-condition supply air.

To facilitate the control of thermal comfort, indoor air quality and air flow in the building, appropriate components can include:

- Manually operated and/or motorised windows, vents or special ventilation openings in the facade- and in internal walls,
- Room temperature, CO_2 and/or air flow sensors,
- A control system with weather station

The CD-ROM contains descriptions of components used for each case study building.

Ventilation Principles in Case Studies

The ventilation principle applied in each case study can be seen in Figure 5. The ventilation principle using both natural and mechanical ventilation is the most common followed by fan-assisted natural ventilation. The ventilation principle using stack- and wind-assisted mechanical ventilation is only represented in one case study. More detailed information on each case study can be found on the CD-ROM.

Example 1: Natural and Mechanical Ventilation

This system is implemented in the case study "Liberty Tower of Meiji University" situated in Tokyo, Japan, see Figure 6. The ventilation system consists of a natural ventilation system for controlling indoor air quality and temperature in intermediate seasons, and a mechanical air-conditioning system for the rest of the year, when the outdoor climate is not comfortable.

In the natural ventilation system air enters via perimeter counter units on every floor and is exhausted through openings at the top of the centre core. The central core is designed to utilize the stack effect at each floor and above the centre core a wind floor is designed to enhance driving forces from the wind. As the wind floor is open to four directions the driving force is expected to be stable through the year regardless of wind direction. Outdoor air intake control is based on CO_2 and temperature sensors and is controlled via a BEMS. The system includes automatically controlled natural ventilation windows at night with an automatic intake of outdoor air and wind floor outlets.

In the mechanical air-conditioning system the supplied air flow rate is controlled by a VAV system, where the fresh air flow rate is automatically controlled based on indoor CO_2 concentration and the air flow rate and inlet temperature is controlled by room temperature and humidity sensors.

Figure 5. Ventilation principle applied in the case studies investigated.

Ventilation Principles	Type	Natural and mechanical ventilation	Fan assisted natural ventilation	Stack and wind assisted mechanical ventilation
Wilkinson building	Office	●		
IVEG building	Office	●		
PROBE building	Office	●		
B&O Headquarters	Office		●	
B. Brecht Gymnasium	School	●		
I Guzzini Illuminazione	Office	●		
Liberty Tower of Meiji University	School	●		
Tokyo Gas Earth Port	Office	●		
Fujita Technology Center	Office	●		
Mediå School	School			●
Jaer School	School		●	
Tånga School	School		●	
Waterland School	School		●	

The use of the natural ventilation system reduces the annual average energy use for cooling the building by 17%, ranging from 90% in April (Spring) to a minimum of 6% in July (Summer), and continues to reduce cooling to about 62% in November (Autumn). The wind floor design on the 18th floor increases the ventilation rate by an average of 30%. Acceptable thermal comfort and IAQ conditions were achieved. The most significant problem was encountered close to the low-positioned openings, where occupants experienced draughts. Another problem was high pressure loss in overflow ducts with smoke and fire dampers between rooms and the centre core. More detailed information can be found in the case study report "CS7 Liberty Tower of Meiji University" on the CD-ROM.

Example 2: Fan-assisted Natural Ventilation

This system is implemented in the case study "B&O Headquarters", Struer, Denmark, see Figure 7. The ventilation system is a natural ventilation system with fan assistance. The inlets are low-positioned narrow hatches (windows) located in front of the floor slab. The inlet air is preheated with a ribbed pipe. The air flows through the occupied space to the staircase and is extracted from the top of the stairs. If needed the system is assisted with a fan located in a cowl on the roof. The large glass facade with the ventilation hatches is orientated north and there is no solar shading. The south facade has a moderate window area with user-controlled windows, which are automatically controlled for night cooling. It is a partly heavy building free from false ceilings and acoustic insulation. For fire protection automatic fire doors close between open-plan offices and staircases.

Figure 6. Example of a hybrid ventilated high rise building based on the principle "Natural and Mechanical Ventilation".

Figure 7. Example of a hybrid ventilated office building based on the principle "Fan-assisted Natural Ventilation".

The ventilation system is demand-controlled by temperature and CO_2 sensors in the offices and run with a constant air flow rate of 1.5 ach in daytime and 3.0 ach in summer during night cooling. The constant-flow is achieved by measurement of the air speed in the extract hood. When ventilation is needed, the hatches and the dampers in the extract cowl open. If the necessary ventilation air flow rate is not achieved by natural means the fan speed is controlled. The hatches on each floor are controlled by the temperature and CO_2 level of the floor. The ventilation is controlled by a building management system with a weather station on the roof. If the external temperature is below 5°C the ventilation system is shut down to protect the ribbed pipes and the window hatches from freezing. The ventilation system is also shut down in case of rain or high wind speeds.

The initial cost of the system is only about 60% of a conventional ventilation system. The displacement air distribution principle works quite well in the building, resulting in a high ventilation efficiency. The energy consumption of the assisting fan is very low (1,7 kWh/m^2 year) and accounts for only about 3% of the electrical energy use. The indoor air quality measured (CO_2 used as an indicator) in the building was very high. The energy demand for heating shows a remarkably larger consumption than expected from the Danish building code. This can be related to the large areas for transmission heat loss, a very large glazed area towards the north, and an infiltration rate larger than expected. The measurements showed that the system only was running in either CO_2 mode or night cooling mode for about 15% of the year , but due to the relative high infiltration rate the indoor air quality was still satisfactory! More detailed information can be found in the case study report "CS4 Bang & Olufsen Headquarters" on the CD-ROM.

Example 3: Stack- and Wind-assisted Mechanical Ventilation

This system is implemented in the case study "Mediå School", Norway, see Figure 8. The hybrid ventilation system is a balanced, low-pressure mechanical system with both air supply and extract in the classrooms.

The air is taken from an inlet tower at some distance from the building, which utilizes wind forces and where the inlet fan is located. Air flows through an underground culvert with large thermal mass to reduce daily temperature swings, and is distributed via a purpose-made basement corridor to low-positioned supply air terminal devices in the classrooms to increase ventilation efficiency. The air is extracted from the classrooms through a high-positioned hatch into a purpose-made lightwell corridor and exhausted through a roof tower with outlet valves that ensure suction by wind from any direction. A heat recovery unit and a low-pressure exhaust fan are located in the tower. The system also includes filtering, preheating of the ventilation air, and heat recovery with bypass, which is located in the basement between the underground culvert and the basement corridor. The flow is driven by low-pressure fans in the supply and extract, supported by wind and stack effects. Window opening is possible and the ventilation system will normally adapt to it.

The ventilation is demand-controlled by a CO_2-sensor in each classroom. If the CO_2 level exceeds the set point the extract hatch is opened and adjusted by a motor. The supply fan is controlled by the pressure in the basement supply corridor to 2 Pa overpressure compared to the external. The extract fan is controlled to maintain a 5 Pa pressure drop between the basement supply corridor and the lightwell extract corridor, in order to avoid overpressure in the building. Both fans are frequency controlled. The ventilation is controlled by the building management system.

The performance shows acceptable indoor air quality and thermal comfort. The cooling effect of the underground culvert and the basement corridor is higher than expected. The energy use corresponds to the reference consumption in Norway, but is higher than predicted. The reasons for this are initial failures in the control system (now solved), and under-prediction of the energy use by BEMS, pumps, etc. More detailed information can be found in the case study report “CS10 Mediå School” on the CD-ROM.

Figure 8. Example of a hybrid ventilated school building based on the principle “Stack- and Wind-assisted Mechanical Ventilation”.

Integrated Ventilation and Building Design

Conventional mechanical ventilation and cooling systems can basically be installed in any building, in any location in any climate and for any application. Even if it is clearly advantageous to integrate installations at an early stage of design, it is possible to design and install a ventilation system without the early involvement. Installations for mechanical cooling are very compact and are easily installed in most buildings.

The use of natural ventilation requires openable windows, doors or other openable elements in the building facade. All openings are part of the building envelope and must be designed in conjunction with other basic construction elements from the start of the design process. Natural cooling can be achieved by exposed room surfaces with high thermal mass. This is often part of the building structure, and certainly something that must be considered early in the design. Natural ventilation can also be achieved by a simple ducted system with intake and exhaust openings at different heights. Intake ducts with large surface areas and high thermal mass can be utilized to cool intake air during the day via night cooling of the thermal mass. This is in addition to using a heavy building structure, which also must be considered very early in the design process.

The success of hybrid ventilation depends on utilizing the benefits of natural ventilation, and the design of hybrid ventilation must be integrated from the very start and in subsequent design stages. This is different from the design process for conventional mechanical ventilation. Another difference is that today's conventional mechanical ventilation design is close to "mass production", using "over-the-shelf" equipment and products, while hybrid ventilation design is "tailored", and some components must be tailored for the installation. More time must be spent on design to successfully integrate building and HVAC design. This chapter focuses on the early design phase for hybrid ventilation, which is very different from conventional ventilation design. Subsequent design phases are only briefly handled here.

The Design Process

Effective ventilation design of indoor spaces has the best chance of success, when the design process is carried out in a logical, sequential manner, with increasing richness of detail as the final design is approached, and in the framework of a design procedure. With hybrid ventilation the need for a design procedure is even more evident due to the comprehensive design team needed, where users, building owners, architects, civil engineers and indoor climate and energy consultants must all be involved – simultaneously. Depending on the possibilities and limitations of the particular building, the preferred ventilation system type may turn out to be mechanical, hybrid or pure natural ventilation. A diagram of a design procedure is shown in Figure 9. Stages for construction, commissioning and operation are also included to achieve a holistic approach. The design procedure for indoor environment ensures that every important issue is considered, that the process is efficient, and that the final design is allowed to evolve in a logical way from idea to construction. The procedure aims at achieving a good indoor climate combined with low energy consumption and a tight integration of the HVAC solution with the building design and the environment. The tight integration requires that many parameters be considered in an organized way, especially at the early stages.

A ventilation design procedure consists of different phases: conceptual design phase, basic design phase, detailed design phase and design evaluation. The conceptual design phase for hybrid ventilation ideally includes decisions on building form, size, function and location. However, a building project often starts with a given building concept in given surroundings and in such cases these parameters can only be influenced marginally. Targets are set for indoor air quality, thermal comfort and energy use as well as cost limits. The conceptual design of the hybrid ventilation system is based on these considerations as well as guidelines and experience from previous buildings. The natural ventilation principle (stack and/or wind-driven, single-sided and/or cross ventilation) to be used is decided together with the principle of the necessary additional mechanical systems. In the basic design phase the building heat, sun and contaminant loads are estimated and the hybrid ventilation system layout designed. The necessary air flow rates as well as expected indoor air quality and temperature levels are calculated. A coarse yearly energy consumption is calculated together with the necessary peak power demands. If the results do not meet the targets, the building and its systems will have to be redesigned before entering the next phase. In the detailed design phase contaminants and thermal loads are re-evaluated and source control options are considered and/or optimized. The types and locations of the hybrid ventilation system components are selected as well as the control strategy and sensor location. Using hour-by-hour calculations for a design year the whole system (building and technical systems) is optimized with regard to indoor climate, energy use and costs. Finally, in the design evaluation phase detailed predictions of indoor air quality and thermal comfort can be performed to check whether the design fulfils the targets of the project.

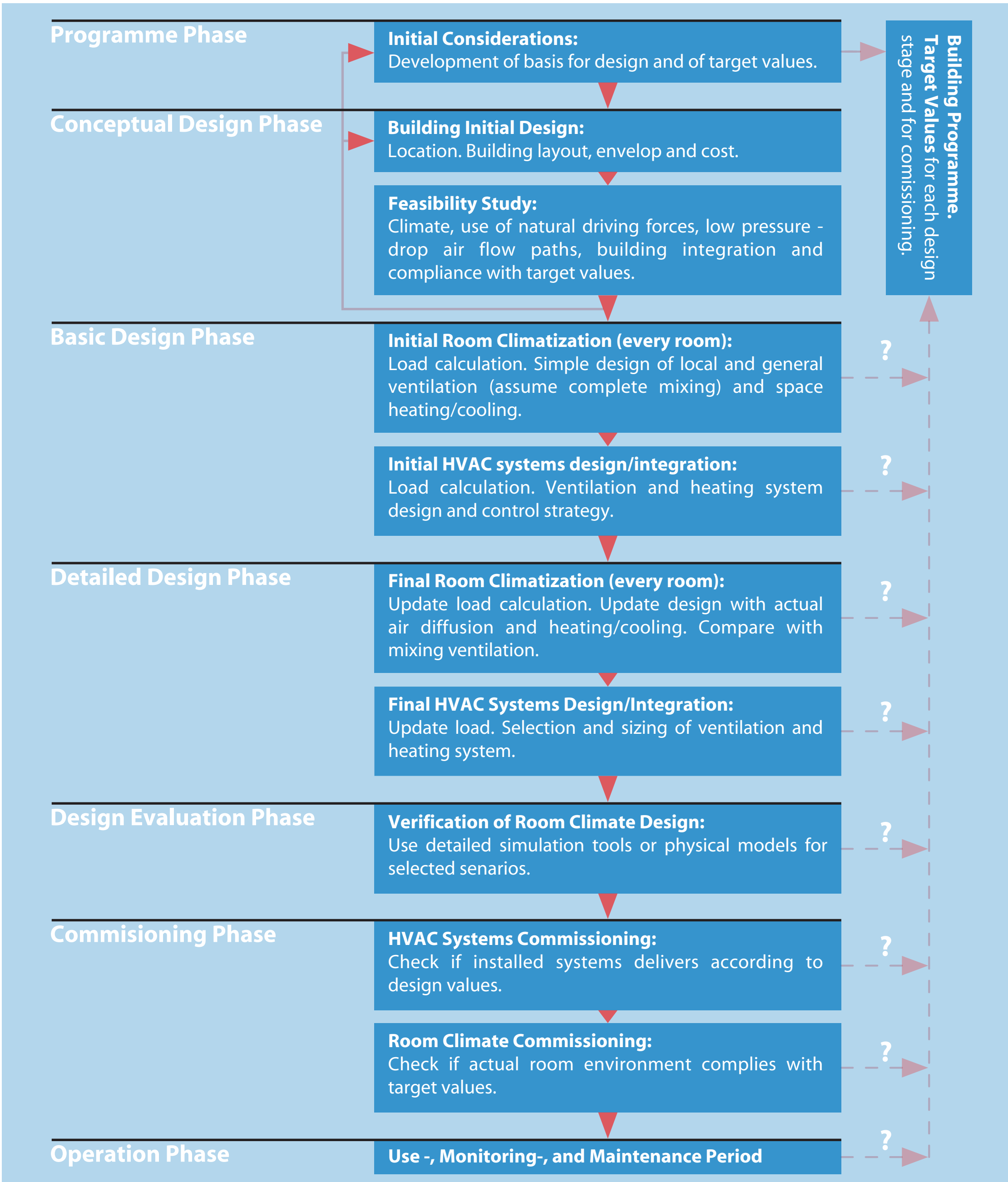
Initial Considerations

Building Programme

The builder or his representative (building project manager) will normally be responsible for setting performance targets and other requirements. It is extremely important that the builder is aware of this responsibility, and puts time and effort into the early stages of the design process, in conjunction with consultants, architects and engineers, to define goals and limits. The builder must also be ready to take decisions during the project. In a larger company or organization, the builder will normally take advice from a construction-project committee. It is important that user interests are well represented in the committee in the early design. The requirements with respect to functions that the building should provide must be documented and used as basis for design.

A set of indoor climate target values should be defined to check if the suggested design is heading in the right direction. The target values may need to be specified at different levels of detail for use at different stages of design. Goals for energy use, release of pollutants to the environment, initial costs and operational costs (preferable LCC) should also be set. Threshold limit values or similar given values for indoor air pollutants are set with regard to health. In many cases these values are too high to ensure comfort and good productivity among workers. Parameters chosen as target values should be measurable and as far as possible monitored during building operation. The set of target values decided should be written down and used as a contract document for design of the building and for maintenance until a possible reconstruction or refurbishment.

Figure 9. Design procedure for hybrid ventilation.


Programme Phase
Initial Considerations:
Development of basis for design and of target values.
Building Programme.
Target Values for each design stage and for comissioning.
Conceptual Design Phase
Building Initial Design:
Location. Building layout, envelop and cost.
Feasibility Study:
Climate, use of natural driving forces, low pressure - drop air flow paths, building integration and compliance with target values.
Basic Design Phase
Initial Room Climatization (every room):
Load calculation. Simple design of local and general ventilation (assume complete mixing) and space heating/cooling.
Initial HVAC systems design/integration:
Load calculation. Ventilation and heating system design and control strategy.
Detailed Design Phase
Final Room Climatization (every room):
Update load calculation. Update design with actual air diffusion and heating/cooling. Compare with mixing ventilation.
Final HVAC Systems Design/Integration:
Update load. Selection and sizing of ventilation and heating system.
Design Evaluation Phase
Verification of Room Climate Design:
Use detailed simulation tools or physical models for selected senarios.
Commisioning Phase
HVAC Systems Commissioning:
Check if installed systems delivers according to design values.
Room Climate Commissioning:
Check if actual room environment complies with target values.
Operation Phase
Use -, Monitoring-, and Maintenance Period
?

It makes sense to collect initial design considerations into a "Building Programme" (BP) that must include:

Building Functions

- functionality, flexibility, PR-value, maintainability, expected lifetime

Architectural Quality

- identity, scale/proportion, integrity/coherence, integration in urban context

Economics

- initial costs, operating costs, maintenance costs, property value outlook

Indoor Environment (target values for different zones in the building)

- visual, thermal, atmospheric, acoustical, mechanical, psychosocial

Environmental Issues

- constructional resources, operational resources, energy use, ecological strain

Basic conditions feasibility study

Using a simple tool such as Figure 10 can be helpful in a first selection of a ventilation system. Proceed as follows: use data from the BP, find the distribution of L's, M's and H's and evaluate options. Decide on one or two ventilation options for further evaluation or consider changes to BP to increase the possibility of applying natural driving forces and use the table again.

General advice on using Figure 10:

- Try to avoid design concepts that will involve "Ls", to ensure that a certain ventilation concept will be possible to implement without extra costs and delays.

- Be ready for extra costs, delays or other problems if the actual design involves an "L". More Ls means more challenges, and risks are involved. This must be considered when building contracts are discussed.

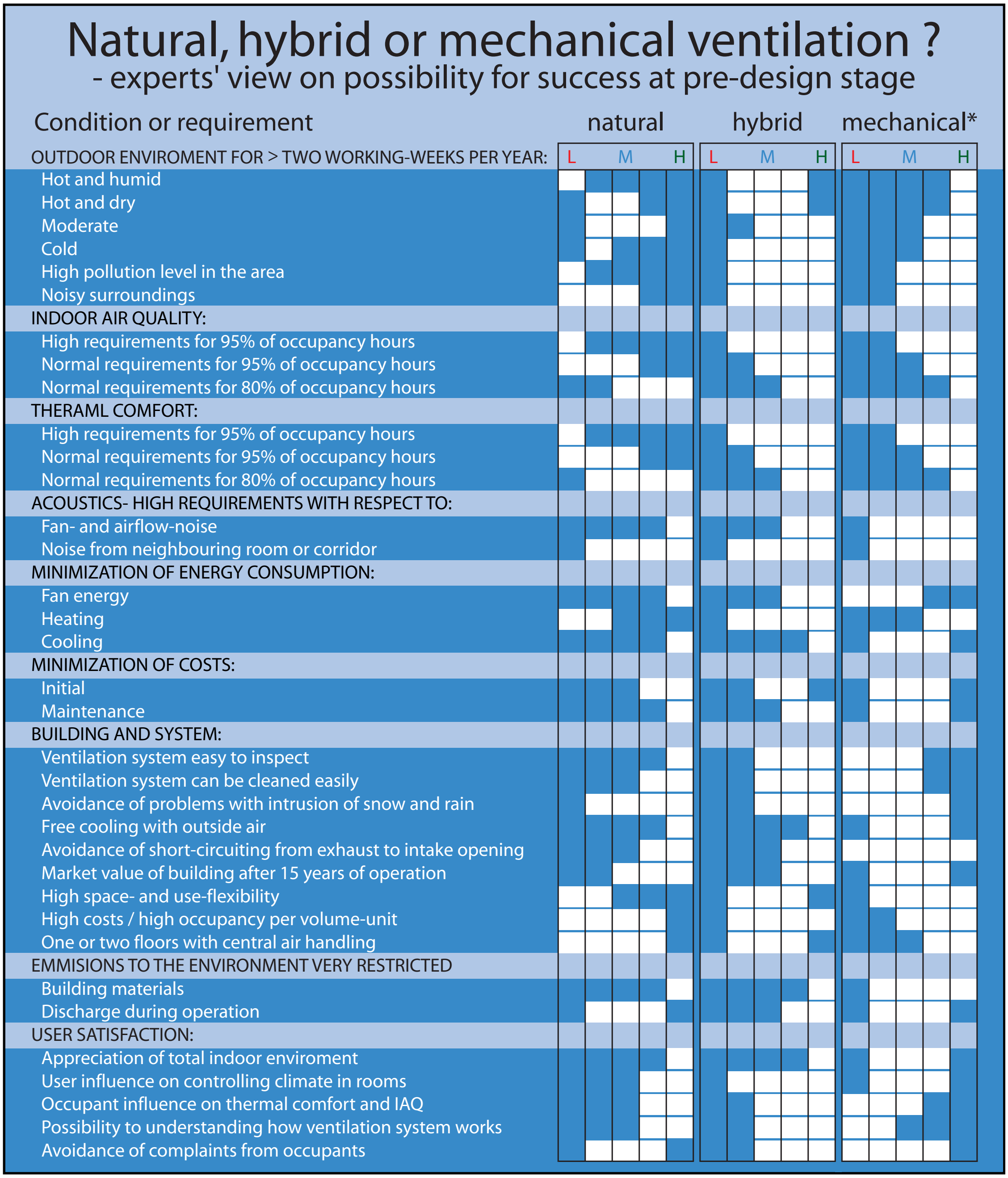
- Study design guides and consult special advisors. Study documented case study buildings for similar outdoor conditions and use

The process of working through Figure 10 may be iterated a few times before a ventilation concept is chosen further. The decision for further work may involve carrying out design for two alternative ventilation concepts.

Figure 10. Evaluation of the possibility of using pure natural ventilation, hybrid ventilation or mechanical ventilation as the main ventilation system.

Interpretation of abbreviations: L(ow) possibility: Solution is very difficult or very costly; M(edium) possibility: Solution is highly possible with appropriate design; H(igh) possibility: Solution is a standard solution or is easy to design.

*** The mechanical ventilation system considered is balanced and has a pressure drop of more than 500 Pa on intake- and exhaust side.**


Natural, hybrid or mechanical ventilation ?
- experts' view on possibility for success at pre-design stage
Condition or requirement
natural
hybrid
mechanical*
OUTDOOR ENVIROMENT FOR > TWO WORKING-WEEKS PER YEAR:
L M H
L M H
L M H
Hot and humid
Hot and dry
Moderate
Cold
High pollution level in the area
Noisy surroundings
INDOOR AIR QUALITY:
High requirements for 95% of occupancy hours
Normal requirements for 95% of occupancy hours
Normal requirements for 80% of occupancy hours
THERAML COMFORT:
High requirements for 95% of occupancy hours
Normal requirements for 95% of occupancy hours
Normal requirements for 80% of occupancy hours
ACOUSTICS- HIGH REQUIREMENTS WITH RESPECT TO:
Fan- and airflow-noise
Noise from neighbouring room or corridor
MINIMIZATION OF ENERGY CONSUMPTION:
Fan energy
Heating
Cooling
MINIMIZATION OF COSTS:
Initial
Maintenance
BUILDING AND SYSTEM:
Ventilation system easy to inspect
Ventilation system can be cleaned easily
Avoidance of problems with intrusion of snow and rain
Free cooling with outside air
Avoidance of short-circuiting from exhaust to intake opening
Market value of building after 15 years of operation
High space- and use-flexibility
High costs / high occupancy per volume-unit
One or two floors with central air handling
EMMISIONS TO THE ENVIRONMENT VERY RESTRICTED
Building materials
Discharge during operation
USER SATISFACTION:
Appreciation of total indoor enviroment
User influence on controlling climate in rooms
Occupant influence on thermal comfort and IAQ
Possibility to understanding how ventilation system works
Avoidance of complaints from occupants

Targets

By definition a hybrid ventilation system uses different modes, for example a natural mode and a mechanical mode. The percentage of time the mechanical mode will be used depends strongly on:

- Local climate
- Local energy availability and price policy
- Running and maintenance costs
- The way the targets are expressed
- The dimensions of the natural part of the system
- Type of hybrid ventilation system and control strategy

In hybrid ventilation design the challenge is to find a solution in which the natural part of the system is used as much as possible, while the mechanical part ensures fulfilment of the requirements in situations where the natural part fails or is less energy efficient. The control strategy plays an important role in this process. Moreover, most standards and regulations specify fixed requirements. Often they do not give information about the proportion of time the required values may be exceeded. If the target is expressed very precisely, or only a very narrow band is allowed, mechanical ventilation is likely to be the chosen option, even if a natural solution, averaged over time, could give the same result. As an example see Figure 11.

Some research work indicates [3] that occupants appreciate some variation in the indoor environment depending on activity levels, clothing choice and factors such as state of health, while the ability to directly influence the indoor environment and variations in temperature provide a positive stimulus. The larger variation over time is a typical characteristic for the natural part of hybrid ventilation systems.

A mechanical system normally gives a constant flow. This constant flow may be adapted to the occupants' needs, in which case we speak about demand control, but even in the demand-controlled situation the flow is constant if the need is constant, see Figure 12 (red curve).
A natural system will, because of the variability of the driving forces (wind and temperature), result in a wider range of air flow rates (green curve). Sometimes the air flow rate exceeds the required flow rate considerably, while at other times the required flow rate cannot be achieved. A hybrid ventilation system can exploit excessive flow rates, to decrease exposure to pollutants when there is no heating or cooling energy penalty; i.e. outside the heating or cooling season. Some limitations on high flow rates may be necessary to ensure thermal comfort. If the natural flow rate is less than the required minimum, the mechanical mode of the hybrid system comes in. The blue curve is a typical characteristic for a hybrid ventilation system.

Figure 11 shows, using the CO_2 concentration as an indicator for IAQ and the air flow rates of Figure 12, the CO_2 concentration in a 100 m^2 office room with 10 persons. For the mechanical ventilation system the CO_2 concentration is constant. For the natural ventilation system the average concentration is almost the same as for the mechanical system, but there are large variations during the day. For the hybrid ventilation system the mechanical mode assists when the natural driving forces are inadequate (25% of the time), and the variations in IAQ is limited to the specified levels.

Figure 11. For three different ventilation systems the diagram shows CO_2 concentration of a typical work day

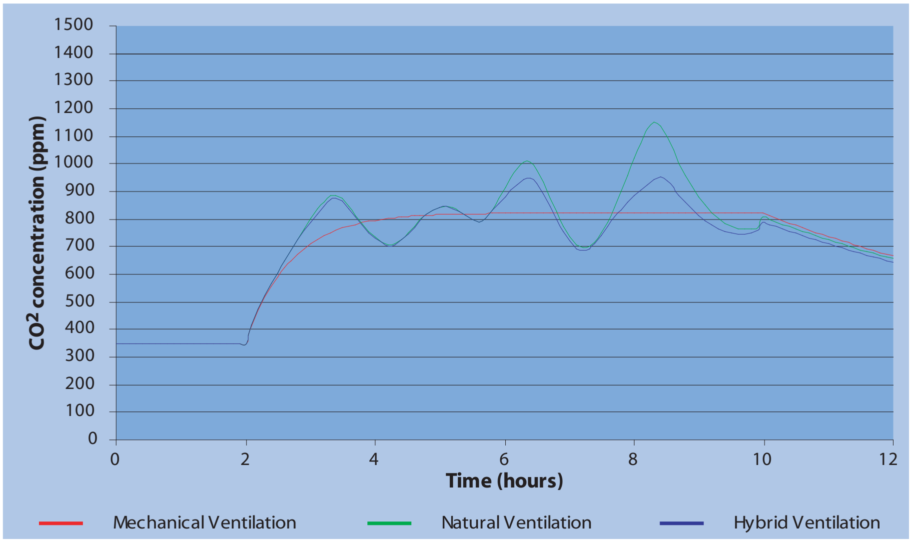
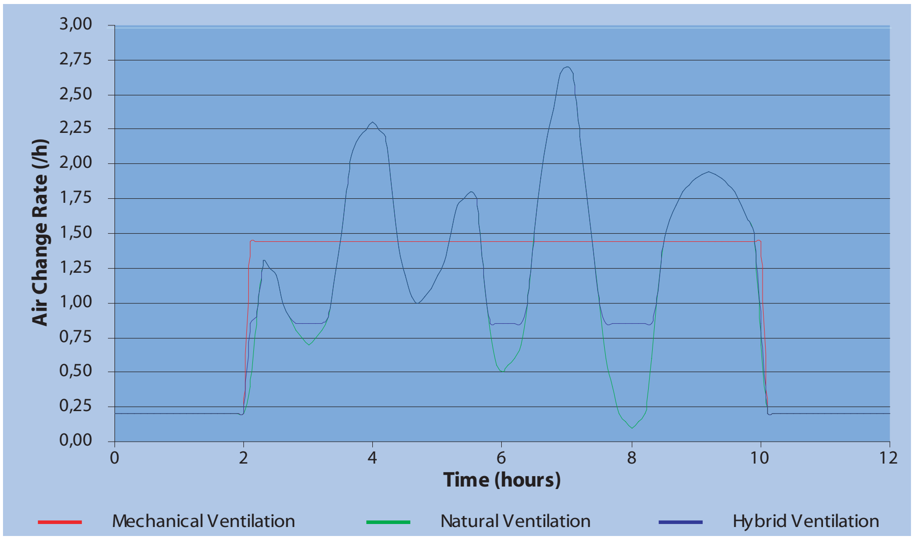


Figure 12. For three different ventilation systems the diagram shows the ventilation rate over the same period.



In the technical report "TR9 Performance assessment of advanced ventilation systems in the framework of energy and IAQ regulations" on the CD-ROM a critical analysis of the possibilities and challenges of hybrid ventilation systems in relation to standards and regulations has been performed. The report also includes recommendations for handling innovative ventilation systems and identifies boundary conditions for correct performance assessment in relation to standards and regulations.

Environmental and cost considerations

To minimize the environmental impact of the hybrid ventilation system it is important to consider its energy demand. The designer should also evaluate the life cycle effect of the system, which means considering both the energy and environmental effects of the components that comprise the system, as well as the effects during break downs. Environmental life-cycle costs can be emphasized by comparing the life-cycle cost of environmentally favourable alternatives and a reference (e.g. VAV instead of CAV).

It is almost impossible to give general energy and environmental targets as they depend highly on the availability and type of energy and its means of production, as well as the energy policy in a country, including energy pricing policy. Important factors relevant to life cycle perspectives are the life span of the building and its ventilation system, environmental impact, ventilation system changes and cost analysis.

Very often the practical life span of a ventilation system is determined by the time a building will be used for its current purpose. During the design phase maintainability and flexibility of the ventilation system must be taken into account, i.e. the fact that the use of, for example, an office building can change several times during its life span. Also, from a cost perspective one has to consider initial cost, running cost, maintenance cost and the cost of demolition.

Building and System Initial Design – Developing a Concept

Initial integration of building and system

The integrated design of heating, cooling, lighting and ventilation of buildings can be accomplished in three separate steps. The first step is the design of the building itself i.e. to minimize heat loss and maximize heat gain in winter, to minimize heat gain in summer and to use daylight and fresh air efficiently. Decisions made at this step determine the size of the heating, cooling and lighting loads. Poor decisions at this point can easily double or triple the size of the mechanical equipment eventually needed. The second step involves the climatic design, where passive heating, passive and natural cooling, daylighting techniques and natural ventilation heat the building in winter, cool it in summer and light and ventilate it all year. The proper decisions at this point can greatly reduce the loads created during the first step. The third step consists of designing the mechanical equipment to handle the loads that remain from the combined effect of the first and second steps, see Figure 13. The heating, cooling, lighting and ventilation design of buildings always involves all three steps, whether consciously considered or not.

The hybrid ventilation process is very dependent on the outdoor climate and the microclimate around the building, as well as the internal layout of the building, the possible air flow paths through it, and its thermal behaviour. Therefore, it is essential that these factors be taken into consideration in the basic design step. The output from the first step is a building orientation, design and internal layout that minimizes the thermal loads on the building in overheated periods, which together with the selected ventilation strategy makes it possible to exploit the dominant driving forces (wind and/or buoyancy) at the specific location, and which ensures proper air distribution through the building. It is also important that issues such as night cooling potential, noise and air pollution in the surroundings, as well as fire safety and security, are taken into consideration. In the second step the natural ventilation mode of the hybrid system is designed. The location and size of openings in the building as well as features to enhance the driving forces, such as solar chimneys and thermal stacks, are designed according to the selected strategy for both daytime and night-time ventilation. Passive methods to heat and/or cool the outdoor air are considered as well as heat recovery and filtration. Appropriate control strategies for the natural ventilation mode are determined and decisions are made regarding the level of automatic and/or manual control and user interaction. In the third step the necessary mechanical systems to fulfil the comfort and energy requirements are designed. These can range from simple mechanical exhaust fans to enhance the driving forces to balanced mechanical ventilation or full air conditioning systems. The hybrid ventilation control strategy and the corresponding whole-system control strategy are determined to optimize energy use while maintaining acceptable comfort conditions. There are many pitfalls on the way, and the

Figure 13. Typical design considerations at each conceptual design step.

	Heating	Cooling	Lighting	Ventilation
Step 1	***Conservation***	***Heat avoidance***	***Daylight***	***Natural ventilation***
Basic design	1. Surface to volume ratio 2. Insulation 3. Infiltration	1. Shading 2. Exterior colours 3. Insulation 4. Thermal mass	1. Windows 2. Glazing 3. Interior finishes	1. Building form and internal layout 2. Location of windows and openings 3. Stacks
Step 2	***Passive solar***	***Passive cooling***	***Daylighting***	***Natural ventilation***
Climatic design	1. Direct gain 2. Exposed thermal mass 3. Sunspace	1. Evaporative cooling 2. Convective cooling 3. Radiant cooling	1. Skylights 2. Light shelves 3. Light wells 4. Solar shading	1. Wind induced ventilation 2. Bouyancy induced ventilation 3. Air distribution 4. Control system
Step 3	***Heating system***	***Cooling system***	***Electric light***	***Mechanical ventilation***
Design of mechanical systems	1. Radiators 2. Radiant heating 3. Warm air system	1. Refrigeration plant 2. Cooled ceiling or floor 3. Cold air system	1. Lamps 2. Fixtures 3. Location of fixtures	1. Mechanical exhaust 2. Mechanical ventilation 3. Air conditioning

Figure 14. Avoid the following when searching for solutions using natural ventilation.

- ✗ Poor insulation and thermal bridges in building envelope.
- ✗ Infiltration/exfiltration (Building tightness should be < 1 ach @ 50 Pa with all openings closed).
- ✗ Pollution from interior building materials, from use of building, activities and from outdoor environment.
- ✗ Solar heating of intake air when room cooling is needed.
- ✗ Direct solar heating of occupants.
- ✗ Noise transfer from outside and from other rooms of building.
- ✗ Negative effects from wind and buoyancy.
- ✗ Air velocities > 1 m/s in air flow paths and 1.5 m/s in components at design load.
- ✗ Inefficient room ventilation.
- ✗ Excess use of lighting, heating and ventilation.
- ✗ Condensation or liquid water leading to mold growth in intake air flow paths and in rooms.
- ✗ Air flow paths which do not allow easy inspection and cleaning.
- ✗ Shutting down ventilation completely for periods.
- ✗ Building design with little thermal mass exposed in intake air flow paths and in rooms.
- ✗ Use of deep spaces and internal rooms.
- ✗ Recirculation of exhaust air to the intake side.
- ✗ Need for mechanical cooling/dehumidification below outdoor air level.

Figure 15. Look for the following when searching for good solutions using natural ventilation:

- ✓ Availability of natural driving forces on construction site.
- ✓ Minimize airflow rate for building while satisfying indoor target values.
- ✓ Minimize pressure drops in ventilation air flow paths.
- ✓ Possibility of using outdoor air without filtering.
- ✓ Possibility of using direct airflow from/to outside without a noise, control, burglary, insect or rain problem.
- ✓ Use large room volumes compared to buildings with mechanical ventilation.
- ✓ Use large floor-to-ceiling height.
- ✓ Use exposed thermal mass in the building structure.
- ✓ Minimize need for ducting of ventilation air.
- ✓ Minimize need for conditioning of ventilation air.
- ✓ Use heat recovery in cold climates.
- ✓ Use demand control.
- ✓ Use air overflow between rooms either for supply or extract side of ventilation system.
- ✓ Use a large height difference between ventilation intake and exhaust to maximize stack effect.
- ✓ Install wind towers and vents that utilize wind (but prevent excess ventilation).
- ✓ Incorporate basement and underground culverts to dampen outdoor temperature swings for natural cooling.

checklists presented in Figure 14 and Figure 15 may be useful to ignite ideas for use in a design concept. The investment costs for a design suggestion should at this stage be coarsely estimated to determine whether the concept is realistic or not.

Building concept feasibility study

When a number of design concepts for the building, including the ventilation systems, have been developed the most promising must be selected for the continuing design process. At this stage the concepts have no details and they primarily consist of a building plan, including room volumes, windows, stairwells and stacks for ventilation. Volumes of different priority for indoor environment quality have been decided. Ventilation air flow paths and zoning for smoke control for the different parts of the building have been considered. The probability that a hybrid ventilation solution will in the end turn out to be both energy-efficient and provide a high indoor environmental quality depends on a number of parameters.

Figure 16, developed for north European climate, can be used as a rough guide to determine whether a building design concept has a satisfactory potential for further development. It can also be used in situations where the starting point of the project is a given building concept and the suitability of hybrid ventilation is to be investigated. When most of the parameters in question have a high or medium probability for success the potential for further

Figure 16. Probability for success for a building concept using hybrid ventilation in North European climate.

Parameter in question	Probability for success		
Building related:	**High**	**Medium**	**Low**
Glass in % of area of facade	30	70	100
Solar protection	Extern. shading	Intern. shading	No shading
Contaminant emission from surfaces	Low	Intermediate	High
Room height (m)	> 3	2.5 – 3	< 2.5
Room depth (m)	< 6	6 – 15	> 15
Thermal mass characterization	Heavy	Intermediate	Light
Thermal mass access	Exposed	Partly exposed	Not available
Intake culvert with thermal mass	Yes	Partly	No
Night cooling	Possible	Partly	Not possible
Need for openings in the facade	No	In some periods	Always
Enhanced use of stack effect and wind	Yes	Partly	No
Exhaust air heat recovery important	Not important	Important	Very important
Heat recovery possible	Yes	Partly	No
Activity related:	**High**	**Medium**	**Low**
Internal heat load (W/m^2)	< 20	20 – 30	> 30
High polluting activities (printing, bphotocopying, pantries)	In separate rooms	Partly in separate rooms	Distributed in occupied zones
Typical occupation duration	8 hours	16 hours	24 hours
Air change demand in heating season	< 2	2 – 4	> 4

development of a hybrid ventilation solution is good and the few parameters, who have not, specify issues to be considered carefully in the design. When most of the parameters in question have a low probability for success a hybrid ventilation solution is not recommended.

Remaining Design Phases

In the conceptual design phase it is beneficial to develop a wide range of solutions to minimize the risk of overlooking good solutions. As a careful evaluation of all proposals is not possible, the first selection must be based on an initial screening, for example by using Figure 16 and very simple calculation methods followed by more detailed methods as the number of potential solutions decreases. Design targets and criteria are adjusted and developed as the project evolves. Solutions are continuously evaluated accordingly.

The result of the conceptual design phase is a few potential hybrid ventilation solutions that in the basic design phase are developed into a single (and perhaps an alternative) solution, which in the detailed design phase is further developed and optimized. Finally, in the design evaluation phase detailed predictions of indoor air quality, thermal comfort and energy use are performed to check if the design fulfils the targets of the project. The richness of detail and the complexity of design tools and methods increases as the design develops, and the level of detail on information as well as expectations of the accuracy of prediction results increases, see chapter 5.
When the building has been constructed the HVAC system and the indoor environment is commissioned to ensure that the system is capable of delivering according to the design values, and that the target values for the indoor environment are fulfilled, see chapter 6.

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[3] Richard de Dear. Adaptive Thermal Comfort in Natural and Hybrid Ventilation. HybVent Forum '99, The University of Sydney, Sydney, September 1999. (Available on CD-ROM)

4. control strategies

The main challenge in the design of control systems for hybrid ventilated buildings is to find the right balance between implementation costs, operation costs, energy use, indoor climate, comfort, users' satisfaction and robustness. The development of an "optimal" control strategy for a specific building will depend not only on technical parameters as building type and design, ventilation system, external noise and pollution, solar shading and internal loads but also on parameters such as dress code, user attitudes and user expectations. In hybrid ventilation the control is as important as the ventilation system itself and there is a strong interaction between the ventilation system and the control system. It is therefore important that the ventilation system and the control system are designed together in one process. Many of the hybrid ventilation components are also an integral part of the building. This makes a strong co-operation between the architect, the HVAC engineer and the control engineer necessary.

One of the advantages of natural ventilation systems is higher user satisfaction due to individual control of windows and indoor environmental conditions. If possible this feature should be maintained in the control of a hybrid ventilation system even if it could conflict with the possibility of guaranteeing a specific level of indoor thermal comfort or air quality in the rooms. Unfortunately the relationship between the indoor climate and user acceptance in user-controlled rooms is not well known. Recent research indicates that users are more tolerant of deviations in the indoor thermal climate if it is controlled by themselves, see de Dear. [4]

Even though users should have the maximum possibility of controlling their own environment, automatic control is needed to support the users in achieving a comfortable indoor climate and to take over during non-occupied hours. In rooms for several people, e.g. open-plan offices, and in rooms occupied by different people, e.g. meeting rooms, a higher degree of automation is needed. In the case study "Bertolt-Brecht-Gymnasium" the users strongly appreciated the manual control and refused a fully automatic system, but measurements showed that the mechanical system was seldom applied and that the air quality in some periods was very low. Automatic control is also needed during non-occupied hours to reduce energy consumption and to precondition rooms for occupation.

Hybrid ventilation systems can be made quite complex. However, it is very important to develop a control strategy and design a control system that is easy to understand for the users and can be operated by the maintenance staff. Therefore, simplicity and transparency of the user/system interface is of the utmost importance. Control system designers need to recognise that most users are not technically literate and are not interested in learning complex operations to suit varying outdoor conditions. They want a system that responds to their needs unobtrusively and allows them to change a condition if it is perceived as unsatisfactory, with rapid feedback.

The control strategy for a building should at least include a winter control strategy, where IAQ normally is the main parameter of concern, and a summer control strategy, where the maximum room temperature is the main concern. It should also include a spring control strategy, to be used in the interval between winter and summer where there might occasionally be a heating demand as well as excess heat in the building. Both the hybrid ventilation strategy and the control strategy are significantly influenced by the general climate in the region where the building is located. Hybrid ventilation can be used in buildings in both cold temperate climates and in warm temperate climates. In cold climates the control strategy should focus on minimising the ventilation energy needed to achieve good IAQ, and on achieving a good indoor climate in summer and spring without mechanical cooling. In warm climates the control strategy should focus mainly on reducing the energy consumption for mechanical cooling in summer.

Control Tasks

The control strategy should determine both time and rate control. It should also determine different control modes in relation to different weather conditions. The actual control strategy should reflect the demands of the building owner, the needs of the users and the requirements in standards and regulations.

IAQ during occupied hours

The control of ventilation for IAQ can either be:

- Manual by the occupants;
- Simple timer control;
- Motion detection (occupants present);
- Based on direct measurement of IAQ;

or a combination of these.

In relation to IAQ control it must be emphasized that the perceived IAQ is higher for occupants in a room than for people entering a room from outside. The difference is that occupants in a room adapt to the IAQ in the room and accept air that is less fresh and more stuffy. Usually the IAQ level is designed for the perceived IAQ for people entering a room. The CO_2 concentration is a useful indicator of IAQ if people are the only pollutant source. If other significant sources influencing IAQ are present, e.g. pollutants from materials and cleaning, then the CO_2 concentration in the room may be less satisfactory as indicator. In small rooms with work desks for one or a few people, e.g. cellular offices, it can normally be expected that the occupants will be able to control the IAQ to their own satisfaction if the ventilation system provides them with the necessary facilities, e.g. user-controlled windows and vents. Experience from several of the case studies shows that users greatly appreciate the possibility of manually controlling the indoor environment. In the case study “Wilkinson Building” occupants in cellular offices were able to adjust the indoor climate to their own satisfaction, and as they preferred to use windows in stead of the supplementary cooling equipment, they were able to do this in an energy-efficient way.

In large rooms for many people, e.g. landscape offices, and in rooms occasionally occupied by different people, e.g. meeting rooms, automatic control of ventilation for IAQ is normally needed. The purpose of the control in this case is to reduce the ventilation energy consumption by limiting the operating hours and the ventilation rate according to the occupancy pattern. The optimum strategy should have both good user control and an automatic back up based on IAQ. The problem with such a strategy is the cost and maintenance of the control system, see later. The strategy is therefore normally only possible in large rooms.

IAQ during non-occupied hours

Even during non-occupied hours there might be a need for IAQ ventilation, especially in tight buildings. Examples are:

- Ventilation after the end of the occupancy period, to remove built-up pollution
- Ventilation during non-occupied periods to remove pollution from materials and cleaning
- Ventilation before occupancy to start the occupancy period with fresh air in the building.

Room temperature during occupied hours in summer

Control of room temperature during occupied hours in summer can be either manual or automatic. People do have a very clear sense of their own thermal comfort. Due to the normally small difference between indoor and external air temperature on hot summer days, the external air has limited potential to reduce the room temperature, even if the flow rate is high. In many cases the body cooling potential of air movement due to open windows might be the most important in relation to thermal comfort. With efficient night cooling or mechanical cooling increased external air flow might increase the room temperature if the external air temperature is higher than the indoor air temperature, see later.

The need for direct automatic control of room temperature in each room during occupancy is mainly related to large rooms catering for many people and to rooms occasionally occupied by different people. Direct automatic control of room temperature is also necessary if comfort is achieved by mechanical means in each room, e.g. mechanical cooling or additional mechanical fan-forced air flow.

Solar shading

External solar shading must normally be centrally controlled, with the possibility of occupants in the individual rooms overriding the central control.
It is also important to have efficient solar shading during non-occupied hours. The central control must be based on the solar radiation on the different facades. More than one control per façade is required if the solar intensity differs considerably on the same façade (e.g. high buildings in a narrow street). The number of control actions applied to the solar shading must be limited so as to not distract the occupants. The local override should be reset after a period, or at least at the end of the occupied hours. In any case it is an advantage to have user-controlled internal shading, e.g. curtains, roller or venetian blinds, to control glare and local discomfort caused by direct solar radiation.

Night ventilation during summer

The control of night ventilation is of great importance to the possibility of achieving acceptable thermal comfort during hot summer days in buildings without mechanical cooling, and in reducing the energy consumption for mechanical cooling. The building structures should be as cold as possible without creating thermal discomfort in the morning.
The control of night ventilation should normally be automatic, but it is possible to have night ventilation with manual user-controlled windows or hatches in the individual rooms. Manual control by the occupants requires clear easy-to-understand instructions. Automatic control can be local per room or central for the building or a section of the building. Local control is normally only relevant in larger rooms and especially if local fan assistance is used. Central control must normally be based on measured temperatures in representative rooms. The selection of the representative rooms is of great importance.

The actual night ventilation strategy depends on the system. If fans are included it is preferable to have a few degrees cooling potential available from the external air before fans are started because of the fan power consumption. Night ventilation must continue until the building is sufficiently cooled or occupied again. If the building structures are cooled to low temperatures it might be necessary to interrupt the night ventilation before the end of the non-occupied period in order to regain acceptable surface temperatures before the start of the occupation.

Preheating of ventilation air
To avoid sensations of draft it might be necessary to preheat incoming external air; this might also be necessary where cooling is needed in the room. Coils or radiators for preheating the supply air should normally be controlled based on the temperature of the inlet air.

Severe weather override
In case of severe weather, e.g. strong wind or precipitation, it may be necessary to override the normal controls, roll up solar shading, or close windows. In case of frost it may also be necessary to close dampers or hatches in front of preheating devices, if they are not protected.

Room heating
Room temperature control in hybrid ventilated buildings can be achieved as in any other building. It is normally recommended to have local control of heating in all rooms independent of the ventilation system and to have central, weather-compensated control of supply water temperature.

Room cooling
The control of room cooling by cooled ceilings, fan coils or cooled ventilation air in hybrid ventilated buildings can be achieved as in any other building. In hybrid ventilated buildings it might be even more important to have a strategy which controls inlets and mechanical cooling, and at the same time gives users' possibility to overrule the system. This call for careful instructions to the occupants on how to operate the windows when cooling is on and to have a control that can avoid condensation on cooled ceilings.

Fan assistance
Assisting fans can be controlled:

- By the temperature or the IAQ in the rooms
- By the pressure in the supply or exhaust ducts
- By the air flow through the fan

If the fan is in the natural ventilation flow path or in a separate path the control can be either on/off, stepped or continuous. If the fan is in parallel to the natural ventilation flow path and uses part of the same flow path it is difficult to have continuous control.

Alternating natural and mechanical ventilation
Alternating natural and mechanical ventilation must normally be controlled based on the external temperature and humidity. Good information for the occupants is needed about the actual mode of the ventilation system.

Sensors

To fulfil the control strategy sensors are needed in the building to measure temperature, IAQ and occupancy. Sensors are also needed to measure the actual weather conditions. Further information on sensors is available in "TR6 A sensor survey for hybrid ventilation control in buildings" on the CD-ROM.

Sensors in the building

Temperature	Ordinary room and duct temperature sensors are reliable and not expensive. Surface temperature sensors exist but there is not so much experience with their use in control systems.
CO_2	CO_2 is an IAQ indicator of body odour but is not harmful to people in the concentrations normally found in buildings. CO_2-sensors are quite expensive and need regular calibration, see "TR5 CO_2 sensors for IAQ" on CD-ROM.
VOC	VOC is an indicator of IAQ. There is little experience with the use of VOC-sensors. It is not clear what they are measuring and how to calibrate them.
PIR	Infrared presence sensors are reliable and not expensive. They are easy to test and can also be used for other purposes e.g. control of artificial light.
Air speed	Air speed sensors can be used to measure the airflow rate in ducts. Air speed sensors are quite expensive and need regular cleaning and calibration

Weather Station

External temperature	External temperature sensors are reliable and not expensive. The problem is often to find a position to install them where the temperature is not influenced by the building or solar radiation.
Wind	Traditionally wind speed is measured with a cup anemometer and wind direction is measured with a wind vane. A new type without moving parts is available where both speed and direction is measured by using Doppler effect in two directions.
Solar radiation	Solar radiation sensors do not need to be very accurate for control purposes. It is preferable to have a sensor on the upper part of each main facade.
Precipitation	Precipitation sensors are reliable and not expensive. They normally only need to produce an on/off signal for overrule purposes.

Control Strategies in Case Studies

The control strategy applied in each case study can be seen in Figure 17. For each case study more detailed information can be found in chapter 7 and in “TR1 Hybrid ventilation and control strategies in the case studies” on the CD-ROM. The following is an extract of the lessons learned about the control strategies used.

In cellular offices, giving users full responsibility for controlling their own indoor climate during occupied hours can work very well. Individual control can be either manual or motorised, operated from a panel or the user’s PC. During non-occupied hours automatic control is needed to gain the benefit of cooling the building structure by night ventilation. In landscape offices automatic control is needed, but it is difficult to find an acceptable strategy for window control. If the windows are operated automatically during occupied hours, and the external temperature is more than a few degrees lower than the room temperature, there is a great risk of user dissatisfaction due to the sensation of draft. If the inlet air is preheated it is best to have separate control of the inlet temperature, because preheating of the inlet air is needed even when there is excess heat in the room. There is a risk that the inlet temperature set point will be raised to compensate for insufficient room heating. The control of the outlets and of night ventilation seems less problematic.

In classrooms a simpler control strategy and control system is often installed. If the users are to operate the ventilation in the classroom themselves there is a great risk of high CO_2 concentrations for some of the time; this risk also applies in classrooms where the inlet air is preheated.

In buildings that also have active mechanical cooling, where the operation mode is automatically switched between hybrid ventilation and

Figure 17. Control strategy applied in the case studies investigated. Man.: Manual control; Aut.: Automatic control; Con.: Constant ventilation; PIR: Demand control with presence detection; CO_2: Demand control with CO_2 sensors.

Case Studies	Type	Control Strategy			
		Indoor air quality	Room temperature	Night ventilation	Mechanical cooling
Wilkinson building	Office	Man.	Man.	-	Man.
IVEG building	Office	PIR	Man.	Aut.	0[5]
PROBE building	Office	PIR	Man.	Man.	-
B&O Headquarters	Office	CO_2	Aut.	Aut.	-
B. Brecht Gymnasium	School	Man.	Man.	Aut.	-
I Guzzini Illuminazione	Office	Man.	Aut.	Aut.	Aut.
Liberty Tower of Meiji University	School	Con.	Aut.	-	Aut.
Tokyo Gas Earth Port	Office	Con.	Aut.	-	Aut.
Fujita Technology Center	Office	Con.	Aut.	Aut.	Aut.
Mediå School	School	CO_2	Aut.	Aut.	
Jaer School	School	CO_2	Aut.	Aut.	
Tånga School	School	CO_2	Aut.	-	
Waterland School	School	CO_2	Man.	Aut.	-

mechanical cooling depending on the temperature or enthalpy difference between external and internal air, there is a risk that once activated the system will stay in active cooling mode. In most of the case study buildings a relatively complex control system is used to operate the hybrid ventilation. The long-term operation of the control systems is not analysed as part of the case studies. It is doubtful whether these control systems will operate well over time if not operated and maintained by personnel with special knowledge.

Developments in Controls

System integration

Integration of all controls for ventilation, heating, solar shading, and lighting into one Building Management System has the following advantages:

- It makes it easy for the operators
- It co-ordinates the control of the different systems
- It reduces the number of sensors

New standards for data interface at a component level, LON (Local Operating Network), make it easier to integrate components from different suppliers into one system without the need for protocols to translate between suppliers. Future developments will also open new possibilities for using information from security and fire safety systems in ventilation control.

Comfort sensors

Use of thermal comfort sensors measuring operative temperature instead of air temperature will give more reliable information on the real comfort conditions for persons in a hybrid ventilated room, where there can be large differences between air temperature and surface temperature. Real thermal comfort sensors are nowadays seldom used for control purposes. In the future the control performance might be improved by using thermal comfort sensors, or at least sensors equally sensitive to air temperature and thermal radiation.

A variation of this is to use an “Artificial Skin” sensor with the same sensitivity as the human skin, see “TR7 Individual thermal comfort controlled by an “artificial skin” sensor” on CD-ROM. The skin temperature sensor can also be used to control individual ceiling-mounted surface cooling or heating devices.

CO_2 sensors

In hybrid ventilation demand control of indoor air quality is very important for increasing the energy efficiency of the system. At present CO_2 is the most promising indicator of air quality in buildings, and to ensure satisfactory conditions an air quality sensor in every building zone is the optimum solution. CO_2 sensors have been applied in some of the case studies, see Figure 17, and with regular calibration they have performed well.

In “TR5 CO_2 sensors for IAQ” on the CD-ROM a market survey of more than 30 CO_2-sensors is documented. The survey shows that the main disadvantage of existing sensors on the market, with acceptable quality for IAQ measurements, is the price, which is about €300-500. The report also shows that there is a potential for development of low-cost and reliable sensors, if the market is developed.

Advanced controls

Advanced control techniques for hybrid ventilation must be able to control several parameters through an “optimised” strategy. They require a number of sensors and actuators and will have to be tuned to get optimum results. The report “TR4 Advanced control strategy” on the CD-ROM describes several advanced control techniques such as: Rule-based control, optimum and predictive control, neural networks, and fuzzy logic control. Rule-based control is the most commonly used technique and even if the other techniques have been known for many years and include much better possibilities for system optimization, they are not widely used in the building industry. The reason for this is mainly implementation difficulties, especially with regard to the need for a very complex and time-consuming tuning process for the systems. The full exploitation of hybrid ventilation potential, including full integration of manual (user) and automatic control, which is understandable from the users’ point of view, will require further developments in this area.

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[4] Richard de Dear. Adaptive Thermal Comfort in Natural and Hybrid Ventilation. HybVent Forum ’99, The University of Sydney, Sydney, September 1999. (Available on CD-ROM)

[5] Mechanical cooling was foreseen, but never used, because the hybrid ventilation system performs very well.

5. performance prediction

The ultimate objective of the environmental control solution for a building is to ensure satisfactory thermal comfort and indoor air quality for the occupants. In addition to fulfilling these primary objectives, the environmental control solution should be energy-efficient and fulfil economic, safety, acoustic, aesthetic and other objectives. Consequently, the HVAC designer needs analytical methods that can assist, evaluate and, where possible, optimize design of hybrid ventilation of buildings. As the environmental and architectural design develops, more data becomes available to the HVAC designer, who should therefore select an analytical method, or methods, of an appropriate level of detail for each stage of the design process. This chapter describes the main available mathematical analysis methods and new findings on the flow processes for hybrid ventilation design. The chapter focuses on methods for prediction of air flow rates, thermal comfort, indoor air quality and energy use and on appropriate selection of methods for the different stages of the design, as they are described in Chapter 3.

The key difference between natural and mechanical ventilation lies in the fact that neither velocity nor flow direction at the ventilation openings is predetermined in the former system. The stack pressure is determined by the temperature difference between the indoor and outdoor air, which is in turn affected by ventilation flow rates. The wind pressure is strongly affected by the microclimate around the buildings, which is again affected by landforms, vegetation and other surrounding buildings. Natural ventilation is more unstable than mechanical ventilation and human behaviour strongly influences the ventilation.

Because hybrid systems combine natural and mechanical ventilation, they present several complex challenges to analysis methods, requiring a global approach that takes into account the outdoor environment, the indoor environment, and the mechanical system. For example, control systems developed for hybrid systems will switch between a natural ventilation mode, which may result in stratified temperatures in the space, and a mechanical mode with mixed air and no stratification. The analysis method must be able to deal with these mode switches, and it must also be able to model the (possibly complex) control strategy itself. Furthermore, because hybrid ventilation systems are often used for temperature control as well as for IAQ control, analysis methods must be able to integrate thermal modelling with ventilation modelling.

The ideal analysis method for hybrid ventilation systems should include modelling of the natural ventilation mode and modelling of the mechanical ventilation mode, as well as modelling of the control strategy. It should be able to answer such questions as if and when the natural driving forces fail to fulfil the ventilation demands, and if and when mechanical ventilation is more energy efficient than natural ventilation.

Prediction Methods

Several methods are available that can be used to analyse air flows and energy use in mechanical or natural ventilation systems such as simple analytical and empirical methods, multi-zone network methods, zonal methods and computational fluid dynamics.

Simple analytical and empirical methods

These methods are generally applied to simple-geometry buildings, e.g. single-sided ventilation and one-zone buildings with two openings.

Multi-zone or network methods
The building is represented by a number of zones. The network methods can predict overall ventilation flow rates for the entire building and individual flow rates through openings. However, they cannot predict detailed flow patterns in each zone of the building. They are compatible with most multi-zone thermal modelling programs.

Zonal methods
The indoor air volume is split into several well-mixed macro-volumes in which parameters such as temperature and contaminant concentrations are assumed to be uniform. The mass flows between zones are calculated by combining experimental/analytical laws for the driving flow elements such as jets, plumes, boundary layer flows, etc., with a predicted pressure field based on a simplified momentum equation. Zonal models can be of varying complexity, and depending on the characteristics of the flow field in the room, be one-, two- or three-dimensional. Zonal models' relative simplicity of use gives them advantages for integration into existing multi-room building energy and air flow analysis programs to predict the performance of hybrid systems composed of both natural and forced-air convective components.

Computational fluid dynamics methods
A geometrical domain is subdivided into a large number of small cells over which the governing equations are discretised and solved. CFD methods are particularly suitable for air movement analysis in and around buildings, and they allow the airflow patterns as well as contaminant and temperature distributions inside a ventilated space to be analysed in detail. CFD simulations are more time-consuming than a multi-zone approach. For whole-building performance modelling of hybrid ventilation over its yearly operation, a full integration of CFD methods and a realistic thermal model is not only beyond the capacity of most computers, but it may also be unnecessary.

Each method has its own area of applicability, e.g. conceptual design, basic design, detailed design, or design evaluation. There are a few tools available that integrate and model the mutual interaction of thermal conditions and natural and mechanical air flow rates. A review of existing analysis tools can be found in the report "State-of-the-art of Hybrid Ventilation" on the CD. This chapter focuses on the developments in Annex 35.

New Developments in Prediction Methods

Vent sizing methods
A simplified method has been developed, that enables the designer to quickly determine, at a first design stage, the permeability of the building envelope in order to satisfy the required air change rate in the building, see "TR21 A simple tool to assess the feasibility of hybrid ventilation systems". The method requires only information about building typology and surrounding terrain, along with the Test Reference Year (TRY) of the location. The first two pieces of information yield two non-dimensional coefficients, which are introduced in a simplified model to determine the effective pressure difference across the envelope as a function of outdoor-indoor temperature difference and wind velocity. A graphical procedure is then used, given the overall permeability of the building envelope, to obtain the time fraction during the heating season for which natural ventilation exceeds the required air change rate. If this fraction is less than one this information allows the designer to determine the required increase in building envelope permeability using natural airing devices, or to determine the time fraction when mechanical ventilation will be necessary.

A number of possible methods for vent sizing in the conceptual design phase are summarized in the technical report "TR13 Methods for vent sizing in the predesign stage". They range from simple rules of thumb to interactive computerized tools.

Analytical solutions in simple buildings

Analytical solutions have been developed which follow the conventional macroscopic approach for analysing natural ventilation and are derived from the Bernoulli equation. The Bernoulli equation (which is based on the conservation of energy) is used to calculate air velocities in openings, while the law of mass conservation applied to an enclosure allows calculation of the mass flow rate.

Annex 35 research work proved that analytical solutions exist for natural ventilation of a simple one-zone building with between two and four openings. No analytical solutions exist for natural ventilation problems with more than four openings. Analytical solutions were developed for buildings with up to three openings and two simple mixed-mode ventilation systems. Three air change parameters were introduced characterizing the effects of thermal buoyancy, wind pressure and envelope heat loss for the heat source given problems. For a temperature-given problem, the solution for the ventilation flow rate can be expressed as a function of indoor/outdoor air temperature differences, wind pressure, flow rate from mechanical fans, the size of ventilation openings and so on. For a heat source given problem, an analytical solution can be expressed for ventilation flow rate as a function of heat source strength, wind pressure, flow rate from mechanical fans, the size of ventilation openings and so on.

The continuity equation has been solved analytically for different cases:

- Single-zone building with two openings
  - Stack-driven flow with fully mixed conditions and heat loss through walls
  - Combined flows with fully mixed conditions
  - Combined flows with thermal stratification

- Single-zone building with two openings and a fan
  - Combined stack and supply-fan driven flows with fully mixed conditions
  - Combined stack and exhaust-fan driven flows with fully mixed conditions

- Single-zone building with three openings
  - Stack-driven flow with fully mixed conditions
  - Multi-zone building with two openings

Solutions can be found in the technical report "TR12 Analysis of natural ventilation – A summary of existing analytical solutions" on the CD-ROM.

Zonal methods, multi-zone methods and Computational Fluid Dynamics

Traditional mixing ventilation systems utilize supply jets to create global circulation in a room, which results in a rather uniform air temperature distribution. In hybrid ventilation the natural ventilation part is driven by thermal buoyancy, where air heated by heat sources in the room rises to the upper part of the space and a vertical temperature gradient is established. In natural ventilation, the thermal driving force is a function of the temperature difference between indoor and outdoor air, and the thermal stratification directly affects the ventilation flow rate as well as the air flow direction at some ventilation openings. It was found that the effect of thermal stratification on air flow can be very significant and can lead to significant underestimation of the neutral level in a building, see "TR15 Integrating thermal stratification in natural and hybrid ventilation analysis", which focuses on when thermal stratification is important and how it should be considered in natural ventilation analysis.

A zonal model, POMA, has been developed, see "TP25 Zonal model; A simplified multiflow element model" on the CD-ROM. It can predict the airflow pattern and temperature distribution in naturally or mechanically ventilated rooms. POMA's prediction has been compared with existing information in the literature, which showed that the model is a feasible approach for thermal simulation from an engineering view point.

Combined thermal and air flow modelling methods

Prediction of the yearly performance of hybrid ventilation systems requires combined thermal and air flow modelling methods. A number of different tools have been developed or are under development. In order to evaluate how well the simulation tools model hybrid ventilation systems and control strategies a test simulation of ventilation in a typical single-zone classroom using four different tools has been performed, see "TR3 The use of simulation tools to evaluate hybrid ventilation control strategies". The purpose was not to perform an inter-program comparison, but to test the robustness of any conclusions drawn about the relative merits of different ventilation systems or control strategies. Clearly, if different tools yield significantly different conclusions, then any conclusion drawn from a single tool must be viewed with caution. The results show that the different tools were quite consistent with respect to IAQ performance and fan energy. There were some deviations with respect to heating energy, possibly because of quite different implementations of the heating controller, which underlines the importance of modelling of control strategies in simulation of buildings with hybrid ventilation systems.

In another study the performance of different ventilation concepts for a three-story office building has been investigated with a combined thermal and air flow model, see "TR2 Performance simulation of hybrid ventilation concepts". The results showed that compared to a mechanical VAV system, the savings in energy cost of a hybrid ventilation system based on fan-assisted natural ventilation would be about 15% for the Finnish climate and that the initial as well as life cycle costs would be lower as well.

A combined model has also been used to simulate the performance of the hybrid ventilation system in the case study "Bertolt-Brecht-Gymnasium", see "TR25 Coupled air flow and building simulation for a hybrid ventilated educational building". Comparison of simulation results with measurements for this building, modelled with 129 zones, showed very good results. Deviations in temperatures were in the range of 0.2-1.0 K, see Figure 8.

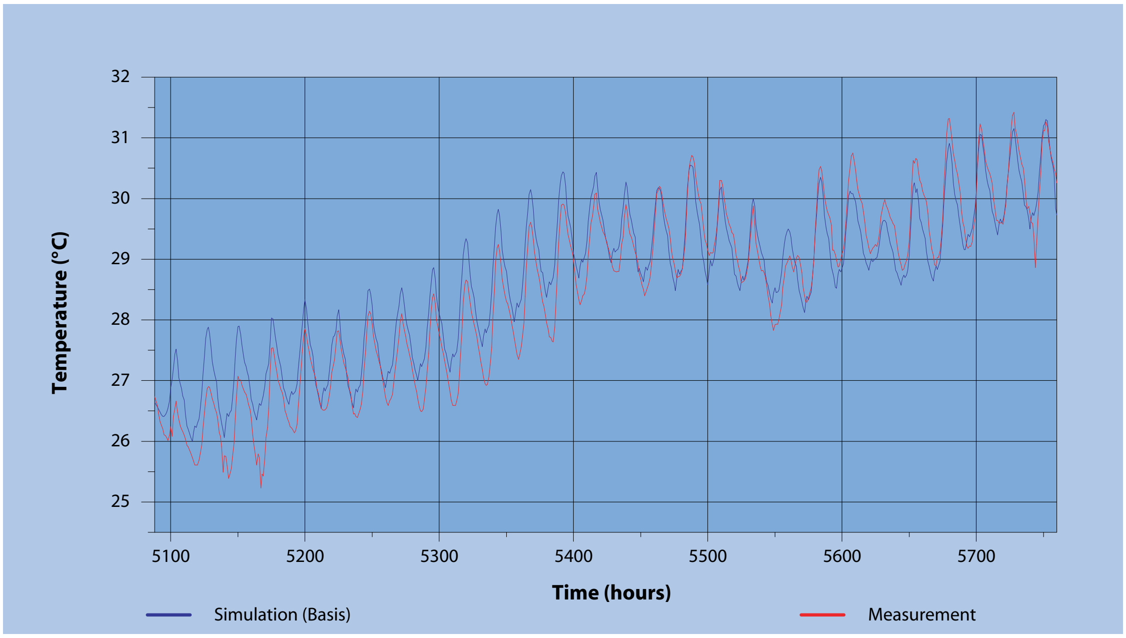
The simulation exercises showed that the combined thermal and air flow modelling method is a powerful tool for analysis of hybrid ventilated buildings and that its accuracy is sufficient for design and optimization of hybrid ventilation systems.

Probabilistic methods

A deterministic approach implies that all input parameters and model coefficients are 100% certain with zero spread. In practice, this is not the case: for example inhabitant behaviour and internal loads may vary significantly and external loads such as wind, external temperature and solar radiation are obviously stochastic in nature. One reason for ignoring randomness is the fact that mechanically ventilated heavy buildings are often highly "damped" and shielded from external loads. These kinds of buildings will also control the influence of the internal load effectively by means of the building energy management system and the HVAC system. However, lighter constructions that are naturally or hybrid ventilated are more sensitive to stochastic load variations.

When using a probabilistic method, some or all of the input parameters are modelled either as random variables or stochastic processes, described by statistics, i.e. mean values, standard deviations, auto-correlation functions, etc. and the results are the corresponding statistics of the output. A stochastic method is thus a formulation of a physical problem, where the randomness of the parameters is taken into account. In principle, any of the above-mentioned methods can be applied stochastically. In the scope of Annex 35, probabilistic methods are applied in thermal building simulation, single zone models, multizone models and CFD, see technical reports "TR17 – TR19 and TR22" on the CD-ROM.

Figure 18. Comparison of simulated and measured temperatures in one of 129 zones of the case study Bertolt-Brecht-Gymnasium in the period of August 1-28, 1997.



The advantage of probabilistic methods is the possibility of not only designing for peak load and estimating annual energy consumption based on a reference year, but also to examine the range of variation and quantify the uncertainty. Probabilistic methods can be used as a tool to evaluate the trade-off between economy (cost, energy and environment) and risk (expectations not met, violation of regulations, etc.) on a firm foundation. It allows a more courageous design, which may in turn result in increased user satisfaction, energy savings and "greener" buildings due to the fact that the uncertainty can be calculated and not just assumed roughly. For instance, a building owner can prescribe the probability allowed for a certain parameter to exceed the bounds of a design interval.

Obviously, consideration of randomness increases the level of complexity of the analysis and the expense in terms of CPU time. Therefore, it should be applied mainly to more complex or unusual design cases. Another application is to use probabilistic modelling to gain further knowledge and develop simple easy-to-use deterministic models. Alternatively, the software applied in the calculations can be supplemented by a user-friendly interface hiding the underlying mathematics, especially if appropriate default values are available.

Selection of Methods

Different phases in the design process call for different types of design methods. Guidelines, decision tools, experience from colleagues, and product catalogues are useful in the conceptual design phase. In this phase input data are not well known and/or can vary within large ranges and output only needs to be accurate enough to make in-principle decisions on which systems and/or combination of systems that are appropriate to use in the given situation.

In the basic design phase analytical calculations and simulation programs are used to develop the design. Input data are known with a much better accuracy and output data should be detailed enough to convince the designer that the system can fulfil the energy targets and comfort requirements for the building. In the detailed design phase the individual components are designed and the system and control strategies are optimized with regard to energy consumption and comfort conditions. The design methods are the same as for the basic design phase, but input data on the building and individual components are well known in this phase and output becomes therefore accurate enough to perform a system optimization. Finally, detailed simulation methods or physical models are used to evaluate the final design. These analysis methods are expensive and time-consuming to use. They require very detailed input data and are able to give precise predictions on the performance (energy, IAQ and thermal comfort) of the building and the ventilation system.

Figure 19 shows the characteristics and usefulness of design tools for hybrid ventilation.

Figure 19. Characteristics and usefulness of design methods for hybrid ventilation.

	Simple analytical and empirical models	Zonal models	Multi-zone air flow models	Thermal models	CFD-models	Combined air flow and thermal models
Design phase	• Conceptual • Basic	• Detailed	• Detailed • Evaluation	• Basic • Detailed • Evaluation	• Detailed • Evaluation	• Detailed • Evaluation
Purpose	• Analysis of air flow rate, thermal comfort and energy use in discrete time steps or on yearly basis	• Analysis of airflow and temperature distribution in a single room.	• Analysis of air flow rate through the envelope on a yearly basis • Analysis of air flow rate between zones on a yearly basis • Analysis of IAQ in buildings	• Analysis of thermal conditions in zones on a yearly basis • Analysis of energy use on a yearly basis	• Analysis of airflow, IAQ and temperature distribution in a single room • Analysis of air flow around buildings • Analysis of surface pressure on envelope	• Optimization of building and system performance through combined analysis of air flow rates, temperature conditions and energy use
Available models	• Flow element models. • Spreadsheet programs • Vent sizing programs	• POMA	• COMIS • CONTAM	• TRNSYS • EnergyPlus • BSIM2000 • CAPSOL • ESP-r • IDA	• Fluent • Flovent • Vortex • CFX • PHOENICS	• TRNSYS + COMIS • Tas-Flows • CHEMIX • IDA-ICE
Outputs	• Mean indoor temperature • Peak temperatures • Draught risk • Heating & cooling load • Energy use	• Distribution of air flow • Distribution of pollutant concentration • Distribution of temperature	• Air flow rates through envelope opening • Air flow rates between zones • Average IAQ in each zone	• Hour by hour temperature variation in zones • Hour by hour heating and cooling loads • Hour by hour energy use	• Detailed distribution of airflow and temperature. • Study of design problems (trouble-shooting). • Mechanism of heat transfer and airflow in enclosures	• Hour by hour variation in temperature, air flow rate, IAQ and energy use • Optimized control strategy
Necessary equipment /computer	• Hand calculator • Personal computer, etc.	• Personal Computer	• Personal Computer	• Personal Computer	• Powerful personal computer • Workstation	• Powerful personal computer • Workstation
User	• Practitioner	• Expert	• Expert/ researcher	• Expert	• Expert/ researcher	• Researcher
Required time for application	• About half day per case to input data.	• About one day per case to input data.	• About two days per case to input data.	• About two days per case to input data.	• About 1 week per case to input data	• About 1 week per case to input data
CPU time	• A few minutes.	• 1-10 hours	• 1-10 hours	• < 1 hour	• 10-100 hours per case	• 10-100 hours per case

Complex Flow Processes in Hybrid Ventilation

Multiple steady state solutions and dynamical phenomena

Like many other physical systems, air flow in buildings can behave as a dynamical system, exhibiting non-linear phenomena such as existence of multiple steady state solutions, periodic and aperiodic flows, chaos, etc. In mechanically ventilated buildings, these nonlinear phenomena are not important as mechanical forces tend to suppress them. However, in naturally ventilated buildings, either during normal operation or in a fire-situation, these dynamical phenomena need to be controlled. It is certainly not desirable to have oscillating flows through a solar chimney or two possible smoke layers in a naturally ventilated building, or even worse, the existence of the situation when a smoke layer can both exist or not exist. But this has been shown to be possible by analyzing problems with very simple geometry, first found in this Annex, see "TR12 Analysis of natural ventilation – A summary of existing analytical solutions" on the CD-ROM. The multiple steady-state solutions are confirmed by small-scale experiments and CFD predictions, see "TP31 Experiment modelling of wind opposed buoyancy-driven building ventilation" on CD-ROM.

The issue of multiple steady-state solutions is associated with the sensitive dependence on initial conditions. This means that the solution obtained for ventilation air flow rates and temperature conditions -not only depends on the present conditions but also on the history - on the solution that preceded the present situation. The problem arises when any uncertainty exists in the initial conditions. It can be easily shown that when there is even very tiny change in the initial conditions, the ventilation states can be very different, e.g. one with a smoke layer and one without a smoke layer.

Air flow through openings in the building envelope

A small opening is an opening with unidirectional flow where the standard model based on the Bernoulli equation is applicable. In predicting the ventilation flow rate through a small opening a correct estimation of the discharge coefficient, C_d, is important. It can be determined experimentally and is related to both the contraction of the streamlines near the opening and to the turbulent pressure losses. The work in Annex 35 has shown that the usual value of 0,65 for a sharp- rimmed orifice is not suitable for openings in building envelopes. The discharge coefficient is not constant, but instead varies for the typical flow conditions for purpose-provided openings in building envelopes as a function of:

- Pressure difference across the opening
- Temperature difference, which modifies the flow through the opening and affects the discharge coefficient
- Opening type, area and local geometrical conditions
- Location of the opening in the facade
- Relative size (porosity) of the opening in relation to the facade area
- The relative size of the inlet and outlet opening and their relative location ("seeing each other or not")

Values of the discharge coefficients can vary between 0,4 and 1,2, see "TR24 Wind-induced air flows through large openings: Summary" on the CD-ROM.

A large opening is by definition an opening where the standard model cannot be applied by using the pressure coefficient from a sealed body. For a wind-driven flow with a wind direction near perpendicular to the facade the model cannot be applied if the size of the opening is more than about 30 % of the facade area. The borderline between an opening and a large opening is not only dependent on the physical size of the opening. The most important factors are:

- Wind direction relative to the opening
- Location of the opening in the facade

As the wind direction becomes more parallel to the opening the discharge coefficient decreases. At first this is caused by a change in the flow direction through the opening, and at a certain wind-direction bi-directional flow occurs over a portion of the opening. Finally, when the wind direction is close to parallel with the opening there is an exchange of air through the openings driven by pressure fluctuations (pumping). Then bi-directional flow occurs over the whole opening. In an opening located close to the boundary of a facade bi-directional flow over a portion of the opening may occur, which reduces the net flow rate.

Besides correct estimation of the discharge coefficient, prediction of the pressure difference across the opening is also very important. This includes both transformation of meteorological wind data to local wind data for the building site and transformation of wind data to surface pressures (C_p-values) on the building envelope. By using different wind data (meteorological, "predicted local data", and measured local data) as well as different pressure coefficients (predicted or measured on the building surfaces) it has been shown that both steps are equally important and together can have a large impact on the accuracy of predictions of natural ventilation air flow rate and thermal comfort, see "TR23 Impact of the uncertainty of wind pressures on the prediction of thermal comfort performances".

Thermal comfort in rooms

In hybrid ventilation systems fresh air is often provided through window openings and/or outdoor air inlets in the building envelope. There is a wide range of possibilities with regard to selection of window type, size and location. The window openings can be regarded as supply air devices and the air flow from the window is often the dominant flow element in the room determining the level of thermal comfort. However, in the design phase this is often ignored due to lack of knowledge of the performance of individual windows, and neither the risk of discomfort because of draught nor the limitations on air flow rate or cooling capacity is quantified. Some window types are regarded as better than others, but this is mainly based on qualitative measures and the differences and limitations in the application of individual window types cannot be quantified.

In Annex 35 the air flow from different types of window openings has been characterised, but most work has focused on a bottom-hung window located close to the ceiling. The velocities and temperatures of the air flow at entry into the occupied zone determines the thermal comfort, provided that the overall heat balances and temperature conditions are acceptable.

Unfortunately, the characteristics of jet flow from window openings depend on both pressure difference and opening area, see "TP58 Window openings – air flow and thermal comfort" on the CD-ROM, and the application of the jet flow models in practice therefore becomes much more complicated for window openings than for inlet devices in mechanical ventilation. The characteristics of window openings show that the resulting comfort level in the room and the controllability of flow rate are not at the same level as for other types of ventilation openings, and that the maximum capacity (air flow and/or cooling) of a natural ventilation system therefore will be less than for a mechanical system. However, the results also show that it should be possible to develop openings for natural ventilation with improved characteristics compared to an open window; such improved openings will in winter reduce the maximum velocity in the occupied zone considerably compared with the velocity obtained by ventilation through a window.

How are mechanical forces and natural forces to be combined?

Ventilation flow in an enclosure driven by combined natural and mechanical forces is fundamental to hybrid ventilation. Annex 35 studied a simple building with either an exhaust fan or a supply fan together with natural ventilation. It was shown that the pressures induced by fans or natural forces alone cannot be added linearly. Linear addition is only valid when the mechanical fans are dominant. The linear assumption for estimating the combined pressures which is used to derive the simple quadratic formula for calculating combined flow rate is not correct. This explains why the quadratic formula does not give a good prediction of the combined flow rate when the natural force and the mechanical force are similar in magnitude. It is noted that in smoke control design of buildings, a linear addition model is often used to calculate the combined pressure (forces). [6]
There is still a lack of information on negative pressures in atria created by atrium exhausts. [7]

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[6] Hinley, P. L.: Smoke and heat venting. In The SFPE Handbook of Fire Protection Engineering, First Edition, National Fire Protection Association, US, 1988, pp. 2-33 to pp. 2-44.

[7] Tamura, G.T.: Smoke movement and control in high-rise buildings. National Fire Protection Association, Massachusetts, pp. 245-161, 1994.

Controlling the quality of ventilation systems is one of the most important aspects of the function and the final occupant appreciation of ventilation systems. This is of special concern for advanced ventilation systems such as hybrid ventilation. There is a strong relationship between the quality achieved (i.e. according the specifications and terms of reference) and the energy use and indoor environment (IAQ, thermal comfort, noise). A ventilation system must perform according to the intended design and specification not only at the time of hand-over of the system, but also during its operation, i.e. during its lifetime. This is expressed as the reliability of a ventilation system. This chapter gives an overview of quality control; more detailed information can be found in “TR10 Quality control for hybrid ventilation”.

Reliability of Ventilation Systems

The air flow during the lifetime of a ventilation system can be influenced by maintenance, basic quality and the load on the system. Figure 20 and Figure 21 show the reliability of a mechanical ventilation system with heat recovery and an average quality level with a normal maintenance level and a poor maintenance level respectively. Reliability is expressed as a fraction between 0 and 1, meaning the probability that a system can fulfil the specified requirements between certain time intervals. Reliability means:

- ensuring the desired air flow under different (climatic) circumstances;
- ensuring the desired air flow during the system’s lifetime.

Quality Control of Climate and Installations

Commissioning is an instrument for ensuring a certain level of quality and reliability. According to ASHRAE guideline 1-1996 [8] commissioning is

Figure 20. Comparison of the reliability of a mechanical ventilation system with heat recovery and average quality level with a normal maintenance level.

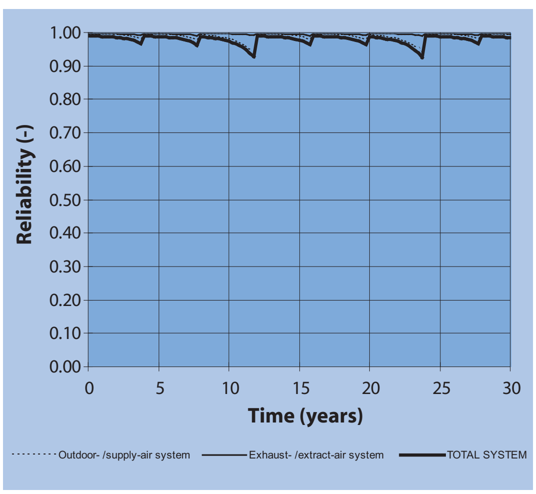
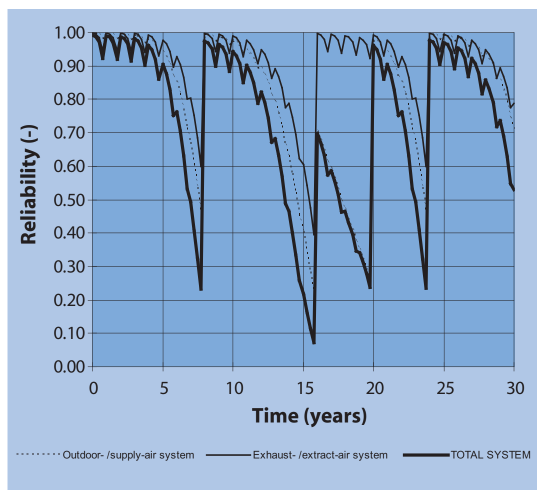


Figure 21. Comparison of the reliability of a mechanical ventilation system with heat recovery and average quality level with a poor maintenance level.



the process of ensuring that systems are designed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent. Therefore commissioning has to be embedded in a total structure for quality control of the process, from programme phase up to and including the operational phase. A structure for this overall quality control is the Model Quality Control Climate Installations (MQC). [9]
Its intention is to control the total production process, including specifications, design, construction, hand-over and operation. It focuses on avoiding failures in all strategic aspects and moments in this process.

The MQC is an instrument for controlling the total process of creating building services. It contains all operational techniques and activities necessary to realise a defined level of quality. The quality level has to be precisely formulated. In this framework "Quality" means that the delivered performance matches the required and precisely formulated requirements and expectations of the building owner, including time planning and budgets, as well as all technical aspects.

MQC is focused on:

- avoiding failings in all phases of the process, from the programme phase up to and including the operational phase;

- ensuring reliability in defined time intervals

MQC is not only for consultants and installers. All partners in the building process have to deal with the MQC and will have to conform to it. The building owner must also be aware of the fact that his responsibility extends beyond just the financial aspects. He has an important role during the programme phase to formulate performance requirements, that can be "translated" by his consultants into a technical design and technical specifications.

MQC Structure

Model Quality Control is a general model that can be applied to all kinds of processes (building, building services, industrial etc.). For ventilation systems it is possible to elaborate an MQC system for either the entire hybrid ventilation system or for separate elements. The most important characteristic of MQC for ventilation systems is that its structure follows all the phases in the building and operational process. This enables a number of strategic decision moments in the (building) process to be built in, and enables an assessment of whether a ventilation system meets the targets and requirements, as defined in the programme phase. As the total quality is determined by several aspects (not only technical but also financial, organisational and communication) 10 different quality control aspects are distinguished.

This leads to a so-called quality matrix. On the horizontal axis of the matrix the phases of the process are listed: I programme, II design, III elaboration, IV realisation and V operation and maintenance. On the vertical axis of the matrix ten distinct quality control aspects are listed: 0 general, 1 organisation, 2 communication, 3 requirements, 4 means, 5 purchase, 6 time, 7 finances, 8 realisation, 9 experience. The main cells in the matrix will refer to other cells. These cells indicate which subjects and partial subjects are addressed. These (partial) subjects are further elaborated In separate specification sheets, see Figure 22.
When using MQC, or creating a document in accordance with the MQC structure, it is not necessary (and often not possible) to fill in all cells. But all information that is available can be "recorded and stored" in a logical way in a cell, and elaborated

in specification sheets. Often this information is spread over two or more phases and consequently over several specification sheets, corresponding with the distinct phases and/or quality control aspects. It is important to analyze exactly for which phase and for what quality control aspect the information is necessary. Therefore, it is important to know the meaning of each different quality control aspect.

Costs

Implementation of MQC for ventilation systems does not mean that the building process or in particular the ventilation systems will be more expensive. Initially the implementation requires extra effort and cost, inherent in the introduction of all new methodologies or technologies. However, it delivers a ventilation concept and system with a high and very well defined level of quality and, in the longer run, cost and time savings.

The impact on the capital costs can be negative as well as positive. Quality control needs extra measurement and control points in an installation. This can lead to extra investments. These investments will be paid back during the operational phase. The reduction in non-scheduled maintenance (i.e. failure and complaint maintenance) resulting from commissioning and scheduled maintenance will especially lead to major cost reductions.

Commissioning Hybrid Ventilation within the MQC Structure

The MQC structure provides a basis for implementing commissioning within a (production) process. Within the matrix cells, items can be identified that should be addressed for commissioning. Specification sheets can be further elaborated. For hybrid ventilation the following specific points in the various phases must be taken into consideration.

Figure 22. Example of a MQC matrix and specification sheets for quality parameters.

MQC MATRIX					
	project phase				
aspect	I	II	III	IV	V
0					
1					
2					
3		II.3			
4					
5					
6					
7					
8					
9					

CELL CONTENTS		
subject	partial subject	specification sheet
II.3-1		
II.3-2		
II.3-3		

SPECIFICATION SHEET II.3-2	
charac-teristic	specification

I Program phase:
Definition of the requirements, in a direct way as well as in an indirect way, is very important. Indirect means that proper specifications and the understanding that a building owner knows what he asks for and what he gets (i.e. that the specifications meets his expectations) is the beginning of good commissioning. Of course all necessary provisions for commissioning (mostly needed in phase IV and V) must be already specified in the programme phase. Of special concern is the specification of components and provisions that allows maintenance and cleaning. This demonstrates the importance of using the MQC for commissioning: if there are no provisions foreseen for commissioning (such as balancing, measurement and control points, provisions for cleaning and maintenance) in the programme phase, commissioning in later phases will not be possible.

II Conceptual and basic design phase:
In the design phase all necessary provisions for commissioning must be taken into account in the final design and specifications. As hybrid ventilation systems have a mechanical and a natural ventilation mode, the traditional HVAC design approach is not sufficient. Only an integration of building design and HVAC systems can lead to a working hybrid ventilation system. Future (hybrid) ventilation systems will most likely have low pressure drops in the air flow paths, be demand-controlled, and will utilize natural driving forces when possible.
These characteristics make hybrid ventilation systems sensitive to disturbances in the air flow paths, ventilation modes that are not tuned to each other, the performance of the control system (including sensors), environmental influences, etc. Analysis of these sensitivities is advisable in the design phase. Only then can suitable components be selected to ensure fulfilment of the overall performance specifications in the operational phase.

III Detailed design and design evaluation:
A special concern is that for the final selection of components special requirements must be specified to allow maintenance and cleaning. Hybrid ventilation provisions in the facade must be selected so that cleaning is possible without the risk of destroying the controls and mechanisms or changing their settings.

IV Construction phase:
In this phase actual commissioning takes place. This means that the organisation of the commissioning must be arranged (i.e. definition of responsibilities, who is doing what, commissioning authority/organisation, installers, etc.). It should be emphasised that commissioning of ventilation systems after completion of construction needs considerable care over a fairly long period of time in order to settle down and calibrate the control system in all weathers.

The innovative and complex nature of hybrid design for a specific set of circumstances can lead to an important feature being overlooked, errors in selection, or some other problem being overlooked which may be rectified easily in the commissioning phase but which may incur some cost. Hence there should be provision to pay for necessary modifications. This is applicable to all buildings but particularly to hybrid examples because of the innovative nature of the technology.

V Operation and maintenance:
In the operational phase the continuous commissioning process is arranged to ensure that systems continue to function in the as-commissioned state. Although the organisation and management structure that was operational during the building process is not available anymore in the operational phase, the organisation of the continuous commissioning can be described. As

hybrid ventilation systems are often equipped with a (sophisticated) control system special attention has to be paid to the documentation and instructions for the operation and maintenance personnel. As a hybrid ventilation system consists of a mechanical ventilation mode and a natural ventilation mode the cleaning and maintenance programme has to cover the HVAC system as well as the building components involved.

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[8] ASHRAE publication 1-1996 »The HVAC Commissioning Process«, 1996, Atlanta, USA

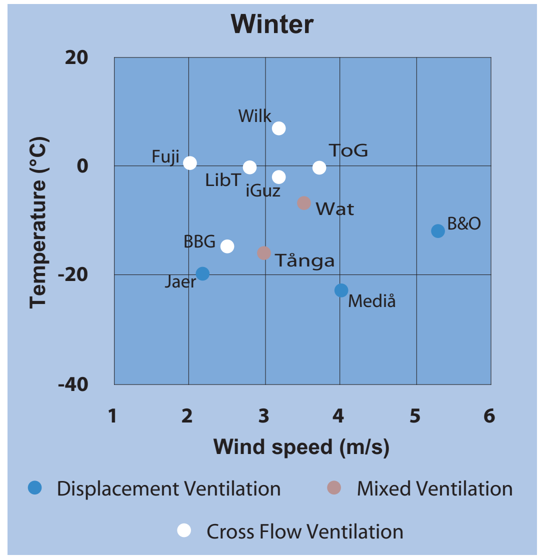
[9] SBR publicatie 346 "Model kwaliteitsbeheersing Klimaatinstallaties", 1996, Rotterdam, The Netherlands

ECBCS IEA Annex 40: Commissioning of Building HVAC Systems for Improved Energy Performance (http://ddd.cstb.fr/annex40/annexe40.htm)

7. examples

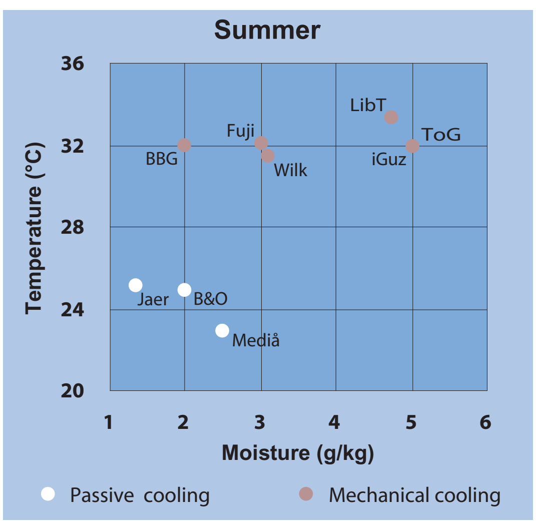
This chapter gives an overview of the characteristics and lessons learned from the case studies investigated in Annex 35.

Figure 23. Variation in outdoor design conditions at the case study locations.



Case Studies Survey

The 13 Case Studies of Annex 35 are located in 9 of 16 participant countries. The climate varies from cold (N, S), through temperate (DK, B, NL, D), to Mediterranean (I) and sub-tropical (AU, J). Buildings located in the last two climatic zones have been supplied with air conditioning plants. All other buildings only have natural cooling. Figure 23 shows outdoor design conditions for the Case Study locations: the design summer temperature is plotted against the design summer air moisture content or average wind speed; the winter design temperature is plotted against average wind speed. In each chart the typology of the ventilation system and whether the building is air conditioned in summer can be identified quickly.



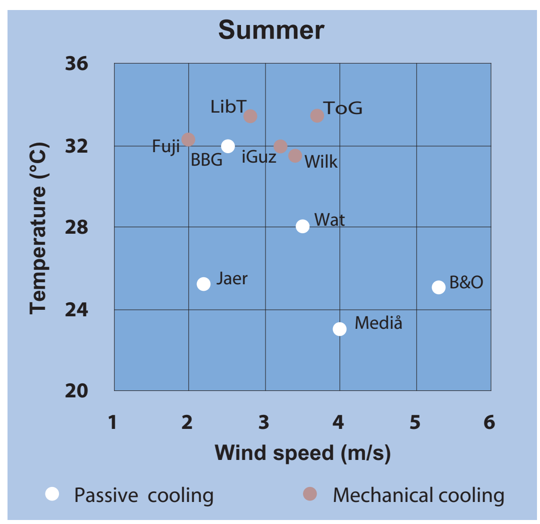


Figure 24 summarizes the case study characteristics. The ventilation strategy used can be found in Figure 5 in chapter 2.

The natural ventilation driving forces are often a combination of stack and wind effect (IVEG, PROBE, B&O, Fujita, Tokyo Gas, Liberty Tower, Mediå and Waterland). The case studies adopt sophisticated (displacement ventilation with preheating) as well as simpler and less expensive (mixed and cross flow ventilation) air distribution systems. Night-time ventilation is largely exploited as a passive cooling strategy. Figure 25 summarizes ventilation concepts used in Annex 35 case studies.

Hybrid Ventilation Components

This section briefly summarizes components used in the Annex 35 case studies. A complete description of the components used can be found in the individual case study reports on the CD-ROM. As mentioned in chapter 2, specific components for hybrid ventilation are not yet available. Nevertheless, the correct adoption of appropriate components is essential for the successful performance of a hybrid ventilation system.

Building-integrated components for natural ventilation play a very important role. Apart from strongly characterizing the building architecture, these components, if well designed, allow supply, distribution and extraction of air from the building at very low pressure drops. The majority of case studies, and all the new buildings, apply at least one building-integrated component, see Figure 26.

Low pressure drops were also ensured by using low-pressure vents and exhaust terminal devices. The control system is an important component in hybrid ventilated buildings. Temperature and IAQ controls were used in almost all the case studies, with appropriate sensors connected to the Building Energy Management System. The Belgian buildings

Figure 24. Main characteristics of the Annex 35 case studies.

Country	Building name	Building type	Year N = New R = Refurbished	Volume m^3 (effective)	Height m (No.of floor)
Australia	Wilkinson Building	Office	1997 (R)	- (1175)	16 (5)
Belgium	IVEG Building	Office	1999 (N)	6300	12 (3)
	PROBE Building	Office	1997 (R)	6066	6 (2)
Denmark	B&O Headquarters	Office	1998 (N)	6046	14 (3)
Germany	B. Brecht Gymnasium	School	1995 (R)	21200 (16800)	11 (4)
Italy	I Guzzini Illuminazione	Office	1997 (N)	10000 (7660)	13 (4)
Japan	Liberty Tower of Meiji University	School	1998 (N)	256697	120 (23 + 3)
	Fujita Technology Center	Office	1999 (N)	170000	18 (3)
	Tokyo Gas Earth Port	Office	1996 (N)	-	27 (4)
Norway	Mediå School	School	1998 (N)	6000 (3500)	5 (1)
	Jaer School	School	1999 (N)	-	12 (2)
Sweden	Tånga School	School	1999 (R)	12031	7 (2)
The Netherlands	Waterland School	School	2001 (N)	17000	3–6 (1–2)

adopted mechanical supply controlled by infrared presence detection. In many cases windows, grilles and louvers (manually or automatically controlled) and fans (speed and frequency controlled) ensured the necessary control of air flow rate, see Figure 27.

Considerable care was taken to ensure that buildings were thermally efficient. High insulation levels and high-performance glazing were used in most cases, but heat recovery was used in only two buildings. Lighting was controlled by presence detection in four buildings. Passive cooling, including automatically controlled internal shading devices, was adopted in many buildings. External shading devices were used in some case studies. To avoid draught risk, the buildings located in the coldest areas preheat supply air by means of specific components (diffusers or fan coils), or by means of radiators located below windows. Filtering of intake air is not very common in these case studies; in fact the supply air is filtered in only one building (Mediå school). In some cases culverts are used to settle large particles. Specially-designed inlets, acoustically insulated to ensure acoustic privacy, were used in the Mediå school, see Figure 28.

Figure 25. Ventilation concepts applied in the Annex 35 case studies.

Ventilation Concepts	Type	Stack effect	Wind driven	Displacement ventilation	Mixing ventilation	Cross flow ventilation	Natural night ventilation	Mech. night ventilation	Natural cooling	Air conditioning	IAQ control by natural means	IAQ control by mechanical means
Wilkinson building	Office		●			●				●	●	
IVEG building	Office	●	●		●	●	●		●			●
PROBE building	Office	●	●		●	●	●		●			●
B&O Headquarters	Office	●	●	●		●	●	●	●		●	●
B. Brecht Gymnasium	School	●										
I Guzzini Illuminazione	Office	●				●	●		●	●	●	
Liberty Tower of Meiji University	School	●	●			●	●	●	●	●	●	
Tokyo Gas Earth Port	Office	●	●			●	●	●	●	●	●	●
Fujita Technology Center	Office	●	●			●	●		●	●	●	●
Mediå School	School	●	●	●			●	●	●		●	●
Jaer School	School	●		●			●	●	●		●	●
Tånga School	School	●	(●)		●		(●)	(●)	●		●	●
Waterland School	School	●	●		●		●	●	●		●	●

Finally, fire regulations often influence the building layout. This is the case for the IVEG office building. In some case studies dampers, windows or doors are automatically closed or opened as required under fire alarm conditions.

Lessons Learned from the Case Studies

The lessons learned from the case studies in Annex 35 are very important for the continuing development of the hybrid ventilation concept, the development of new components, and the process of cost and performance optimization.

Building and ventilation system design

Hybrid ventilation is a very new technology and there is not a large body of experience on which designers can draw. Most of the case study buildings were designed and built in the late nineties and are pioneering buildings in their respective countries. The innovative and complex nature of hybrid design for a specific set of circumstances has, in some cases, led to important features being overlooked, errors in selection, or some problem being overlooked, which have had to be rectified in the commissioning phase and which in some cases have incurred some cost - typically involving specific components (such as

Figure 26. Application of building integrated components in the case study buildings.

Building Integrated Ventilation Components	Type	Chimneys, turrets	Atria	Stairwells	Corridors	Underground ducts, culverts	Windfloor
Wilkinson building	Office						
IVEG building	Office	●					
PROBE building	Office						
B&O Headquarters	Office			●			
B. Brecht Gymnasium	School		●				
I Guzzini Illuminazione	Office	●	●				
Liberty Tower of Meiji University	School			●			●
Tokyo Gas Earth Port	Office	●	●	●	●		
Fujita Technology Center	Office		●			●	
Mediå School	School	●			●	●	
Jaer School	School	●	●			●	
Tånga School	School	●					
Waterland School	School	●					

openable windows, preheating coils, fans, sensors, etc). The commissioning process of the ventilation system after completion of construction has in some cases also needed considerable care over a fairly long period of time in order to settle down and calibrate the control system in all weathers, and the hybrid ventilation potential has not been realized in all cases within the measurement period of this project.

Therefore, the demonstrated performance and the conclusions obtained from the 13 case studies in Annex 35 are very diversified. In some cases excellent performance has been achieved at considerably lower initial and running costs than for conventional systems. In most cases either the performance or the cost has been lower than for conventional systems, while the other has been at the same level. In a few cases either the cost has been higher than for conventional systems or the performance has been poorer.

Sensors and control strategies

Hybrid systems, as with any ventilation system, are more acceptable to occupants when the control system permits intervention by individuals to establish conditions that match their current perceived requirements. These will vary between individuals and throughout the day for any particular person. The possibility of manually operating hybrid ventilation was greatly appreciated by the occupants, and in some cases users even required the ability to overrule the central control system. Users in cellular offices also proved to be quite capable of controlling the indoor environment in an energy-efficient way, and manual override is more readily achieved in cellular offices, mostly with only one occupant, than in open plan offices.

Demand control is very important in hybrid ventilation systems, and in many of the case studies demand control also proved to be very energy-efficient. However, one of the main problems encountered in automatic control of IAQ was the cost and reliability of CO_2 sensors used to control the ventilation demand. If a sensor is needed in each building zone, it can become expensive both in initial cost and in regular calibration. In some cases the ventilation demand was controlled by infrared detection. The major advantage of this system is its relatively low cost (compared to CO_2 sensors) and its autonomy (it can work on a long-life battery, no wiring is required). The major disadvantage is that the airflow is only indirectly correlated to the demand. Sometimes the airflow can be too low, or too high. Presence detection proved to be a good way to control the ventilation demand in rooms with low occupancy variation, such as cellular offices. In some cases it has also been successfully applied in school classrooms. For rooms such as conference rooms, a CO_2 strategy is more suitable because it usually better estimates the real needs. There is a strong need for reliable and cheap CO_2 sensors to be developed.

Temperature and CO_2 are often the controlling parameters and the best solution is probably a combination of both. In one case study (Fujita Technology Centre - J), enthalpy was used as controlling parameter in the early working stage (summer 2000). Results obtained with this control were not satisfactory and the number of natural ventilation hours increased significantly when ventilation was controlled by indoor and outdoor air temperatures, wind speed and direction (summer 2001). The total number of natural ventilation hours during 2001 was 5 times greater than in 2000, and the total cooling load for 2001 was reduced by approximately 20%, although the average air temperature during the cooling period was almost the same.

Figure 27. Application of hybrid ventilation components in case study buildings.

Hybrid Ventilation components	Wilkinson building	IVEG building	PROBE building	B&O Headquarters	B.Brecht Gymnasium	I Guzzini Illuminazione	Liberty Tower of Meiji University	Tokyo Gas Earth Port	Fujita Technolgy Center	Mediå School	Jaer School	Tånga School	Waterland School
Ensuring low pressure drop													
Low pressure vents and exhaust terminal devices				●								●	●
IAQ Control													
Presence detector controlled mech. Supply		●	●										
CO2 sensors linked with BEMS				●			●	●		●	●	●	●
Temperature control													
Automatically controlled solar shading devices		●	●						●			●	
External solar shading		●	●			●				●		●	
Fancoils connected to a variable flow cond. Unit	●												
Local, user operated, Temperature setting	●		●			●							
Intranet occupant vote linked with BEMS									●				
Temperature sensors linked with BEMS		●		●		●	●	●	●	●	●	●	●
Control air flow rate													
Manually controlled windows	●		●	●					●		●	●	
Automatically controlled windows				●		●	●	●	●				
Automatically controlled grills		●										●	●
Low pressure fans				●								●	●
Speed, frequency controlled fans				●			●		●	●	●	●	●

Figure 28. Application of hybrid ventilation components in case study buildings.

Hybrid Ventialtion components	Wilkinson building	IVEG building	PROBE building	B&O Headquarters	B.Brecht Gymnasium	I Guzzini Illuminazione	Liberty Tower of Meiji University	Tokyo Gas Earth Port	Fujita Technolgy Center	Mediå School	Jaer School	Tånga School	Waterland School
Draught													
Low velocity preheated supply diffusers											●		
Radiators below windows		●	●	●						●	●		
Supply air preheated by convectors below windows				●								●	
Energy Conservation													
Heat recovery		●								●			
Lighting controlled by presence detection		●	●	●								●	
Lighting reduction according to daylight availability		●	●										
Outdoor air pollution													
Filters										●			
Culverts										●	●		
Security													
Burglar proof louvers		●	●										
Acoustic privacy													
Specially designed inlets, acoustically insulated										●			
Fire Regulations													
Automatically closing/opening of grills, windows, doors		●	●	●									
Building design layout influenced		●	●										

Components
A hybrid ventilation system usually has many distributed and some centralised components. The number of distributed components can result in time-consuming fault detection. In some cases windows with automatic opening devices were technically unsatisfactory or needed to be modified. Typical problems observed for windows serving as inlets were: variations in tightening of openings by actuators resulted in either air leakage or excessive tensions, leading to cracks in the glazing; in other cases the weight of windows was excessive, which resulted in deformation of actuator arms.

The combination of a natural exhaust chimney and a low-pressure axial fan proved to be very sensitive, giving rise to difficulties in the following areas: insufficient natural flow in the natural mode, a high noise level in the mechanical mode, and insufficient flow in the mechanical mode. Noise from assisting fans was in some cases unacceptable, and was reduced to an acceptable level by setting a maximum rotational speed of fans. Sometimes the sound level from outside was high and should preferably be lowered by designing and installing sound absorbers in the outdoor air vents of the hybrid ventilation system. The market uptake of such systems can probably substantially accelerate, if advanced technologies were to be offered at an attractive price.

Energy performance
Energy performance evaluations generally show a reduction in overall energy consumption of about 20-30%, and of about 50% in electricity for ventilation. In one case (B&O HQ - DK), excessive air infiltration contributed to high measured heating consumption (42% higher than national building code requirements) due to poor building performance (poor insulation and tightness).

Comfort and IAQ
Schools:
In classrooms with high density of occupancy, the CO_2 level quickly exceeded the limit in winter, if assisting fans or mechanical ventilation systems were not operating. In schools, where the occupants were responsible for the indoor air quality control, the air quality did not always meet high standards. Automatic control is therefore advisable in school buildings with the possibility of manual override. In some cases under particular outdoor conditions draughts were observed because of inefficient preheating of incoming air or inappropriate location of inlets. The problems were solved, but it emphasizes that inlet conditions are one of the most critical parts of the system and need careful attention.

Offices:
In cellular offices, good comfort conditions have been observed in general and giving the users full responsibility for controlling their own indoor climate during occupied hours works very well. The occupants have demonstrated a sparing use of supplementary mechanical cooling/heating equipment. They appear to have a preference for using windows and clothing to modify conditions in mild mid-season weather. However, most occupants appear to have upper and lower “tolerance” limits, beyond which active intervention will be applied if the opportunity is available. These observations suggest the potential of applying adaptive comfort theory to hybrid ventilated buildings.

In open plan offices thermal comfort and indoor air quality complaints were more often observed than in cellular offices and hybrid ventilation systems showed the same difficulties as other ventilation principles in fulfilling the individual requirements of the occupants.

Initial and running costs

The results from the case study buildings do not indicate that hybrid ventilation application has a great potential for savings in initial costs. However, a substantial energy saving has been achieved in most case study buildings, mainly because of a very substantial reduction in energy use for fans and a reduced energy use for cooling. The life cycle costs for hybrid ventilated buildings is often lower than for reference buildings, but the relationship between initial, operating and maintenance costs is different.

Running costs seem to be low and any extraordinary and expensive maintenance or repair work is not known to have been required to data. In some cases service access to operable windows for maintenance and replacement work required a lift, with a consequent increase in maintenance costs.

Conclusions

Hybrid ventilation proved to be quite effective in achieving good IAQ and thermal comfort, in spite of diffuse fears held by potential users and designers. Energy performance was generally good but not excellent. The application of hybrid ventilation to retrofitted buildings achieved good results, but was problematic in some cases. In general, these first generation hybrid ventilated case study buildings proved that hybrid ventilation has very good potential. This potential was achieved in some cases, but it was not realized well in all cases.

Giving users the possibility of manual control during occupied hours, and utilizing their preference for adapting their clothing and using window opening before using mechanical equipment, suggests that hybrid ventilation exploitation can be optimized in cellular offices. The case studies showed that it was difficult to avoid comfort complaints in open plan offices; this is also seen in buildings with natural or mechanical air-conditioning systems. It was difficult (or perhaps impossible) to control the local conditions, which was probably perceived by the users as a personal limitation, and which influenced their thermal comfort evaluation.

Hybrid ventilation systems have proved to be suitable for schools. However, automatic control with manual override is necessary, if the occurrences of inadequate IAQ levels are to be minimized.

Hybrid ventilation is a very new technology and several problems are still to be solved. Many hybrid ventilation components are designed for a specific building project, and the use of advanced technologies to develop hybrid ventilation-specific components and systems could significantly improve the performance and consequently the uptake of hybrid ventilation. In many cases the application of hybrid ventilation requires careful design in the early design phases, and the scarcity of simple and fast design tools is one of the most important issues. Further development of robust control strategies and more reliable and cheap CO_2 sensors (or alternative sensors for demand control) is also very important.

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international energy agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organization 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 twenty-four 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 forty-two Implementing Agreements, containing a total of over eighty separate energy RD&D projects. This publication forms one element of this programme.

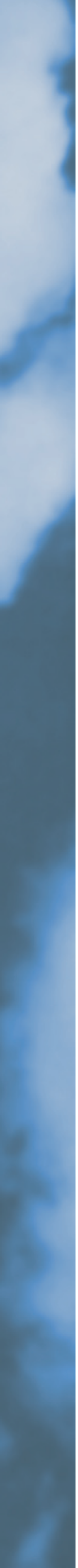
Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy. Seventeen countries have elected to participate in this area and have designated contracting parties to the Implementing Agreement covering collaborative research in this area. The designation by governments of a number of private organizations, as well as universities and government laboratories, as contracting parties, has provided a broader range of expertise to tackle the projects in the different technology areas than would have been the case if participation was restricted to governments. The importance of associating industry with government sponsored energy research and development is recognized 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 (completed projects are identified by (*).

Annex 1: Load Energy Determination of Buildings *
Annex 2: Ekistics & Advanced Community Energy Systems *
Annex 3: Energy Conservation in Residential Buildings *
Annex 4: Glasgow Commercial Building Monitoring *
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities *
Annex 7: Local Government Energy Planning *
Annex 8: Inhabitant Behaviour with Regard to Ventilation *
Annex 9: Minimum Ventilation Rates *
Annex 10: Building HVAC System Simulation *
Annex 11: Energy Auditing *
Annex 12: Windows and Fenestration *
Annex 13: Energy Management in Hospitals*
Annex 14: Condensation *
Annex 15: Energy Efficiency in Schools *
Annex 16: BEMS-1: Energy Management Procedures *
Annex 17: BEMS-2: Evaluation and Emulation Techniques *
Annex 18: Demand Controlled Ventilating Systems *
Annex 19: Low Slope Roofs Systems *
Annex 20: Air Flow Patterns within Buildings *
Annex 21: Thermal Modelling *
Annex 22: Energy Efficient Communities *
Annex 23: Multizone Air Flow Modelling (COMIS) *
Annex 24: Heat, Air and Moisture Transfer in Envelopes *
Annex 25: Real Time HVAC Simulation *
Annex 26: Energy Efficient Ventilation of Large Enclosures *
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems *
Annex 28: Low Energy Cooling Systems *
Annex 29: Daylighting in Buildings *
Annex 30: Bringing Simulation to Application *
Annex 31: Energy Related Environmental Impact of Buildings
Annex 32: Integral Building Envelope Performance Assessment *
Annex 33: Advanced Local Energy Planning *
Annex 34: Computer Aided Fault Detection and Diagnosis *
Annex 35: Hybrid Ventilation in New and Retrofitted Office Buildings
Annex 36: Retrofitting in Educational Buildings – Energy Concept Adviser for Technical Retrofit Measures
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings
Annex 38: (Solar) Sustainable Housing
Annex 39: High Performance Thermal Insulation
Annex 40: Commissioning of Building HVAC Systems



This book and CD-ROM contains the results of the joint activities in IEA-ECBCS Annex 35. With a focus on office and educational buildings, the principles of hybrid ventilation technologies, design, control strategies and algorithms, as well as analysis methods are described.

The book is aimed at newcomers in the field and gives an introduction to hybrid ventilation. A secondary aim is to function as a gateway for the more detailed information that can be found on the CD-ROM.

The CD-ROM is a source of information, containing a number of technical reports and papers, etc. with detailed information about research results. Included among these are detailed reports with measurement results and conclusions from the 13 case studies investigated.

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