Energy in Buildings and
Communities Programme

Ventilative Cooling

STATE-OF-THE-ART REVIEW

Edited by

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IEA – EBC Programme – Annex 62 Ventilative Cooling

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PREFACE

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-eight IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

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The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the EBC - Energy in Buildings and Communities Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshop, held in April 2013. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas of R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the Executive Committee on Energy in Buildings and Communities (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and 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: Inhabitants 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 and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone 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: Daylight 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 Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Energy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)

Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy & CO_2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO_2 Emissions for Building Construction
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Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

(*) – Completed

FOREWORD

This report summarizes the work of the initial working phase of IEA ECB Annex 62 Ventilative Cooling and is based on the findings in the participating countries.

The report is an official Annex report that describes the state-of-the-art ventilative cooling potentials and limitations, its consideration in current energy performance regulations, available building components and control strategies and analysis methods and tools. In addition, the report provides twenty six examples of operational buildings using ventilative cooling ranging from domestic to offices and other non-domestic buildings such as schools and exhibition spaces and located in different outdoor climates.

There have been many people involved in the writing of this report. A list of authors and contributors can be found in "Acknowledgements" as well as a list of involved research institutes, universities and companies.

On behalf of the participants we hereby want to acknowledge the members of the Executive Committee of IEA Energy in Buildings and Communities Programme (EBC) Implementing Agreement as well as the funding bodies.

Maria Kolokotroni and Per Heiselberg

Editors

Contents

1 Executive Summary

Overheating in buildings is emerging as a challenge at the design stage and during operation. This is due to a number of reasons including high performance standards to reduce heating demand by high insulation levels and restriction of infiltration in heating dominated climatic regions; the occurrence of higher external temperatures during the cooling season due to changing climate and urban climate not usually considered at design stage; and changes in internal heat gains during operation are not factored in the design. Such factors have resulted in significant deviations in energy use during operation which is usually termed the energy 'performance gap'. In most energy performance comparative studies energy use is higher than predictions and in most post-occupancy studies overheating is a frequently reported problem. Ventilative cooling can be a solution.

Ventilative cooling refers to the use of natural or mechanical ventilation strategies to cool indoor spaces. This effective use of outside air reduces the energy consumption of cooling systems while maintaining thermal comfort. The most common technique is the use of increased ventilation airflow rates and night ventilation, but other technologies may be considered. Ventilative cooling is relevant in a wide range of buildings and may even be critical to realize renovated or new NZEB[1].

Ventilation is designed for and is present in buildings through mechanical and/or natural systems for IAQ purposes and it can be used additionally to remove both excess heat gains as well as increase air velocities and thereby widen the thermal comfort range. However, to realise this potential, it is important that the technology is covered in future regulations and it must be supported by appropriate technical solutions (distinct from IAQ ventilation) which are compatible and accounted for in standards and regulations.

This report describes the state of the art in ventilative cooling. Each chapter covers a particular topic as follows:

- Potentials and limitations
- Ventilative cooling in existing Energy Performance Regulations
- Exemplary Existing Buildings
- Available Building Components and Control Strategies
- Existing Methods and Tools

Exemplary existing buildings precede chapters dedicated to component and control strategies and methods and tools of performance prediction. This is not typical in such reports where case-studies are described in the last chapter. For this report, it was decided to present case-studies of existing buildings using Ventilative Cooling before the description of the technology and performance prediction tools. This was so that the building is presented first in its totality and all features of its design; the ventilative cooling strategy is highlighted and described in more detail than other elements of the building. Then, the strategies/technologies/components highlighted in the case-studies is categorised in the following chapter and the methodologies for predicting their performance follow as the last chapter.

[1] Venticool: http://venticool.eu/

Chapter 2: Potentials and Limitations to Ventilative Cooling

According to its definition, ventilative cooling is dependent on the availability of suitable external conditions to provide cooling. It also depends on the building type and its thermal characteristics which determine its cooling demand and the acceptability of internal environment by its users.

Section 1 reviews existing methods suitable to estimate the cooling potential of climatic conditions considering (a) the type of building, (b) time of cooling (day or night); (c) availability of natural driving forces; and (d) the impact of the urban environment. The section provides definition and worked examples of the 'climate cooling potential' (CCP) index which was developed initially to estimate cooling potential of night cooling for European buildings. CCP index could be suitable for all ventilative cooling estimations and is based on (a) degree-day calculations and (b) on a building temperature variable within a temperature band determined by summertime thermal comfort. CCP can be used to calculate ventilative cooling potential of regions and an example for Europe is presented. It is concluded that in the whole of Northern Europe (including the British Isles) the climatic cooling potential is favorable, and therefore passive cooling of buildings by night-time ventilation seems to be applicable in most cases. In Central, Eastern and even in some regions of Southern Europe, the climatic cooling potential is still significant, but due to the inherent stochastic properties of weather patterns, series of warmer nights can occur at some locations, where passive cooling by night-time ventilation might not be sufficient to guarantee thermal comfort. If lower thermal comfort levels are not accepted during short periods of time, additional cooling systems are required. In regions such as southern Spain, Italy and Greece climatic cooling potential is limited and night cooling alone might not be sufficient to provide good thermal comfort during all the year. Nevertheless, night-time ventilation can be used in hybrid cooling systems during spring and fall.

This is one area that Sub-task A of Annex 62 is focusing by developing a climate evaluation tool with the aim of assessing the potential of Ventilative cooling and taking into account building envelope thermal properties, internal gains and ventilation needs.

Section 2 first outlines critical barriers to ventilative cooling, specifically outdoor noise and air pollution which provides indicative ranges for design possibilities. It continues by outlining current research on possible reduction of cooling energy use and/or decrease of the indoor temperature. Current studies mainly focus on office buildings for which simulations indicate that ventilative night cooling has the potential of eliminating or reducing cooling demand. Studies on residential buildings are limited but available studies indicate that there is potential.

A wider variety of building types is considered within Annex 62. Educational and exhibition buildings are presented as part of the case-studies of this report; this is also repeated in the case-study selection for sub-task C where residential, office and educational buildings are included. Solutions for retrofit were also identified as lucking in the literature; one sub-task C case-study addressed this point by studying in detail a retrofit solution.

Section 3 presents thermal comfort indices used to evaluate internal environment cumulatively and considers their distribution within the building. It discusses the Percentage outside the Range method introduced by ISO 7730 and EN 15251 and the percentage of occupied hours above a reference temperature. Cumulative indices are presented such as PPD-weighted criterion and exceedance$_M$ as well as risk indices such as overheating criteria. Finally averaging indices such as average PPD are presented. It concludes that such indices although suitable for mechanically conditioned buildings might be misleading in the cases of naturally ventilated buildings.

Work presented in this section will form the basis for the definition of Key Performance Indicators (KPI) to be developed in Sub Task A on reporting overheating risk, thermal comfort and energy use.

Chapter 3 Ventilative Cooling in Existing Energy Performance Regulations

This chapter presents important results of surveys through questionnaires on the treatment of ventilative cooling in national codes and standards completed by participants of Annex 62. Two questionnaires were designed and completed by Annex 62 participants focussing on ventilative cooling aspects in (a) building codes, and (b) national energy demand calculations and (c) implementation of ventilative cooling in current national building regulations. Results of these questionnaires are presented in detail. It concludes that ventilative cooling requirements in regulations are complex and five categories of parameters were identified; these are (a) Energy consumption for cooling, (b) Building parameters influencing ventilative cooling, (c) Ventilation requirements, both ventilation amounts and ventilation openings and positions, (d) Safety, and (e) Temperature, Air velocity and Humidity requirements. It is proposed that these need clarification in the national codes to facilitate ventilative cooling.

The second survey revealed that energy performance calculations in many countries do not explicitly consider ventilative cooling. Therefore available tools used for energy performance calculations might not be well suited to model the impact of ventilative cooling, especially in annual and monthly calculations. There might be scope for the development of an international standard on ventilative cooling which will also address calculation methods.

Chapter 4: Exemplary Existing Building using Ventilative Cooling

This chapter presented twenty-six existing and operational buildings using principles of ventilative cooling. All buildings were built after 2000 and are located in different climates to include hot summer/cold winter (9), mild summer/cold winter (4) and mild summer/mild winter (5). The type of the buildings range from residential (6) to office (10), educational (8) and exhibition (2). Most buildings are newly built with one retrofit (CDdl Arfrisol Ceder). The buildings were proposed by Annex 62 participants who completed a 2-page description of each building.

In the first page of the 2-page summaries, the buildings are described by providing details of type, year of completion, location, climatic zone, size, orientation, the design team and an external photograph. Site data in the form of heating and cooling degree days, location within the urban environment, and indications of potential barriers to ventilative cooling such as air pollution, external noise, external humidity, prevailing wind direction and altitude are indicated. The architectural design philosophy for the reduction or possible removal of cooling demand and risk of overheating is described.

The second page of the 2-page summary for each building provides specific information on ventilative cooling; the principle is described together with the components used and control strategies. The descriptions highlight the commonality of components used in various building types and climatic regions; these are thermal mass, grills, fans, CO_2 and temperature sensors, manually operated windows, motorised windows, special ventilation openings in many cases in the form of wind towers, solar chimneys and atria. In most cases control strategies focus on guaranteeing thermal comfort, indoor air quality and minimise energy use. Some of the components and control strategies are described in more detail in chapter 5.

The final part of the 2-page summary for each building presents a description of the overall performance of the building including lessons learned.

A common feature in the design of the presented buildings is that first passive energy strategies are used; when passive strategies are not enough to achieve comfort, active strategies are applied. In most cases for the summer period, automatically controlled natural ventilation is used to provide good indoor air quality and natural ventilative cooling. During the heating season, mechanical ventilation with heat recovery is used for indoor air quality and natural ventilative cooling is used in case of overheating.

Some common components were used in most buildings. These include thermal mass, grills, fans, CO_2 and temperature sensors, manually operated and/or motorised windows or special ventilation openings, and wind towers, solar chimneys or atria for exhaust.

It was identified that control strategies is one of the important parameters to guarantee indoor comfort levels, indoor air quality and minimize energy consumption. These should include temperature and CO_2 to ensure that the ventilation not only reduces energy consumption but also ensures thermal comfort and sufficient supply of fresh air.

It was also identified that user behaviour has shown to be a crucial element for successful performance. In many buildings it was reported that when occupants had learned how to operate the system, energy use reduction was achieved for satisfactory comfort level and indoor air quality.

Chapter 5: Available Building Components and Control Strategies for Ventilative Cooling

Chapter 5 presents an important table concerned with the application of ventilative cooling on all levels of climate sensitive building design. These are:

a. site design and architectural design,
b. ventilation components classified into guiding, enhancing and cooling,
c. actuators and sensors.

The chapter then focuses on the description of (b) and (c); all illustrated with photographs of available building components in the market and/or as installed in operational buildings including integrated building elements. The building components presented are:

- **Airflow Guiding Ventilation Components:** Windows, Rooflights, Doors | Dampers, Flaps, Louvres | Special Effect Vents
- **Airflow Enhancing Ventilation Building Components:** Chimneys | Atria | Venturi Ventilators | Wind Towers, Wind Scoops
- **Passive Cooling Components:** Convective Cooling Comp. | Evaporative Cooling Comp.| Phase Change Cooling Comp.
- **Actuators:** Chain Actuators | Linear Actuators | Rotary Actuators
- **Sensors**

Information presented in this chapter is a first step for the classification of building components suitable for Ventilative cooling and highlight the lack of specific information on control strategies. Work on subtask B will use this chapter as a starting point for further investigation.

Chapter 6: Existing Methods and Tools

Chapter 6 presents existing methods and tools suitable for designing ventilative cooling aspects during building design. It starts with early stage design tools using widely accepted first principle and empirical equations to calculate air flow rates based on available driving forces. These are useful for two reasons; firstly they can be referred to in the calculation of climatic potentials of ventilative cooling (chapter 2.1) and secondly are useful when interpreting building codes and regulations presented in chapter 3. The chapter continues with a useful listing of detailed modelling tools used for ventilation calculations such as network models, empirical/mathematical models, CFD models and coupled models. A table with commonly used public domain and commercial models together with some details of inputs and outputs required is given at the end of the chapter.

This chapter will be used as the starting point for work carried out within sub-task A. Sub task A will carry out work to assess design tools limitation (including uncertaincy and required input data) and which tools to be used in each design stage. This will assist in recommendations on how to include Ventilative cooling in labelling and performance assessment certification schemes. Simulations tools and calculation methods used for the design of Ventilative cooling strategies will also be investigated in sub-task C as part of the case-study buildings performance evaluation.

Conclusion

The state-of-the-art review reveals that ventilative cooling is an attractive option for the reduction of energy use in residential and non-domestic buildings with materialised examples in a variety of climates. As a cooling strategy has, thus, the potential to contribute significantly to the reduction (even elimination for certain buildings and climates) of the end use cooling energy demand. The state-of-the-art has also revealed that in many national building codes and energy performance regulations ventilative cooling is not explicitly referred to as a cooling option for achieving energy performance. Therefore the treatment of ventilation (air flow rate) requirements for ventilative cooling and its effect on cooling demand reduction are not clear. This has an impact on the architectural design of the building as well as the specification of components and controls facilitating ventilative cooling. Furthermore, the risk of overheating in buildings is not linked to the potential of ventilative cooling to eliminate it for certain climatic areas especially those heating dominated. These issues will be addressed within work to be carried out with the three subtasks of

Annex 62 by specifying Key Perfromance Indicators for the integration of ventilative cooling in energy performance evaluation methods and regulations and evaluate and develop (if necessary) suitable design methods and tools (subtask A), by developing solutions (subtask B) and by demonstrating performance through well documented case-studies (subtask C).

2 Potentials and Limitations to Ventilative Cooling

The ventilative cooling potential and application challenges primarily depends on the difference between outdoor and indoor air temperature. During cold periods the cooling power of outdoor air is very large, but due to the low outdoor air temperature the risk of draught is also very high and solutions need to be able to handle this risk. During warm periods outdoor air cooling power might not be available during daytime and application of ventilative cooling will be limited to the night period to remove accumulated heat gains during daytime in the building constructions. The system cooling effectiveness will depend on the air flow rate that can be established – naturally or mechnically, the thermal capacity of the building constructions, the air distribution and the heat transfer ability between air flow and the building construction.

When natural forces are used for air distribution, a free running operation mode is often used, where control of the thermal environment is adapted to the changing outdoor environment to increase applicability and reduce energy use. To evaluate the highly varying thermal comfort conditions it is necessary to use indices that assess thermal comfort during a longer time period and that estimate the probability of maintaining thermal conditions within acceptable limits as well as the risk of exceeding these.

A state-of the art review of passive cooling technologies is provided in [1], which among other technologies includes description of recent studies related to design and operation of night-time ventilative cooling. This chapter focuses on the description of state-of-the-art medthodologies for assessing the climatic potential of ventilative cooling as well as the impact of the urban environment on this potential and on application constraints. It also reviews different indices and methods to asses the quality of the thermal environment.

2.1 Physical potentials of ventilative cooling in different climates and building types

2.1.1 Potential for ventilative cooling and methods to assess it.

In the conceptual design phase where decisions about application of ventilative cooling is made, it is important to be able to assess the climatic cooling potential of the location without the need for rigorous analysis. Several simplified methods have been developed that makes this possible or can be used to easily analyse the potential based on climatic data [2-8].

In an assessment of the potential it is important to limit the evaluation of the cooling potential to period where cooling is needed, therefore it is necessary both to look at the outdoor climate as well as the expected cooling need of the building. This section presents a few examples of the methods developed to assess the climatic cooling potential.

A method is proposed in [4] that includes building characteristics, comfort range and local climate in the assessment of cooling need and ventilative cooling potential. The building is characterized by the temperature difference in free-running mode; the comfort is characterized by the temperature mean, range and seasonal shift and the local climate is characterized by the time series of outdoor temperature. The method allows for a quick estimation of energy need for cooling and of the potential of energy savings by ventilative cooling. As dynamic effects (thermal inertia) is ignored the method is mainly applicable to cold climate or buildings with limited thermal mass.

The method uses the concept of the free-running temperature to evaluate the need for cooling and to determine the period to assess the ventilative cooling potential. The free-running temperature is the indoor temperature of the building when no heating, cooling and ventilation is used. From the thermal balance of the building:

$$K_{\mathrm{tot}}(T_{\mathrm{fr}} - T_{\mathrm{o}}) - q_{\mathrm{gain}} = 0 \quad (2.1)$$

Where K_{tot} is the total heat loss coefficient of the building [W/K], T_{fr} is the free running temperature [K], T_o is the outdoor temperature [K] and q_{gain} is the total internal and solar heat gains [W]. Heat loss due to air leakages in the building and/or minimum air flow rate to ensure indoor air quality can be included in the total heat loss coefficient or regarded as part of the ventilative cooling.

This results in a free running temperature defined as:

$$T_{\mathrm{fr}} = T_{\mathrm{o}} + \frac{q_{\mathrm{gain}}}{K_{\mathrm{tot}}}. \quad (2.2)$$

Cooling will be needed if the free running temperature is higher that the upper limit of comfort temperature, T_{cu}. The condition for cooling is:

$$\delta_{\mathrm{c}} = \begin{cases} 1, & \text{if } T_{\mathrm{fr}} > T_{\mathrm{cu}}, \\ 0, & \text{if not.} \end{cases} \quad (2.3)$$

The cooling load may be balanced by ventilative cooling or by mechanical cooling. If the outdoor temperature, $\mathbf{T}_o$, is lower than the upper limit of the comfort range, $\mathbf{T}_{cu}$, then ventilative cooling is possible. The condition for free-cooling is:

$$\delta_{\mathrm{fr}} = \begin{cases} 1, & \text{if } T_{\mathrm{fr}} > T_{\mathrm{cu}} \text{ and } T_{\mathrm{o}} < T_{\mathrm{cu}}, \\ 0, & \text{if not,} \end{cases} \quad (2.4)$$

If the outdoor temperature, **T**o , is higher than the upper limit of the comfort temperature, **T**cu , then mechanical cooling is required. The condition for mechanical cooling is:

$$\delta_{\mathrm{mc}} = \begin{cases} 1, & \text{if } T_{\mathrm{fr}} > T_{\mathrm{cu}} \text{ and } T_{\mathrm{o}} \geqslant T_{\mathrm{cu}}, \\ 0, & \text{if not,} \end{cases} \quad (2.5)$$

The conditions described above are shown in figure 2.1. The comfort range is delimited by lower and upper comfort limits, T_{cl} and T_{cu}. These limits can be defined according to the Fanger model or an adaptive comfort definition.

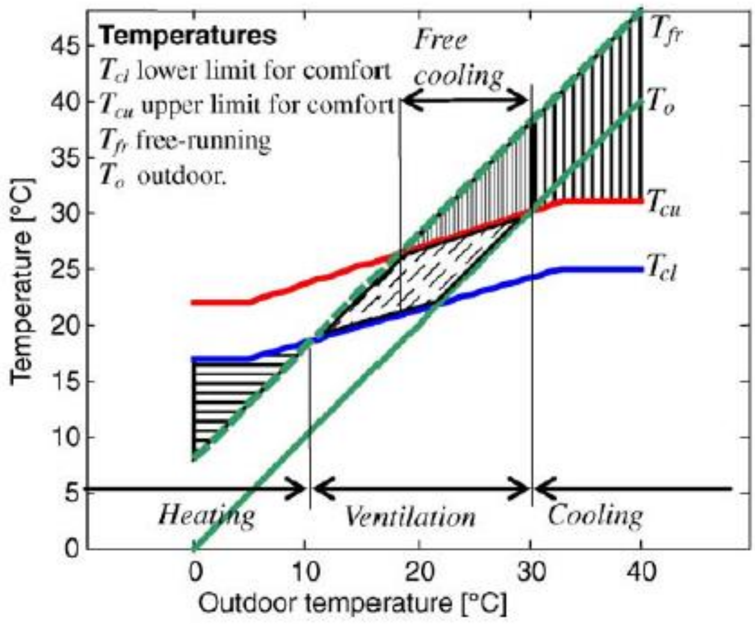


Figure 2.1. Ranges for heating, free-cooling and mechanical cooling when the free-running temperature is higher than the outdoor temperature. [4].

[4] Expresses the need for cooling in a building by a summation of the cooling degree-hours during the year given by the following equation:

$$DH_c = \sum_i[(T_{fr}(i) - T_{cl}(i))\Delta t(i)\delta_c] \quad (2.6)$$

Similarly is the free cooling potential given by:

$$DH_{fc} = \sum_i[(T_{fr}(i) - T_{cu}(i))\Delta t(i)\delta_{fc}] \quad (2.7)$$

And the mechanical cooling need by:

$$DH_{mc} = \sum_i[(T_{fr}(i) - T_{cu}(i))\Delta t(i)\delta_{mc}] \quad (2.8)$$

The energy saving potential by ventilative cooling may be estimated by comparing these summations of cooling degree-hours.

The energy use for cooling will depend on the adopted standard for comfort, which may be different for mechanically and naturally ventilated buildings. Figure 2.2. shows a comparison of the comfort zones for the European climatic conditions from [4]. The comfort range in real HVAC controlled buildings [9] is compared to the ASHRAE comfort zone [10, 11] and the standard for natural ventilation [12].

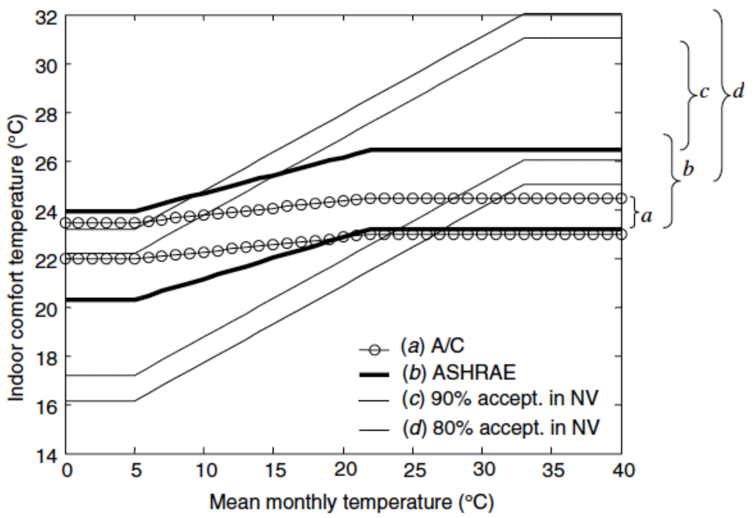


Figure 2.2. Comfort range for air conditioning and for natural ventilation: (a) air conditioning; (b) ASHRAE comfort range; (c) natural ventilation, 90% acceptability limits; (d) natural ventilation, 80% acceptability limits. [4].

If the adaptive comfort definition is used the wider acceptable range of temperatures will decrease the need for cooling but also increase the ventilative cooling potential. This is illustrated in figure 2.3, where [4] shows results for a zone in an office building (length 10 m, width 7,5 m and room height 2,5m) occupied by 10 persons and with a heat load of 30 W/m^2. Figure 2.3 shows the calculated degree hours for Europe, where each row shows the results for the different comfort ranges defined in figure 2.2. Comparison reveals that the distribution is almost the same but the cooling degree hours in air conditioned buildings would be almost halved if the ASHRAE comfort range were used. The reduction would be even more important if the standard for natural ventilation were used,the pattern of energy savings is similar. For all comfort ranges, free-cooling may save more than 50% for regions located north of Danube and Loire but the need for cooling is much lower in these regions.

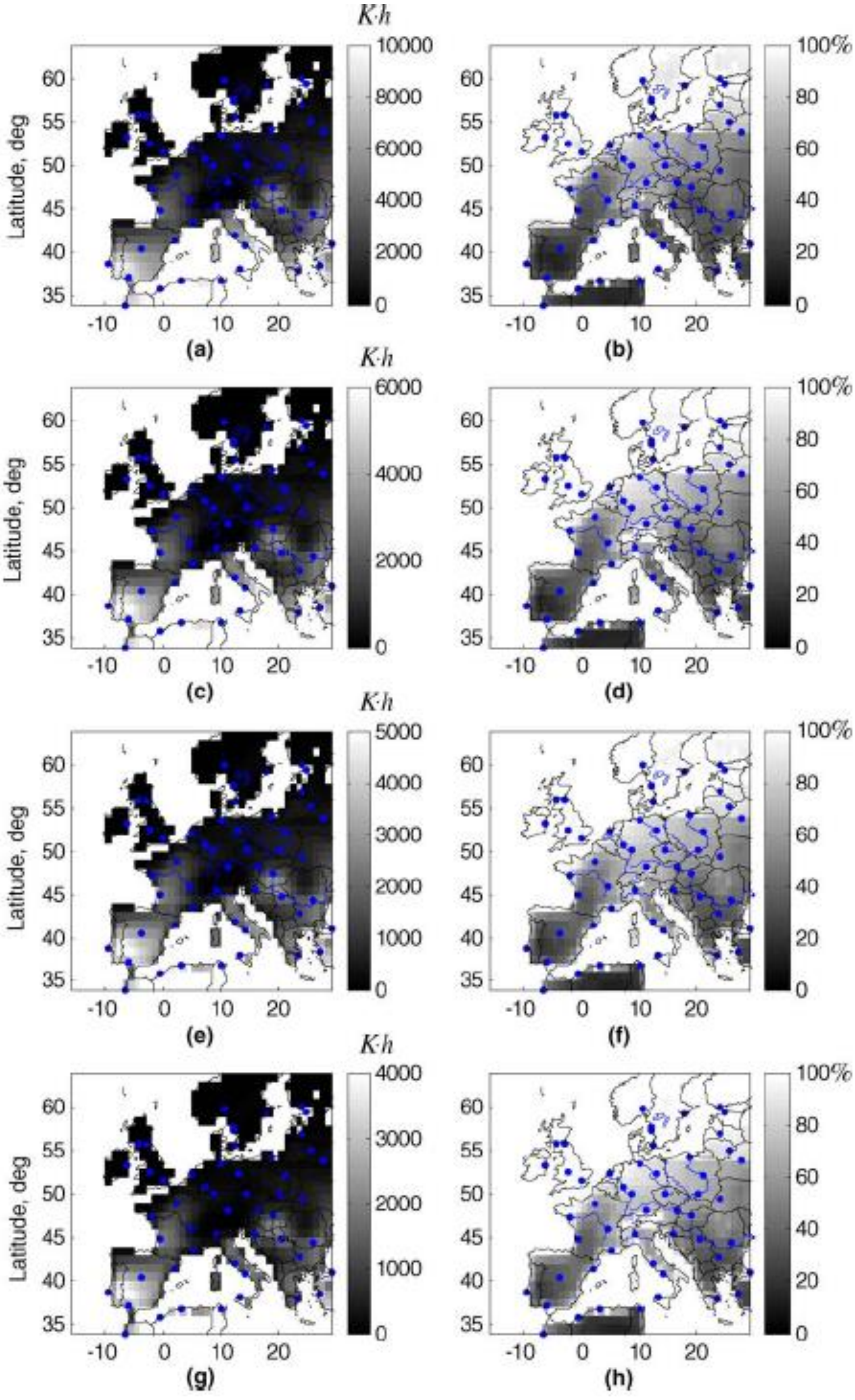


Figure 2.3. Energy consumption and savings for an office building as a function of comfort standards. Case of comfort range of fully HVAC buildings: (a) degree-hours for cooling; (b) percentage of free-cooling. Case of ASHRAE comfort range: (c) degree-hours for cooling; (d) percentage of free-cooling. Case of natural ventilation with 90% acceptance: (e) degree-hours for cooling; (f) percentage of free-cooling. Case of natural ventilation with 80% acceptance: (g) degree-hours for cooling; (h) percentage of free-cooling. [4].

[3] Applies a very similar approach. The starting point is the same heat balance, but instead of the free running temperature of the building they calculate a heating balance point temperature, $T_{o\text{-}hbp}$, which is the outdoor temperature below which heating must be provided to maintain indoor temperatures at the desired heating set point, $T_{i\text{-}hsp}$. The heating balance point temperature is calculated as:

$$T_{o-hbp} = T_{i-hsp} - \frac{q_i}{\dot{m}_{\min} c_p + \sum UA} \tag{2.9}$$

Where m_{min} is the minimum ventilation mass flow rate [kg/s] for indoor air quality control and q_i is the total internal and solar heat gains [W].

For outdoor temperatures below $T_{o\text{-}hbp}$ ventilative cooling is not useful, but a minimum ventilation flow rate will still be needed to maintain indoor air quality. When the outdoor temperature exceeds $T_{o\text{-}hbp,}$ but is below the cooling set point temperature, $T_{i\text{-}csp}$ ventilative cooling is useful to offset heat gains. For outdoor temperatures above $T_{i\text{-}csp}$, mechanical cooling is required. By identifying the number of hours where the outdoor temperature is within suitable limits for ventilative cooling, the percentage of time, where ventilative cooling will be effective during the year can be assessed.

In periods where ventilative cooling can offset heat gains, the required mass flow rate, m_{cool}, can be estimated by a steady state model:

$$\dot{m}_{\text{cool}} = \frac{q_i - \sum UA(T_i - T_0)}{c_p(T_i - T_o)} \tag{2.10}$$

To provide users with easier access, the method has been implemented via a web-based program (available from http://www.bfrl.nist.gov/IAQanalysis/software/CSTprogram.htm).

To illustrate the use of the method table 2.1 shows results from 4 US cities with different climate conditions and based on hourly climate data. The percentage of time of the year ventilative cooling is useful is found for three different definitions of acceptable comfort ranges:

1. Fixed heating (20°C) and cooling (26°C) setpoints with a 17 ◦C dewpoint limit.

2. Adaptive thermal comfort with 80% acceptability and a 17 ◦C dewpoint limit.

3. Adaptive thermal comfort with 80% acceptability and no dewpoint limit.

The percentage of hours, where outdoor conditions is either too cold, too hot or to humid is also given.

For hours during the year where ventilative cooling is suitable, the average ventilation air exchange rate (ceiling height of 2,5 m) and standard deviation of these ventilation rates were predicted for different levels of cooling loads (10-80 W/m2) to be removed from the space.

A

Climate suitability statistics for fixed thermal comfort zone (results from NIST Climate Suitability Tool).

Direct cooling				
Combined internal gain	10 W/m²	20 W/m²	40 W/m²	80 W/m²
Los Angeles				
Ventilation rate	1.48 ach ± 0.774	2.96 ach ± 1.55	5.92 ach ± 3.1	11.8 ach ± 6.19
% Effective	93.4	93.4	93.4	93.4
% Too cold	0	0	0	0
% Too hot	0.457	0.457	0.457	0.457
% Too humid	5.67	5.67	5.67	5.67
Phoenix				
Ventilation rate	1.82 ach ± 1.58	3.64 ach ± 3.17	7.29 ach ± 6.33	14.6 ach ± 12.7
% Effective	52	52	52	52
% Too cold	0	0	0	0
% Too hot	44	44	44	44
% Too humid	5.16	5.16	5.16	5.16
Miami				
Ventilation rate	2.27 ach ± 1.64	4.53 ach ± 3.28	9.06 ach ± 6.55	18.1 ach ± 13.1
% Effective	21.1	21.1	21.1	21.1
% Too cold	0	0	0	0
% Too hot	42.5	42.5	42.5	42.5
% Too humid	76	76	76	76
Kansas City				
Ventilation rate	1.26 ach ± 1.1	2.05 ach ± 2.06	4.09 ach ± 4.13	8.19 ach ± 8.26
% Effective	56.4	56.4	56.4	56.4
% Too cold	19.2	19.2	19.2	19.2
% Too hot	12.9	12.9	12.9	12.9
% Too humid	21.6	21.6	21.6	21.6

Note: Night cooling for subsequent days when direct cooling is not effective.
For direct cooling % = hours effective/8760 h; for night cooling % = days effective/days needed.
white = 0–5 ACH.
light gray = 5–10 ACH.
medium gray = 10–15 ACH.
dark gray > 15 ACH.

B

Climate suitability statistics for adaptive thermal comfort cases (80% acceptability with 17 °C dewpoint limit).

Direct cooling				
Combined internal gain	10 W/m²	20 W/m²	40 W/m²	80 W/m²
Los Angeles				
Ventilation rate	1.36 ach ± 0.662	2.71 ach ± 1.32	5.42 ach ± 2.65	10.8 ach ± 5.3
% Effective	93.8	93.8	93.8	93.8
% Too cold	0	0	0	0
% Too hot	0.331	0.331	0.331	0.331
% Too humid	5.67	5.67	5.67	5.67
Phoenix				
Ventilation rate	1.99 ach ± 1.81	3.97 ach ± 3.63	7.95 ach ± 7.26	15.9 ach ± 14.5
% Effective	63.1	63.1	63.1	63.1
% Too cold	0	0	0	0
% Too hot	30.5	30.5	30.5	30.5
% Too humid	5.16	5.16	5.16	5.16
Miami				
Ventilation rate	1.95 ach ± 1.55	3.89 ach ± 3.11	7.79 ach ± 6.21	15.6 ach ± 12.4
% Effective	23.6	23.6	23.6	23.6
% Too cold	0	0	0	0
% Too hot	10.9	10.9	10.9	10.9
% Too humid	76	76	76	76
Kansas City				
Ventilation rate	1.2 ach ± 1.1	2.06 ach ± 2.1	4.12 ach ± 4.21	8.25 ach ± 8.42
% Effective	63.2	63.2	63.2	63.2
% Too cold	13.9	13.9	13.9	13.9
% Too hot	6.86	6.86	6.86	6.86
% Too humid	21.6	21.6	21.6	21.6

Table 2.1. Climate suitability statistics for four US cities at a fixed thermal comfort case (A) and at an adaptive thermal comfort case with 80% acceptability with a 17°C dewpoint limit (B). Adapted from [3].

2.1.2 Climatic potential for night time cooling

Night-time ventilation is also highly dependent on climatic conditions, as a sufficiently high temperature difference between ambient air and the building structure is needed during the night to achieve efficient convective cooling of the building mass. The climatic potential for the passive cooling of buildings by night-time ventilation in Europe is evaluated in [13]. A method was developed which is basically suitable for all building types, regardless of building-specific parameters. This was achieved by basing the approach solely on a building temperature variable within a temperature band given by summertime thermal comfort.

DEFINITION OF CCP

Degree-days or degree-hours methods are often used to characterise a climate's impact on the thermal behaviour of a building. The daily climatic cooling potential, CCP_d, was defined as degree-hours for the difference between building temperature, T_b and external air temperature, T_e (Figure 2.4):

$$CCP_d = \sum_{t=t_i}^{t_f} m_{d,t}\left(T_{b(d,t)} - T_{e(d,t)}\right) \qquad \begin{cases} m = 1\text{h} & \text{if } T_b - T_e \geq \Delta T_{crit} \\ m = 0 & \text{if } T_b - T_e < \Delta T_{crit} \end{cases} \tag{2.11}$$

Where t stands for the time of day, with $t \in \{0, \ldots, 24\text{h}\}$; t_i and t_f denote the initial and the final time of night-time ventilation, and ΔT_{crit} is the threshold value of the temperature difference, when night-time ventilation is applied. In the numerical analysis, it was assumed that night-time ventilation starts at t_i = 19 h and ends at t_f = 7 h. As a certain temperature difference is needed for effective convection, night ventilation is only applied if the difference between building temperature and external temperature is greater than 3 K.

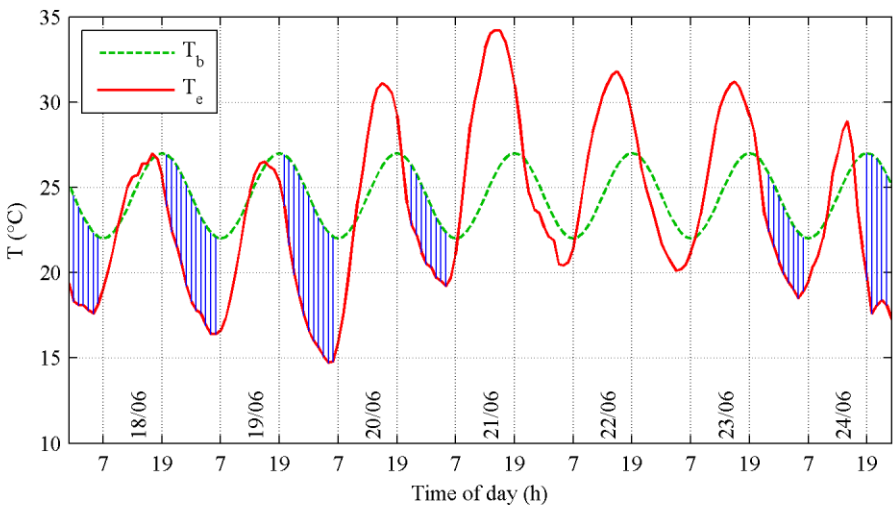


Figure 2.4. Building temperature, T_b and external air temperature, T_e during one week in summer 2003 for Zurich SMA (ANETZ data). Shaded areas illustrate graphically the climatic cooling potential, CCP. [13]

As heat gains and night-time ventilation are not simultaneous, energy storage is an integral part of the concept. In the case of sensible energy storage, this is associated with a variable temperature of the building structure. This aspect is included in the model by defining the building temperature as a harmonic oscillation around 24.5°C with amplitude of 2.5 K:

$$T_{b(t)} = 24.5 + 2.5\cos\left(2\pi\frac{t-t_i}{24}\right) \tag{2.12}$$

The maximum building temperature occurs at the starting time of night ventilation, and given a ventilation time of 12 hours, the minimum building temperature occurs at the end time (Figure 2.4). The temperature range T_b = 24.5 °C ± 2.5 °C corresponds to that recommended for thermal comfort in offices [14].

PRACTICAL SIGNICICANCE OF CCP

To discuss the practical significance of the calculated degree-hours, an example shall be given. It is assumed that the thermal capacity of the building mass is sufficiently high and therefore does not limit the heat storage process. If the building is in the same state after each 24 h cycle, the daily heat gains Q_d(Wh) stored to the thermal mass, equal the heat which is discharged by night ventilation:

$$Q_d = \dot{m} \cdot c_p \cdot CCP_d \tag{2.13}$$

The effective mass flow rate is written as $\dot{m} = A_{Floor}\, H\, \eta\, ACR\, \rho$, where A_{Floor} is the floor area [m^2] and H the height of the room [m], ACR the air change rate [h^{-1}] and η a temperature efficiency, which is defined as $\eta = (T_{out}-T_e)/(T_b-T_e)$ and takes into account the fact that the temperature of the outflowing air T_{out} is lower than the building temperature T_b. The density and the specific heat of the air are taken as ρ = 1.2 kg/m$_3$ and c_p = 1000 J/(kgK). Assuming a room height of H = 2.5 m and a constant effective air change rate of η ACR = 6 h^{-1} yields:

$$\frac{Q_d}{A_{Floor}} = H \cdot \eta \cdot ACR \cdot \rho \cdot c_p \cdot CCP_d = \frac{2.5\ \text{m} \cdot 6\ \text{h}^{-1} \cdot 1.2\text{kg/m}^3 \cdot 1000\ \text{J/kgK}}{3600\ \text{s/h}} CCP_d = 5\frac{W}{m^2K} CCP_d \tag{2.14}$$

For the climatic cooling potential needed to discharge internal heat gains of 20 W/m^{2}K and solar gains of 30 W/m^{2}K during an occupancy time of 8 h follows:

$$CCP_d = \frac{Q_d}{A_{Floor}} \Big/ 5\frac{W}{m^2K} = \frac{(20+30)\cdot 8}{5}\text{Kh} = 80\ \text{Kh} \tag{2.15}$$

This example should be seen as a rough estimation only, as solar and internal gains of an office room can vary substantially depending on the type of building use, local climate, and the solar energy transmittance and orientation of the façade.

COOLING POTENTIAL

The degree-hour method was applied for a systematic analysis of the potential for night time cooling in different climatic zones of Europe. Semi-synthetic climate data [15] from 259 weather stations was used to map the climatic cooling potential (Figure 2.5). Additionally the cumulative frequency distribution of CCP was plotted for 20 European locations (Figure 2.6). These charts show the number of nights per year when CCP exceeds a certain value.

In the whole of Northern Europe (including the British Isles) a very significant climatic cooling potential was found, and therefore passive cooling of buildings by night-time ventilation seems to be applicable in most cases. In Central, Eastern and even in some regions of Southern Europe, the climatic cooling potential is still significant, but due to the inherent stochastic properties of weather patterns, series of warmer nights can occur at some locations, where passive cooling by night-time ventilation might not be sufficient to guarantee thermal comfort. If lower thermal comfort levels are not accepted during short periods of time, additional cooling systems are required. In regions such as southern Spain, Italy and Greece climatic cooling potential is limited and night cooling alone might not be sufficient to provide good thermal comfort during all the year. Nevertheless, night-time ventilation can be used in hybrid cooling systems during spring and fall.

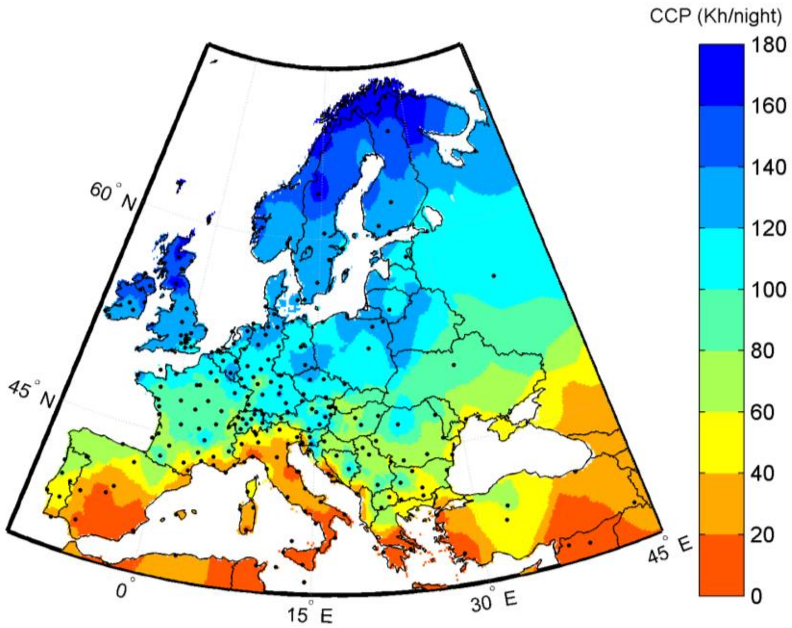


Figure 2.5. Map of mean climatic cooling potential (Kh/night) in July based on Meteonorm data [13].

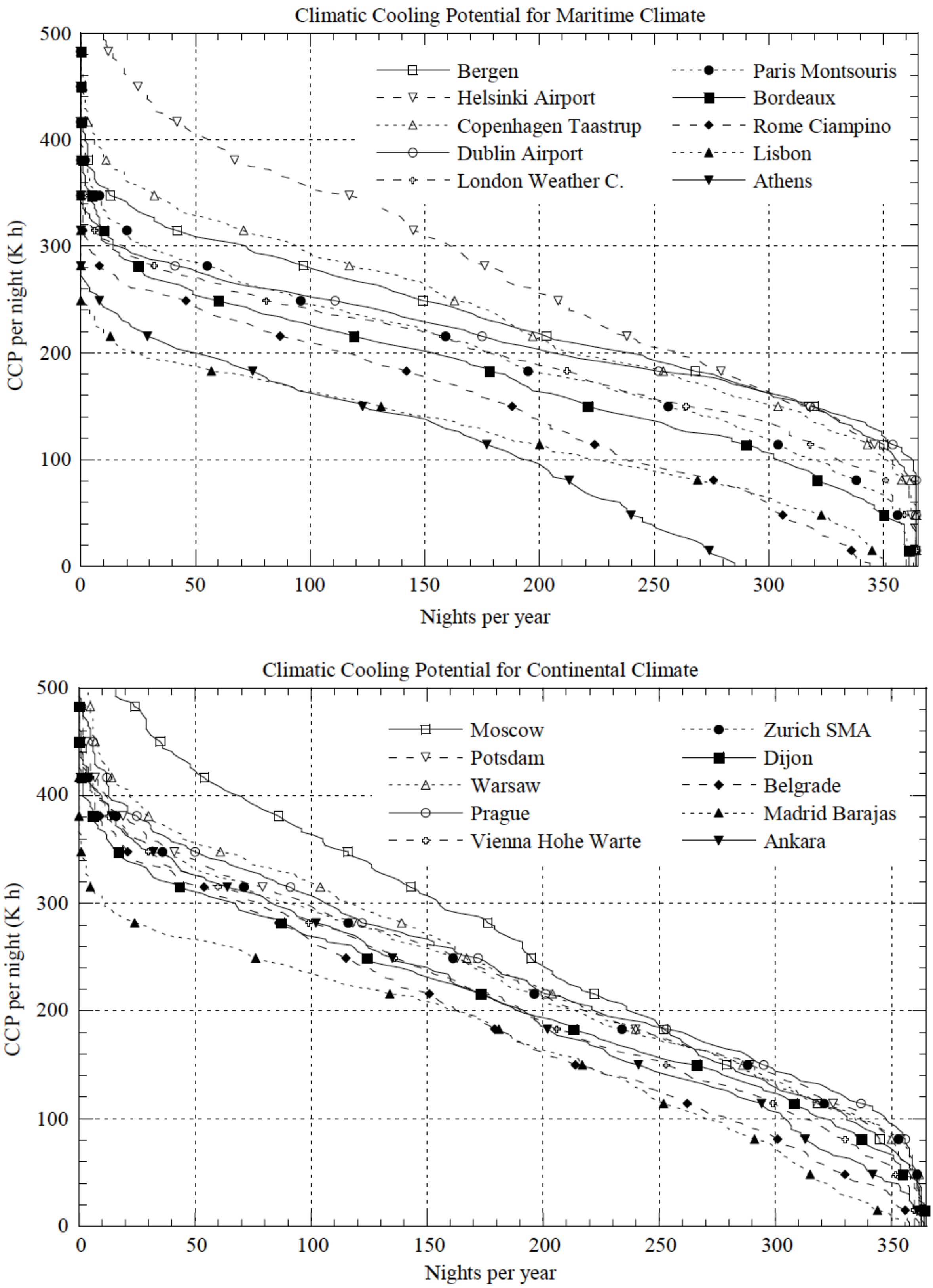


Figure 2.6. Cumulative frequency distribution of CCP for maritime (top) and continental (bottom) locations. [13].

2.1.3 Potential for application of ventilative cooling through natural driving forces

In many cases ventilative cooling is based partly or fully on natural driving forces for air transport. In such cases it is very important to be able to assess the availability and strength of the natural driving forces in the early design phases in a simplified way.

Several methods have been developed for this purpose that based on available climatic data and simplified assumption on building location and design can estimate the ventilative cooling potential, when air transport is based on natural driving forces, [8,20, 21,22, 23,24].

A method was presented in [8] which integrates the British Standard natural ventilation calculation method [25] for a single zone within a thermal resistance network model [24] and is called the Thermal Resistance Ventilation (TRV) model to assess the natural ventilative cooling potential of office buildings in different climate zones in China.

Figure 2.9 shows the structure of the coupled thermal and air flow model.

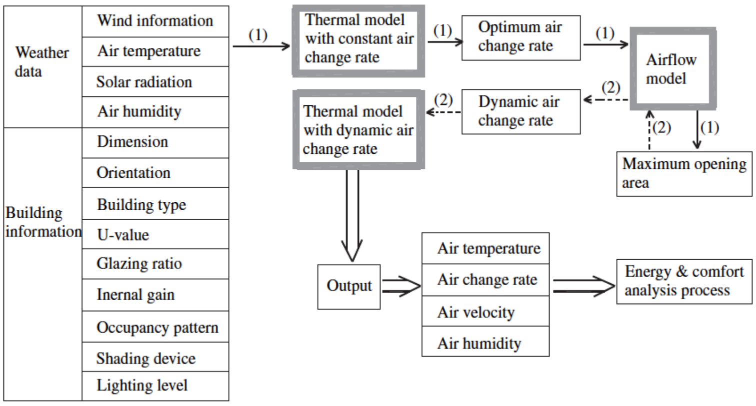


Figure 2.9. Structure of the two-coupled thermal and airflow model, [24].

The dynamic thermal model is based on energy balance equations. The thermal model is based on the energy balance equation. In order to simplify the problem, it is assumed that all the surfaces of the space are at the same temperature. The mechanics of heat balance then include the total convective internal casual gain (Φpc) (heat emitted from people and equipment), lighting gain ($\Phi light$), solar gain ($\Phi solar$), which are absorbed partly by room furniture and partly by internal wall surfaces. The heat loss includes ventilation heat loss, and conductive heat loss via external walls and windows.

Figure 2.10 shows an illustration of the thermal balance of a room. The heat flow of the room can be modelled as a four-node simplified thermal resistance network model that consists of three mass nodes: N1 a room node (air and content), N2 a surface node, N3 a deep mass node and an outdoor ambient node. N1 corresponds to room air and room contents having a time constant much less than one time step (1 h). N2 corresponds to the surface plus a mass layer with a time constant much less than 24 h, and N3 corresponds to mass at a depth sufficient to have a time constant greater than 24 h. **Ta** is ambient temperature, **T**1 is room node temperature, **T**2 is surface temperature and **T**3 is deep mass temperature.

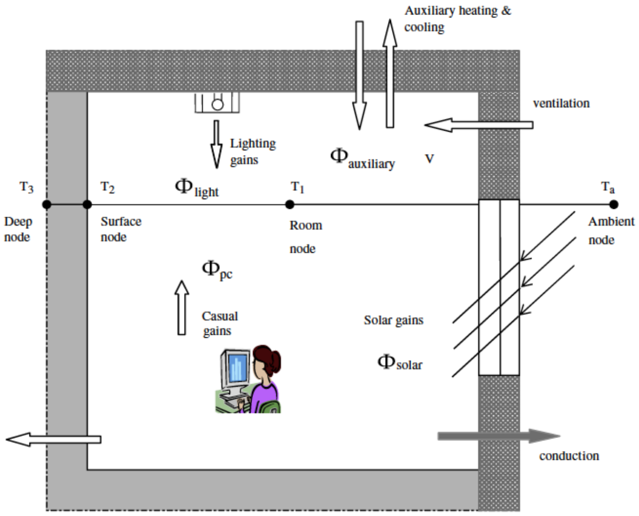


Figure 2.10. Illustration of a room thermal balance, [24].

The simplified thermal balance model illustrated in Figure 2.10 can be expressed in the following energy balance equations for each node:

Node room:

$$C_1\frac{dT_1}{dt} = \alpha_1\left(\Phi_{pc} + \Phi_{solar} + \Phi_{light} + \Phi_{auxilary}\right) + g_{12}(T_2 - T_1) + g_{1a}(T_a - T_1) \quad (2.16)$$

Node surface:

$$C_2\frac{dT_2}{dt} = \alpha_2\left(\Phi_{pc} + \Phi_{solar} + \Phi_{light} + \Phi_{auxilary}\right) + g_{12}(T_1 - T_2) + g_{23}(T_3 - T_2) \quad (2.17)$$

Node deep mass:

$$C_3\frac{dT_3}{dt} = g_{23}(T_2 - T_3) + g_{3a}(T_a - T_3)$$

$$g_{1a} = A_{glaze} \times U_{glaze} + 0.3Vn \quad (2.18)$$

Where

A_{glaze} (m^2) is the glass area
U_{glaze} ($W/m^2\,^oC$) is the U-value of the window
V (m^3) is the volume of the room
n (ac/h) is the air change rate
g_{12} ($W/^oC$) is the conductance* partly radiative and partly convective;
g_{23} ($W/^oC$) is the conductance of the massive material;

g_{3a} is conductance between the deep mass node and the outdoor node, when the wall is an internal wall, g_{3a} equals zero;
Φsolar (W) is the solar gain delivered to the room;
Φpc (W) is the casual gain (equipment and people) delivered to the room;
Φlight (W) is the artificial lighting gain delivered to the room;
Φaux (W) is auxiliary heating or cooling delivered to the room;
C_1 (Wh/^{o}C) is the thermal capacity of the room, which includes contents;
C_2 (Wh/^{o}C) is the thermal capacity of the shallow surface material of the room;
C_3 (Wh/^{o}C) is the thermal capacity of deep material of the room;
a_1 is the proportion of the gain delivered to room node;
a_2 is the proportion of the gain delivered to surface node.

The thermal mass in shallow surface and deep mass are the assumed values for the different type of buildings, which are calculated from typical building construction. The internal gains (including lighting and causal gain) and solar gain are assumed 70% delivered to the room node and 30% delivered to shallow surface node.

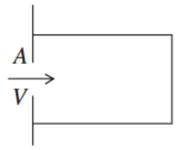
The air flow model is developed for a single zone building and included the following models, [26]:

(1) Formulae for single-sided ventilation

(a) Ventilation due to wind

$$Q = 0.25AV$$

where A is the opening surface and V is the wind velocity.



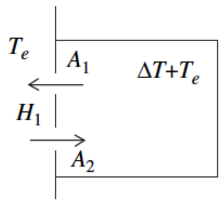
Cross-section

(b) Ventilation due to temperature difference with two openings

$$Q = C_d A\left[\frac{\xi\sqrt{2}}{(1+\xi)(1+\xi^2)^{1/2}}\right]\left(\frac{\Delta T_g H_1}{T}\right)$$

$$\xi = A_1/A_2, \quad A = A_1 + A_2$$

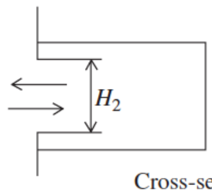
where C_d is the discharge coefficient



Cross-section

(c) Ventilation due to temperature difference with one opening

$$Q = C_d \frac{A}{3}\sqrt{\frac{\Delta T_g H_2}{T}}$$



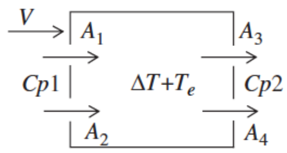
Cross-section

(2) Formulae for cross-ventilation

(a) Ventilation due to wind only:

$$Q_w = C_d A_w V\sqrt{\Delta Cp}$$

$$\frac{1}{A_w^2} = \frac{1}{(A_1+A_2)^2} + \frac{1}{(A_3+A_4)^2}$$



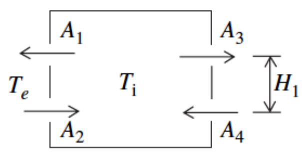
Cross-section

(b) Ventilation due to temperature difference only:

$$Q_b = C_d A_b\left(\frac{2\Delta T_g H_1}{T}\right)^{0.5}$$

$$\frac{1}{A_b^2} = \frac{1}{(A_1+A_3)^2} + \frac{1}{(A_2+A_4)^2}$$

$$T = \frac{T_e + T_i}{2}$$



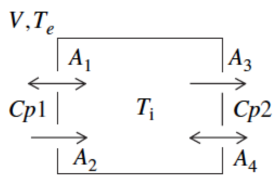
Cross-section

(c) Ventilation due to wind and temperature difference:

$$Q = Q_b \text{ for } \frac{V}{\sqrt{\Delta T}} < 0.26\sqrt{\frac{A_b}{A_w}\frac{H_1}{\Delta Cp}}$$

$$Q = Q_w \text{ for } \frac{V}{\sqrt{\Delta T}} < 0.26\sqrt{\frac{A_b}{A_w}\frac{H_1}{\Delta Cp}}$$

$$\Delta T = T_i - T_e$$



Cross-section

This model was used by [24], to assess the natural ventilative cooling potential of a typical office building in different climate zones in China. The natural ventilative cooling potential was estimated for different natural ventilation profiles (day, night, day and night), levels of heat gain (low, medium, high), natural ventilation principle (single-sided, cross). Figure 2.11 shows an example of the estimated natural ventilative cooling potential (NVCP) for a low energy demonstration building in Beijing depending on the required comfort level.

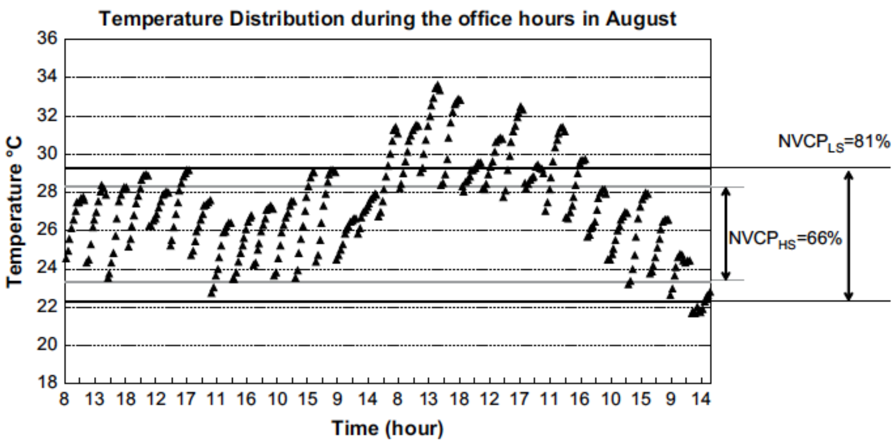


Figure 2.11. Temperature distribution and natural ventilative cooling potential of a Low-Energy Demonstration Building in Beijing in August, depending on the selected comfort criteria, [8].

2.1.4 Possible reduction of cooling energy use and/or decrease of the indoor temperature

Research discussed so far has estimated the climatic potential for application of ventilative cooling and taken into consideration constraints imposed by the urban environment and to overcome critical barriers. However, an important consideration is whether an effect on energy use for cooling and/or improvement of thermal comfort can be expected and/or realised. Several researchers have investigated the potential reduction of cooling energy use through the use of ventilative cooling by simulations for office buildings, while information on residential buildings is very limited as well as on experimentally documented energy savings.

2.1.5 Office Buildings

Ventilative cooling analysis based on simulations of energy use and thermal comfort in single offices in a typical multi-storey, narrow-plan, middle size office building under Belgian climatic conditions is presented in [5]. Compared to a standard air-conditioned office building the use of single-sided natural ventilative cooling during daytime would result in an energy saving for cooling of about 30% and with additional night cooling, the saving would increase to 40%. In order to achieve the necessary air flow rates (daytime 4h-1, night-time 8h-1) and opening area of 0,6m^2 (daytime) – 1,2 m^2 (night time) was needed, corresponding to 3-6% of the floor area.

Based on simulations the feasibility of ventilative cooling for office buildings in the temperate climate of Belgium was assessed [32]. They investigated two ventilative cooling schemes: diurnal manual window operation and the combination of diurnal manual window operation and natural night-time ventilative cooling. Additionally, external solar shading and daylighting were considered to limit heat gains, see figure 2.14.

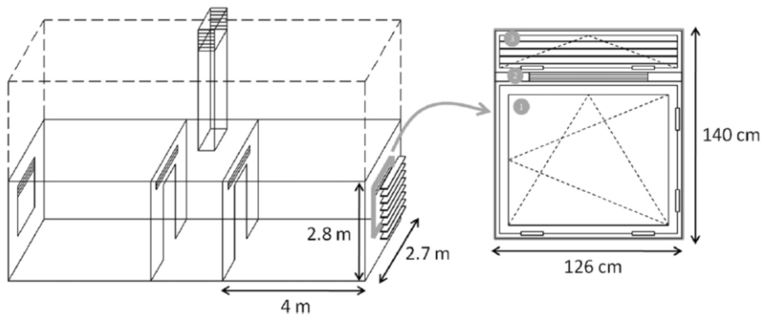


Figure 2.14. Overview of office geometry with shading device and design of the passive stack night ventilation openings with detail of the fenestration system (1: Operable window; 2: self-regulating ventilation grill; 3: night ventilation inlet opening), [32].

The feasibility was evaluated through uncertainty analysis of the simulated weighted time exceeding comfort for different building designs with varying insulation level, glazing-to-wall-ratio, glazing type and air tightness. The results indicate that it is possible to cool office buildings solely by diurnal manual window operation, even for highly insulated and air tight buildings. This requires minimizing heat gains to about 900 kJ/m^2 per working day during summer months. When a combination of diurnal window operation and night ventilation is available, limiting the heat gains to about 1500 kJ/m^2 per working day suffices. These target values can be achieved only when solar gains are minimized through sensible façade design.

A study is presented in [33] on the effect of night time ventilative cooling in three classrooms in La Rochelle, France. They found that the relative effect of night-time ventilative cooling depended on the cooling setpoint during daytime, see figure 2.15. For a 22 ^oC temperature setpoint, night-time ventilative cooling leads only to a 12% decrease in cooling energy use, while it is 54% for a 26 ^oC setpoint. The cooling of the building during daytime reduces the efficiency of night-time ventilative cooling as it reduces room and construction temperatures and the combined effect of the two techniques will be less than the sum of each individual.

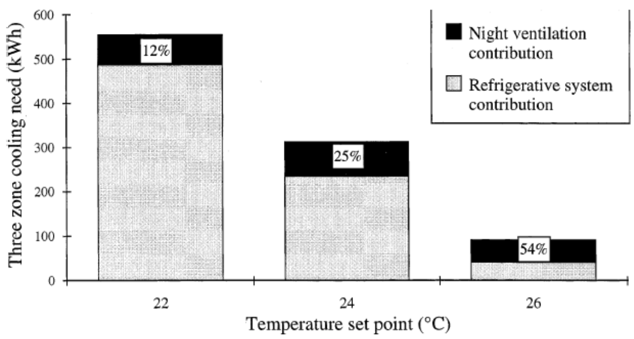


Figure 2.15. Daytime cooling needs of rooms A, B and C with and without night ventilation. [33].

The impact of several buildings, climatic and cooling plant parameters on the potential saving of nighttime ventilative cooling in a typical office building under UK climatic conditions were investigated in [34]. They found that night ventilative cooling energy savings could be further increased if some of the building parameters were optimised in line with 'low energy' design principles. An exposed concrete ceiling or exposed concrete/brick walls or another form of exposed thermal mass would increase energy benefits. The highest energy savings were found for west orientations of the façade. Other less important parameters included reduced glazing ratio, reduced internal heat gains and increased airtightness. In optimum cases, mechanical night-time ventilative cooling would also be beneficial.

The performance of several low-energy cooling systems for an office building under UK (London) climatic conditions were compared in [35] through simulation. It was concluded that ventilative cooling with outside air is very effective in the mild UK climate. The annual energy cost for displacement ventilation and VAV systems that use ventilative cooling is about 20% less than for the existing building, which uses a fixed minimum supply air rate that does not take advantage of free cooling of outdoor air, see figure 2.16. They also concluded that night-time ventilative cooling is most effective, when thermal mass is directly exposed to the occupied space.

For the studied building by [35] natural ventilation alone could not maintain appropriate summer comfort conditions. However, a hybrid system where VAV was used to maintain comfort during extreme periods was very beneficial. For the hybrid ventilation system the year is divided into three seasons: natural ventilation, cooling, and heating. During the natural ventilation season, the mechanical system does not operate and no energy is used. During the cooling (June 15-August 31) and heating seasons (November 1- March 31), the VAV system operates, with night cooling during the cooling season. As can be seen in figure 2.16 this type of hybrid system is the best choice for the office building simulated, using at least 20% less energy than any purely mechanical system. The energy use estimate presented represents an upper bound for the hybrid ventilation system, where the system is switched into a mechanical mode for an entire season. An actual hybrid system might switch between mechanical and natural modes on a daily basis during the heating and cooling seasons, further reducing the system energy use. However, it was not possible to simulate such control with the model used.

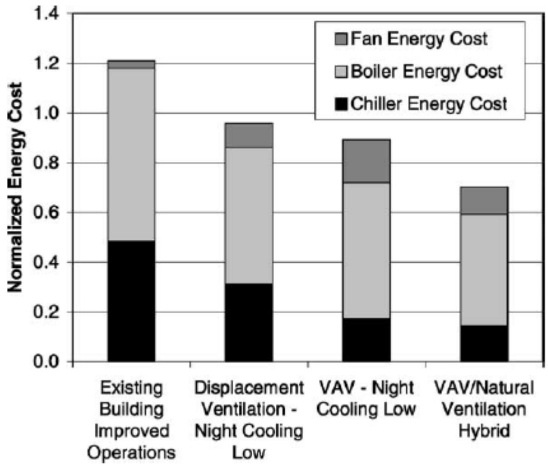


Figure 2.16. Normalized total annual energy cost of best-case systems [35].

The cooling saving potential of hybrid systems but for an arid climate are presented in [36]. The paper presents a study through simulation of a set of hybrid cooling systems and common active air-conditioning systems for a prototypical office building configuration and four different set of arid climate data (Madinah, Saudi-Arabia; Manama, Bahrain; Alice Springs, Australia and El Arish, Egypt). The office building design adopted incorporated features such as high exposed thermal mass, good shading and openable windows.

Three active cooling systems were included:

A) CAV air conditioning,
B) VAV air conditioning
C) Radiant cooling combined with CAV fresh air supply.

Eight different hybrid systems were included:

B1) or C1) Hybrid ventilation – natural ventilation during working hours alternated with an active system (B or C) in peak conditions.
B2) or C2) Hybrid ventilation as above and a night convective cooling strategy.
B3) or C3) Hybrid ventilation combined with direct evaporative cooling.
C4) Hybrid ventilation with the radiant cooling elements coupled to a cooling tower (indirect evaporative cooling).
C5): Hybrid ventilation with the radiant cooling elements coupled to borehole heat exchangers (earth cooling).

Figure 2.17 shows the estimated energy savings by applying the eight hybrid systems compared to system B (VAV air conditioning).

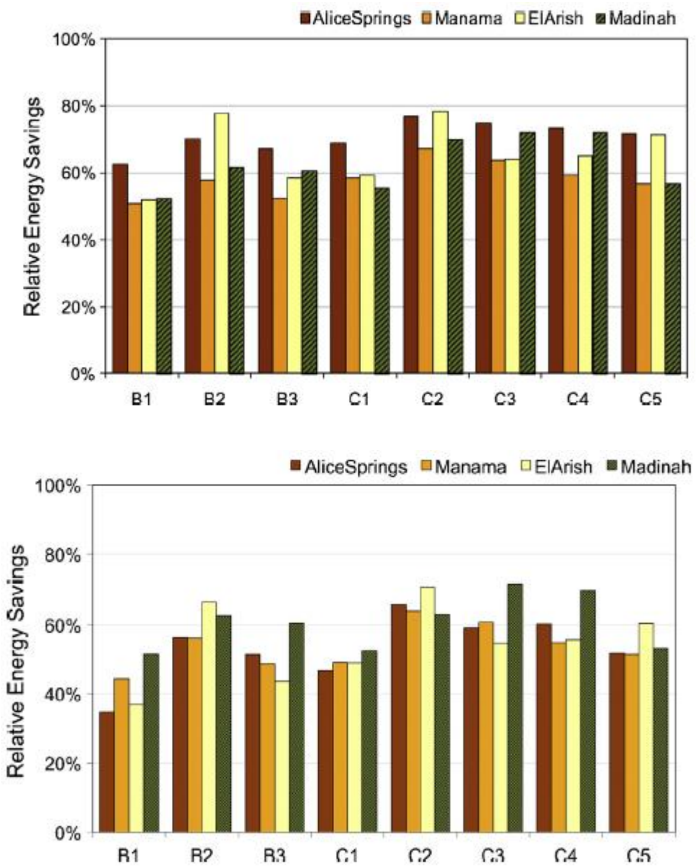


Figure 2.17. Savings in plant energy due to the application of hybrid cooling strategies for low (upper figure) and high (lower figure) internal heat gain relative to energy use of system B (VAV) [36].

The results showed that adopting a hybrid cooling strategy by allowing user control of windows and facilitating adaptive behavior, enabled significant plant energy savings (more than 40%) by simply alternating between natural ventilative cooling and VAV cooling. Greater savings were demonstrated where night-time ventilative cooling formed part of the operating strategy. Night-time ventilative cooling proved to be effective during the equinox seasons even in the hottest climates.

It was found that low air set-point temperatures were required to offset radiant gains in designs with conventional air conditioning in order to satisfy the comfort criteria. In contrast, given the exposed thermal mass in the prototypical building and allowing for comfort to be judged according to an adaptive model, much higher air temperatures could be accepted and so cooling demands reduced by operating at higher set-point temperatures in the case of buildings with hybrid cooling systems.

The results also demonstrated that a range of systems incorporating slab radiant cooling were more energy efficient when operated in a hybrid strategy by virtue of moderating radiant temperatures and allowing higher air set-point temperatures. In all cases direct evaporative cooling of the fresh air supply was shown to make a useful contribution to energy reduction – even after possible desalination energy penalties were considered.

Figure 2.18 shows potential for window opening during occupied hours (ventilative cooling) and non-occupied hours (night-time ventilative cooling) for El-Arish.

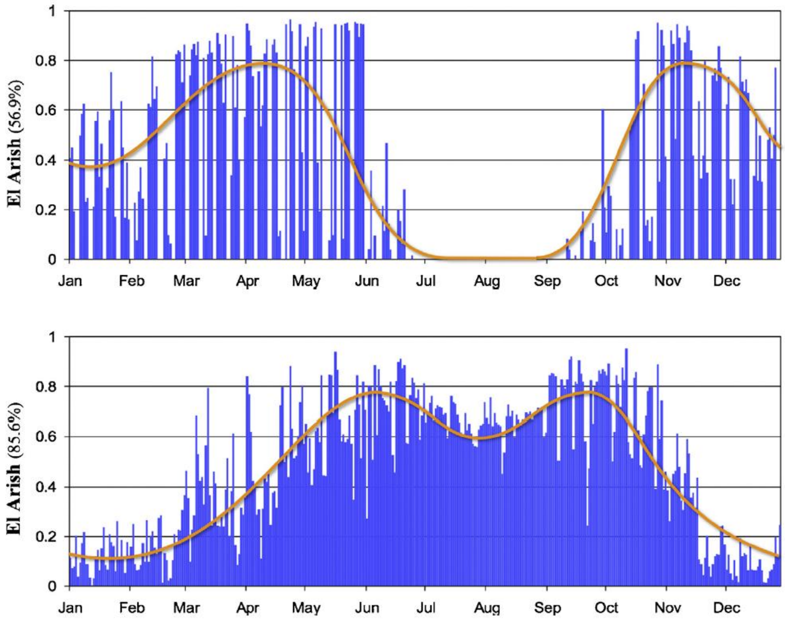


Figure 2.18. Window opening area of the optimal designs during the occupied hours and non-occupied hours. The annual proportion of night ventilation is noted in the vertical axis caption [36]

Natural ventilative cooling was enabled most during the equinoxes, and decreased during the winter season. There are extended periods in the summer season where windows are not opened during occupied hours. These summer periods are longer at the hotter arid locations in the study (Manama and Madinah). The proportion of total occupied hours of natural ventilative cooling ranges from 37% in Madinah to 57% in El Arish. In contrast, night ventilative cooling was enabled most often during the equinoxes and decreased during both the mid-summer and mid- winter seasons. The proportion of non-occupied hours of night ventilation ranged from 64% in Alice Springs to 86% in El Arish.

2.1.6 Residential Buildings

In order to investigate the effect of night-time ventilative cooling techniques, analysed energy data from two hundred fourteen air conditioned residential buildings using night ventilative cooling are presented in [37]. All buildings were single houses located in suburban or rural areas in Greece. They were mechanically air conditioned and with a quite high thermal mass level. Their envelope surface area ranged between 55 and 480m^2 and the buildings represented the whole spectrum of cooling load levels, from very low (5kWh/m^2/y) to very high (90kWh/m^2/y), while the applied air changes per hour varied between 2 and 30. Median summer night temperatures in the considered areas varied between 24 and 24.8 ◦C, while the corresponding range for the maximum and minimum temperatures were 38.8–40 ◦C and 10.6–10.9 ◦C, respectively.

Based on specific information on energy consumption and operational conditions of each building a dynamic thermal model was calibrated and used to investigate the potential benefit of night time ventilative cooling. All performance data were homogenized for the same climatic and operational conditions. It was found that night-time ventilative cooling applied to residential buildings might decrease the cooling load up to 40kWh/m^2/y with an average contribution close to 12kWh/m^2/y, see figure 2.19.

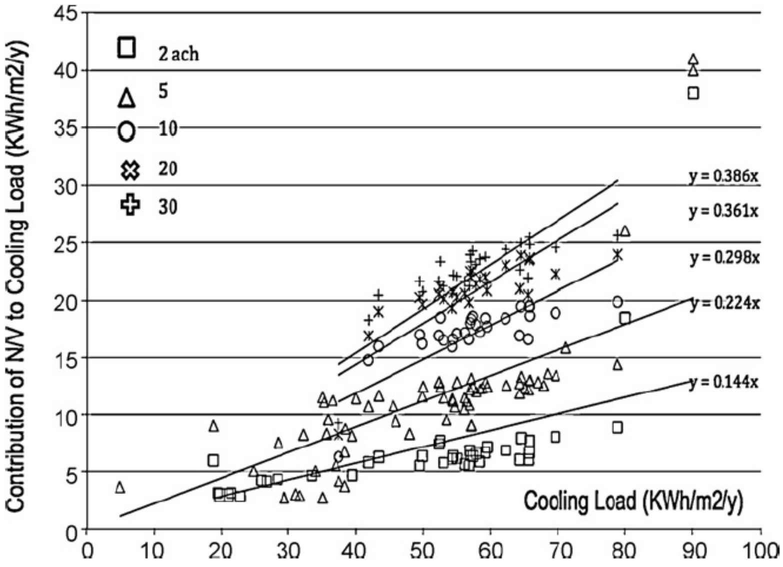


Figure 2.19. Calculated energy contribution of night-time ventilative cooling as a function of the initial cooling load for various levels of air flow rates, [37].

Figure 2.19 also shows that the utilisability of the energy offered by night-time ventilative cooling techniques increases as a function of the initial cooling needs of the buildings, those with high cooling loads benefit a much higher absolute contribution than buildings presenting a low cooling demand. The correlation between the cooling needs of the buildings and the energy contribution of night-time ventilative cooling was found to be almost linear. The utilisability of the energy stored during the night increases as a function of the air flow rate although the energy contribution per unit of air flow is decreasing.

Despite the dissimilarity of the energy amount stored in buildings and the variability of the night-time ventilative cooling utilisability for each individual building, the percentage energy contribution of night-time ventilative cooling was found to be independent of the initial cooling load of buildings and varying between 10 – 40 %.

For the hot humid climate of Israel [38] investigated by simulations the influence of night-time ventilative cooling on maximum indoor temperature in summer in residential buildings with different levels of thermal mass (very light to very heavy) and air flow rates (2-30 h^{-1}).

The results obtained showed that in the hot humid climate of Israel it is possible to achieve a reduction of indoor temperature of 3–6 ^{o}C in a heavy constructed residential building without operating an air conditioning unit. The exact reduction achieved depended on the amount of thermal mass, the rate of night ventilation, and the temperature swing of the site between day and night, see figure 2.20.

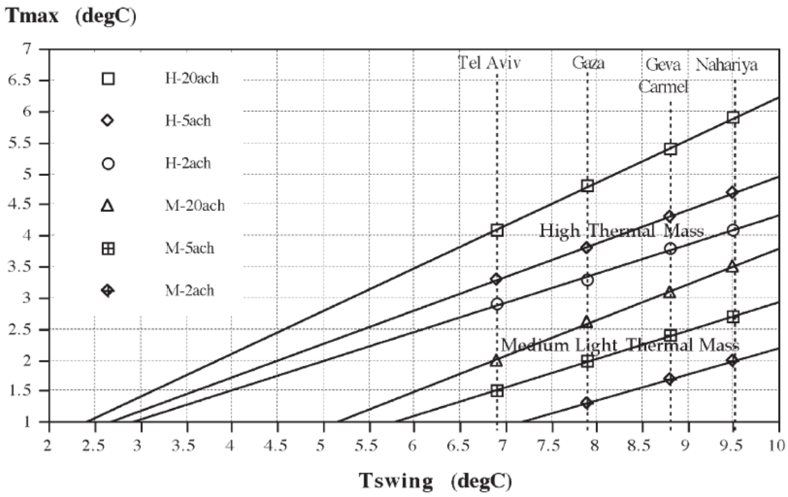


Figure 2.20. The reduction in **T**max in the hot-humid climate of Israel, as a function of **T**swing, [38].

2.2 Critical Limitations and Barriers to Ventilative Cooling

2.2.1 Impact of global warming on potential for night time ventilation

In order to quantify the impact of climate warming on the potential for night cooling, [16] presents developed linear regression models to estimate the daily climatic cooling potential (CCP_d) from the minimum daily air temperature, T_{min}. For eight case study locations representing different climatic zones across a North-South transect in Europe, CCP was computed for present conditions (1961 - 1990) using measured T_{min} data from the *European Climate Assessment* (ECA) database. Possible future changes in CCP were assessed for the period 2071 - 2100 under the *Intergovernmental Panel on Climate Change* (IPCC) “A2” and “B2” scenarios for future emissions of greenhouse gases and aerosols defined in the Special Report on Emission Scenarios [17]. The “A2” storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than in other storylines. The “B2” story-line and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than “A2”, intermediate levels of economic development, and less rapid and more diverse technological change than in the “A1” and “B1” storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels. The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

The analysis of climate change impacts was based on 30 *Regional Climate Model* (RCM) data sets obtained from the European *PRUDENCE* project [18]. This project represents an attempt to integrate European climate projections of different institutions, and its website provides a large database of RCM simulation results for Europe. These were based on boundary conditions from 6 global simulations with two *Atmosphere-Ocean General Circulation Models* (AOGCM), Arpege/OPA and

ECHAM4/OPYC, plus three atmosphere-only *Global Climate Models* (GCM), ECHAM5, HadAM3H and HadAM3P that were driven with sea-surface temperature and sea-ice boundary conditions taken from simulations with the HadCM3 AOGCM. More information about the climate simulation models can be found on the PRUDENCE website.

For Zurich and Madrid Figure 2.7 shows significant changes in the percentage of nights per season when the daily cooling potential, CCP_d exceeds a certain value. For Zurich, under current climate conditions CCP_d is higher than 80 Kh (roughly necessary to discharge heat gains of 50 W/m^2, see section 2.2) throughout most of the year, except for about 10 % of summer nights. Under the "A2" scenario CCP_d was found to fall below 80 Kh in more than 50 % ("B2": 45 %) of summer nights.

For the studied locations in Southern Europe CCP_d values under present climatic conditions were found to be below 80 Kh throughout almost the entire summer, but a considerable cooling potential was revealed in the transition seasons. For the whole year the percentage of nights when CCP_d exceeds 80 Kh in Madrid was found to decrease from 70 % under present conditions to 52 % under "A2" conditions

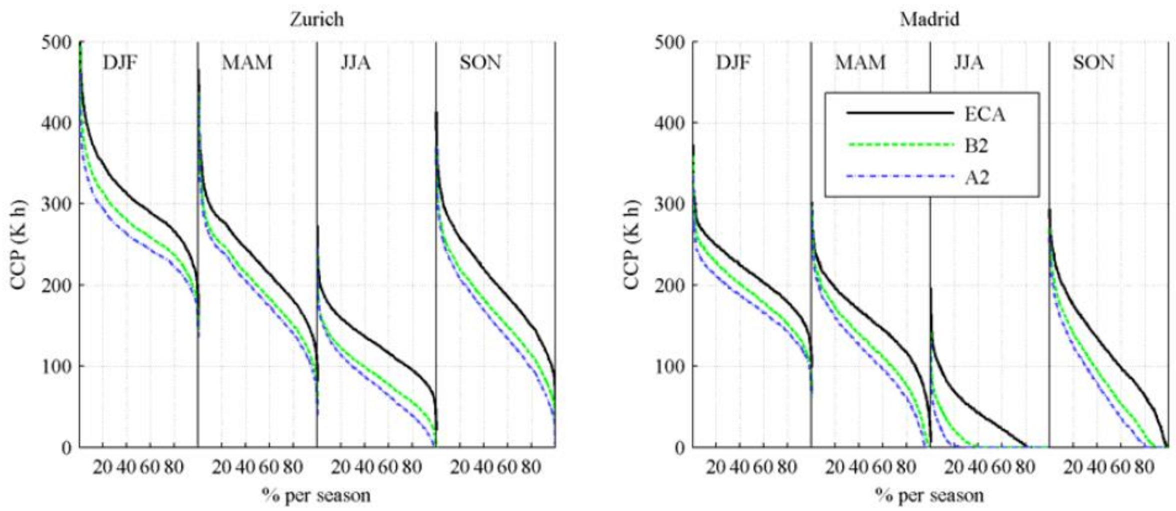


Figure 2.7. Seasonal cumulative distributions of CCP_d in Zurich (left) and Madrid (right) for current climate (ECA) and averages for forcing scenarios "A2" and "B2". [16].

Transient scenarios were based on upper and lower bounds for the change in global temperature as provided by [19] (their Figure 9.14, "several models, all SRES envelope"). These bounds accounted for a much broader range of radiative forcing scenarios and possible global temperature responses to a given forcing (climate sensitivities) than the PRUDENCE scenarios. However, it should be noted that these do still not account for the full range of possible future development.

Figure 2.8 shows a range of the possible development of the mean climatic cooling potential, CCP during the summer (June, July ,August) from 1990 to 2100 for three European locations. The lower limit indicates a rapid decrease in night cooling potential, especially after 2030. In the case of Madrid the slope of the lower limit tails out as it approaches zero. The upper limit shows a flatter slope and levels to a constant value at the end of the 21st century.

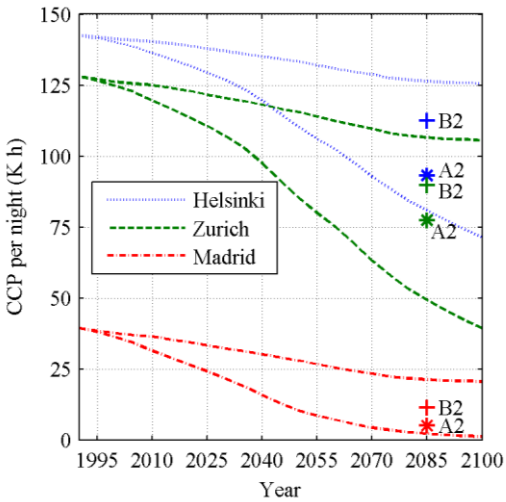


Figure 2.8. *Time-dependent change in mean climatic cooling potential during summer (JJA); upper and lower scenario based on mean global temperature scenarios ([19] Figure 9.14, "several models, all SRES envelope") and mean values of selected PRUDENCE models for "A2" and "B2".*

The decreases found in mean cooling potential have regionally varying implications. In Northern Europe the risk of thermal discomfort for buildings that use exclusively ventilative night cooling is expected to steadily increase up to possibly critical levels in the second half of the 21st century. In Central Europe extended periods with very low night cooling potential – where thermal comfort cannot be assured based on night-time ventilation only – could already become more frequent in the next few decades, if a strong warming scenario became real. For Southern Europe the potential for ventilative night cooling will sooner or later become negligible during summer and will decrease to critical levels in the transition seasons.

It should be noted that although cooling by night-time ventilation is expected to become increasingly ineffective during summer, it is likely to remain an attractive option in the transition seasons. This will be even more the case, if it is considered that under general warming the cooling season will tend to start earlier in spring and end later in autumn. In fact, the decreasing cooling potential and the simultaneously increasing cooling demand result in a shift of possible applications of night-time ventilation in Europe from South to North and from summer to the transition seasons.

Any assessment of possible changes in future climate is subject to large uncertainties. Nevertheless, the extent and rate of the expected climatic changes and the long service life of buildings imply the need for designing buildings capable of providing comfortable thermal conditions under more extreme climatic conditions.

2.2.2 Impact of urban environment (heat island and reduced natural driving forces)

The urban environment will have an impact on the ventilative cooling potential and also impose constraints for the use of natural driving forces. Urban environments have typically lower wind speeds, higher temperatures and higher noise and pollution levels [27].

In many cities the heat island effect with higher temperatures causes a decrease in the potential for ventilative cooling in the urban area compared to surrounding rural areas – where climate data usually originate. The CCP concept was applied to assess the implications of heat islands for night-time ventilative cooling [28]. A reduction in CCP during summer of about 9 % was found for London

Even larger effects were found for Adelaide, Australia (up to 26 %) and Sde Boqer, Israel (up to 61 %).

Measured temperatures in 10 street canyons in Athens are presented in [29]. Results showed that the temperatures during daytime were lower in the street canyons than outside, but too high for ventilative cooling, while the temperatures during nighttime, when ventilative cooling was possible, were higher in the street canyons than outside.[29] also presented measured wind speeds in street canyons and showed that these were considerably lower in the canyons than outside decreasing the natural driving forces for ventilation in the urban environment.

In order to evaluate the impact of the urban environment on the potential for application of night-time ventilative cooling a typical building zone was defined. The ventilative cooling was driven by natural forces, either in a single-sided ventilation case or in a cross ventilation case. The measured climatic data was used and the thermal behavior of the zone was simulated by combining a dynamic thermal simulation model and an air flow model. The simulated typical zone was considered as semi exposed to the external environment. The floor area of the zone was 36 m^2, while its volume was 144 m^3. The operation schedule of the zone was from 9:00 to 18:00. The set point temperature for the operation of the A/C system was equal to 27 ^oC, during the operation schedule of the zone. The application period of night ventilation was from 22:00 to 6:00.

Table 2.2 shows the average difference of the air flow rates for both ventilation strategies for the zone either located inside or outside the urban canyon. The differences are more important for cross ventilation, which is very dependent on wind speed and direction. The differences of ventilation air exchange rates are considerable and vary among the different canyons. For each case the difference depends on how the urban canyon modifies the temperature, the direction of the wind (sometimes the two directions are opposite) and at which degree the velocity of the wind is reduced inside the canyon.

Urban canyon	Single sided ventilation average difference of ACH	Cross-ventilation average difference of ACH
Ippokratous	0.2	12.6
Solonos	0.4	17.8
Kavalas	3.0	34.6
Papastratos	2.5	4.2
Valaoritou	2.2	34.9
Mavromihali	10.0	60.0
Kodrou	2.9	52.9
Giannitson	1.6	27.4
Omirou	2.6	69.3
Evrota	3.2	53.8

Table 2.2. Average difference of air flow rates during night ventilation. [28].

The zone is air-conditioned during daytime and table 2.3 shows the difference in cooling load for each location of the typical zone, for each urban canyon and for both the single-sided and cross ventilation case. The relative difference between the cooling load for a location inside and outside the urban canyon is also shown as well as the average indoor temperature difference during the night-time. It can be seen that effect of night-time ventilative cooling can be reduced considerably and the energy use for cooling easily increase with 25-50%.

Urban canyon	Cooling load inside the canyon (Wh/m^2)		Cooling load outside the canyon (Wh/m^2)		Relative difference of the cooling load (%)		Indoor temperature difference during the night (°C) In-out]	
	Single sided	Cross	Single sided	Cross	Single sided	Cross	Single sided	Cross
Ippokratous	4240	5330	3850	4320	9.2	19.0	0.6	1.4
Solonos	4660	5190	4120	4160	11.6	20.0	0.8	1.6
Kavalas	1390	1660	650	470	53.2	71.7	1.5	2.6
Papastratos	50	42	46	48	8.4	−17.6	1.4	1.6
Valaoritou	1070	1350	1130	1280	−5.6	5.0	0.0	0.4
Mavromihali	1500	1570	1200	1190	20.4	24.0	1.2	1.5
Kodrou	870	940	830	820	3.8	12.1	0.5	1.4
Giannitson	1030	1080	780	670	24.7	37.3	0.6	1.2
Omirou	22	84	2	48	88.8	42.9	1.4	1.9
Evrota	180	110	140	121	22.5	−9.7	1.2	1.5

Table 2.3. Cooling load and indoor temperature results under air-conditioned operation of the zone with single-sided and cross-ventilation. [29].

2.2.3 Outdoor Noise levels

Outdoor noise levels in the urban environment can be a major barrier for application of ventilative cooling by natural driving forces and methods for estimating noise levels in urban canyons is needed to assess the potential as well as to assess the risk that occupants will close windows to keep out noise but also compromise the ventilative cooling strategy. In urban canyons the noise level increases with traffic density and decreases with height above the street at the attenuation increases with distance to the source. The attenuation decreases with increasing street width. Based on these relationships and measurements performed in 9 different urban canyons in Athens [30] developed a simple model calculating the direct as well as the reverberant noise component at a certain height above the street level. Calibration of the model with measurements showed that the noise attenuation was almost entirely a function of the street width and the height above the street. Making the assumption that traffic level is a function of the street width the noise level becomes purely a function of the street geometry.

[30] Suggest that a tolerable noise level in European offices to be around 60 dB. At the same time the noise attenuation at an open window is accepted as 10– 15 dB. Thus an outdoor noise level of 70 dB or less is likely to be acceptable. Using special methods and window designs, a further 3– 5 dB attenuation is possible. Figure 2.12 shows the expected noise levels in Athens at different street widths and heights above the street and the implications of this for use of the natural ventilative cooling potential at different heights above street level according the above rules of thumb.

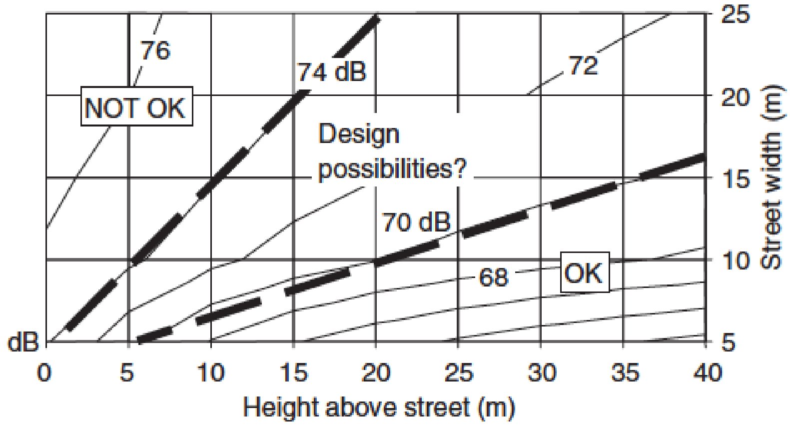


Figure 2.12. Contours of noise level at different heights above the street and street widths. Configurations in which natural ventilation is possible are indicated (OK), as are those in which it is ruled out (NOT OK). Between these two extremes is a region in which there are possibilities for design solutions. [30].

2.2.4 Outdoor air pollution

Key outdoor pollutions like NO_2, SO_2, CO_2 O_3 and suspended particulate matter PM are usually measured continuously in larger urban environments and are often considered as a major barrier for application of natural ventilative cooling.

The mean levels of SO_2 are equal outdoors and indoors, while NO_2 and O_3 reacts with the building materials resulting in a lower concentration indoors than outdoor for an airtight building. The transport of PM depends on the particle size. Estimation of the indoor/outdoor pollution ratio is the key to an assessment of the potential use of natural ventilative cooling in an urban environment.

[27] Reported the indoor/outdoor pollution ratio in nine school buildings with different facade permeability, see figure 2.13.

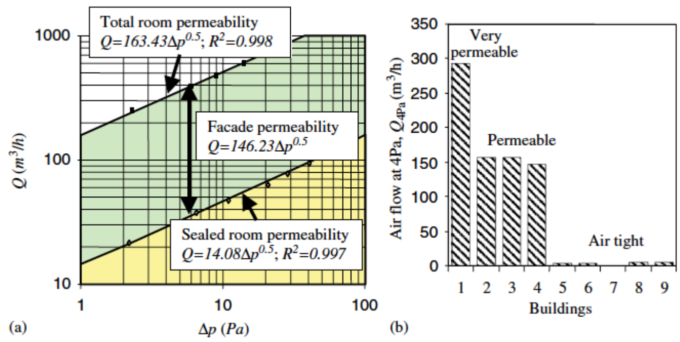


Figure 2.13. Building permeability for nine school buildings used in experiments on indoor/outdoor pollution ratio ([27], original data from [31]).

In the experiments the indoor/outdoor (I/O) pollution ratio were studied for ozone, nitrogen dioxide and 15 sizes of PM. The ratio of indoor/outdoor concentration was found to be a function of airflow through the façade (façade airtightness) and of the outdoor concentration. The indoor concentration was smaller inside than outside. Ozone presented the lowest I/O ratio (0.1–0.4), with higher I/O ratios measured for higher outdoor ozone concentration. The I/O ratio for nitrogen dioxide was between approximately 0 and 0.95 with lower values for higher outdoor concentration. The I/O ratio for PM depended on the particle size. The most important variation (0.25–0.70) was measured for particles of small size (0.3–0.4 mm); particles of larger size (0.8–3 mm) represented lower, but comparable, variation of the I/O ratio (0.3–0.7).

2.3 A review of Indices for long-term evaluation of the general thermal comfort conditions in buildings

The following review is adapted from Carlucci and Pagliano [38].

2.3.1 Description of the indices for long-term evaluation of general thermal discomfort

In case of a multi-zone building, EN 15251 is not univocal: (i) in the Section "8.3 Calculated indicators of indoor environment" states that: "the building meets the criteria of a specific category if the rooms representing 95% of building volume meet the criteria of the selected category"[39], whilst (ii) in the Annex I at the Section "I.2 Whole year computer simulations of the indoor environment and energy performance" it states: "It is then calculated how the temperatures are distributed between the 4 categories. This is done by a floor area weighted average for 95% of the building spaces" [39]. Therefore it indicates to weight for the building volume (it is also not explicitly specified that it is the net volume), but is uses in the Annex I the floor area; of course, the two coincides if the height inside each zone of the building is constant. On the contrary, ISO 7730 does not specify how to calculate long-term evaluation indices in multi-zone buildings.

Since the exceedance of the comfort limits at a given outdoor air temperature is a distribution rather than a single value (i.e. the building performs differently in different spaces even in correspondence to the same value of outdoor air temperature), [41], assuming that such exceedance is normally distributed over all the zones of a building, recommend to use the floor area weighted average for 84% of the building spaces, for those zones where the room operative temperature remains within the specified comfort ranges.

2.3.2 Percentage indices

According to this family of indices, comfort performance of a building is assessed by calculating the percentage of likely discomfort hours with respect to the total number of occupied hours. They differ in that some use a comfort model, others only a reference temperature as a proxy for describing thermal comfort condition.

2.3.2.1 Percentage Outside the Range

Percentage outside the Range method (*POR*) was at first, introduced by ISO 7730 and then re-proposed by EN 15251. It requires to calculate the number or the percentage of hours of occupation (*Oh*) when the — actual or simulated — *PMV* or indoor operative temperature are outside a specified comfort range related to the chosen comfort category.

$$POR \equiv \frac{\sum_{i=1}^{Oh} wf_i \cdot h_i}{\sum_{i=1}^{Oh} h_i} \in [0;1] \quad (2.19)$$

It is, thus, applicable both to Fanger and to adaptive comfort models. When referring to the Fanger model, comfort range is expressed in terms of *PMV*. In this case, the index can be indicated with $POR_{Fanger,PMV}$ and:

$$\mathrm{POR}_{\mathrm{Fanger,\,PMV}} = f\left(wf_i\right): \begin{cases} \mathrm{wf}_i = 1 \Leftarrow \left(\mathrm{PMV} < \mathrm{PMV}_{\mathrm{lower\ limit}}\right) \vee \left(\mathrm{PMV} > \mathrm{PMV}_{\mathrm{upper\ limit}}\right) \\ \mathrm{wf}_i = 0 \Leftarrow \left(\mathrm{PMV}_{\mathrm{lower\ limit}} \leq \mathrm{PMV} \leq \mathrm{PMV}_{\mathrm{upper\ limit}}\right) \end{cases} \quad (2.20)$$

Moreover, the *PMV* boundaries of a selected category can be translated into operative temperature by making assumptions about clothing, metabolic rate, air speed, relative humidity and the relationship between indoor dry-bulb air and mean radiant temperatures. This however, results in a relevant level of uncertainty; ISO 7730 reports it in Appendix E and EN 15251 in Table A.3. In this case the index can be indicated with $POR_{Fanger,\theta op}$ and:

$$\mathrm{POR}_{\mathrm{Fanger},\,\theta\mathrm{op}} = f\left(\mathrm{wf}_i\right): \begin{cases} \mathrm{wf}_i = 1 \Leftarrow \left(\theta_{\mathrm{op,\,actual\ PMV}} < \theta_{\mathrm{op,\,lower\ PMV\ limit}}\right) \vee \left(\theta_{\mathrm{op,\,actual\ PMV}} > \theta_{\mathrm{op,\,upper\ PMV\ limit}}\right) \\ \mathrm{wf}_i = 0 \Leftarrow \left(\theta_{\mathrm{op,\,lower\ PMV\ limit}} \leq \theta_{\mathrm{op,\,actual\ PMV}} \leq \theta_{\mathrm{op,\,upper\ PMV\ limit}}\right) \end{cases} \quad (2.21)$$

When referring to the adaptive model, the comfort range is expressed in terms of operative temperatures.

According to the definition, this index is comfort-based and category-dependent, so it will consider both upper and lower exceedances from the boundaries, it is a symmetric index. Moreover, it can be theoretically applied to summer and winter. It is also possible to define an upper threshold in terms of discomfort hours, as suggested by the EN 15251:"*The parameter in the rooms representing 95% of the occupied space is not more than as example 3% (or 5%) of occupied hours a day, a week, a month and a year outside the limits of the specified category*"[2] [39].

The percentage of hours outside a certain comfort range is a straightforward and simple method to compare the comfort performance of different buildings in different climates. On the other hand, it does not give information about the severity of the uncomfortable conditions and it introduces a discontinuity at the boundaries of the category, which has no correspondence with physics and physiology.

2.3.2.2 Percentage of occupied hours above a reference temperature

Chartered Institution of Building Services Engineers (*CIBSE*) proposed two design overheating criteria to be used when performing building simulation using the Design Summer Year (*DSY*). The first one, called here $CIBSE_J$, requests that the dry resultant temperature should not exceed 25°C for more than 5% of the occupied time [41]. The second one, called here $CIBSE_A$, requests that the dry resultant temperature should not exceed 28°C - or 26°C for bedrooms - for more than 1% of occupied hours in naturally ventilated buildings [42].

The two indices are only used for assessing overheating likelihood, thus they are asymmetric indices. They are not related to comfort models and do not depend on comfort categories.

[2] Citation from the EN 15251:2007; p46.

[43] presents some identified problems in using a fixed threshold temperature and a simple exceedance criterion in free-running buildings: (i) in this type of buildings field surveys show that comfort temperature varies with the outdoor dry-bulb temperature (in the form of running-mean or monthly mean) and it is not a fixed value, (ii) indices based only on the hours of exceedance provide only the occurrence of overheating, but not its severity, (iii) methods based on a threshold temperature are sensitive to the assessment method for indoor temperatures.

2.3.3 Cumulative indices

According to this family of indexes, discomfort is the result of accumulation of thermal stress during the occupied period. They are not expressed as percentages. They differ from each other in using or not a comfort model and how they assess the weight of the hourly thermal stress.

2.3.3.1 PPD-weighted Criterion

PPD-weighted Criterion (*PPDwC*) is only proposed for the Fanger comfort model and assumes that time during which PMV exceeds the comfort boundaries is weighted with a weighting factor, wf_i. Then, the index is calculated by the summation hour by hour of the products of wf_i per time.

$$PPDwC \equiv \sum_{i=1}^{Oh} wf_i \cdot h_i \in [0;+\infty[$$

(2.22)

The assessment for warm and cold periods is separated:

$$\begin{cases} PPDwC_{warm\ period} = f(PPD) \Leftrightarrow (PMV > PMV_{upper\ limit}) \\ PPDwC_{cold\ period} = f(PPD) \Leftrightarrow (PMV < PMV_{lower\ limit}) \end{cases} \qquad (2.23)$$

Where $PMV_{lower\ limit}$ and $PMV_{upper\ limit}$ are respectively the lower and upper limits of a specified comfort range (see Table 2). The calculation of the wf_i is different in EN 15251 and ISO 7730, however the sole difference between the two versions is that ISO 7730 increases the value of the discomfort index even if the *PMV* is equal to the boundary value of *PMV*. The distinction would disappear if one would consider the uncertainty with which *PMV* can be estimated, based on the uncertainty, which affects each of the input parameters. It is in fact a good opportunity to underline here that *PMV* estimate is indeed affected by uncertainty as any other quantity, which is measured or derived from measurements [44].

An interesting feature of this index (in both versions) is that it takes into account the predicted percentage of dissatisfied (PPD) and the long-term evaluation of general discomfort conditions is calculated as the hourly accumulation of the estimated percentage of dissatisfied. The limits of this method in both formulations are: (i) it cannot be applied for characterizing free-running buildings, (ii) it does consider the effect of overcooling during summer and overheating during winter,(iii) it cannot be plotted on a fixed scale and (iv) it strongly depends on the category boundaries, which are subject to a certain debate in the scientific literature [44], [45].

2.3.3.2 Accumulated PPD

Accumulated *PPD* (*SumPPD*) consists in the summation of all the *PPDs* during occupied hours. It was introduced by ISO 7730 and proposed for the sole Fanger model. It does not depend from comfort categories and it is a symmetric index. Since it is a simple summation of percentages over time, with a time step of one hour, it has the unit of measure of a percentage, but it varies from zero to plus infinity.

$$Sum\_PPD \equiv \sum_{i=1}^{Oh} PPD_i \in [0;+\infty[\qquad (2.24)$$

Even if it uses the predicted percentage of dissatisfied, (i) it is not able to allow a comparison of the severity of possible thermal conditions inside a building: the same value can be reached in case of few hours with high *PPD* or in case of a larger number of hours with lower predicted discomfort conditions. Other limits are: (ii) it can only be applied with the Fanger comfort model, (iii) it cannot be plotted on a fixed scale, for example the comfort footprint, and (iv) it is difficult to define the rules for assigning comfort categories.

2.3.3.3 Degree-hours Criterion

Degree-hours Criterion (*DhC*) was introduced by ISO 7730 and was subsequently included with some modifications in EN 15251. According to it, time during which actual operative temperature exceeds the specified comfort range during occupied hours is weighted by a factor that depends by the module of the difference between actual or calculated operative temperature, θ_{op}, at a certain hour, and the lower or upper limit, $\theta_{op,limit}$, of a specified comfort range. If comfort range is specified in terms of *PMV*, the limits have to be translated into operative temperature by making assumptions on clothing, metabolic activity, air velocity, relative humidity and the relationship between air and mean radiant temperatures.

The weighting factor *wf* has two different formulations according to the two standards:

$$wf_i\Big|_{Fanger}^{ISO\ 7730} \equiv 1 + \frac{\left|\theta_{op,i} - \theta_{op,\mathrm{limit}}\right|}{\left|\theta_{op,comfort} - \theta_{op,\mathrm{limit}}\right|} \qquad (2.25)$$

$$wf_i\Big|_{Fanger}^{EN\ 15251} \equiv \left|\theta_{op,i} - \theta_{op,\mathrm{limit}}\right| \qquad (2.26)$$

The last formulation can be easily extended also to the adaptive comfort model.

$$wf_i\Big|_{Adaptive}^{EN\ 15251} \equiv \left|\theta_{op,i} - \theta_{op,\mathrm{limit}}\right| \qquad (2.27)$$

For a characteristic period (year, season, …), the index is calculated summing the products of weighting factor and time (in time steps of an hour).

$$DhC \equiv \sum_{i=1}^{Oh} wf_i \cdot h_i \in [0;+\infty[\qquad (2.28)$$

For both the standards during the warm period (summer, according to EN 15251), the summation is extended exclusively to those occupied hours when $\theta_{op,i} > \theta_{op,upper\ limit}$. Similarly during the cold period (winter, according to EN 15251), the summation is extended only to those occupied hours when $\theta_{op,i} < \theta_{op,\text{upper limit}}$; thus, both the standards are asymmetrical when proposing the *DhC*.

$$DhC_{warm\ \ period} = f\left(wf_i\right): \begin{cases} wf_i > 0 \Leftarrow \left(\theta_{op,i} > \theta_{op,\text{upper limit}}\right) \\ wf_i = 0 \Leftarrow \left(\theta_{op,i} \le \theta_{op,\text{upper limit}}\right) \end{cases} \tag{2.29}$$

$$DhC_{cold\ \ period} = f\left(wf_i\right): \begin{cases} wf_i > 0 \Leftarrow \left(\theta_{op,i} < \theta_{op,\text{lower limit}}\right) \\ wf_i = 0 \Leftarrow \left(\theta_{op,i} \ge \theta_{op,\text{lower limit}}\right) \end{cases} \tag{2.30}$$

This index is based on comfort models and is also category-dependent. A limit of this index is that (i) it cannot be plotted on an absolute scale and (ii) it is not normalized to the total number of occupied hours: the comparison of buildings characterized by different number of occupation hours can be misunderstood. (iii) As all the indices based on categories, it introduces a discontinuity at the boundaries of the category which has no correspondence with physics and physiology.

2.3.3.4 Exceedance$_M$

This index was proposed in [46]. It predicts discomfort summing over summer occupied hours (*Oh*) when indoor operative temperature is higher than the reference given by the upper limit of the 80% acceptability range, each hour being weighted on the number of occupants in that hour. This sum is then divided by a summation over the number of occupants in the various hours.

$$Exceedance_M \equiv \frac{\sum_{i=1}^{Oh} n_i \cdot B_i}{\sum_{i=1}^{Oh} n_i} \in [0;1]$$

(2.31)

$$Exceedance_M = f\left(B_i\right): \begin{cases} B_i = 1 \Leftarrow \left(Acceptability < 80\%\right) \\ B_i = 0 \Leftarrow \left(Acceptability \ge 80\%\right) \end{cases} \tag{2.32}$$

Where n_i is the number of occupants inside a given thermal zone at a certain hour *i*.

The *Exceedance$_M$* can be calculated using both the Fanger (and the index is called *Exceedance$_{PPD}$*) and the ASHRAE adaptive (and the index is called *Exceedance$_{Adaptive}$*) comfort models. It is an asymmetric index based on a comfort model and it depends on category. It has been proposed only for the summer assessment against overheating.

The *Exceedance$_M$* is the only index among the ones reviewed that is calculated using the occupation rate. This seems an interesting feature that aims at overcoming the hard cut-off due to the occupancy binary code: 0 for an unoccupied hour and 1 for an occupied hour and might be useful to incorporate in other indices. On the other side, the hard cut-off at 80% acceptability can cause an anomalous evaluation if consecutive values are just little up or down of the specified threshold. Moreover, this index does not take into account the severity of the thermal exceedance.

2.3.4 Risk indices

Such indices measure human thermal perception of the thermal environment to which an individual or a group of people is exposed, using a nonlinear relationship between perception of discomfort and the exceedance from a comfort temperature.

2.3.4.1 Nicol et al.'s overheating risk

Nicol et al.'verheating risk (*NaOR*) was introduced in [43] and proposes that thermal discomfort is not related to a specified temperature threshold, but to the difference ΔT between the actual operative temperature and the EN adaptive comfort temperature. It was derived from the analysis of comfort questionnaires collected in European naturally ventilated office buildings during the SCATs Project [47] and takes into account that some people may feel uncomfortable even at the theoretical comfort temperature.

The index is derived from the offsets from theoretical comfort temperature for each hour in a specified period, and shows the nonlinear relationship between thermal discomfort and the exceedance from the theoretical comfort temperature [48]. The index predicts the percentage of individuals, $P(\Delta T)$, voting +2 or +3, respectively *warm* or *hot*, on the ASHRAE thermal comfort scale:

$$P(\Delta T) \equiv \frac{\exp(0{,}4734 \cdot \Delta\theta - 2{,}607)}{1 + \exp(0{,}4734 \cdot \Delta\theta - 2{,}607)} \in [0{,}069;1] \qquad (2.33)$$

NaOR was derived from the EN 15251 adaptive comfort model and it is not related to comfort categories. It is an asymmetric index which aims at predicting overheating phenomena and cannot be applied in mechanically cooled buildings.

2.3.4.2 Robinson and Haldi's overheating risk

Robinson and Haldi's overheating risk (RHOR), proposed in [49], is based on the assumption that charging and discharging of human tolerance to overheating may be modelled with the charge and discharge of an electrical capacitor. This is an analytical model that requires two coefficients (a time constant for charging 'α' and a time constant for discharging 'β') that must be tuned empirically in relation to a specific situation. This index refers to satisfaction with accumulated overheating *stimuli* instead of instantaneous satisfaction. According to this model, the heat *stimuli* are related to the exceedance of a reference temperature of 25°C and it can be calculated with the equations:

$$P_{OH}(t_n) \equiv 1 - \exp\left(-\alpha \sum_{i=1}^{n} Dh_{t_0,t_i}\right)\left(1 - P_{OH}(t_0)\right) \in [0;1] \qquad \text{for charging}$$

$$P_{OH}(t_n) \equiv \exp\left(-\beta \sum_{i=1}^{n} Dh^{*}_{t_0,t_i}\right) P_{OH}(t_0) \in [0;1] \qquad \text{for discharging} \qquad (2.34)$$

Where $P_{OH}(t_n)$ is the probability of overheating at time n, $P_{OH}(t_0)$ is the probability of overheating at the time of transition from charging to discharging, Dh are the number of the degree-hours above the reference temperature (25°C) during the calculation period and Dh^* are the number of the degree-hours below the reference temperature (25°C) during the calculation period. The model is based on the hypothesis that occupants are tolerant of occasional offsets from comfort conditions and that the discomfort due to overheating derives from an accumulation of heat stress events rather than a single event. The authors suggest a threshold for the probability of overheating of 20%, since: *"current thermal comfort standards target a PPD of ≤20%"* [49].

However, the model: (i) is for continuous period and not just for occupied hours, (ii) uses only the indoor dry-bulb air temperature and it does not take into account the mean radiant temperature of the room, clothing and activity adaptation or occupants' ability to control the indoor environment, (iii) has also been calibrated only for a temperate climate, (iv) is based on a reference temperature of 25°C which was chosen without a justification based on existing comfort models or independent observations and (v) the time constants for charging and discharging need a big number of observations to be tuned (the value for the constant 'β' was just assumed and not derived from measurements).

2.3.5 Averaging indices

Such indices are calculated averaging or the indoor *PPD*, or the outdoor air temperature during a specified period.

2.3.5.1 Average PPD

Introduced by ISO 7730 and not included in EN 15251, *Average PPD* (*<PPD>*) consists in calculating the mean *PPD* over the occupied hours. It is an index based on a comfort model, but it does not depend on comfort categories. In the way it is defined it is a symmetric index.

Its most important feature is that it takes into account the actual discomfort stress assessed through the PPD, according to the Fanger comfort model, without introducing a discontinuity as the indexes based on comfort categories. It can be used for comfort optimization procedures and for comparing the thermal comfort performance of different buildings. However, since it relies only on the Fanger model, it would not respond to the needs of designers/researchers willing to design/evaluate a naturally ventilated building by using the adaptive model.

2.3.5.2 Difference between peak temperature and annual average temperature

It is the simplest index among the ones proposed. It measures the maximum temperature difference between the indoor summer operative temperature and the annual average outdoor dry-bulb temperature. It relates the highest temperature recorded inside a building with the annual average climate.

It does not consider the frequency and the severity of overheating events inside a building and the actual thermal stress perceived by occupants, hence it seems to deliver too little information for most design and evaluation objectives.

2.3.6 Long-term Percentage of Dissatisfied and ASHRAE Likelihood of Dissatisfied

In order to base design choices on existing thermal comfort models, Carlucci [50] developed a optimization procedure called *Long-term Percentage of Dissatisfied* (*LPD*), which quantifies predicted long-term thermal discomfort by a weighted average of discomfort over the thermal zones of a given building and over time of a given calculation period:

$$LPD(LD) \equiv \frac{\sum_{t=1}^{T}\sum_{z=1}^{Z}\left(p_{z,t} \cdot LD_{z,t} \cdot h_t\right)}{\sum_{t=1}^{T}\sum_{z=1}^{Z}\left(p_{z,t} \cdot h_t\right)} \qquad (2.35)$$

Where t is the counter for the time step of the calculation period, T is the last progressive time step of the calculation period, z is the counter for the zones of a building, Z is the total number of the zones, $p_{z,t}$ is the zone occupation rate at a certain time step, $LD_{z,t}$ is the *Likelihood of Dissatisfied* inside a certain zone at a certain time step and h_t is the duration of a calculation time step (e.g. one hour).

The *Likelihood of Dissatisfied*, *LD*, is an analytical function that estimates *"the severity of the deviations from a theoretical thermal comfort objective, given certain outdoor and indoor conditions at specified time and space location"* [50]. Since the theoretical thermal comfort objective depends on the reference comfort model, the equation used in combination with the EN adaptive model is the so-called *Overheating Risk* [51]

$$LD_{Adaptive}^{EN} = \frac{e^{0.4734 \cdot \Delta\theta_{op} - 2.607}}{1 + e^{0.4734 \cdot \Delta\theta_{op} - 2.607}} \qquad (2.36)$$

Where $\Delta\theta_{op}$ is the absolute value of the difference between the indoor operative temperature and the optimal comfort temperature calculated accordingly to the European adaptive model.

The equation used in combination with the ASHRAE adaptive model is the so-called *ASHRAE Likelihood of Dissatisfied* (*ALD*) [50]

$$LD_{Adaptive}^{ASHRAE} = ALD = \frac{e^{0.008 \cdot \Delta\theta_{op}^2 + 0.406 \cdot \Delta\theta_{op} - 3.050}}{1 + e^{0.008 \cdot \Delta\theta_{op}^2 + 0.406 \cdot \Delta\theta_{op} - 3.050}} \qquad (2.37)$$

Where $\Delta\theta_{op}$ is the absolute value of the difference between the indoor operative temperature and the optimal comfort temperature calculated accordingly to the ASHRAE adaptive model. It is a continuous function obtained by the authors *via* the statistical analysis of the comfort surveys in the ASHRAE RP-884 database [52].

On the other hand, the analytical model used for the Fanger model is *PPD*, which is directly computable from *PMV,* using the equation (in [53])

$$LD_{Fanger} = PPD = 100 - 95^{-0.03353 PMV^4 - 0.2179 PMV^2} \qquad (2.38)$$

The *LPD* is calculated for both summer and winter, and it is used for optimizing the building in free-floating mode and in mechanically conditioned mode. According to [50](Carlucci 2013) the *LPD* in the ASHRAE adaptive version and in the Fanger version have a similar ranking capability of indoor thermal discomfort. Therefore, such two versions of the *LPD* are used to construct the objective functions needed for the proposed two-step optimization procedure.

2.3.7 Conclusions

Since the indices for long-term evaluation of general thermal comfort conditions in buildings are mainly single values — being a single numerical value summarizing the variety of comfort conditions encountered in a building over a certain period of time — they cannot provide a substitute for a detailed design of a building, rather they can guide its optimization. Any of them might be used in the design phase to drive an optimization process. But care should be taken in the choice among them and in the actual way to use them in the process. To obtain a reliable result which can be clearly interpreted, all the boundary conditions which affect their calculation should to be made explicit; moreover, if they are used for comparing the thermal comfort performance of different buildings or building variants, they also require that the boundary conditions must be harmonized among buildings/variants (e.g. as codified in a standard). But for example both the standards ISO 7730 and EN 15251 do not clarify when warm or cold periods start and their duration or a methodology to define them. This is an important limit of both the standards, since long-term evaluation indices vary considerably in consequence of variations of the calculation period. Nicol wrote: *"Merely increasing the hours of occupation may 'solve' an overheating problem, which is clearly unrealistic"* [43].

Moreover a harmonized common method for calculating the overall index for a multi-zone building should be included in the standards. EN 15251 suggests to calculate the indices in 95% (or 97%) of the space and to weight the indices calculated for each zone for the respective air volume. This approach could have the advantage of being simple, but the objective of long-term evaluation indices is to estimate the likelihood that uncomfortable conditions can be perceived by the occupants of a building. According to this, a possibility is to weight discomfort index of each zone for the respective rate of occupation (following the example of the $Exceedance_M$). This could also overcome the hard cut-off due to the occupancy binary code (0 for an unoccupied hour and 1 for an occupied hour) that characterizes some of the indices (*e.g.* percentage and cumulative indices).

Clearer and more precise rules for zoning of large or complex buildings are essential if long-term evaluation discomfort indices have to be used for assessing thermal comfort conditions in existing buildings or as guidance for design. On this issue also, agreed guidelines for zoning have to be proposed and hopefully included in a standard.

The indices based on the comfort categories suffer for the difference of the category definition in ASHRAE and EN standards. Some authors have discussed limitations of the current formulation of the comfort categories: (i) [45] based on their analysis argue that the range proposed by EN 15251 for the Category I (and for the Category A of ISO 7730) is too narrow to be detected by the occupants of a building and (ii) using Alfano et al.'s words: *"the PMV range required by A-category can be practically equal to the error due to the measurements accuracy and/or the estimation of parameters affecting the index itself"* [44] and the same ISO 7730 admits an objective difficulty in measuring the input parameters due to the accuracy of instrumentation for the verification that *PMV* conforms to Category A requirement and the standard suggests to refer to equivalent operative temperature ranges; however, this means that the uncertainties on all the other variables beside air and mean radiant temperatures (or globe-thermometer temperature) are not taken into account [54].

The issue of uncertainty in the uncertainty affecting *e.g.* the evaluation of the *PMV* estimate due to the errors of measurement of the physical variables and the errors in estimating the personal variables (clo and met) has also an implication on how sharp can be the change of the weighting factors in correspondence of the boundaries of the categories.

Every calculation rule like based on the comparison between the actual value and the boundary values of a certain comfort category either expressed in term of *PMV* seems to require a discussion about the precision by which *PMV* can be assessed/calculated. In response to this and other problems, Nicol and Wilson [55] propose to relate the selection of the comfort category exclusively with the expectations of the occupants.

The indices based on the percentage of time outside the comfort range, (i) suffer for the step function that determines when a likely condition of discomfort occurs, which implies an abrupt change in comfort perception not corresponding to reality; (ii) they measure the frequency of overheating, but do not take into account its severity.

As for the indices based on a fixed reference temperature, they have to be used carefully, since, even if the reference temperature is associable to a theoretical comfort temperature, *e.g.* derivable from the Fanger comfort model according to specified assumptions, they may be reliably used for only assessing comfort in mechanically conditioned building and only if such assumptions are valid. For example in naturally ventilated buildings, where (according to the adaptive model or using the Fanger model and taking into account changes in clothing and possibly metabolism correlated with season) summer theoretical comfort temperature varies with the outdoor dry-bulb temperature (monthly average or running-mean), a fixed overheating threshold might not be reliable for estimating the likelihood of discomfort.

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3 Ventilative cooling in existing Energy Performance Regulations

3.1 Introduction

This chapter presents the results of several questionnaires about ventilative cooling in national standards of the Annex 62 countries. Significant work has already been done to embed the effects of ventilative cooling accurately in the energy performance regulations, but there are still aspects that need further research and clarifications before ventilative cooling is easily implemented in the national standards.

3.2 Survey Method

Three questionnaires were sent out to the country representatives. The first questionnaire is about ventilative cooling aspects in the Building Code, the second about ventilative cooling aspects in the National Energy Demand calculation, the thirdthrough the venticool platform, is an online questionnaire for architects and advisors on implementing ventilative cooling in current building regulations.

Residential and non-residential buildings are treated separately as several countries differentiate in their regulations between residential and non-residential buildings.

3.2.1 Questionnaire Ventilative cooling aspects in the Building Code

For this questionnaire, aspects influencing ventilative cooling are identified in the national Building code. The main aspects are determined through discussions within the Annex 62 meeting in Lausanne (April 2014) and collaboration with the Venticool international platform on ventilative cooling.

The aspects identified are:

- Energy consumption for cooling
- Building parameters influencing ventilative cooling
- Ventilation requirements, both ventilation volume and ventilation openings and positions
- Safety
- Temperature, Air velocity and Humidity requirements

These aspects constitute of both advantages and disadvantages of ventilative cooling. It is always possible that there are more aspects in the National Building Codes that influence the application of ventilative cooling, but it is expected that these are the main aspects that influence the application of ventilative cooling in most countries. By identifying the aspects, future research should then identify the impact of these aspects on the application of ventilative cooling. If necessary thenchanges to existing Building Codes can be proposed based on this future research.

3.2.2 Questionnaire Ventilative cooling aspects in National Energy Demand calculation.

If the energy demand for cooling is required in the national building code, it should be possible to include ventilative cooling. This second questionnaire identifies which aspects of ventilative cooling are integrated in national energy demand calculations.

The aspects identified are:

- Energy needs (net energy balance) at “room level”, separated into

  - hygienic ventilation system
  - intensive ventilation system
- Energy needs of air handling unit
- Energy use of emission, distribution and storage system
- Delivered energy (“cold source” or “heat dump”)
- Auxiliary and parasitic consumption

3.2.3 Questionnaire Ventilative cooling aspects in Venticool international platform on ventilative cooling.

Ventilative cooling has two, related, objectives: to reduce the indoor temperatures by ventilation and to reduce the energy demand for cooling by ventilation.

To acknowledge the advantages of ventilative cooling in building regulations, it is necessary to look at different parts of the national building regulations:

- the regulations on indoor thermal comfort
- the regulations on maximum energy demand
- building regulations influencing the practical application of ventilative cooling (such as maximum window size, burglary prevention, etc.)

The results of this questionnaire are not presented in this report. However, questionnaire responses have been collected from European country participants and will be presented in a separate paper.

3.3 Survey results

3.3.1 Building Code

3.3.1.1 Residential

3.3.1.1.1 Energy consumption for cooling

	Italy	NL	UK	DK	Ireland	China	Norway	Japan	CH	Belgium	USA Cal.
Is energy consumption for cooling considered?	No	Yes	Yes	Yes	No	No	No[3]	Yes	Yes	Yes	Yes
Is energy consumption for cooling considered separately?	No	No	Yes	No	No	No	No	Yes	Yes[4]	No	No
Is auxiliary and parasitic consumption from mechanical ventilation considered separately?	No	No	Yes	No (1)	Yes	No	No	Yes	--	No	No[5]
Is the energy consumption for (de-) humidifying considered separately?	No	No	Yes	No	No	No	No	No	Yes	No	?

Countries in the European Union are required to implement the Energy Performance of Buildings Directive (EPBD). The countries in this Annex 62 that are part of the European Union are: Austria, Denmark, Finland, France, Greece, Ireland, Italy, The Netherlands and the UK. However, for some countries within the European Union, such as Italy, national implementation is expected but not yet realised. And even if an energy performance is required, energy demand for cooling is not necessarily considered. This leads to the unwanted situation that a calculation of energy demand for cooling is not required for all countries, thus rendering the energy benefit of ventilative cooling invisible in national regulations.

In the USA every state has its own regulations. Arizona does not have a building code, Alabama, Massachusetts and California do have a Building Energy Code. In this report only the California building codes are discussed in detail. Compared to the European codes, the California building code has no fixed value for the energy demand, or equivalent coefficient, for a building, but a comparison to an energy calculation of a standard building which is described in the code is necessary. The California building code specifies: “A building complies with the performance standard if the energy

[3] Although energy demand for cooling is not explicitly mentioned in the Building Code, it is included in the total energy budget or energy measures required in the Building code.

[4] Electricity is separated from heat and hot water consumption. Cooling is part of electricity (1. lighting, 2. ventilation, 3. cooling, 4. auxiliary installations)

[5] But taken into account in the entire calculation

budget calculated for the proposed design ... building is no greater than the energy budget calculated for the standard design building...."

Massachusetts	International Energy Conservation Code 2009 (IECC 2009)
Alabama	2009 International Building Code ANSI/ASHRAE/IESNA Standard 90.1-2007 Energy Standard for Buildings Except Low-Rise Residential
Arizona	No building energy code!
California	https://law.resource.org/pub/us/code/bsc.ca.gov/

For several countries, The Netherland, Belgium, Denmark, and Norway, the energy performance certificate requires a total energy demand calculation over a year, not separated in heating and cooling. If energy demand for cooling is not considered separately, the energy demand for cooling can be compensated by other means (reduced heating, sustainable energy production) diminishing the usefulness of ventilative cooling in the regulations.

Several countries include the energy demand from mechanical ventilation and de-humidification in the energy demand calculation. These aspects have an influence on ventilative cooling by influencing the choice for mechanical or natural ventilation if auxiliary and parasitic consumption from mechanical ventilation is considered separately. If de-humidification is considered, this might pose extra demands on the type of ventilative cooling that can be installed, being with or without de-humidification.

In Switzerland active cooling is part of electricity in the regulations. That means that if you want to apply active cooling, it poses limits on lighting, ventilation and the use of auxiliary installations. However, ventilative cooling may reduce cooling needs in Switzerland up to zero according to dynamic calculations ISO 15 591.

3.3.1.1.2 Building parameters influencing ventilative cooling

Requirements on	Italy	NL	UK	DK	Ireland	China	Norway	Japan	CH	Belgium	USA Cal.
window size	No	No[6]	Yes	Yes	No	Yes	indirect	Yes	Yes[7]	No	Yes
window size per orientation	No	No	No	No	No	Yes	indirect	Yes	No[8]	No	Yes
solar shading	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes[9]	No	Yes
solar shading per orientation	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No	Yes
thermal mass	Yes	No	No	No	No	No	No	No	Yes[10]	No	[11]
thermal mass per orientation	No	No	No	No	No	No	No	No	No	No	

A minimum or maximum window size might limit the amount of ventilative cooling through operable windows. The different countries have different reasons to pose limits on window size, solar shading and thermal mass, the main reasons being maximum temperatures, e.g. China, or minimal daylight access, e.g. the Netherlands or maximum solar irradiation e.g. California and Switzerland.

Too high temperatures and too high demands on ventilative cooling can be caused by a combination of no regulations for maximum solar shading in combination with no energy demand for cooling. On the other hand, only ventilative cooling might be able to reduce the energy demand and indoor thermal comfort if there is no solar shading applied.

Thermal mass influences the usability of ventilative cooling by influencing the time the maximum temperatures in buildings are reached. Only Italy and Switzerland pose restrictions on the thermal mass of a residential building.

If the effects of ventilative cooling on the energy demand and on the indoor temperatures are to be correctly taken into account in the regulations, window size, solar shading and thermal mass should be taken into account as well.

[6] only for daylight access

[7] 5% of floor area

[8] This is not in the Energy code but in the norm for protection from overheating

[9] 0.1 or see graph in appendix.

[10] 45 Wh/m2K according to EN 13786

[11] Not found by Regina Bokel

3.3.1.1.3 Ventilation

	Italy	NL	UK	DK	Ireland	China	Norway	Japan	CH	Belgium	USA Cal.
Does the hygienic ventilation system require minimum air flow rates?	Yes [12]	Yes	Yes [13]	Yes	Yes [14]	Yes	Yes	Yes	Yes[15]	Yes[16]	Yes [17]
Does the hygienic ventilation system require maximum air flow rates?	No	Yes	No	No	No	No	No	No	Indirect[18]	No	No
Does the hygienic ventilation system require different air flow rates in summer and winter?	No	No	No	No	No	No	No	No	Yes[19]	No	No
Does the intensive ventilation system require minimum air flow rates?	No[20]	Yes	Yes [21]	Yes	~~No~~ Yes [22]	Yes	[23]	Yes	Yes[24]	No	No
Does the intensive ventilation system require maximum air flow rates?	No	No	No	No	No	No		No	Yes[25]	No	No
Does the intensive ventilation system include night-time ventilation?	No	No [26]	No	No	No	No		Yes	Yes	No	No

[12] depends on person/m^2
[13] The requirement is in l/s, varies according to the room use e.g. 8l/s for bathroom, 13l/s for kitchen and for the whole house depends on number of bedrooms e.g. 21l/s for a house with three bedrooms or minimum of 0.3l/s per floor area
[14] Airflow requirements are based on opening area and subject to use.
[15] 25-30 m^3/h per person
[16] 3.6 $m^3/h.m^2$ supply
17 See section 120 of California Code of Regulations, Title 24, part 6
[18] through thermal balance equation
[19] 3 m^3/m^2h, 10 m^3/m^2h
[20] A heat recovery ventilation is required if total airflow and number of operation hours is above the value in the table in DPR 412/93 Art.5, comma 13 e Allegato C
[21] It is called 'purge' ventilation and is required in every habitable room, minimum 4 air changes per hour
[22] Answer changed by editor based on the response on the question "Are there requirements for indoor air quality"
[23] Not filled out
[24] 3 m^3/m^2h
[25] 10 m^3/m^2h
[26]Night time ventilation is not mentioned in the building code.

Are there requirements for indoor air quality?	No[27]	Yes	Yes	Yes[28]	Yes[29]	Yes	Yes[30]	Yes	Yes[31]	No	Yes[32]

Although, as expected, all discussed building codes have minimum air flow rates for hygienic ventilation, only the Netherlands and Switzerland have maximum air flow rates for hygienic ventilation. The requirement of maximum hygienic air flow rates can lead designers to think that this is also the maximum air flow rate for intensive ventilation, thus posing a threat to ventilative cooling.

3.3.1.1.4 Ventilation openings and position

	Italy	NL	UK	DK	Ireland	China	Norway	Japan	CH	Belgium	USA Cal.
Does the position of inflow air relative to the outflow air influence ventilative cooling?	No	?[33]	Yes	[34]	No	No	[35]	Yes	No	No	No
Is a minimum inflow opening area required for outside walls?	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes[36]	No	Yes
Is a minimum inflow opening area for outside walls required per orientation?	No	No	No	No	No	No	No	No	No	No	No
Is a minimum inflow opening area required for inside walls?	No	No	No	Yes	Yes	No	No	No	No	No	No
Is a minimum outflow opening area required for outside walls?	No	No	Yes	No	Yes	No	No	Yes	No	No	No[37]
Is a minimum outflow opening area for outside	No	No	No	No	No	No	No	No	No	No	No

[27] For NON-residential buildings, the standard "UNI EN 13779: Ventilazione degli edifici non residenziali-Requisiti di prestazione per i sistemi di ventilazione e di climatizzazione" gives indications on the minimum airflow rates. However, usually regional legislations state in general terms that internal spaces must present minimum quality of healthiness/salubrity, but without specifying requirements.
[28] Transfer of air from more to less polluted rooms is not allowed; requirements on Formaldehyde, Radon and Asbestos concentration.
[29] These are descriptive rather then defined quantitative values. habitable room - Purge Ventilation - 1/20th floor area
[30] Formaldehyde
[31] INT2 (<950 ppm CO_2)
[32] CO_2, 600 ppm + outdoor (default 400 ppm)
[33] Possible
[34] no answer
[35] no answer
[36] 5% of the floor area
[37] No difference between inflow and outflow

walls required per orientation?											
Is a minimum outflow opening area required for inside walls?	No	No	No	Yes	Yes	No	No	No	No	No	No
Are there requirements for grid flow characteristics?	No	Yes	Yes[38]	Yes[39]	No	No	No	[40]	Yes	No	Yes[41]
Other aspects?	No	No	No	No	No	No	No	No	No	No	No

Most countries require minimum airflow rates for intensive ventilation. This is good for ventilative cooling. A minimum required opening is good for minimum amounts of ventilation. However, for ventilative cooling it should be emphasized that the minimum opening can be too small.

The requirements for grid flow characteristics are mainly that it is not allowed to transfer air from more to less polluted rooms. In the USA (California) there are requirements on the position of the openings, they should be readily accessible to building occupants, and the openings should be within 20 feet of the naturally ventilated spaces.

3.3.1.1.5 Safety

	Italy	NL	UK	DK	Ireland	China	Norway	Japan	CH	Belgium	USA Cal.
Do the fire regulations influence ventilative cooling?	No[42]	?	[43]	Yes[44]	No	Yes	No	Yes	Yes	[45]	No
Do the burglary regulations influence ventilative cooling at night-time operation?	No	Yes		Yes[46]	No	No	No	No	Yes	Yes	?
Do the burglary regulations influence ventilative cooling	No	Yes		Yes[47]	No	No	No	No	Yes		?

[38] These are described in the compliance software (SAP) and is known as annex Q
[39] Transfer of air from more to less polluted rooms is not allowed
[40] no answer
[41] Naturally ventilated spaces shall be permanently open to and within 20 feet of operable wall or roof openings to the outdoors. Operable openings shall be readily accessible to building occupants whenever the space is occupied.
[42] Fire protection may actually pose limits to the use of ventilative cooling solutions, in particular for buildings exceeding 500m^2. The legislation is rather complex and addresses specific building types (e.g. residential, hotels, schools, hospitals...). For example, the DM 246/1987 reports the requirements that residential buildings must respect in terms of internal, smoke-proof subdivisions (see aside)
[43] All these aspects are considered in 'purge' ventilation calculations and included in the min recommendation of 4 air changes per hours
[44] Yes, fire sections have to be intact, but natural ventilation in a way is promoted since it is highlighted that it could serve as smoke venting in case of fire.
[45] the empty grids in this table had no answer from Belgium
[46] For automatically operated windows for venting
[47] For automatically operated windows for venting

at daytime during absence?											
Does the rain tightness regulation influence ventilative cooling?	No	No		No	No	Yes	No	No	Yes		No
Do the controllability regulations influence ventilative cooling?	No	Yes		No	No	No	No	No	No	Yes	?
Do the cleaning regulations influence ventilative cooling?	No	No		No	No	Yes	No	No	No		No
Do the acoustical regulations influence ventilative cooling?	No[48]	Yes		Yes[49]	No	Yes	No	No	No		No
Do the insect-proof regulations influence ventilative cooling?	No	Yes		Yes[50]	No	No	No	No[51]	Yes		Yes
Other aspects	No	No		No	No	No	No	No	No		flood

There are large differences between the safety regulations in the different countries. More detailed research is needed to find out how the regulations should be adapted so that ventilative cooling in buildings can be applied and how ventilative cooling can safely be applied in residential buildings if there are no national regulations on safety. The problem with these safety regulations is that they do make sense for standard buildings or for the winter situation, but do not always make sense when ventilative cooling is applied. For the Dutch controlling regulations, for example, a ventilation system needs three stages; this led to increased application of ventilation grills that already have three stages in favour of a simple, small operable window above the big window that can only open or close. However, the ventilation grills generally have a lower maximum airflow than a small window thus reducing the possibility of ventilative cooling.

[48] The Decree DPCM 5/12/97 "Determinazione dei requisiti acustici passivi degli edifici" gives indications on the "potere fonoisolante apparente" (sound reduction index) , and other 4 acoustic performance indices. However, these indices do not take into account the specific location of the buildings (urban/rural...). This may actually pose severe limitations to ventilative cooling at a design stage

[49] Noise limits indoors are 58DBfor trafic noise and 64DB for Railroad

[50] It is stated that openings directly to outside should not allow access of microorganisms

[51] inlet/outlet opening of outdoor air and the top of the exhaust opening needs insect-proof installation in sanitary meaning

3.3.1.1.6 Temperature, Air velocity and Humidity

	Italy	NL	UK	DK	Ireland	China	Norway	Japan	CH	Belgium	USA Cal.
Are maximum summer temperatures included in the building code?	No[52]	No	No	Yes	No	Yes	Yes	No	Yes	Yes[53]	Yes[54]
Is the maximum summer temperature determined by the adaptive comfort theory?	No	No	No	No	No	No	No	No	Yes	No	Yes[55]
Other aspects	No	No	No	No	No	No	Yes[56]	No	No	No	No
Is there a maximum air velocity required in a room?	No[57]	Yes	No	Yes	No	Yes	No	No	Yes	No	Yes[58]
Is this maximum air velocity related to the room air temperature?	No	No	No	Yes	No	No	No	No	Yes	No	No[59]
Other aspects	No	No	No	No	No	No	No	No	No	No	No
Is there a maximum RH required?	No[60]	No	No	Yes	No	Yes	No	No	Yes	No	No?
Is there a minimum relative humidity required?	No	No	Yes[61]	Yes	No	Yes	No	No	Yes	No	No?
Do the maximum and minimum RH depend on the inside air temperature?	No	No	No	No	No	No	No	No	Yes	No	

[52] The recent Presidential Decree 74/2013 sets lower air temperature threshold for the cooling period, calculated as the average of the monitored temperatures: 26°C with a 2 degrees tolerance, except for some particular cases (e.g. buildings with swimming pools, buildings housing diplomatic offices or international organization) for whom local authorities can decide that limits may not be respected.
[53] overheating indicator
[54] 85 °F, section 6, 120 2 c
[55] at least for the calculation, and from ASHRAE 55 or ASHRAE handbook, fundaments volume, Chapter 8 (except for winter humidification and summer dehumidification)
[56] Windows should be openable
[57]No national requirements, UNI EN 7730 reports maximum air velocities as a function of the air temperature, but to our best knowledge local legislation does not refer explicitly to this standard. The Presidential Decree 74/2013 sets the lower air temperature threshold for the cooling period but does not address adaptive-model logics, nor the exploitation of devices to increase the indoor air velocity during the cooling season.
[58] discharge velocity at 15 feet of the unit
[59] Although implicit in ASHRAE 55
[60] Usually regional legislations state in general terms that internal spaces must present minimum quality of healthiness/salubrity, but without specifying requirements. The standard "UNI EN 13779: Ventilazione degli edifici non residenziali-Requisiti di prestazione per i sistemi di ventilazione e di climatizzazione" provides some indicative parameters, such as a RH range between 40 and 60%
[61] A very complex method of calculating humidity activity in residential rooms to prevent mould growth is included in the Building Regulations.

Do the maximum and minimum relative humidity depend on the outside air temperature?	No	No	No	No	No	No	No	No	Yes	No	
Other aspect	No	No	No	No	No	No	No	No	No	No	No

A pro for ventilative cooling is the requirement of a maximum summer temperature. If there is no requirement for a maximum temperature, there is no need for cooling. However, the energy calculation method might implicitly determine the maximum summer temperature, and not show up in this table, as is the case in the Netherlands.

The requirement for a maximum air velocity is a danger to ventilative cooling as ventilative cooling requires higher air velocities. However, if the maximum air velocity is related to the temperature, this is positive for ventilative cooling.

How the relative humidity requirement influences the application of ventilative cooling is not clear yet, but should be subject to further research. It might be a positive or negative influence depending on the required relative humidity and the outside relative humidity.

3.3.1.2 Non-Residential

With respect to the building code, there is little difference between residential and non-residential buildings. Therefore no detailed analysis is given here. The differences found are given in the table below.

country	**difference residential and non-residential buildings**
Italy	the same
NL	similar
UK	residential buildings have more requirements related to ventilative cooling than non-residential buildings
Denmark	no change
Ireland	energy demand for cooling, fire regulations and maximum temperatures are only considered for non-residential buildings
China	only minimum relative humidity requirement is required for non-residential buildings
Norway	only filled out residential, probably non-residential is similar
Japan	higher requirements on air velocities and humidity in non-residential buildings
Switzerland	
Belgium	non-residential has no overheating indicator (?), no burglary regulations that influence ventilative cooling, regulations for indoor air quality[62], different minimum air flow rates for hygienic ventilation[63]
USA Cal.	As far as I can see there is no big difference for ventilative cooling

[62] EN 13779, bijlage X

[63] 22 m^3/h.pers

3.3.2 Energy Performance

3.3.2.1 Residential Buildings

3.3.2.1.1 General Questions

	Italy	NL	UK	DK	Ireland	China	Norway	Japan	CH	Belgium	USA Cal.
Is an Energy Performance (calculation) required for a building?	Yes	Yes	Yes[64]	Yes	Yes	No	Yes[65]	Yes	Yes	Yes	Yes
To which version of the EP-regulation do the answers of this questionnaire refer to?	[66]	[67]	[68]	[69]	[70]	No	[71]	[72]	[73]	2013	2013 [74]
In the determination/ calculation of the overall EP, is the consumption for cooling considered?	[75]	Yes		Yes	No	No	Yes	Yes	No[76]	Yes	Yes
If no (active or passive) cooling system is installed in the building, is there a cooling penalisation in the EP?	No	Yes[77]		Yes	No	No	No	?	No	Yes[78]	No
Is the EP-requirement (Epr) different if a cooling system is installed or not?	No	No		Yes[79]	No	No	No	No	No	No	No
In which classification category falls the calculation method?	BmSm	BmSm		BmSm	BmSm	-	BhSh or BmSm	[80]	BmSm	?	BhSh [81]

[64] All systems are considered because buildings are modelled as whole system using SAP for domestic and NCM for non-residential.
[65] In the calculation of the energy need for cooling the ventilative cooling can be included as a heat loss.
[66] The main Decree on energy performance of buildings are: Legge 373/1976, Legge 10/1991, DPR 412/1993, D.Lgs. 192/2005, D.Lgs. 311/2006, D.P.R. 2 aprile 2009 n. 59, D.M. 26 giugno 2009, DM 11 Marzo 2010, DM 26 Gennaio 2010. The standards are into force from 1976. They have been updated regularly.
[67] The standards are into force from 1995. They have been updated regularly. The method concerning cooling has been changed in the past. When what changes were made is beyond the scope of this questionnaire (will take a lot of time to find these details)
[68] Building Regulations Part L or F, 2014
[69] BR2010
[70] Residential - 2011
[71] Directive 2002/91/EC
[72] 2013.10, Act on the Rational Use of Energy (Energy conservation Law)
[73] no information
[74] Califonia Energy Code, 2013, Title 24, part 6
[75] The Legislative Decree 63/2013, which implements at national level the European Directive 2010/31, states that the Energy Performance Certificate will include the energy consumption for (heating and) cooling. However, at present the comprehensive EP Certificate has not been finalized.
[76] Calculation necessary for heating demand. Cooling demand is supposed to be implicitly considered not necessary.
[77] if no cooling system is present, fictitious cooling is taken into account (Residential buildings only)
[78] value depends on overheating indicator
[79] If a cooling system is installed you are allowed to use the actual COP else needed cooling is calculated with a COP of 2
[80] no answer
[81] http://bees.archenergy.com/referencemethod.html

As expected, all European countries require an energy performance (calculation). Countries in the European Union are required to implement the Energy Performance of Buildings Directive (EPBD). The countries in this Annex 62 that are part of the European Union are: Austria, Belgium, Denmark, Finland, France, Greece, Ireland, Italy, The Netherlands and the UK.

Almost all EU countries that answered the questionnaire have an energy performance requirement for cooling, although Italy has not finalized the Certificate and Ireland has no requirement for residential buildings. The calculation method is mainly based on NEN-EN-ISO 13790: 2008 (Energy performance of buildings - Calculation of energy use for space heating and cooling), although many countries have made their own separate document [1].

The route from design of a building to an energy performance value is given in Figure 3.1.

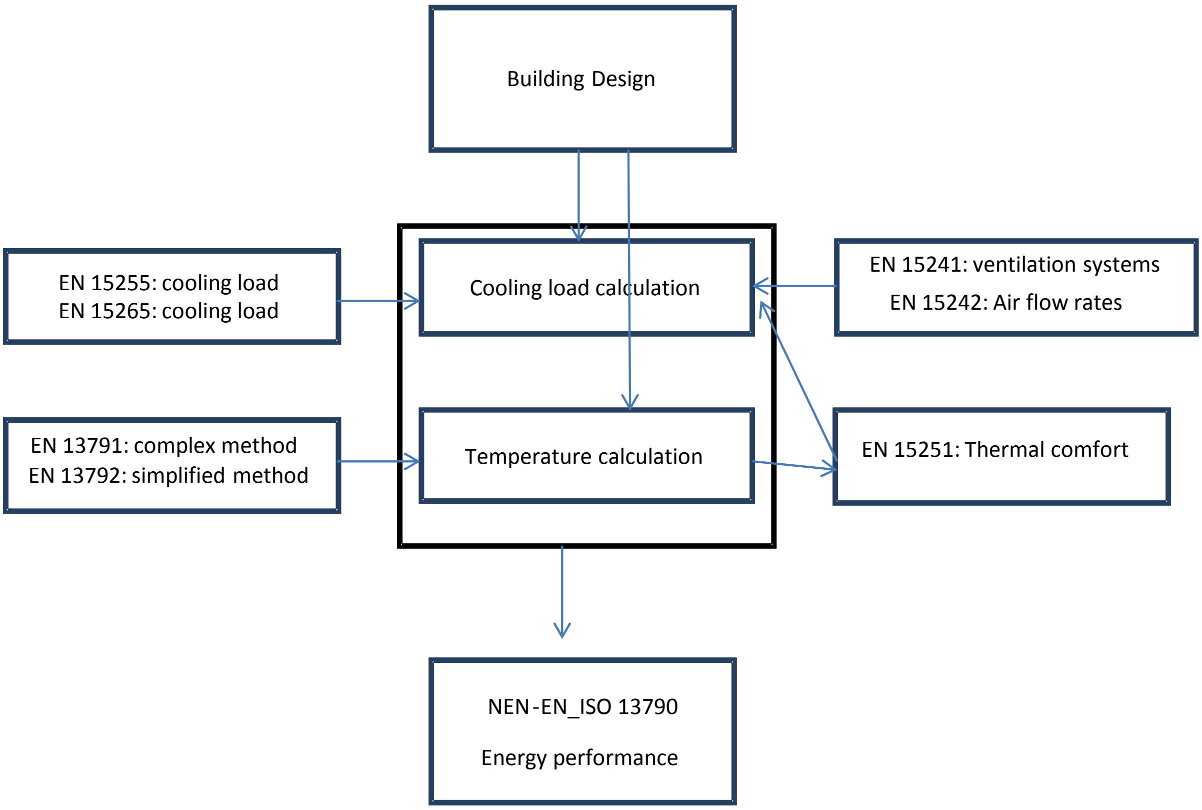


Figure 3.1: From Design to Energy performance Value in accordance with the European Union Standards.

- The NEN-EN-ISO 13790 needs direct information for ventilative cooling from two other standards: NEN 15241 and NEN 15242, see figure 1.
- EN 15241, *Ventilation for buildings — Calculation methods for energy losses due to ventilation and infiltration in commercial buildings*
- EN 15241 needs information from EN 15242 in order to know the air flow rates in buildings due to ventilative cooling.
- EN 15242, *Ventilation for buildings — Calculation methods for the determination of air flow rates in buildings including infiltration*

- *EN 15251 deals with temperature guidelines and also includes adaptive thermal comfort where the indoor air temperature is allowed to be higher when the outdoor temperature is also higher.*

This whole procedures looks at first, to be a very good way to determine the effect of ventilative cooling in energy performance calculations. However, the calculation procedure is very complex and not surprising since these standards consist of 30 (EN 15241) to 162 (EN 13790) pages. This means that the calculation procedure can take a long time, and you preferably need an expert to complete the input.

Some countries have a penalty when no cooling is installed in the building. This penalty raises awareness for the necessity of cooling and encourages the implementation of an actual system instead of a default system.

Most countries use the Building Monthly and Simulation Monthly (BmSm) method. This method requires average monthly values for the efficiency of ventilative cooling. However, calculation procedures and values for ventilation systems with strong dynamic aspects (such as ventilative cooling) are not easy to implement in a Building Monthly, Simulation Monthly calculation procedure. There usually is a procedure given in the regulations (as in NEN-EN-ISO 13790) to calculate these monthly values, but this procedure is usually quite complex and time consuming. Sometimes tables are already given, such as in the Dutch NEN 8088 for purge ventilation and mechanical ventilation bypass. The Danish Compliance tool Be10 can help in determining monthly values, but is still not very user friendly.

Further research should be done to investigate the already existing predetermined monthly values for the different countries and whether, and how, all ventilative cooling possibilities can be given as monthly values.

Another option is to ask for hourly calculations within the energy performance, but this increases the complexity of the energy performance calculation and can introduce a large error by inexperienced users due to the larger amount of parameters that are required. Hourly calculations also increase the calculation time of the energy performance significantly.

3.3.2.1.2 EP-calculation method: which of the following design variables is taken into consideration?

The other questionnaire questions about which design variables are taken into consideration in the energy performance calculation were too detailed to be discussed in this chapter. Most countries using the Energy performance calculations do have some method or other to take all aspects of ventilative cooling into account. The questionnaire, however, did not ask how easy it was to use these methods. The most interesting part of the questionnaire is the questions themselves, as given below. Further research should investigate how and how easy all these aspects of ventilative cooling are taken into account in the Energy Performance Calculation.

3.3.2.1.3 Energy needs (net energy balance) on room level

Heat transfer hygienic ventilation system		
	preliminary passage of incoming air through ground-air heat exchanger	
	recovery heat exchanger (when outside temperature is lower than return temperature, e.g. during the night)	
	direct evaporative cooling	
	indirect evaporative cooling (with the incoming air being cooled through a heat exchanger)	
	special night-time operation of the hygienic ventilation system (e.g. in non-residential buildings)	
Intensive ventilation		
	100 % natural	operable facade windows
		operable roof windows
		Vents integrated in and around windows
		wall louvres
		natural extract chimney
		natural extract duct
	mechanical ventilation	
		mechanical extract and /or supply fan
		whole house fan (USA)
		air-side economiser (USA)
Latent heat		
	intentional dehumidification	
	non-intentional dehumidification	

3.3.2.1.4 Energy needs air handling units

Preliminary passage of incoming air through ground-air heat exchanger?
Recovery heat exchanger? (when outside t0 is lower than return to, e.g. during the night)
By-pass of recovery heat exchanger? (when outside t0 is lower than return to, e.g. during the night)
Direct evaporative cooling?
indirect evaporative cooling (with the incoming air being cooled through a heat exchanger)
Special night-time operation of the hygienic ventilation system? (e.g. in non-residential buildings)
sensible cooling
latent cooling
reheat

3.3.2.1.5 Energy use (emission, distribution and storage system)

Cold storage	
	sensible storage (e.g. cold water tanks, rock/pebble beds, ...)
	latent storage (e.g. Ice storage)

3.3.2.1.6 Delivered energy (cold source or heat dump)

Passive systems (natural, spontaneous heat flow to a natural sink at lower temperature)	
	ambient air (direct, central, intake of outside air)

3.3.2.1.7 Auxiliary and parasitic consumptions

fans (e.g. for intensive ventilation)
circulation pumps
controls and activation devices

3.3.2.2 Non-Residential Buildings

For Non-Residential buildings the same questions are asked as for Residential Buildings. There are differences between Residential and non-residential buildings, but the differences between the countries are as large as the differences between residential and non-residential buildings aretherefore the results of the questions for non-residential buildings which is not discussed in detail.

	Italy	NL	UK	DK	Ireland	China	Norway	Japan	CH	Belgium	USA Cal.
Is an Energy Performance (calculation) required? If not, do not answer the other questions!	Yes	Yes	Yes[82]	Yes	Yes	No	Yes[83]	Yes	Yes	Yes	Yes
To which version of the EP-regulation do the answers of this questionnaire refer to?	[84]	[85]	[86]	[87]	[88]	No	[89]	[90]	[91]	2013	2013[92]
In the determination/ calculation of the overall EP, is the consumption for cooling considered?	[93]	Yes		Yes	No	No	Yes	Yes	Yes[94]	Yes	Yes
If no (active or passive) cooling system is installed, is there a cooling penalisation in the EP?	No	Yes[95]		Yes	No	No	No[96]	?	No	No	No
Is the EP-requirement (Epr) different if a cooling system is installed or not?	No	No		Yes[97]	No	No	No[98]	No	No[99]	No	No

[82] All systems are considered because buildings are modelled as whole system using SAP for domestic and NCM for non-residential.
[83] In the calculation of the energy need for cooling the ventilative cooling can be included as a heat loss.
[84] The main Decree on energy performance of buildings are: Legge 373/1976, Legge 10/1991, DPR 412/1993, D.Lgs. 192/2005, D.Lgs. 311/2006, D.P.R. 2 aprile 2009 n. 59, D.M. 26 giugno 2009, DM 11 Marzo 2010, DM 26 Gennaio 2010. The standards are into force from 1976. They have been updated regularly.
[85] The standards are into force from 1995. They have been updated regularly. The method concerning cooling has been changed in the past. When what changes were made is beyond the scope of this questionnaire (will take a lot of time to find these details)
[86] Building Regulations Part L or F, 2014
[87] BR2010
[88] Non Residential - 2008
[89] Directive 2002/91/EC
[90] 2013.10, Act on the Rational Use of Energy (Energy conservation Law)
[91] no answer
[92] Califonia Energy Code, 2013, Title 24, part 6
[93] The Legislative Decree 63/2013, which implements at national level the European Directive 2010/31, states that the Energy Performance Certificate will include the energy consumption for (heating and) cooling. However, at present the comprehensive EP Certificate has not been finalized.
[94] Calculation of heating demand. Cooling demand is necessary if air conditioning is present.
[95] if no cooling system is present, fictitious cooling is taken into account (Residential buildings only)
[96] Actually there is a small potential energy "credit" when cooling is not provided as the baseline building used for assessment will have mechanical cooling operated to a set point of 27C
[97] If a cooling system is installed you are allowed to use the actual COP else needed cooling is calculated with a COP of 2
[98] No the baseline building used for assessment comparison purposes does not change whether or not cooling is installed in the actual building being assessed
[99] Cooling energy consumption is considered in electricity consumption. Heat and hot water is treated separately. Cooling needs are calculated with a dynamic separate calculation and translated to energy consumption with machine COP and added to the electricity consumption

In which classification category falls the calculation method?	BmSm	BmSm		BmSm	BmSm	-	BhSh or BmSm	[100]	BmSm heating, BhSm cooling	?	BhSh [101]

3.3.2.3 Existing other calculation tools

3.3.2.3.1 Existing other cooling calculation tools

The energy performance procedure works very well when there is a good design of which you want to know the energy performance. This procedure does not work well during the design process at the moment. Following this procedure would mean that for every change in design you have to redo the whole calculation.

Therefore, besides the national and international standards, there are also other tools widely used that can be used as a design tool and that can also calculate the amount of ventilative cooling, see table below. These other design cools must be investigated in order to determine 1. their use as an input aid when performing an energy performance calculation, 2. their application as a design tool in the design phase, 3. their use as a template for a new energy performance calculation in the National Energy Performance calculation.

	Italy	NL	UK	DK	Ireland	China	Norway	Japan	CH	Belgium	USA Cal.
Outside the scope of the regulations, are there other cooling calculation methods widely used?	No	Yes[102]	[103]	Bsim	[104]	No	No	Yes[105]	Yes[106]	Yes[107]	?

[100] no answer
[101] http://bees.archenergy.com/referencemethod.html
[102] in the non-residential sector overheating calculations are done regularly for bigger buildings. But how often I don't know
[103] no answer
[104] Residential: PHPP software is widely used in Ireland for assessing energy performance of residential buildings and is not covered under the building regulations; Non-residential: Dynamic simulation is widely used for the design of non residential buildings and for the assessment of overheating risk
[105] no specification
[106] It is necessary to justify overheating protection for all buildings. One of the 3 methods is simulation (hour). It is also necessary to simulate the building behaviour to prove the need of a cooling system after all compulsory measures for thermal protection specified by the norm have been taken.
[107] For Non-residential buildings: BES simulations or PHPP

3.4 Conclusions

1.1. Ventilative cooling in Building Code

Ventilative cooling requirements in regulations are complex. For ventilative cooling to be applied, a lot of aspects indirectly required by the building code are identified in this chapter. Having identified these aspects, future research should then identify the impact of these aspects on the application of ventilative cooling. If necessary, changes to existing national Building Codes should be proposed based on this future research.

Main aspects that are identified are:

- Energy consumption for cooling
- Building parameters influencing ventilative cooling
- Ventilation requirements, both ventilation amounts and ventilation openings and positions
- Safety
- Temperature, Air velocity and Humidity requirements

1.2. Ventilative cooling in Energy performance calculations

Most countries require the calculation of an Energy performance for a building. It must be possible to enter ventilative cooling in this energy performance calculation. The result from the questionnaire on energy performance shows that it is generally possible to enter ventilative cooling in the energy performance calculation, however, the results of the questionnaire do not show how easy it is to enter ventilative cooling in the energy performance calculation. Most countries have as their default a monthly energy calculation, which is not well suited for ventilative cooling. More complex calculations are generally possible in the energy performance calculations, but you need to be an expert and the complex calculations are time-consuming. By drawing up the questionnaire, an overview of all the aspects that are related to ventilative cooling was created. This overview is more interesting than the answers to the questions as countries either provided a calculation method for almost all aspects or a calculation for none of the aspect. This overview is a good starting point for further research simplifying the procedure for entering ventilative cooling in the Energy performance regulations.

The aspects identified are:

- Energy needs (net energy balance) at "room" level", separated into
  - hygienic ventilation system
  - intensive ventilation system
- Energy needs of air handling unit
- Energy use of emission, distribution and storage system
- Delivered energy ("cold source" or "heat dump")
- Auxiliary and parasitic consumption

1.3. Existing other calculation tools

The energy performance procedure works very well when there is a good design of which you want to know the energy performance. This procedure does not work well during the design process, at the moment. Following the official procedure would mean that for every change in design you have to redo the whole calculation. Therefore, besides the national and international standards, there are also other tools widely used that can be used as a design tool and that can also calculate the amount of ventilative cooling. These other design tools must be investigated in order to determine 1. Their use as an input aid when performing an energy performance calculation, 2. Their application as a design tool in the design phase, 3. Their use as a template for a new energy performance calculation in the National Energy Performance calculation.

3.5 References

[1] Implementing the Energy Performance of Building Directive (EPBD), featuring country reports 2012, also to be found at www.epbd-ca.eu and www.buildup.eu, accessed 8-12-2014.

[2] Assessment and improvement of the EPBD Impact (ASIEPI) website: www.asiepi.eu, accessed 8-12-2014

[3] Recent Development to Integrate Ventilative Cooling in the Danish Regulatory Context., Heiselberg, Per; Duer, Karsten, Proceedings of the 34th AIVC Conference. 2013.

[4] Recent developments to integrate ventilative cooling in the Austrian regulatory context, Peter Holzer, Proceedings of the 34th AIVC Conference. 2013.

[5] Ventilative cooling in national energy performance regulations: Requirements and sensitivity analysis, I. Pollet, S. Germonpre, A. Vens, Proceedings of the 35th AIVC Conference 2014.

3.6 Appendix

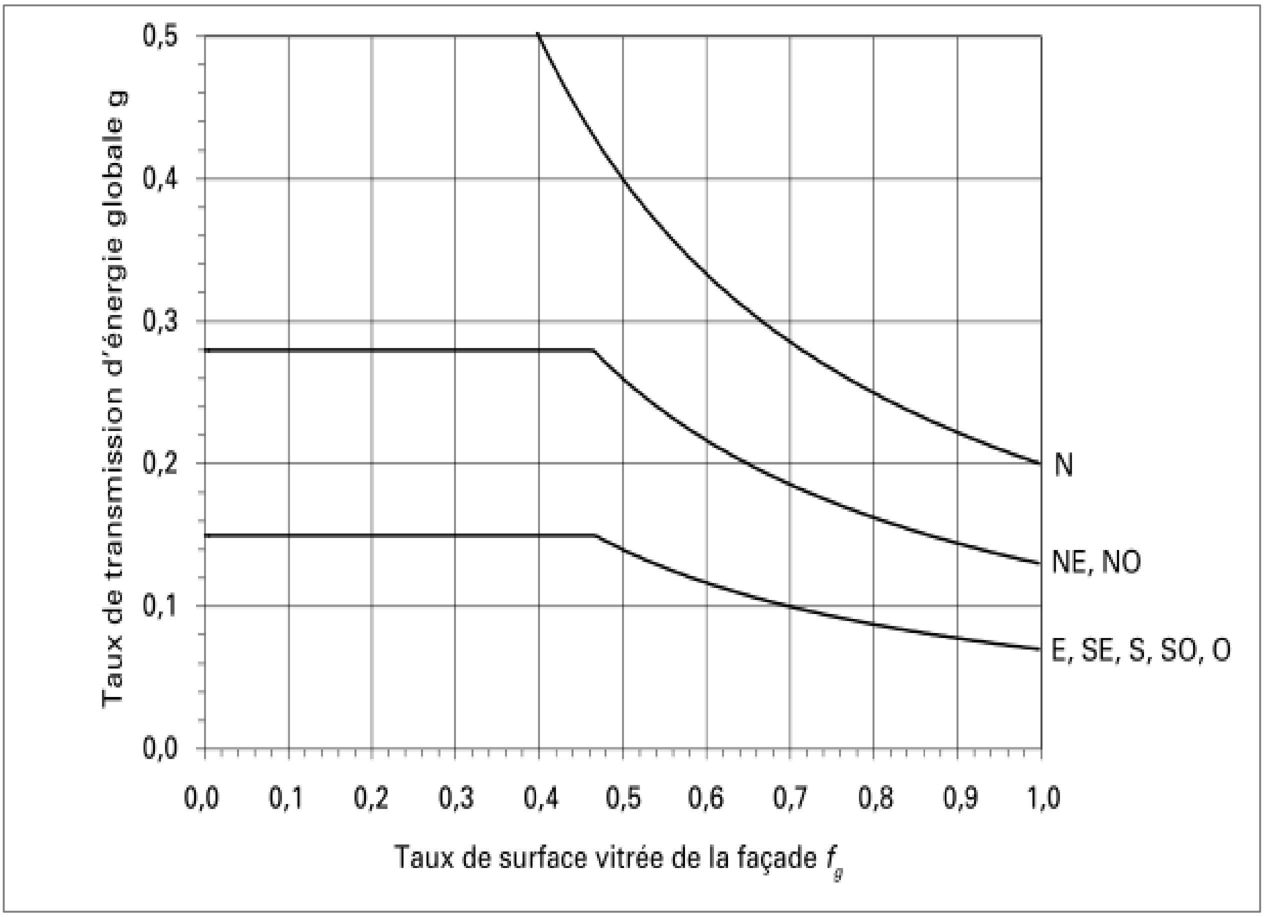


Figure A1: Requirements on solar shading in the Swiss regulations:

4 Exemplary Existing Buildings using Ventilative Cooling

4.1 Introduction

A large number of buildings using ventilative cooling have already been built around the world, and more are planned or about to be built. Chapter 4 surveys 26 existing buildings from fourteen of the countries recommended by the participants in the Sub-Task C of Annex 62. Particular topics of interest in this survey were the overall design philosophy used for the reduction/removal of cooling demand and risk of overheating, and the components and the control strategies used. It is clear from the descriptions of the overall design philosophy that a successful ventilative cooling design depends on an integrated approach, in which optimal use is made of one or more ventilative cooling technologies such as night ventilation (including Phase Change Materials -PCM), evaporative cooling (particularly effective for dry climates), cross ventilation, air cooling by ambient woods or water surface (lake, driver, sea), buoyancy, cooling by soil, cooling through underground, natural or mechanical driving forces, increased air velocity, wind inducing external wall, etc. In particular it requires low energy design strategies and components, and in a number of buildings solar chimneys combined with intensive night ventilation (using natural forces or fan assistance) is exploited to eliminate the need for cooling all year.

The buildings surveyed are low to medium-rise buildings, located in different climates areas (9 buildings in hot summer and cold winter zones, 4 buildings in cold zones, 5 building in temperate zones). Further examples of high-rise ventilative cooling buildings, or buildings in more challenging environments, will be useful to demonstrate that innovative solutions can be found for a wide variety of applications and environments.

Some basic components were used in most buildings. These include thermal mass, grills, fans, CO_2 and temperature sensors, manually operated and/or motorised windows or special ventilation openings, and wind towers, solar chimneys or atria for exhaust. This chapter surveys some recent existing ventilative cooling buildings, design philosophy for reduction/removal of cooling demand and risk of overheating, control strategies and components. Key information is presented via two-page reviews of example ventilative cooling buildings from each country participating in Sub-Task C of Annex 62, and via summary tables giving some basic data for each building.

4.2 Overview

The buildings are all recommended by the participants in the Subtask C of Annex 62. In this sense this review provides significant examples of how ventilative cooling is currently exploited, developed and studied around the world.

The contributors to the cases were asked to describe:

1. Basic building details including location, year of completion, type of building, size and design team
2. Relevant site data including climatic data in the form of HDD and CDD calculated to a base temperature (t_b)
3. Architetural design philosophy for reduction/removal of cooling demand and risk of overheating
4. Principle of ventilative cooling
5. Components used for ventilative cooling
6. Control strategies
7. Overall performance and lessons learnt

The overall building data and technical information is presented in each individual building review and summarized in Table 4.1 and Table 4.2. A total of 26 buildings are presented.

The following observations can be made:

- Most are office buildings (10 out of 26). There are 8 educational buildings including libraries, kindergartens and schools, 6 residential buildings and two exhibition buildings. All buildings (or their retrofit) were recently completed (the oldest in 2001).
- To reduce the cooling load and avoid overheating of both new and renovated buildings, many of the buildings make use of night ventilation and a hybrid ventilation system.

Control strategies in the buildings surveyed are usually intended to guarantee indoor comfort levels, indoor air quality and minimize the global energy consumption. The first priority is to utilize passive energy strategies; when passive strategies are not enough to achieve comfort, active strategies are applied. Usually in the summer, automatically controlled natural ventilation is used to providing good air quality and natural ventilative cooling. During the heating season, mechanical ventilation with heat recovery is used for air quality and natural ventilative cooling is used in case of overheating.

The components used for ventilative cooling include automatically openable windows, external solar shading, thermal mass, air handing unit (balanced mechanical ventilation system) and building management system(temperature and CO_2 sensors) etc. User behaviour has shown to be a crucial element for ventilative cooling.

From the 26 low energy buildings, the lessons we can learn are:

- The control parameters for window opening must be improved if the concentration of CO_2 is taken into consideration as much as the temperature in the room; this will ensure that the ventilation not only reduces energy consumption but also ensures thermal comfort and sufficient supply of fresh air.
- It is important that occupants know how to operate the ventilative cooling system. In many buildings is observed that when occupants had learned how to operate the system, energy use reduction was achieved for satisfactory comfort level and indoor air quality.
- Solar chimneys are a good ventilation strategy when operated by occupants.
- Façade design is an important consideration to achieve thermal comfort with the least energy consumption.

4.2.1 C-DdI ARFRISOL PSA

Building name	C-DdI ARFRISOL PSA	Year of completion	2007	Type of building	Office building
Location	Tabernas, Almería, Spain	Climate Zone	dry hot summer and cold winter		
Net floor area	1007.40m^2	Orientation of main facades	S		
Design Team	ACCIONA with advisory from CIEMAT's Energy Efficiency in Buildings R&D Unit				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
1001	18	155	24	x	x	✓	Yes	No	No	SW	600

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

This building prototype is a one floor building, with most of the regularly occupied offices facing south.

A double-wing structure, installed on the roof all along the building main axis, protects the building from solar radiation. This structure also supports two different types of solar collectors. On the north-facing wing, uncovered collectors are operated as radiant coolers by night, while flat plate collectors on the south-facing wing supply hot water for the heating, cooling and DHW systems. The central part of this structure also includes small solar chimneys to promote night ventilation of the offices. This is under users' control

An overhang protects south windows providing shade during the summertime and winter passive heating.

Principle of ventilative cooling

Night cross ventilation: During the summer, night-time the solar energy stored during the day, in the concrete walls of the chimney, is transferred to the air in the chimney channel, forcing cross ventilation in the offices, replacing indoor warm air by outdoors cool air and, reducing the indoor offices temperature.

Buoyancy: Another strategy uses the east-west corridor between north rooms and south offices, which is higher than the rest of the building, to take advantage of the solar radiation coming in through high windows, providing natural lighting all year long and cross ventilation by convection (by opening the windows) in summer. In winter this corridor would minimise thermal losses.

Components used for ventilative cooling (see chapter 5 for examples)

Solar Chimneys for night ventilation in summer that were modelled by ventilation rate of 1.4 ren/h from 0 to 7 am with external air temperature. This value is chosen from studies performed at a scale model at CIEMAT installations.

Control Strategies

The building has a BMS that guarantees the comfort levels of users and minimises energy consumption, giving priority to the use of passive energy strategies. When passive strategies are not enough to achieve thermal comfort, the active solar heating and cooling system is used to provide the energy required.

Solar Chimneys are controlled such that, during the summer, night-time the solar energy stored during the day, in the concrete walls of the chimney, is transferred to the air in the chimney channel, forcing cross ventilation in the offices, replacing indoor warm air by outdoors cool air and, reducing the indoor offices temperature.

The radiant cooling system work as night sky radiant cooler. This cooling collector field is connected to the circuit in the radiant floor and removes the heat stored in the massive floor and walls, reducing the average temperature of the building by several degrees. The combination of cross ventilation, radiant cooling system, and thermal-inertia walls, produces lower indoor temperatures in the morning and a delay in temperature rise, improving thermal comfort.

In winter, the passive heating strategies (large south-facing openings promoting solar gains and thick insulated walls minimising heat losses) are supplemented when necessary by the radiant floor heated by solar collectors.

Overall performance and lessons learned

A high degree of thermal comfort has been achieved during the whole year. Solar chimneys are a good ventilation strategy when operated by occupants. Ground insulation is a key point to take care of. Optimal control algorithm development in such complex buildings still faces a challenge.

4.2.2 C-DdI ARFRISOL CEDER

Building name	C-DdI ARFRISOL CEDER	Year of completion	2009	Type of building	Refurbishment Office building
Location	Altos de Lubia, Soria, Spain	Climate Zone	hot summer and cold winter		
Net floor area	1088 m^2	Orientation of main facades	South-North axis		
Design Team	ALIA, S.L with advisory from CIEMAT's Energy Efficiency in Buildings R&D Unit				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2850	18	0*	24	×	×	√	No	No	88%	Northwest	1090

*NOTE: Cooling Degree Days for CEDER, calculated with daily average temperatures, are zero. However, the average of the summer maximum temperatures is close to 27º C, which indicates the cooling needs for this location.

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The refurbishment of this office building has been designed with the coupling of several bioclimatic techniques to reduce the energy demand among the year.

During the summer time, the combination of windows and intake chimneys to produce natural ventilation, the differential insulation treatment of façades according to orientation, the appropriate placement of shading devices, the adiabatic refrigeration provided by the evaporative systems and the night refrigeration produced by the exchange of heat of the radiant collectors with the clear sky, reduces the operation of the borehole-coupled absorption pumps fed by solar collectors or biomass boilers.

Principle of ventilative cooling

This building is located in an area (Soria) with high temperatures, low humidity and sunny skies during the overheating period. Taking into account these hygrothermal characteristics, different cooling strategies such as evaporative devices and natural ventilation technologies have been analysed with the aim of minimize the energy demand of the building. The building shape, the orientation of the main axis and the control over the openings generated a cross ventilation inside the building. This ventilation has been enhanced by the operation of south intake chimneys which take the incoming air on the North façade. This process has been amplified by the action of evaporative pads installed on the top of the north windows, which reduce the inlet ambient temperature. One ventilated pergola has been constructed on the top of the building to shade the roof and produce natural ventilation to cool this constructive element during the summer months. The hot and dry conditions achieved during the summertime highlight the potential of evaporative systems, which cooling the incoming air by means of an adiabatic process. This system injects micronized water to the ambient air, reducing the temperature and increasing the moisture content of the air.

Components used for ventilative cooling (see chapter 5 for examples)

1. Cross ventilation. The windows distribution along the main façades as well as its control system, produce pressure differences between orientations giving as result heat and mass exchanges between the rooms.
2. Intake chimneys to enhance the natural ventilation inside the building.
3. Evaporative pads placed on top of the windows to reduce the inlet temperature to the offices through an adiabatic cooling.
4. A ventilated pergola on the top of the roof, composed by solar thermal collectors, to reduce the overheating during the summer months.
5. Direct evaporative systems inside the Air Handling Unit to pre-treat the incoming air up to a comfort temperature.

Control Strategies

This building has been controlled to guarantee the indoor comfort levels and minimize the global energy consumption. The first priority of the controller corresponds to the use of bioclimatic strategies (cross ventilation, evaporative systems, shading devices) and the proper adaptation of users to the building performance. When these solar passive techniques are not able to supply the energy demands, renewable systems such as radiant collectors, solar thermal field, photovoltaic panels, absorption pumps and biomass boilers start to operate. The global performance of both stages has been optimized previously by means of dynamic models.

Overall performance and lessons learned

The proper operation of the evaporative pads requires compromise from the inhabitant.

In this building, user behaviour has shown to be a crucial element for cross ventilation.

Difference façade design is a good strategy to achieve thermal comfort at the least energy consumption.

Night sky coolers delay at the first hours in the morning the operation of the Air Handling Unit.

4.2.3 GRUPO LINCE HEADQUARTERS

Building name	GRUPO LINCE HQ	Year of completion	2011	Type of building	Office building
Location	Valladolid, Spain 41º39'N, 4º46'O	Climate Zone	Hot summer and cold winter		
Net floor area	1000 m^2	Orientation of main facades	South (curved). North with air reservoir.		
Design Team	ALIA, S.L. with advisory from CIEMAT's Energy Efficiency in Buildings R&D Unit				

Outside view of building

Site data[108]

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
3239	18	0	24	×	√	×	No	No	100% maximum	N/A	698

[108] **Important remark**: For this location Cooling Degree Days, as calculated by means of the daily average temperature, are zero. However, the average of the maximum temperatures is close to 28º C, which indicates clearly the cooling needs for this location.

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

Green roof and optimized south glazing shadowing. Air solar collectors integrated in south façade: heat recovery in winter and ventilated in summer for heat extraction.

Open areas under offices and the roof have gardened areas. The advantage is that surface temperatures are maintained at the ambient temperature so building envelope is not overheated. Rainwater and irrigation water are collected and reused. Drip irrigation system is used to save water.

Atrium located at the central part of the building with a 350m^2 circular sector shaped area, improves the thermal conditioning of surrounding areas thanks to its own natural conditioning. A mobile roof ameliorates comfort conditions by increasing natural light during winter and protecting the area during summer periods to avoid overheating. An inside garden also ameliorate comfort conditions using spray irrigation systems.

Principle of ventilative cooling

Night ventilation:

Evaporative cooling in building(Fountain):

Crossing ventilation:

Mechanical driving forces:

Components used for ventilative cooling (see chapter 5 for examples)

Lucernaires: homogeneously distributed at the central office area, produce in summer night an ascending airflow from the garden area under offices. Cold air enters the air exchange system reducing thermal loads for summer period. This element also improves natural illumination.

Air collectors integrated in façade are used as a ventilated façade in summer.

Cross ventilation is used through grilles inside the building.

Control Strategies

Mechanical ventilation is used to take and mix air from the different sources, as a function of the natural temperature obtained through the different subsystems.

When needed, active systems provide cooled air to the system. The cooling system is a solar thermal-driven absorption pump combined with a geothermal heat pump.

Overall performance and lessons learned

Global performance has shown to be good, since the active systems are working at a low level.

In this office buildings with heat exchange trough façades air movement must be forced. Buoyancy by itself is not enough to assure the needed exchange.

4.2.4 POLICE OFFICE SCHOTEN

Building name	Police office Schoten	Year of completion	2009	Type of building	Police station
Location	Gasketelplein 10, 2900 Schoten, Belgium	Climate Zone	moderate		
Net floor area	2514 m²	Orientation of main facades	NW - SE		
Design Team	Huiswerk architecten (architect) and Arcadis Belgium (engineering office MEP and structural engineering)				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2363	16.5	296	16.5		√		No	No	No	SW	10

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The building is designed as a low energy building in winter and summer.

The internal and solar heat gains are reduced. Energy efficient lighting and equipment are used. Area of the windows is restricted, the window-to-floor ratio varies from 11% to 30%. There is a large overhang on the west side of the building. Moving blinds are provided as external solar shading devices on the east, west and the south façade and automatically controlled.

The building has a high thermal mass to store the heat by day. All walls are constructed of thermal capacitive materials (e.g. concrete brickwork in façade, hollow core concrete slab in floor) and the internal surfaces are unfinished so that heat can be stored in the internal structure.

Natural ventilation by day and night is installed to ensure good indoor air quality and thermal comfort.

Principle of ventilative cooling

In this building, natural ventilation by day and night is designed to guarantee a good thermal comfort and indoor air quality. Driving force is buoyancy. The air enters the building in the offices and leaves the building at the top of 4 atria in the centre of the building.

The area of the supply ventilation openings, in relation to the floor area, varies between 0.7 and 1.7%. The height difference between supply and exhaust openings measures 2m and 5m on respectively the first and ground floor. The openings are designed to deliver an airflow of 5 ac/h, considering a temperature difference of 7°C.

Components used for ventilative cooling (see chapter 5 for examples)

1. Supply: motorised bottom hung windows. The same bottom hung windows are used for hygienic ventilation and maximally opened for 25% by day.
2. Exhaust: motorised bottom hung windows
3. Internal: grilles (passive and motorised)
4. Building management system, including sensors (temperature, weather station,…)

Control Strategies

The supply openings for night ventilation are automatically controlled. Night ventilation is in operation between 10 pm and 6 am. Night activation requirements are an indoor temperature more than 21°C and an indoor-outdoor temperature difference larger than 1°C. Openings are closed if wind speed exceeds 10m/s and rain is noticed. Daytime activation requirements are a maximum indoor temperature exceeding 24°C and an average outdoor temperature exceeding 12°C. The exhaust openings in an atrium are opened when the supply openings in at least one ventilation zone are opened and the indoor temperature in the atrium exceeded 24°C by day. The day ventilation is controlled by occupancy in the individual offices and by CO_2-concentration in the landscaped offices i.e. opening when the concentration is higher than 900ppm and closing when it is lower than 600ppm. In addition, the users can manually open and close these windows.

Overall performance and lessons learned

A good thermal summer comfort is measured during normal and warm summer periods. Only when the maximum outdoor temperature exceeds 30°C, high indoor temperatures are measured. Too low temperatures in the morning are noticed in some landscaped offices in normal summer periods. This can be solved by raising the set point for indoor temperature. The users have a large impact on the achieved thermal comfort by manual opening and closing the windows or blinds by day.

4.2.5 MELLOMHAGEN

Building name	Mellomhagen	Year of completion	2010	**TYPE OF BUILDING**	School
Location	Mellomhagen 31, 3261 Larvik, Norway	Climate Zone	cold		
Net floor area	3500 m^2	Orientation of main facades	NE		
Design Team	Øyvind Beyer, Larvik				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
3945	19	0	26	×	√	×	No	No	100%	Winter: NNE Summer:SSE	37

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

Mellomhagen School is the case of a school originally built in the 1960s and retrofitted in 2010. The objective of the renovation was to improve the IAQ without excessive investment costs and without closing the school for a long period of time The school was renovated through the installation of new insulation, new windows and a hybrid ventilation system. The ventilation system is mixed mode type based on natural ventilation which promotes air exchange, but without a heat recovery mechanism. It combines the controlled opening of motorised windows and the use of an extraction fan during periods when natural ventilation is either inadequate or inadvisable due to too low outdoor temperatures. The fan is installed in a false ceiling between two rooms and only removes stale air. Each window is divided into an upper and a lower part. The lower part functions as a normal window, while the smaller, upper, part is opened and closed by a motorised system. Opening and closing these windows is key to regulating both air quality and temperature in the rooms.

Principle of ventilative cooling

In this building, natural ventilation is fully applied to remove cooling needs and to maintain acceptable thermal environment (but not necessarily air quality). The natural ventilation is mainly wind driven cross ventilation.

Components used for ventilative cooling (see chapter 5 for examples)

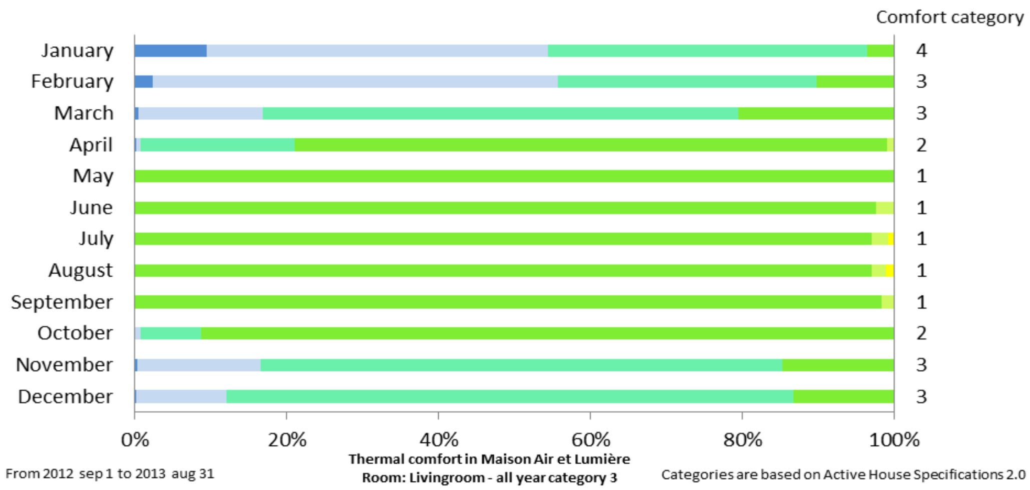
1. Top hinged, motorized windows with smart control.
2. Exhaust air damper controlled together with the window.
3. Exhaust air fan.

Control Strategies

1. During winter, window operation is limited in order to prevent cold draught and large heating demands. Operation of the window control system and exhaust fan is based on the outdoor temperature, wind conditions, and the CO_2 concentration and temperature in the classroom in question. Window operation is only allowed when the indoor temperature exceeds 21 °C, and is limited to 50 % of maximum opening. In case of CO_2 concentrations over 1300 ppm the windows will be opened as well. A local weather station records wind conditions, temperature and rainfall. These values are combined with classroom occupancy schedules to control the timing of window opening and aperture. Under conditions of low temperatures or high rainfall the exhaust fan will then control the ventilation as the windows will not open, unless the occupants override the control system. Fresh air pulses are provided through window opening at scheduled times.
2. During summer the zone set point temperature for window opening is 22 °C. Exhaust fan operates with a CO_2-setpoint at 1300 ppm. A summer operation also allows night-time cooling. If zone temperatures exceed 23 °C after working hours, the building will use window ventilation to cool down the zones to a minimum of 18 °C with a limitation in window opening of 50 %.

Overall performance and lessons learned

From measurements and simulations it can be concluded that the control parameters for window opening must be improved so that the concentration of CO_2 is taken into consideration as much as the temperature in the room. The control parameters must be such that the ventilation not only reduce energy consumption but also ensures thermal comfort and sufficient supply of fresh air. The education of the caretaker in charge of the ventilation system proves to be very important as when the caretaker had learned how to control the system the indoor quality was improved.



4.2.6 SOLSTAD

Building name	Solstad	Year of completion	2011	Type of building	kindergarten
Location	Agnesveien 14, Stavern, Larvik, Norway	Climate Zone	cold		
Net floor area	788 m^2	Orientation of main facades	NE		
Design Team	Architect: Pushak As, Oslo, advisor Energetica , Arne Førland Larsen				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
3870	19	0	26	×	√	×	No	No	100%	Winter: NNE Summer: SSE	43

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

Solstad kindergarten is a low-energy, two storey building in operation since January 2011. Their goal was to reduce the energy consumption to half in comparison with TEK 07 (Norwegian building code). The installed solution had to be cost effective.

Solstad combines the controlled opening of motorised windows and the use of mechanical ventilation during periods when natural ventilation is either inadequate or inadvisable due to too low outdoor temperatures.

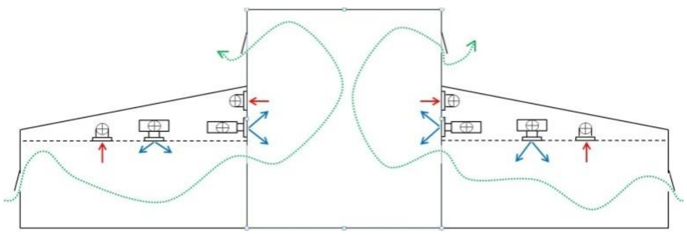
The use of window opening removes cooling demand due to average low outdoors temperatures.

]

Principle of ventilative cooling

The kindergarten has hybrid mixed-mode ventilation combining motor controlled operable windows with balanced mechanical ventilation. In total, the building consist of 54 top hinged, operable windows, and five separate decentralized mechanical ventilation systems, each consisting of supply- and exhaust air terminals, ductwork and an air handling unit with air heat recovery and a heating coil.

Natural ventilation from the operable windows is performed as combination of cross and stack ventilation. There is a large common room called Agora in the centre of the kindergarten, and all branches are connected to it through open air hatches. As the Agora ceiling height is fairly large, air supplied to the wings will exit through operable windows placed at the top of Agora



Components used for ventilative cooling (see chapter 5 for examples)

(1)Top hinged, motorized windows with smart control. (2) Interior hatches. (3) Energy efficient fan.

Control Strategies

1. During winter, window operation is limited in order to prevent cold draught and large heating demands. Mechanical ventilation operates with a zone setpoint of 900 – 1200 ppm CO_2, whereas window operation has a CO_2-setpoint of 950 – 1500 ppm. Window operation is only allowed when the indoor temperature exceeds 19 °C, and is limited to 50 % of maximum opening. This setup entails that mechanical ventilation handles most of the ventilation needs as it has a stricter CO_2-setpoint than the windows. Window operation will only occur if the mechanical system is insufficient in controlling the CO_2 concentration in the zone.
2. During summer, the zone set point for window operation is an indoor temperature exceeding 21 °C. Mechanical ventilation operates with a CO_2-setpoint of 900 – 1300 ppm. Seeing that indoor temperatures will exceed 21 °C much of the summer season, mechanical ventilation is not utilized very often as air flow rates needed in order to remove surplus heat often are larger than air flow rates needed for CO_2 control. A summer operation also allows night-time ventilation. If zone temperatures exceed 23 °C after operating hours, the building will use window ventilation to cool down the zones to a minimum of 18 °C with a limitation in window opening of 50 %.

Overall performance and lessons learned

From measurements and simulations it can be concluded that the control algorithm of the window opening optimize the use of natural ventilation ensuring good indoor climate. Simulation results show that the annual energy consumption for the mix mode system is 13 % lower than for the mechanical ventilation. The mix mode system keep an average lower temperature during summer periods without increasing the energy consumption for cooling as the cooling is provided by passive means.

4.2.7 HOME FOR LIFE

Building name	Home for Life	Year of completion	2009	Type of building	Residential
Location	Lystrup, Denmark	Climate Zone	Temperate coastal climate		
Net floor area	190 m^2	Orientation of main facades	S		
Design Team	AART Architects A/S, Esbensen IngeneeringA/S				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2906	17	45	20	×	√	×	No	No	Moderate	Winter: NNW Summer: SSE	~30

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The principal architectural idea in Home for Life is to unite single-family house requirements to indoor environment qualities, experience, functionality and very low energy consumption in an integrated design. The window area constitutes 40% of the building floor area and it is the light incidence, the active facade, the relationship between indoors and outdoor and the flexibility of the house that gives the house its high architectural quality. Even though the Danish climate is cool, many new-build low energy house have shown serious overheating, even outside the summer period. In Home for Life, a combination of controlled solar protection, natural ventilation through automated window openings and moderate thermal mass in the building secures that a cooling demand is avoided despite the large window area and the very well insulated building envelope.

Principle of ventilative cooling

Window opening areas are distributed over the whole building envelope: All facades and the roof are equipped with operable windows, giving potential of utilising both cross ventilation and stack effect as well as single sided ventilation. Solar shading and natural ventilative cooling is controlled by a building management system opening and closing windows according to indoor temperature and outdoor climate.

Components used for ventilative cooling (see chapter 5 for examples)

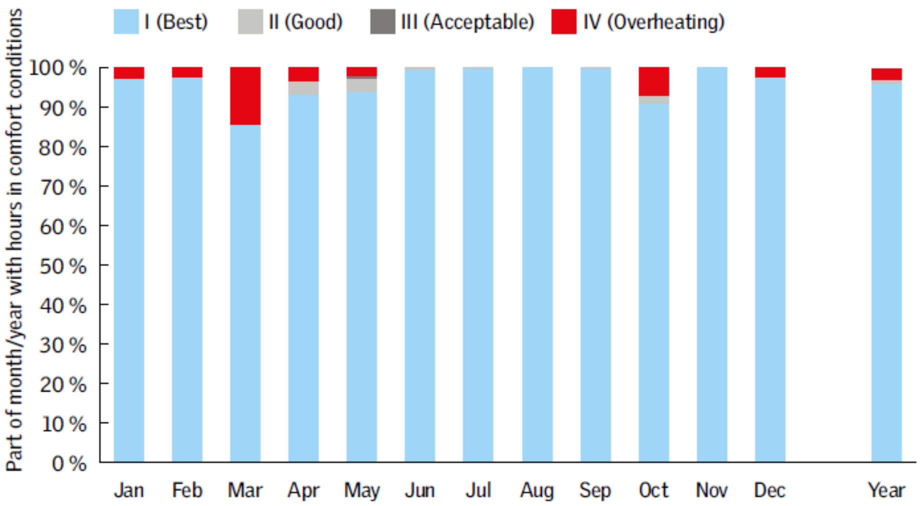
Integrated design of the building according to the needs of the inhabitants; Operable windows; External solar shadings; Thermal mass; Automatic control

Control Strategies

The house is managed in such a way that electricity and heat are used to a minimum. In the summer, the automatically controlled natural ventilation is used to air the rooms providing good air quality and natural ventilative cooling. During the heating season, mechanical ventilation with heat recovery is used for air quality and natural ventilative cooling in case of over-heating. Intelligent control regulates the outdoor and indoor sun screening for optimising heat and light intake as well as switching off the light when the room is not in use. Feed-back on indoor air quality, temperatures, energy use etc to the users is provided by an information and control screen. The users can override all controlled elements, giving full personal control if wished.

Overall performance and lessons learned

The building has been carefully monitored over two years of occupancy by two different families. Experience shows that when the control system is adjusted correctly, the thermal performance of the building is very good and the users are very content and consider the control as a clear benefit. The multi-purpose room where the family spend most of their time has the largest South-facing window area but still the over-all thermal comfort corresponds to Class I of EN 15251. Interesting that the month with the most risk of over-heating is March, indicating that the control may still be improved. No over-heating at all takes place during the summer (June-Sept).



4.2.8 MAISON AIR ET LUMIERE

Building name	Maison Air et Lumière	Year of completion	2012	**Type of building**	Residential
Location	Verrières-le-Buisson, France	Climate Zone	Oceanic climate, warm summer, cool winter,		
Net floor area	130 m^2	Orientation of main facades	S		
DESIGN TEAM	Nomade Architects, Cardonell Ingénierie				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2200	17	160	20	×	√	×	No	No	Moderate	SW	~100

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

Maison Air et Lumière, using a design principle that integrates architectural quality and energy efficiency, manages to place the emphasis on interior comfort whilst respecting the most ambitious energy and environmental objectives for new detached houses for 2020. The window area is large constituting about 33% of the floor area.

According to the season and weather conditions, ventilation is provided by a hybrid system that combines the advantages of mechanical ventilation with heat recovery in winter and, in summer, natural ventilation by window opening provide both good indoor air quality and ventilative cooling. Combined with dynamic external solar shading, thermal mass and a building management system, the design is intended to eliminate the need for cooling all year.

Principle of ventilative cooling

Window opening areas are distributed over three facades and the roof, giving potential of utilising both cross ventilation and stack effect as well as single sided ventilation. Solar shading and natural ventilative cooling is controlled by a building management system, opening and closing windows according to indoor temperature and outdoor climate.

Components used for ventilative cooling (see chapter 5 for examples)

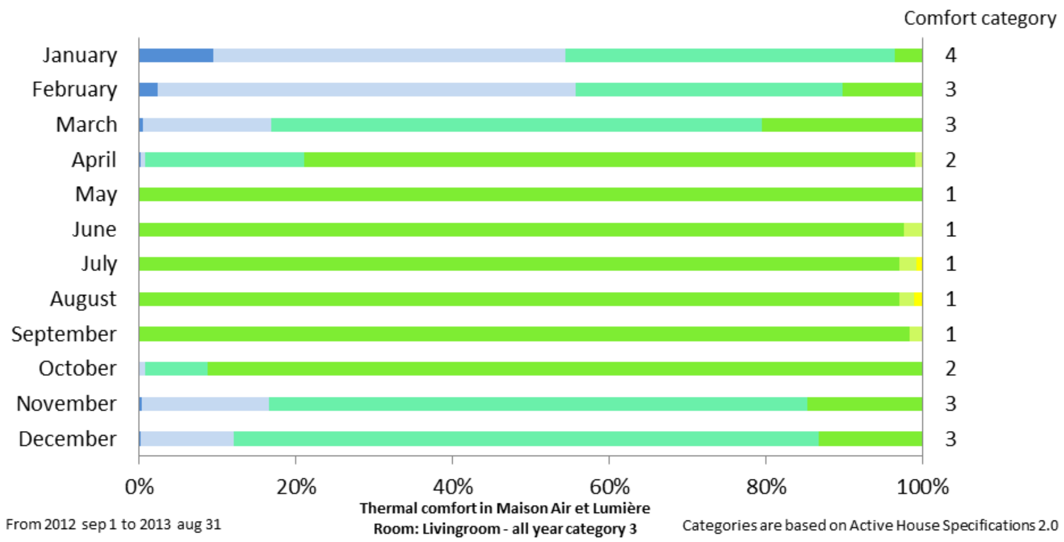
1. Integrated design of the building according to the needs of the inhabitants.
2. Operable windows.
3. External solar shadings.
4. Thermal mass.
5. Automatic control.

Control Strategies

The house is managed in such a way that electricity and heat are used to a minimum. In the summer, the automatically controlled natural ventilation is used to air the rooms providing good air quality and natural ventilative cooling. During the heating season, mechanical ventilation with heat recovery is used for air quality and natural ventilative cooling is used in case of over-heating. Intelligent control regulates the outdoor and indoor sun screening for optimising heat and light intake as well as switching off the light when the room is not in use. Feed-back on indoor air quality, temperatures, energy use etc to the users is provided by an information and control screen. The users can override all controlled elements, giving full personal control if wished.

Overall performance and lessons learned

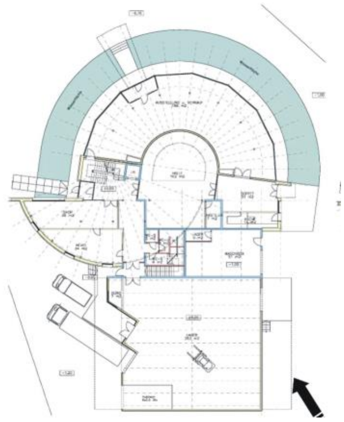
The building has been carefully monitored over one year of occupancy with a family of four. Maison Air et Lumière experiences no overheating in summer despite the large window area, which could have led to overheating. All rooms achieve EN 15251 category 1 (best) with regards to high temperatures during summer, based on the adaptive method of EN 15251. From November to March, between 15% and 50% of the hours fall in category 2 or 3 as the temperature is less than 21°C. Most of these hours is in category 2, between 20°C and 21°C. It is reasonable to assume that the family chose this temperature, as they could otherwise have increased the temperature with the heating system.



4.2.9 CHH-CHRISTOPHORUSHAUS

Building name	CHH - Christophorushaus	Year of completion	2001	Type of building	Multifunctional: offices, public areas and internal vehicle loading zone
Location	Miva, Stadl-Paura, Austria	Climate Zone	High heating load		
Net floor area	1,215 m^2 (offices)	Orientation of main facades	No specific orientation		
Design Team	*Tenant:* BBM Austria. *Architect:* Schmidt Dipl.Ing. Albert P. Böhm and Mag. Helmut Frohnwieser, Linz. *Engineering consultant:* AEE Intec, Gleisdorf. *Main Building contractor:* Bliek en Vos bv.				

Outside view of the building



Ground floor of the building

Site data

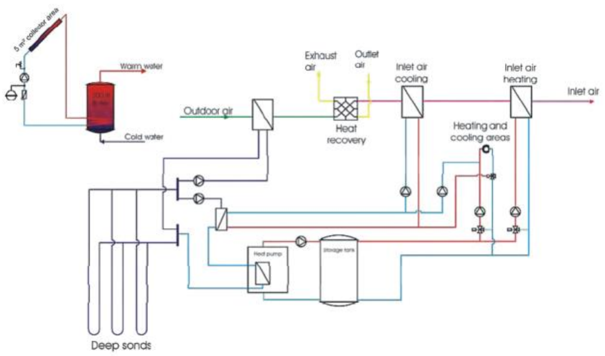
HDD		CDD		Developed environment	Dust pollution:	☐
No.	T_b	No.	T_b	○ Urban	Noise pollution:	☐
3,923	15	-	-	○ Suburban	High humidity:	☐
Altitude (m):		**360**		○ Rural	**Prevailing wind direction:**	**None**

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

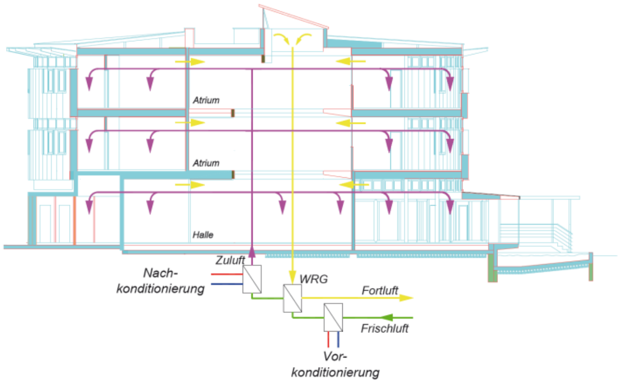
The building was designed to reduce energy demand to 'passivhaus' standards, with the remaining energy demand covered as far as possible from renewable sources, while providing occupants with a high standard of comfort. Heating loads were minimized by the use of a high level of insulation and limited glazing area with the aim of reducing heating consumption to 15 kWh/m^2. Infiltration losses were reduced by designing for an air tightness of 0.6 ach at 50 Pa. The air supply system incorporates heat recovery. In summer, cooling is provided by circulating water through the ceiling panels and heat exchangers in the air supply system. Additional reduction in peak summer temperatures is achieved by using high thermal mass inside the building and natural ventilation at night. Domestic hot water is served by 5 m^2 solar collector. Photovoltaic collectors on the façade and roof provide 9.8 kW_{peak} electricity

Principle of ventilative cooling

The office and seminar rooms are each served by a balanced mechanical ventilation system supplying 2800 m^3/h and 1000 m^3/h respectively. Each system is fitted with a rotary heat exchanger with efficiencies of 78% and 86% respectively. The seminar rooms are equipped with CO_2 sensors which allow the supply to be regulated to ensure that concentration does not exceed 1000ppm. Additional cooling is provided at night by natural stack ventilation through automatically controlled vents in combination with the internal thermal mass. The principles used are mechanical ventilation and night-time natural stack ventilation.



Schematic arrangement of the heating/cooling system



Schematic diagram of the balance mechanical air distribution system

Components used for ventilative cooling (see chapter 5 for examples)

Architectural components. High level of insulation and limited glazing area. Technical components. Airflow enhancing ventilation components: atrium. Mechanical ventilation system with heat recovery, cooling is provided by circulating water through the ceiling panels and heat exchangers in the air supply system. High thermal mass in the interior of the building and night-time natural ventilation.

Control Strategies

The building has a mechanical system to provide heating and cooling. Additional cooling is provided at night by natural stack ventilation through automatically controlled vents. In combination with the internal thermal mass, this assists in reducing the cooling load.

Overall performance and lessons learned

Indoor temperatures remained within the band 22°C and 23°C during the winter months and between 23°C and 26°C during the summer. The fresh air supply to the more densely occupied rooms was controlled by measuring the carbon dioxide concentration and ensuring that there was sufficient supply to maintain this below 1000 ppm. The results of a representative survey of 42% of the occupants indicate a very high level of satisfaction with the indoor environment.

Sensor-controlled lighting and shading devices are very efficient in ensuring optimum use of daylight. The use of a ventilation system controlled by CO_2 sensors provides a high level of air quality. It is important to ensure that the ventilation and heating systems are turned off during periods when the building is not occupied. Systems should be monitored on a 24 hour basis so that action can be taken by in the event of a problem occurring. Monitoring of the whole energy system is very useful to find out if the design of the building and its energy supply worked well.

4.2.10 EDIFICIO SOLAR XXI

Building name	Edifício solar XXI	Year of completion	2006	Type	Office& laboratory
Location	Lisbon, Portugal	Climate Zone	High cooling loads		
Net floor area	1500 m^2	Orientation of main facades	South		
Design Team	*Client:* INETI. *Tenant:* INETI – Renewable Energy Department. *Main Responsible and Coordinator:* Dr. Hélder Gonçalves. *Architects*: Pedro Cabrito and Isabel Diniz. *Engineering coordination:* Eng. Luis Alves Pereira. *HVAC project:* Eng. Manuel Nogueira. *Structural project:* Grepes SA. *Electrical Installations project*: Lomarisco Lda. *Construction:* Obrecol SA. *Photovoltaic systems*: Eng. António Joyce and Eng. Carlos Rodrigues.				

Outside view of the building

Site data

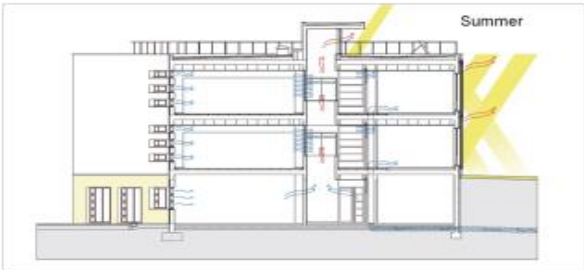
HDD		CDD		Developed environment	Dust pollution:	☐
No.	T_b	No.	T_b	◯ Urban	Noise pollution:	☐
1,727	20	85	24	◯ Suburban	High humidity:	☐
Altitude (m):		Sea level		◯ Rural	Prevailing wind direction:	None

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

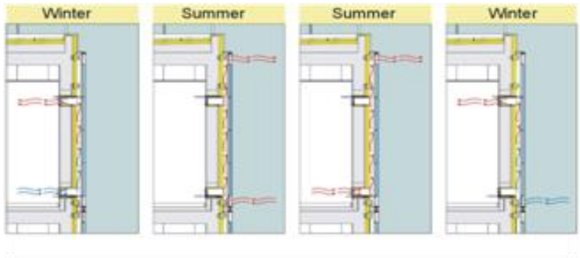
This building was created to make extensive use of solar exposure. The building provides high internal thermal capacity with 5 cm expanded polystyrene external insulation to reduce heat conduction gains and losses. Solar XXI has no active cooling system and a number of design measures are incorporated to reduce the summertime heat load. Venetian blinds were placed outside the glazing to limit direct solar gains. Natural ventilation during favourable conditions is promoted through the use of openings in the façade and between internal spaces, together with openable clerestory windows at roof level. When these methods are insufficient, incoming air can be pre-cooled by being drawn by small fans through an array of 32 underground pipes. Each pipe has a diameter of 30 cm, length of 20 m and is buried at a depth of 4.6 m.

Principle of ventilative cooling

Ventilation is provided by three methods: (i) natural ventilation; (ii) assisted ventilation due to convection phenomena from the photovoltaic panels heat losses and (iii) fan driven air drawn through a system of buried pipes.The openings in the different facades are designed to allow cross ventilation with adjustable openings above each door that connects south and north rooms to main corridor. Then the air moves up through the central lightwell and is extracted through openings in the skylight at roof level. The mounting of the photovoltaic panels is designed to assist ventilation of the south-facing rooms.The principles used are natural ventilation with mechanical assistance, pre-cooling through buried pipe system.



Cross and vertical ventilation systems acting together with the buried pipes system



Mode of operation of the photovoltaic panels to supplement ventilation

Components used for ventilative cooling (see chapter 5 for examples)

Architectural components: 5 cm expanded polystyrene external insulation to both walls and roof slab to reduce heat conduction gains and losses. Façade design to incorporate daylighting, shading and natural ventilation. **Technical components:** Airflow guiding ventilation components: openings in the façade and between internal spaces, openable clerestory windows at roof level, gap behind photovoltaic panels. Airflow enhancing ventilation components: small fans and buried pipes to pre-cool air.

Control Strategies

In addition to natural ventilation system, combined with high thermal mass, air is drawn through the buried pipe system. This is achieved by fans situated in each room on the south façade. Flow is adjusted by regulating the fan speed and the use of moveable doors. The main control is done manually, this is one of the possible methods of improvement commented below.

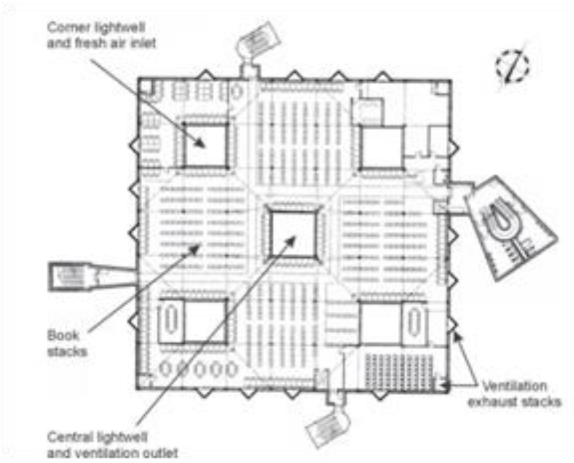
Overall performance and lessons learned

The energy needs for Solar XXI were assessed as 6.6 kWh/m^2 for heating and 25 kWh/m^2 for cooling, much lower than the required levels for regulations in Lisbon (51.5 kWh/m^2 for heating and 32 kWh/m^2 for cooling). In addition, the heating requirement is reduced by the hot-water solar panels and the cooling requirement by the use of the buried pipe system for pre-cooling. As regards electricity, only 30% of demand is drawn from the national electricity grid. Maximum mean temperatures are below 28°C and mean temperatures are close to 26°C, providing satisfactory comfort conditions. In winter, mean temperatures are always above 20°C, in accordance with Portuguese regulations. In all cases the concentration was below 600 ppm and in most cases below 500 ppm. In general, occupants were very satisfied with conditions in both summer and winter.It is important that occupants know how to operate shading and the inlet and outlet vents. A possible method of improvement would be the installation of an automatic control system that would respond according to indoor and outdoor conditions. Another option would be the extension of ground air cooling to serve the north-facing rooms.

4.2.11 FREDERICK LANCHESTER

Building name	Frederick Lanchester Library	Year of completion	2000	Type of building	Library
Location	Coventry, UK	Climate Zone	Moderate heating and cooling loads		
Net floor area	9,100 m^2	Orientation of main facades	No specific orientation		
Design Team	*Client:* Coventry University. *Architect:* Short and Associates.				

Outside view of the building | **Ground floor of the building**



Site data

HDD		CDD		Developed environment	Dust pollution:	☑
No.	T_b	No.	T_b	○ Urban	Noise pollution:	☑
2,284	15.5	18	18.3	○ Suburban	High humidity:	☐
Altitude (m):		80		○ Rural	Prevailing wind direction:	None

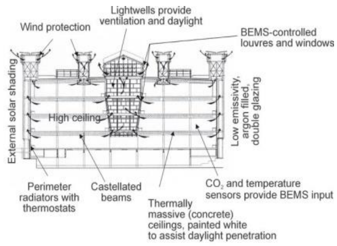
Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

Apart from a basement (12% of total gross floor area), the building is naturally ventilated. The deep plan of the building is broken up by multiple light-wells to provide both daylight and air flow paths. Heavyweight construction is used with exposed concrete ceilings. Apart from air-conditioning for the basement, summer temperatures are controlled by a combination of internal blinds, deep window reveals, fixed screens and night cooling by ventilation. High-frequency lighting is provided with daylight-linked dimming. The T5 luminaires have a 60%/40% split down/up distribution. Medium temperature hot water provided by high efficiency, non-condensing boilers, supplies perimeter heating (principally radiators) and pre-heats incoming air through the natural ventilation system, using trench heaters. The heating, lighting and ventilation installations are controlled by a BEM system using temperature and carbon dioxide sensors for each 6 m by 6 m zone throughout the building.

Principle of ventilative cooling

In order to provide natural ventilation, a tapering central lightwell provides extract ventilation, supplemented by 20 perimeter stacks with a 1.8 m by 1.8 m cross section. The stacks terminate 6 m above roof levels with fittings to prevent reverse flow due to wind pressure. Air entry is via a plenum under the ground floor to the base of four 6 m by 6 m square corner lightwells. Under the influence of stack effect air is drawn via the four corner lightwells into each floor and extracted via the central lightwell and the smaller perimeter stacks. In winter the incoming air is warmed by preheating coils at the base of the supply lightwells and by trench heating at the point that the air from the lightwells enters each floor. Cooling is provided passively by thermally heavy-weight exposed concrete ceilings.There is primarily natural ventilation, with air conditioning for separate basement. The cooling system is based in night-time free cooling.

(a)



Components used for ventilative cooling (see chapter 5 for examples)

Architectural components. Ventilation towers; **Technical components.** Airflow guiding ventilation components: windows and dampers controlled by the BEM system, light-wells to provide light and extract ventilation, plenum under the ground floor for air entry. Airflow enhancing ventilation components: Stacks of different sizes. Cooling is provided passively by thermally heavy-weight exposed concrete ceilings. Management system with actuators to control dampers and windows.

Control Strategies

The BEM system controls dampers and openable windows depending upon indoor and outdoor temperatures, wind speed and direction and internal carbon dioxide concentrations. The system incorporates a self-learning algorithm to estimate the need for overnight cooling. Over-cooling is prevented by monitoring slab temperature.

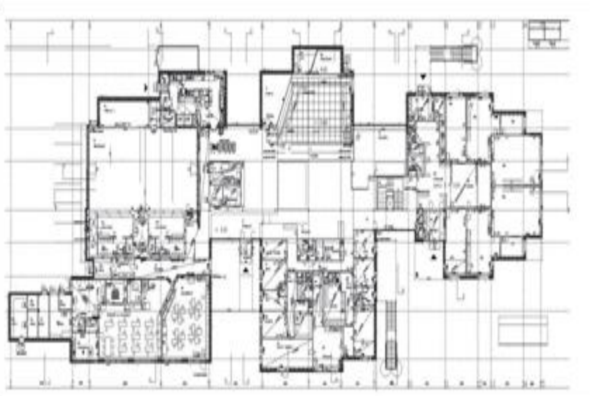
Overall performance and lessons learned

The total annual delivered energy consumption for 2004 was 198 kWh/m² with a breakdown as follows: (i) gas for space heating and DHW – 95 kWh/m², (ii) electricity – 86 kWh/m² and (iii) cooling (basement HVAC only) – 17 kWh/m². Consumption is considerably better than for air-conditioned buildings and comparable with good practice naturally-ventilated open-plan buildings. Air temperatures never exceed 27ºC during occupied hours. Carbon dioxide did not exceed 350 ppm above ambient during the measurement period, indicating that it would be fall within Category I according to EN 15251. Occupants are satisfied with conditions in the summer but are less so in the winter. Dissatisfaction is primarily with thermal comfort in the winter with complaints of cold and draught, particularly by occupants located on the north-east and north-west sides of the building. Areas which are occupied for longer periods of time could be co-located and access to other areas limited. This would enable night-time ventilation to be operated without affecting the comfort of night-time occupants. The performance in summer can be improved if air inlet dampers are closed down when the indoor dry-resultant temperature is below outdoor temperature. Carbon dioxide control can be used to override such closure if required. Consideration could be given to controlling the extent of opening of automatic vents on a seasonal basis. This would reduce the risk of over-ventilation in the winter, thereby reducing both energy consumption and the possibility of draughts. Experience has also shown that is important that facilities management staff are fully aware of the principles of the natural ventilation system and its controls.

4.2.12 POIKKILAAKSO SCHOOL

Building name	Poikkilaakso School	Year of completion	2001	Type of building	School
Location	Helsinki, Finland	Climate Zone	High heating load		
Net floor area	3,132 m^2	Orientation of main facades	No specific orientation		
Design Team	*Developer:* Helsingin kaupunki (City of Helsinki). *Tenant:* Helsingin kaupunki. *Architect:* Arkkitehtitoimisto Markus Lindroos ky. *HVAC Planning*: Climaconsult Finland Oy.				

Outside view of the building



Ground floor of the building

Site data

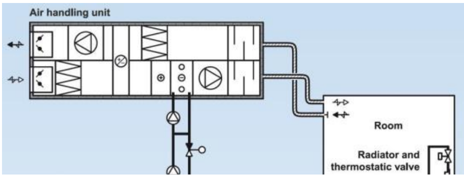
HDD		CDD		Developed environment	Dust pollution:	☐
No.	T_b	No.	T_b	○ Urban	Noise pollution:	☐
3,989	17	194	15	○ Suburban	High humidity:	☐
Altitude (m):	20			○ Rural	Prevailing wind direction:	None

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The building is connected to the Helsinki area district heating distribution system. Customers receive heat from the hot water circulating in the heating distribution network. The temperature of the district heating water varies usually between 65°C and 115°C for the supply and between 40°C and 60°C for the returning water, depending on the outdoor air temperature. In the summer the heat is needed only for the domestic hot water production. Heat extracted from the district heating network is used in the building for domestic hot water and space heating through the hot water radiators and central air handling unit. The Poikkilaakso School was a pilot project in which some elements typical for hybrid systems were combined with mechanical ventilation. The ventilation system is a fully mechanical low pressure system, having central air-handling unit including filtering, heat recovery, fans, heating coil and silencers. The aim was to achieve low heating and electricity consumption by using demand controlled supply ventilation to individual rooms, with air transferred via internal rooms to a single central exhaust and heat recovery between main exhaust and supply ducts.

Principle of ventilative cooling

The building has mechanical supply and exhaust ventilation system with heat recovery with AC fro computer rooms. An air handling unit mounted at roof level serves a large supply air duct on the roof, from which two vertical ducts lead to each classroom and terminate in displacement diffusers. There is a central extract duct from the main hall. The building serves as the return airflow route avoiding the need for suspended ceilings or visible ducts. The supply air is tempered and the principal source of heating of the rooms is by low temperature hot water radiators. Photo below shows the schematic layout of the heating and ventilation system. Air is heated and filtered in an air handling unit before it is supplied to the rooms. Mechanical ventilation, district heating and a small A/C system for computer rooms are used.



Schematic of heating and ventilation system


Main air supply duct at roof level.

Components used for ventilative cooling (see chapter 5 for examples)

Technical components. Airflow guiding ventilation components: Air handling unit on the roof, two vertical ducts for each classroom terminating in displacement diffusers, dampers for each classroom. Airflow enhancing ventilation components: speed-controlled fan. Management system with temperature, CO_2 and occupancy sensors in classrooms.

Control Strategies

Control of the ventilation is based on temperature, CO_2 and occupancy sensors. There are supply airflow dampers for each classroom and a speed-controlled fan keeps constant 50 Pa pressure in the main supply duct on the roof. Design ventilation flow rates were 3 l/s per m^2 in classrooms, 5 l/s per m^2 in the dining room and 2 l/s per m^2 in offices.

Overall performance and lessons learned

District heating energy use for space heating and domestic hot water was higher than expected for such a modern building with a demand-controlled ventilation system. Electrical energy use for lighting, HVAC and equipment was 63 kWh/m^2 which is slightly more than average electricity use in Helsinki schools of 52 kWh/m^2 Measurements showed relatively low air speeds. The exception was at 0.1 m, near the diffusers, where speeds of 0.25 m/s were measured. These are the limitations of displacement ventilation air distribution in crowded classrooms. Air temperatures remained between 21°C and 23°C for 55% and between 20°C and 24°C for 87% of occupied hours in heating season. In the cooling season temperature was below 25°C in occupied hours for the full measurement period. Indoor air quality was assessed as category II based upon the design ventilation rate of 3 l/s per m^2 and the use of very low polluting materials for up to an occupancy of 23 persons per classroom. A very high proportion of the occupants were satisfied with the internal environment. Some complaints of draught may be explained by occasional low temperatures measured in the heating season in some of the classrooms. The use of displacement ventilation air distribution was found to pose problems, because in the classrooms desks and small cupboards were placed directly near the diffusers, in some cases blocking 20 to 50% of the diffuser area. Previous measurements show that south façade classrooms overheated during hot periods. This is a result of poor solar protection and the lack of other relevant measures such as night ventilation cooling or air conditioning. All these operating problems have been solved in similar schools designed subsequently.

4.2.13 BOURNEMOUTH UNIVERSITY

Building name	Bournemouth University	Year of completion	2012	Type of building	Education
Location	Bournemouth, United Kingdom	Climate Zone	Moderate heating and cooling loads		
Net floor area	To be completed	Orientation of main facades	NA		
Design Team	*Client:* Bournemouth University, *Ventilation:* Monodraught Ltd				

Outside view of the building

Inside view of the Lecture room

Site data

HDD		CDD		Developed environment	Dust pollution:	☐
No.	T_b	No.	T_b	○ Urban	Noise pollution:	☐
2463	15.5	213	15.5	◉ Suburban	High humidity:	☐
Altitude (m):		40		○ Rural	Prevailing wind direction:	SW

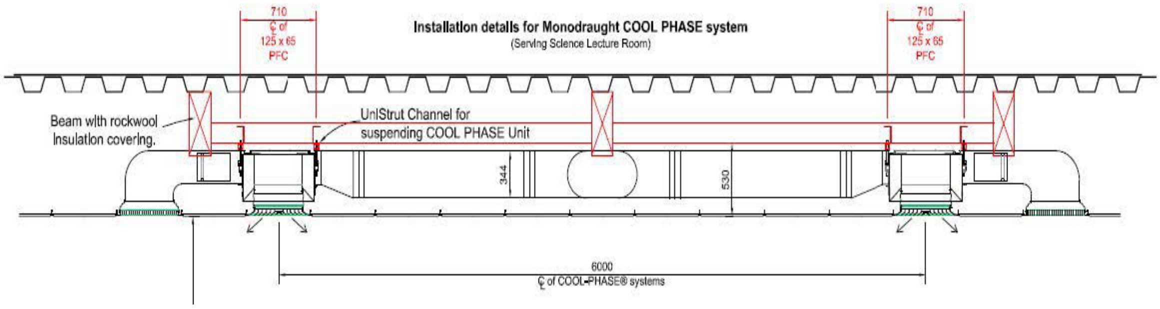
Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The principles used are ventilative cooling with natural driving force and night ventilation, using Phase Change Materials (PCM) and a low energy fan.

Principle of ventilative cooling

Two Monodraught Cool-phase systems were installed in the Science Lecture Room at the University; these provide ventilation and natural cooling via thermal batteries to maintain thermal comfort and air quality levels throughout the year.The Cool-phase system uses the concept of a 'Thermal Battery' consisting of Phase Change Material (PCM) plates within the ventilation path to capture and store heat. Therefore, the Thermal Batteries use the latent heat property of materials to store energy, which is charged and discharged by passing air through a heat exchanger.

Detail of the ceiling void with the Cool-phase unit installed



Cool-phase units installed in the ceiling void.

Components used for ventilative cooling (see chapter 5 for examples)

Technical components. Airflow guiding ventilation components: Two Cool-phase system units, consisting of an air supply duct, the air handling unit and the thermal battery module. Airflow enhancing ventilation components: Phase Change Materials used as Thermal Batteries and a controlled fan.

Control Strategies

The units are controlled to provide good air quality and comfortable temperatures during the year. A wall mounted user control with room temperature, humidity and CO_2 sensors is installed. The Cool-phase control system includes temperature and humidity sensors. The control has a master/slave mode to control multiple units in a single zone. PCM changes state from solid to liquid when exposed to temperature. During the day as warm air is passed over the PCM it absorbs thermal energy from the air to turn from a solid to a liquid thus cooling the air. Overnight as cooler air is passed across the PCM it releases the thermal energy it absorbed from the warm air during the day returning to its solid state. Thus providing a cooling cycle using only a low energy fan that is automatically controlled.

Overall performance and lessons learned

During 14 months of monitored data, the Cool-phase system has maintained a temperature within the rooms of less than 25ºC for the majority of the time, never exceeding 28ºC. CO_2 level is approximately 400 parts per million (ppm), never exceeding the 1000 ppm level. The two Cool-phase units installed used 138.5 kWh (electricity) during the monitoring period of 14 months. Assuming 0.11 £/kWh that amounts to £15.24 or an average of £0.25 per week.

4.2.14 CIT ZERO 2020 BUILDING

Building name	CIT Zero 2020 Building	Year of completion	2012	Type of building	Office Building (Retrofit)
Location	Cork Institute of Technology,	Climate Zone	Warm summer and mild winter		
Net floor area	222.5m^2 (TFA)	Orientation of main facades	W		
Design Team	CIT zero2020 research team – PROJECT CONCEPT DESIGN, Arup Engineers - PROJECT DESIGNERS & DESIGN TEAM LEADERS, Henry J Lyons - PROJECT ARCHITECTS, David McGrath & Associates - QUANTITY SURVEYORS, Summerhill Construction - MAIN CONTRACTOR, AMS Ltd – ENVELOPE MANUFACTURER				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
639	11	447	11	×	√	×	No	No	90%	Winter: S Summer: W	22

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The building is designed to act as an exemplar retrofit case study. It is a pilot project for the full building retrofit (30,000m^2). The concept was to deliver a low energy externally applied scalable retrofit solution that relied on passive ventilation techniques. Natural ventilation is utilised throughout with purpose provided ventilation openings. A high performance thermal envelope is employed to reduce thermal coupling to the external environment. The existing envelope is retained in place and provides an internal exposed thermal mass to stabilise internal temperatures. Interstitial blinds for solar shading with high performance glazing are also used throughout. The project sought to explore retrofit solutions given the constraints imposed when working with an existing building.

Principle of ventilative cooling

Single sided natural ventilation is the over-arching principle adopted due to the cellular nature of the existing internal layouts and constraints imposed regarding continued operation of the existing building. Large opening heights are employed to promote buoyancy forces in hot summer periods. Some instances of cross flow in the open plan office space. Cooling is available during occupied hours through the activation of the openings. A combination of manual and automated openings is available for increasing ventilative cooling. A night cooling strategy is available but has not yet been fully automated implemented. This is due to be activated in 2015.

Components used for ventilative cooling (see chapter 5 for examples)

In the retrofit space the ventilation module uses a *flush faced external louvre* with individual air inlet sections. Inside this louvre ventilation is supplied using *side hung, inward opening, dedicated insulated doors controlled either manually or automated* based on conditions in the enclosed spaces. These insulated doors are purpose provided ventilation openings and there are a number of operating configurations available with the individual opening sections split into low level and high level. The low level unit relies on manual operation by the occupants while the high level doors are controlled by an automated control system.

Control Strategies

There is currently a simple control strategy in operation at the building. There is one open and one closed position setting for the high level automated ventilation doors. The opening is activated on internal air temperature of 21°C within the zone being serviced. There are also actuation overrides based on external temperature conditions (< 15°C) to avoid over cooling during shoulder seasons. These set-point values are still being optimised. Manual night cooling has been implemented during previous summer months. The occupants can leave the low level manual doors open if they feel the office was uncomfortable that day. Night cooling is available on the control platform and is due to be implemented in 2015.

Overall performance and lessons learned

The retrofit project was completed in September 2012. In terms of recorded performance to date June 2013 was the warmest in 9 years. In June there were 26 hours with indoor air temperatures above 25°C. July 2013 had mean outside air temperatures well above average with the majority of national weather stations reporting their warmest July on record, with many observation lengths of over 50 years. During July the indoor air temperature in the building was generally above 28°C for 36 hours with 37% of the time above 25°C (based on 24hour time periods). August 2013 experienced temperatures on or above average everywhere with over half of the national stations reporting their warmest August in 5 to 27 years. Indoor air temperatures were above 23°C for 29% of the time with no recorded air temperatures above 25°C. Overall occupant feedback has been generally positive.

Ventilation rates have also been measured at the building with average ACH values between $2.3h^{-1}$ and $3.8h^{-1}$ depending on the opening configuration.

4.2.15 ENERGY FLEX HOURSE

Building name	Energy Flex House	Year of completion	2009	Type of building	Residential
Location	Taastrup ,Denmark	Climate Zone	Temperate		
Net floor area	216 m^2	Orientation of main facades	S		
Design Team	Henning Larsen Architects				

Outside view of buildings

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2909	17	-	26	-	√	-	No	No	90%	Winter: SW Summer: SE	10

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

EnergyFlexHouse comprises two identical buildings designed as very energy efficient (nZEB) single-family houses. The houses are designed in two stories with a large combined living room/kitchen at the first floor and sleeping as well as additional rooms below.

One of the houses is an inhabited “living lab” with main focus on the interaction between the end user and technology. To reduce overheating risk and cooling need the houses have a limited glazed area towards south, solar shading (external and internal), exposed thermal mass and natural ventilation with night cooling strategy.

Principle of ventilative cooling

The houses are equipped with different ventilation systems that are tested: Demand-controlled mechanical ventilation with heat recovery, demand-controlled natural ventilation with night cooling and mechanical free night-time cooling with cold recovery during the daytime.

The ventilative cooling design makes use of both cross and stack natural ventilation principles. Stack ventilation operates with lower air inlets located in two automatically openable windows in each end of the hallway in the ground floor, and upper exhaust openings located in two automatically openable skylights in the roof at the first floor. An open connection exist between the floors. Besides air can enter through manually openable windows in each room on the ground floor as well as on the first floor. Air moves from each room to the hallway and further to the large living room, located on the first floor.

The natural ventilation principle is combined with the night cooling strategy, which is activated during summer season.

Components used for ventilative cooling (see chapter 5 for examples)

1. Automatically openable windows in hallway (east and west facing) and manually openable windows in all rooms for air inlet.
2. Automatic openable skylights in living room for air outlet.
3. Mechanical exhaust in kitchen and bathroom
4. External solar shading.
5. Weather station monitoring outside air temperature, wind speed and wind direction to control degree of window opening.
6. Temperature and CO_2 sensor in all rooms.

Control Strategies

Natural ventilation is activated, when the indoor temperature reaches 24°C in summer and 25°C in winter and if the outdoor temperature is lower than the indoor. The night cooling is activated in summer if the indoor temperature is above 24°C and is stopped again, when the temperature becomes below 18°C.

The house is divided in 5 zones, where temperature setpoints for heating, cooling and solar shading can vary between zones depending on season and time of day. The automatic control overrules user settings twice a day.

Occupation sensors are used to determine is the house is occupied or not leading to different control strategies (energy strategy for unoccupied, comfort strategy for occupied periods). Skylights close when it is raining and automatic façade windows closed for wind speeds above 7 m/s on the façade (± 90 degrees). This means that one of the windows can always be open.

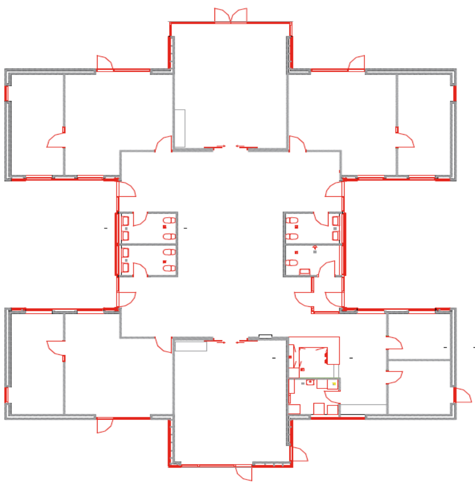
Overall performance and lessons learned

Final report is under development and is expected to be completes by the end of 2015.

4.2.16 PIREHUSET

Building name	Spirehuset	Year of completion	2005	Type of building	Kindergarten
Location	Søndergade 20 A9850 hirtshals, DenmarkDenmark	Climate Zone	Temperate		
Net floor area	500 m^2	Orientation of main facades	Square		
Design Team	Bjerg Arkitektur A/S				

Outside view of building | **Building Plan**



Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2909	17	-	26	-	√	-	No	No	90%	Winter: SW Summer: SE	10

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The building is naturally ventilated, except for toilets and kitchen, which have a mechanical exhaust. As part of the natural ventilation design, there are a number of windows in the roof. These not only provide openings for the air to leave the building but also provide natural lighting.

Roller blinds are installed in the windows as an option for internal shading. However these are rarely used, as the shape of the building protects the large glazing areas from direct solar gains.

Principle of ventilative cooling

The design of Spirehuset makes use of both cross and stack natural ventilation principles. Stack ventilation operates with lower air inlets located in the windows, at a normal window height, and upper exhaust openings located in the roof. The air enters smaller zones, on the periphery of the building. Air moves from these to the large common room, located in the centre. To encourage the stack effect, the roof of the common room is designed to be higher than those of the other rooms.

The natural ventilation principle is combined with the night cooling strategy, which is activated during warmer seasons.

Components used for ventilative cooling (see chapter 5 for examples)

1. Automatic openable windows in all rooms for air inlet.
2. Automatic openable skylights in central room for air outlet.
3. Internal roller blinds for solar shading.
4. Weather station monitoring outside air temperature, wind speed and wind direction to control degree of window opening.
5. Temperature and CO_2 sensor in all rooms

Control Strategies

Natural ventilation is automatically controlled, but users have a possibility for manual control (opening windows) and can change the control strategy in the building, if needed. If the air temperature in a smaller zone exceeds the set point, then the roof openings in the centre zone are also activated to provide exhaust openings.

Pulse ventilation is used; windows are opened automatically for short periods (180 seconds) according to a time schedule. The degree of opening of the windows depends upon wind direction and outside temperature, which are monitored as part of the control system. In addition, the building is subdivided into 11 thermal zones, in each of which the air temperature is monitored. If the air temperature exceeds a maximum set point, windows are opened outside of schedule for pulse ventilation.

Night cooling is automatically controlled according to set point for air temperature in the building. Minimum air temperature for night cooling is fixed at 18°C and average air temperature is set to 23°C.

Overall performance and lessons learned

Long-term measurements taken from the automatic control system through a year, in general showed a satisfactorily level of the air temperature. The average number of occupied hours with a temperature above 26°C was found to be below the 100 hours required by the Danish regulations. Excessive temperatures were found in one zone but only when occupancy levels exceeded the design level by 200%.

A questionnaire survey was carried out to determine the occupants' perception of the indoor environment. The survey shows that occupants are generally very satisfied with the environment in the summer and slightly less satisfied in winter. A possible reason is a combination of the situation of work desks beneath roof windows and a lack of air tightness or high U-value of these windows, giving rise to draughts.

4.2.17 RIJKSWATERSTAAT BUILDING

Building name	Rijkswaterstaat building	Year of completion	2000	**Type of building**	Office
Location	Terneuzen, Netherlands	Climate Zone	Moderate heating and cooling loads		
Net floor area	1,750 m^2	Orientation of main facades	No orientation		
Design Team	Tenant: Netherlands Ministry of Transport. Architect: opMAAT duurzame architectuur en systeemontwikkeling, Delft.				

Site data

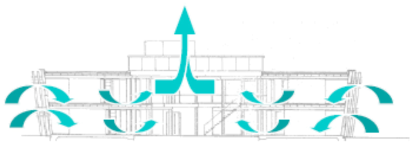
HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2863	**18**	**-**	**-**	**-**	**-**	**-**	**No**	**No**	**yes**	**Winter: SW Summer: SE**	**10**

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

This is a sustainable and ecological building, integrated with its surroundings and providing a high level of individual control and comfort for occupants. Sustainable materials, principally wood, were used in the construction of the building and a high level of insulation was provided. The adjacent canal water is used as the source for a heat pump which supplies a low temperature wall and under-floor heating system. The layout of the building is designed to make best use of natural lighting and, in winter, solar gain for passive heating. In summer, heat gain is reduced by the use of external shading and its effects reduced by the provision of thermal mass in the walls and ceilings in conjunction with night ventilation. The building is naturally ventilated, using a system with electronically-controlled inlet openings. Domestic hot water is supplied by a solar collector and 54 m² of photovoltaic cells contribute to satisfying the electrical load.

Principle of ventilative cooling

The external walls incorporate openable widows and inlet vents. In winter, the building management system controls the vents in the external wall to ensure a constant flow rate during occupied hours and to close the vents overnight. In summer, the flow of air can be increased by the manual opening of windows. The building management system allows the inlets to be open overnight to provide cooling. Sound-proofed openings in the internal walls provide an air flow path to the atrium. Air is extracted from the atrium via a 7 m tall 'chimney' with a diameter of 1 m. The location of the 'chimney' in a low wind pressure region, combined with stack effect, is designed to give a flow pattern as shown in the following figure. The principles used are ventilative cooling with natural driving force and night ventilation.



Components used for ventilative cooling (see chapter 5 for examples)

Architectural components. Sustainable materials providing a high level of insulation. Thermal mass in the walls and ceilings. **Technical components.** Airflow guiding ventilation components: manual windows, sound-proofed openings in the internal walls. Airflow enhancing ventilation components: atrium with chimney. Management system with actuators to control vents in order to achieve a constant air flow.

Control Strategies

An advanced natural ventilation system provides fresh air and assists in controlling thermal comfort in summer. In winter, the building management system controls the vents in the external wall to ensure a constant flow rate during occupied hours and to close the vents overnight. Occupants have the facility to over-ride the automatic system if required. The potential for draughts from the inlet vents is reduced by the provision of perforated shelf with 100 mm borders immediately under each inlet. In summer, the flow of air can be increased by the manual opening of windows. The building management system allows the inlets to be open overnight to provide cooling.

Overall performance and lessons learned

The total measured electrical energy consumed by the building over one year was 43.7 kWh/m² per annum. This was distributed as follows: heat pump, for heating – 32.0 kWh/m² per annum; lighting – 11.4 kWh/m² per annum and domestic hot water – 0.3 kWh/m² per annum. The performance of the Rijkswaterstaat building with a total primary energy consumption of 730 GJ/annum is substantially better than the reference case in the Netherlands, 1 270 GJ/annum. No overheating was found in summer for moderate conditions (i.e. external temperature in the range 10-15 °C; cloudy sky). Some overheating in the south orientated offices during the afternoon but this only occurred for a restricted period of time when the shading device in the atrium was not installed. In winter, for medium occupant activity and average winter clothing, the measurements in all office rooms, except one, and the atrium showed a high level of satisfaction (-0,23< PMV < +0,02). During working hours concentrations of CO_2 increased from a baseline level of 360ppm to between 400 and 600ppm with occasional peaks of between 700 and 850. The occupants perceive the building and the indoor climate as pleasant and have substantially fewer complaints than those in other buildings with a similar use. Although the building performs well, with an annual primary energy consumption of 57% of the reference building, energy saving is less than the 46% predicted by simulation at the design stage. Difficulties were experienced in sourcing sustainable materials (wool, loam plaster, wood) of a sufficiently high quality.

4.2.18 LIBRARY OF SHANDONG JIAOTONG UNIVERSITY

Building name	library of Shandong Jiaotong University	Year of completion	2003	TYPE OF BUILDING	Library
Location	No. 5001, hai-tang Road, jinan, Shandong Province, China	Climate Zone	Cold		
Net floor area	22666.76m^2	Orientation of main facades	WE		
Design Team	BEIJING TSINGHUA ANDI ARCHITECTURAL DESIGN CONSULT CO.,LTD SCHOOL OF ARCHITECTURE OF TSINGHUA UNIVERSITY				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
1757	18	170	26	√	×	×	No	No	56%	Winter: ENE Summer:SSW	117

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The building utilizes the central atrium of the library and three draught chimneys at the top of the atrium to produce the thermal pressure drawing effect to enhance natural ventilation, and reduce air conditioning time. Also two tunnels underground are set up in the building, one north and one south; each tunnel in the terminal has two branches, respectively, and passes into the library from 1st to 3rd floors, there are 6 fresh air rooms, and tunnel ventilation system only supplies for air preheating/precooling requirements from 1st to 3rd floors.

Principle of ventilative cooling

In this building, thermal pressure ventilation and tunnel wind are fully applied to reduce the time span of the air-conditioning switched. The doors and windows inside and outside are opened in transition season, the atrium top draught chimney is used to introduce outdoor air from 1st to 4th floors, creating a good indoor thermal and humidity environment. The two traffic nuclear enclosed staircases on the eastern side of the library between 5th and 6th floors are set as ventilation shaft to pull the wind. The doors and windows are closed in summer and winter, and the tunnel wind is used to precool (in summer) and preheat (in winter) fresh air which is imported to 1st to 3rd floors.

Components used for ventilative cooling (see chapter 5 for examples)

1. The draught chimney: the black heat collecting material is arranged on the top of the chimney, so as to improve the heat absorption of the chimney tops, and strengthen the effect of heat pressure.
2. Electronically controlled shutter grille: it is adopted in atrium air curtain wall.
3. Tunnel: the summer wind tunnel air temperature ranges from 22 to 27℃ (consider fan temperature rise) , and the vast majority of time meet the fresh air supply air temperature requirements; winter tunnel wind temperature range from 8 to12℃,wind tunnel can preheat fresh air; transition seasons for supply air temperature in tunnel wind ranges from 13 to 20℃,by increasing the quantity of fresh air to the indoor temperature.

Control Strategies

In transition season: the inside and outside doors and windows are opened, the atrium top draught chimney from 1st to 4th floor is used to introduce outdoor air, creating a good indoor thermal and humidity environment. The two traffic nuclear enclosed staircases on the eastern side of the library between 5th and 6th floors are set as ventilation shaft to pull the wind.

In summer: the doors and windows are closed, the low temperature wind tunnel introduced into indoor in 1st to 3rd floors, hot air gathered in top atrium of 1st to 3rd floors is derived by the chimney, and the 4th to the top floor adopts air conditioner.

In winter: chimney opening of top atrium is closed; wind tunnel is used to preheat fresh air of 1st to 3rd floors; the whole building adopts air-conditioning system.

Overall performance and lessons learned

The cooling effect of wind tunnel in summer proves significant, and tests show that the decrease of average temperature can reach 8℃ when the outside temperature is higher than 30℃; The cooling ability of tunnel wind can solve the 90% of fresh air load; Natural ventilation in summer at night can realize thermal pressure ventilation of 2.5-3.5 times /h, the cooling effect is about 1.5℃ and cold storage capacity is about 90kW.

4.2.19 FANSHION EXHIBITION CENTRE OF GREEN BUILDING

Building name	Franshion Exhibition Centre of Green	Year of completion	2014	Type of building	Exhibition building
Location	No. 850, Lu-jing Road, changsha,Hunan Province, China	Climate Zone	Hot summer and cold winter		
Net floor area	12125.15m^2	Orientation of main facades	SSE		
Design Team	SHANGHAI JIANKE ARCHITECTURAL DESIGN INSTITUTE CO.,LTD				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
1570	18	360	26	√	×	×	No	No	90%	Winter: NNW Summer: SSE	39.8

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The concept of passive building design with variable shape coefficient has been used in the building. The building shape coefficient can be changed by opening or closing the windows of concave balconies during different seasons for decreasing cooling demand. As demanding air-conditionings, the windows of concave balconies will be closed. Thus, all concave balconies belong to the indoor air-conditioned transition zone, which can reduce the surface area of external wall and plenty of heat loss. In transition seasons, the windows of concave balconies will be opened, and then the concave balconies directly connect with outdoor. And the concave balconies belong to outdoor which leads to the external surface area increased for effective natural ventilation. Indoor thermal comfort can be adjusted well by the natural ventilation.

Principle of ventilative cooling

In this building, natural ventilation is fully applied to reduce the time span of the air-conditioning switched. Air-conditionings turn on as the indoor temperature is higher than 28 ℃, and contrarily air-conditionings turn off. In Changsha, air-conditionings usually open in June, July and August because it is very hot and humid. The windows of concave balconies usually open in the transition seasons such as May and September, which might increase the area of heat transfer and the ventilation opening area, simultaneously reduce the building depth. Thus, during May and September, natural ventilation, approximately more than 30 days, will meet the demand of thermal comfort.

Components used for ventilative cooling (see chapter 5 for examples)

1. The concave balcony. The building shape coefficient will be changed in different seasons by opening or closing the windows to reduce the energy demand of building.
2. The electric sunshade glass louver with thermal insulation function. It can increase the ventilation opening area and reduce the building depth.
3. Lots of windows install in front and back of the building, and the windows facing the prevailing wind direction.
4. Green roof and vertical greening. The roof of building designs as garden, and some lianas climb on the west wall as vertical greening.
5. Energy efficient fan. The energy-saving fan is used, and the ventilation air-change rate is about 12 times per hour.

Control Strategies

The electric sunshade glass louver with thermal insulation function is designed for the concave balcony. It makes the building shape coefficient variable. The electric sunshade glass louver interlinks with air-conditioning system. The louvers automatically shut down as air-conditionings system turn on.

1. Turn on: In spring and autumn, the natural ventilation could be used as only way to cool down the building. The louver will automatically be opened for better natural ventilation. At the same time, the building's external surface becomes equally larger, and the building shape coefficient is 0.21.
2. Turn off: During winter and summer, indoor air conditionings turn on, and the glass louvers automatically shut down. The external area of surface reduced, the volume becomes larger. At the same time, the building shape coefficient changes into 0.16.

Overall performance and lessons learned

The natural ventilation has been used as the indoor temperature is below 28 degrees in May or September, and air conditionings will turn on as the indoor temperature is above 28℃. Natural ventilation has been used many days in the transition seasons since changeable of building shape, hence the time of using air conditioning could be shorten and the energy will be saved about 5.2% every year.

4.2.20 VANKE CENTER

Building name	Vanke Center	Year of completion	2009	TYPE OF BUILDING	multifunction
Location	No.33 Huangmei Road Yantian, Shenzhen,	Climate Zone	Hot summer and warm winter		
Net floor area	121,300m^2	Orientation of main facades	SE		
Design Team	Steven Holl Architects and CCDI				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b							
384	18	492	26	√	×	No	No	82%	Winter: NE Summer: SE	1

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

In order to maximize the area available for gardens beneath and then create a good natural ventilation environment, the structure spreads out under the 35 meter height limit on the site, which was supported on eight cores to 15m by using bridge-building technology and a concrete frame to maximize the area available for gardens beneath, create views over the lower development of surrounding sites to the South China Sea. Viewing from the plane, Vanke Center is similar to 'Dendritic' shape with the function of reducing the impact on natural light, blocking off strong light and reducing the impact on natural ventilation simultaneously. The louver system was designed to utilize buoyancy-driven ventilation.

Principle of ventilative cooling

1. Natural ventilation: The building main facade faces the southeast across the prevailing wind direction, forming a larger wind pressure differences between the windward side and the leeward side. Each floor of the building can keep 2~4 Pa of wind pressure differences and improve indoor ventilation environment. At the height of 1.5m (above the terrain), the wind velocity around the human activity region is approximately 1~3m/s and the air age is under 300s in the most regions.
2. Louver system: the louvers with a double appearance can formulate a channel that can generate chimney effect. Therefore, cold air flows into the building from the bottom and then exhausts hot air through the roof of the building.

Components used for ventilative cooling (see chapter 5 for examples)

1. Natural ventilation of ground open floor: The horizontal skyscraper was propped up by eight legs, leaving the structure about 15 meters higher than the ground to create a continuous large space and generate the largest possible green space open to the public on the ground level. Thus, it can satisfy people of fresh air in the leeward area and regulate microclimate as well.
2. Underfloor air distribution: in order to satisfy the design requirements of thermal comfort, the underfloor air distribution system was installed.
3. Sunshade system: To satisfy the indoor light and temperature requirement, the louvers was designed according to the bamboo leaves and glass curtain wall with fixed horizontal exterior shading louvers, fixed vertical exterior shading louvers and electric sunshade louvers was established.
4. Cooling pond and reclaimed water system was installed for cooling the environment.
5. Green roof can cool the environment and increase the humidity of the atmosphere environment by creating a microclimate.

Control Strategies

Based on the solar heat absorption of each facade, the louver system was designed. In order to save energy, the automatic louvers can be adjusted according to the direction of the solar. When the porous louvers are closed, the system is mainly used to provide enough natural light. The fresh air system of the underfloor air distribution is controlled by the concentration of CO_2.

Overall performance and lessons learned

1. The microclimate with convection ventilation has been created by the bottom overhead, which can meet the demand of thermal comfort at the height of pedestrian level in the most regions. To improve wind environment effectively, gibbous landscape should be arranged in the place where there is bad wind environment.
2. The sunshade louver system have been established with the function of ensuring the best state of light and temperature distribution and protecting the glass facade of the building against the sun and wind .The window opening rate could be 30% to realize good natural ventilation.
3. Good performance, including flexibility, adaptability, economic benefits, energy saving, better comfort level and IAQ, has been realized through the underfloor air distribution system.

4.2.21 SHANGHAI ECO-HOUSING

Building name	Shanghai Eco-Housing	Year of completion	**2010**	**TYPE OF BUILDING**	**Residential**
Location	No. 564, south railway Station Road Lu-jing Road ,Shanghai, China	Climate Zone	**Hot summer and cold winter**		
Net floor area	3147m^2	Orientation of main facades	**SN**		
Design Team	East China Architectural Design & Research Institute				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
1648	18	203	26	√	×	×	No	No	85%	Winter: NNW Summer: ESE	4

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating are mainly manifested in the following aspects：

The "Shanghai Eco-Housing" was designed to cater to the dominated summer monsoon direction in Shanghai, former north to south and strip layout. Cross-ventilation in summer can effectively reduce the indoor temperature and decrease cooling demand.

There was a distance of the balcony between every two layers from the second floor. it can form shading effect on the building structure and then can reduce cooling load to a certain extent.

Principle of ventilative cooling

1. Night ventilation. Night ventilation has been used as the outdoor temperature is below 28℃ and velocity is below 7 m/s during the not rainy summer night (20:00~7:00).
2. Wind cooling by ambient water surface. In spring and autumn the airflow was cooled by running through the vertical plants and landscape pond outside the south semi-basement then enter into the building through the opened windows.
3. Natural or mechanical driving forces. The building was arranged in the north-south direction to cater to the summer prevailing monsoon and multiple horizontal airflow corridors was set running through the "Ecological nuclear" atrium. Under the effect of thermal pressure the airflow went up along the atrium. Windows were designed on side of the top of the atrium as the outlet, combining the mechanical fans to increase the efficiency of natural ventilation. In addition, the elevators with potential energy recovery and variable speed function activated the movement of the airflow as they moving up-and-down.

Components used for ventilative cooling (see chapter 5 for examples)

1. Green roof and vertical greening. The roof was designed as garden, and some lianas climb on the west wall as vertical greening.
2. Wind inducing wall. The underlying waiting area was picked an empty to form a north-south ventilation corridor. In order to overcome the shortcoming of insufficient bottom wind pressure, fans were arranged above the ventilation channel and wind inducing wall was built in the north toward the group.
3. The electrical sunshade double window. It could adapt to a variety of climatic conditions, which is consist of inside and outside window, both can be opened or closed.
4. Recycling old brick wall. The wall blocked solar radiation heat gain and forms vertical ventilation in the cavity by chimney effect to reduce cooling load in summer, and prevented air convection to store heat by the greenhouse effect in winter.
5. Ecological nuclear atrium. The atrium was designed in the north of the building and unit module greening was set on the basis of rotating upward wind direction to promote airflow and adjust the indoor microclimate. Besides windows were designed as the outlet on side of the top of atrium, combining the mechanical fans to increase the efficiency of natural ventilation.
6. The roof with opening and closing functions. The state depends on outdoor meteorological conditions.

Control Strategies

The natural ventilation has mainly been used during summer nights (20:00~7:00) and the transition season. In the transition season, the controllable windows would be opened when outdoor temperature is in 16~28℃ and the dew point temperature above 16℃, also the weather is not rainy or snowy. Similarly, in summer night the windows would be opened as outdoor temperature is below 28℃ and the weather is fine.

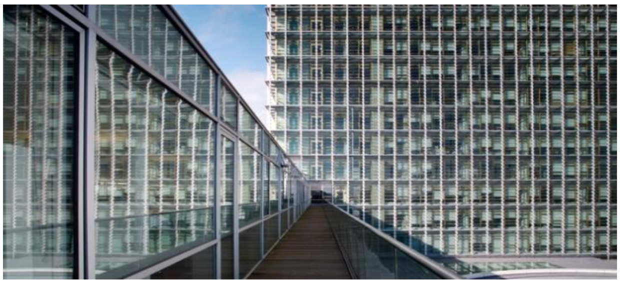
Overall performance and lessons learned

The building was arranged in the north-south direction to cater to the summer prevailing monsoon and multiple transverse airflow corridors were set, so cross-ventilation can effectively lower the indoor temperature.Vertical mechanical ventilation devices were installed in the stairs space and the top of the ecological atrium, which could strengthen the indoor vertical air flow and provide fresh air for the atrium.

4.2.22 CORK COUNTY HALL

Building name	Cork County Hall	Year of completion	2006	Type of building	Office Building
Location	Carrigrohane Rd,	Climate Zone	Warm summer and mild winter		
Net floor area	16,000m² (TFA)	Orientation of main facades	E/W		
Design Team	Arup Engineers - Project Engineers; Shay Cleary Architects – Project Architects;Bruce Shaw Partnership – Quantity Surveyors;BAM Construction - MAIN CONTRACTOR				

Outside view of building



Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2044	15.5	15.5	15.5	×	√	×		√	90%	Winter: S Summer: W	7

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

Introduction of an automated double skin façade using glass cladding installed externally to the existing 1960's concrete and window envelope. This provided improved solar protection reducing incident solar radiation and also enhanced the control aspect of the façade enabling night cooling as a strategy as well as removal of heat build-up in summer months. The external louvers incorporated a 'hard' coating to reduce the 'g' value (solar transmission reduced). This improved thermal performance.

Principle of ventilative cooling

The primary principle of ventilative cooling relies on single sided ventilation primarily. The external operable glazed louvers protects the natural ventilation openings from wind and rain which allows the windows to be opened in any weather conditions. The tall building can get very windy at the upper floors and the new external louvers make it possible to achieve effective natural ventilation. On the west façade, the effects of evening solar gain can be mitigated through 'free' cooling through the night.

Components used for ventilative cooling (see chapter 5 for examples)

The components used in this ventilative cooling application include:

Automated external glass louvers

Actuation devices

Manual and automated Window components

Control Strategies

The control strategy relies on monitoring of external wind speeds, rain precipitation & air temperature. When conditions are acceptable the internal temperature then determines the level of cooling ventilation. Night cooling is also implemented and is controlled on air temperature.

In Summer operation before 12 noon louvres on the east façade track sun and reflect excessive solar gains away from the building while louvres on the west façade are open. After 12 noon the functions are reversed respectively. In winter louvres are open to allow beneficial heat gains into the building during the daytime. Rain sensors drive the external façade louvres to the 45 degree position when protection is required. Finally the louvres close when outside air temperatures are less than 6°C or wind speeds are greater than 10 m/s.

Overall performance and lessons learned

The project has been a major success in rejuvenating an old 1960's high rise naturally ventilated building. The old façade had no thermal retention properties. In effect, its thermal performance was similar to a greenhouse. Now the building has superb thermal insulation performance, and can avail of natural ventilation and free cooling without having paper on desks blown all over the floor! The natural light levels are much improved, with reduced glare while eliminating artificial light during the day on all perimeter offices. The operation and maintenance of an active façade is considerable. While providing a passive role in maintaining a comfortable indoor environment, it is important to keep the client informed of the need to provide adequate resources to maintain the louver actuators and clean the glass. The appearance of the building is very appealing, and the new façade will give this old building a new life for at least another 50 years.

4.2.23 CASACLIMA IN BERNATE

Building name	CasaClima in Bernate	Year of completion	2013	Type of building	family house
Location	Bernate Ticino, Milano ,ITALY	Climate Zone	Hot summers, cold winters		
Net floor area	305 m^2	Orientation of main facades	NW-SE		
Design Team	Progettista L.G., Progettista CasaClima O.P.C				

Outside view of building

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2.673	20	150	26	×	√	×	No	No	90% summer	none	130

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The building was designed according to bioecological criteria, with very low energy consumption levels even in absence of a mechanical ventilation system. The building uses a radiant wall system, requiring lower temperatures compared to traditional systems, while a proper hygroscopic behaviour is guaranteed by the large natural wooden surfaces plastered with natural clay and including the heating panels in clay.

The upper floor protrudes on the ground floor in order to shade the large window surfaces. At the upper floor an external shading system was adopted (external lamellae). The building is mainly made of X-LAM panels, with thick load-bearing walls (30.6 cm, λ=0.08W/mK) externally insulated with an additional layer of 12 to 17 cm of wood fibre panels (fir wood and kenaf). The layers are connected by means of wooden dowels and nails, without using metallic elements or glues. The total transmittance value is between 0.12

and 0.18 W/m^{2}K. The south-west façade presents a ventilated cavity in order to enhance the wall transpiration and so improve the thermal behaviour during the cooling season.

A thin-film (or membrane) PV system is integrated in the flat roof. The window disposition at the ground floor and the upper floor has been designed in order to increase the potential for cross-ventilation. The building has successfully passed the blower door test (air change rate below 0.6 h^{-1}at 50 Pa).

Principle of ventilative cooling

No mechanical ventilation systems are used, since the cooling strategy is based on natural ventilation and a high thermal wave shift (>12 hours) thanks to the thick walls.

A dehumidification system has been considered necessary in order to cope with the high humidity levels in summertime. A covered balcony at the upper floor smoothes the external temperature variations when windows are kept open during the mid-seasons. Cross ventilation and ground cooling are exploited.

Components used for ventilative cooling (see chapter 5 for examples)

Several windows installed at the southern façade for the exploitation of solar gains in the winter time and windows on all sides to enable cross-ventilation in the summer time.

A green roof at the upper floor helps cooling down the building by evaporate transpiration.

A fan coil dehumidification system is used during the cooling season.

Control Strategies

The floor overhangs limits the shading period to the hot hours when the sun is at the zenith. The shading at the first floor is guaranteed by an external lamellae system, activated by external light sensors.

The building is conceived to maximize the efficiency of the envelope, while a geothermal heat pump coupled with a radiant wall system provides the remaining heating and cooling need. The building makes use of natural ventilation and thermal inertia. Foundations are also ventilated to offer additional heat storage.

Overall performance and lessons learned

The challenge consisted in the construction of a 'climate-sensitive' building that uses the thermal mass of the envelope while reducing considerably the need for active heating and cooling.

It uses natural materials such as wood and clay to create a healthy and comfortable indoor environment. The energy autonomy is guaranteed by a PV system and a geothermal heat pump for the domestic hot water. It uses exclusively materials with a low environmental impact on the basis of a Life Cycle Assessment. It reaches very low levels of energy consumption (being actually a ‘positive energy’ house), while the CO_2 balance shows that over its life cycle the building absorbs more CO_2 than the CO_2 emitted for its construction, operation and dismantling. In fact, 85% of materials used are bioecological or recycled, obtaining the certification “CasaClima Nature” according to CasaClima certification.

4.2.24 BASISSCHOOL KA ETTERBEEK

Building name	Basisschool KA Etterbeek	Year of completion	2012	Type of building	School building
Location	Edmond Mesenslaan 2, 1040 Etterbeek,	Climate Zone	moderate		
Net floor area	924.7 m²	Orientation of main facades	SW		
Design Team	evr-architecten (architect), 3E (energy expert: design to operational phase), Istema (HVAC systems), Fraeye and Partners (structural engineering)				

Outside view of buildingSite data

HDD		CDD		Urban	Suburban		Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2363	16.5	296	16.5		√		No	No	No	SW	

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

The building is designed according to the Passive House Standard. The building is compact, has an intelligent orientation and zoning, an excellent insulation and air tightness of the envelope, a qualitative ventilation system and a well thought solar shading.

The school building is located on a site with tall broad-leaved trees giving natural shading in intermediate and summer season. Moreover the large South-Western glazed façade is completed with a large overhang and randomized integration of opaque panels.

The building has a medium to heavy thermal capacity, which is accessible. The balanced mechanical ventilation system with heat recovery has a summer bypass for free cooling. This ventilation system is also used at night to ensure good thermal comfort.

Principle of ventilative cooling

Night ventilation with mechanical driving forces. Maximum air flow rate is 5535 m^3/h for a total conditioned volume of 3321.1 m^3.

Components used for ventilative cooling (see chapter 5 for examples)

1. Air handling unit (balanced mechanical ventilation system) with summer bypass
2. Building management system, including sensors (temperature, weather station,…)

Control Strategies

The summer bypass is activated if indoor temperature exceeds 23°C and outdoor temperature is smaller than the indoor temperature.

Night ventilation is activated when indoor temperature at night exceeds 22°C and indoor-outdoor temperature difference is larger than 2°C.

Overall performance and lessons learned

Adjustment of the control system of the HVAC systems between installation and completion as well as after occupation is very important to guarantee a good comfort in the building. The more complex the systems are by optimizing and fine tuning the control systems, the less robust they seem to be. It is difficult in practice to detect and solve all these faults and failings.

4.2.25 LIXIL PASSIVE FIRST PAVILION (GALLERY)

Building name	LIXILPassive first Pavilion (Gallery)	Year of completion	2014	Type of building	Exhibition house
Location	3-11 Motoshiro-cho, Toyota city, Aichi, 471-0024 JAPAN	Climate Zone	Hot and humid in summer, cold and dry in winter		
Net floor area	150.91m^2	Orientation of main facades	SW		
Design Team	LIXIL Corporation and A-seed Associates				

Outside view of building (Left side building)

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	Normal humidity day, night	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
2110	18	52	26	✓	X	X	No	No	74%, 94%	Winter: NW Summer: SSW	34.5

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

This exhibition house has designed to use passive energy, especially natural ventilation. Large windows are set on the windward (in Summer) wall, and partition walls were reduced as much as possible. Therefore, the air flows fluently from balcony to the jalousie (glass louver) windows on the monitor roof, going through the living room and stairwell. Besides, the balcony has side walls to take various direction of external wind into living room, which can increase cross ventilation rate in the occupied area. In cooling season, the deep eaves and balcony shade the sunshine to prevent getting solar direct gain.

Principle of ventilative cooling

When the external wind blows from SSE, S, SSW, SW, WSW, W, WNW directions, the walls at balcony work as guides to flow the wind into living room, and cross ventilation rate is raised by the wind caught at the balcony's wall (wind catcher effect). When only the windows on the monitor roof and near the wind-catch wall are opened, external wind flows into living room through the window at the balcony. Because there is difference in height between balcony and monitor roof, the dynamic pressure of inflow air generates circulating flow in the room, which raises airflow velocity in the occupied zone of the room and also drops effective temperature. When the external wind blows from the other directions, outward projection windows catch the airflow running along external walls. When the external wind is calm, natural ventilation is driven by buoyancy with opening windows on the monitor roof and downstairs.

Components used for ventilative cooling (see chapter 5 for examples)

1. The balcony with sidewalls. The walls take external wind into living room.
2. Large windows on the windward wall.
3. windows on the monitor roof.
4. Windows whose bottom is set on the floor of downstairs.

Control Strategies

In cooling and intermediate seasons, the side walls of balcony catch various direction of external wind and take the wind into living room. The jalousie windows on monitor roof can be opened and closed automatically, but basically, HEMS system displays current condition (internal and external) on monitor, tablet computers or smart phones, and suggests opening or closing of windows to occupants. The sliding windows and projection windows are operated manually.

Overall performance and lessons learned

The 3-D vectors of airflow were measured in the living room, and it was found that circulating airflow was generated in the occupied area of the room when the windows at the balcony and monitor roof were opened. The verification is still on going.

4.2.26 M-smart city kumagaya

Building name	M-smart city Kumagaya	Year of completion	2014	Type of building	Housing
Location	Beppu 5 Chome Kumagaya-shi Saitama Prefecture, Japan	Climate Zone	hot summer and cold winter		
Net floor area	12125.15m^2	Orientation of main facades	SSW, S, SSE		
Design Team	MISAWAHOMES INSTITUTE OF RESEARCH AND DEVELOMPMENT CO.,LTD				

Outside view of the city

Site data

HDD		CDD		Urban	Suburban	Rural	Dust pollution	Noise pollution	High humidity	Prevailing wind direction	Altitude (m)
No.	T_b	No.	T_b								
1977	18	111	24	X	✓	X	No	No	90%	Winter: NNW Summer: SSE	31.6

Architectural design philosophy for reduction/removal of cooling demand and risk of overheating

Double glazed window glasses of the houses are coated with solar heat preventing Low-e material. The houses have unique system that senses outdoor and indoor temperature to automatically control the opening or closing the air intake opening and heat exhaust sky window. The system also controls the room air conditioner to minimize the cooling energy. Several passive cooling items utilizing evaporative cooling technologies are developed and (located) around the house so that the inlet air for passive cooling may be much effective compared to conventional air intake.

Principle of ventilative cooling

Combination of natural ventilation and mechanical air-conditionings is fully applied to reduce the time span of the air-conditioning switched. Air-conditionings turn off as the outdoor temperature becomes3℃ lower than indoor temperature and simultaneously air-intake opening and heat exhaust sky window are opened. Kumagaya is known as the hottest city in Japan but the temperature usually becomes effectively low for ventilative cooling in the evening. The system automatically detects the outdoor cooling potential and controls the room air-conditioner and the openings. Inlet air temperature of the home becomes even lower than the ambient temperature since ground or the newly developed fence are cooled by evaporative methods.

Components used for ventilative cooling

(1) Ventilative cooling control system: The system controls the status of the openings, air-conditioner and the ceiling fan according to the outdoor and indoor temperature.

(2) Passive Cooling Items: Greenery, sprinklers, water retentive pavement, and evaporating cooled fences.

(3) “Ranma”: Air passage opening at the top of each room door.

(4) Room air-conditioner: Device with HA port.

(5) Sky window and air intake opening: Both of them are connected to the control system to utilize the outdoor cooling potential. Each opening may be closed automatically if it rains.

(6) Ceiling fan: It is fixed right underneath the sky window so that the heat exhaust rate may become even higher.

Control Strategies

Cool air may be taken in from the air intake opening in the morning. Internal heat of the house may be exhausted from the sky window. When the outdoor temperature becomes high, air intake opening and the sky window is closed. Interconnected air-conditioner turns on to keep the indoor climate comfortable. As the outdoor temperature becomes lower in the afternoon, the air-conditioner may be turned off automatically and the openings are opened again so that the ventilative cooling may become even effective than ever.

Overall performance and lessons learned

Conventionally, ventilative cooling is controlled by the occupants. They do not know when is effective and when is not. They seldom open windows after they turned on the air-conditioner even if the outdoor temperature becomes effectively low. Natural ventilation may be used especially inthe transition seasons According to one of our simulations, the time of using air conditioning during summer in Tokyo could beshortenedup to 300 hours. Actual performance of the newly introduced system may be evaluated from now on.

4.3 Summary tables of exemplary existing buildings

Table 4.1 Building data

ID	Building Name	Recommender	Country(City)	Type of Building	Year of Completion	Net Floor Area(m^2)	Climate Zone
1	C-DdI ARFRISOL PSA	Giulio Cattarin	Tabernas, Almería, Spain	Office building	2007	1007.40	Dry Hot summer and cold winter
2	C-DdI ARFRISOL CEDER	Giulio Cattarin	Altos de Lubia, Soria, Spain	Refurbishment Office building	2009	1088	Hot summer and cold winter
3	GRUPO LINCE HEADQUARTERS	Giulio Cattarin	Valladolid, Spain	Office building	2011	1000	Hot summer and cold winter
4	Police office Schoten	Hilde Breesch	Schoten, Belgium	Office building	2009	2514	Moderate
5	Mellomhagen	Hilde Breesch	Larvik, Norway	School	2010	3500	Cold
6	Solstad	Hilde Breesch	Larvik, Norway	kindergarten	2011	788	Cold
7	Home for Life	Karten Duer	Lystrup, Denmark	Residential	2009	190	Temperate coastal climate
8	Maison Air et Lumière	Karten Duer	Verrières-le-Buisson, France	Residential	2012	130	Oceanic climate, warm summer, cool winter,
9	CHH - Christophorushaus	Maria Kolokotroni	Miva, Stadl Paura, Austria	Multifunctional: offices, public areas and internal vehicle loading zone	2001	1215	High heating load

10	Edifício Solar XXI	Maria Kolokotroni	Lisbon, Portugal	Office and Laboratory	2006	1500	High cooling loads
11	Frederick Lanchester Library	Maria Kolokotroni	Coventry, UK	Library	2000	9100	Moderate heating and cooling loads
12	Poikkilaakso School	Maria Kolokotroni	Helsinki, Finland	School	2001	3132	High heating load
13	Bournemouth University	Maria Kolokotroni	Bournemouth, UK	Education building	2012	--	Moderate
14	CIT Zero 2020 Building	Paul OSullivan	Cork, Ireland	Office Building	2012	222.5	Warm summer and mild winter
15	Energy Flex House	Per Heiselberg	Taastrup , Denmark	Residential	2009	216	Temperate
16	Spirehuset	Per Heiselberg	Denmark	Kindergarten	2005	500	Temperate
17	Rijkswaterstaat building	Per Heiselberg	Terneuzen, Netherlands	Office	2000	1750	Moderate heating and cooling loads
18	The library of Shandong Jiaotong University	Jie Han	Jinan, Shandong Province, China	Library Building	2003	22 666.76	Cold
19	Franshion Exhibition Centre of Green Building	Jie Han	Changsha ,Hunan Province, China	Exhibition building	2014	12125.15	Hot summer and cold winter

20	Vanke Center Shenzhen	Jie Han	Shenzhen, Guangdong, China	Multifunctional: offices, public areas and residential	2009	12130	Hot summer and warm winter
21	Shanghai Eco-Housing	Jie Han	Shanghai, China	Residential Building	2010	3147	Hot summer and cold winter
22	Cork Country Hall	Paul O'Sullivan	Carrigrohane Rd, Cork, Ireland	Office Building	2006	16000	Warm summer and mild winter
23	CasaClima in Bernate	Giulio Cattarin	Bernate Ticino, Milano, Italy	Family house	2013	305	Hot summer and cold winter
24	Basisschool KA Etterbeek	Hilde Breesch	Edmond Mesenslaan 2,1040 Etterbeek, Belgium	School building	2012	924.7	Moderate
25	LIXILPassive first Pavilion (Gallery)	Hisashi Kotani	3-11 Motoshiro-cho, Toyota city, Aichi, 471-0024 Japan	Exhibition house	2014	150.91	Hot and humid in summer, cold and dry in winter
26	M-smart city Kumagaya	Hisashi Kotani	Beppu 5 Chome Kumagaya-shi Saitama Prefecture, Japan	Housing	2014	12125.15	Hot summer and cold winter

Table 4.2 Technical information

NO	Building Name	Ventilative technology used	Components used	control strategies
1	C-DdI ARFRISOL PSA	Solar chimneys for night ventilation	solar chimneys	The building has a BMS that guarantees the comfort levels of users and minimises energy consumption, giving priority to the use of passive energy strategies.
2	C-DdI ARFRISOL CEDER	Cross ventilation, evaporative systems	1. The windows distribution along the main façades as well as its control system, produce pressure differences between orientations giving as result heat and mass exchanges between the rooms. 2. Evaporative pads placed on top of the windows to reduce the inlet temperature to the offices through an adiabatic cooling. 3. Direct evaporative systems inside the Air Handling Unit to pre-treat the incoming air up to a comfort temperature.	This building has been controlled to guarantee the indoor comfort levels and minimize the global energy consumption. The first priority of the controller corresponds to the use of bioclimatic strategies (cross ventilation, evaporative systems, shading devices) and the proper adaptation of users to the building performance.
3	GRUPO LINCE HEADQUARTERS	(1)Green roof and optimized south glazing shadowing. (2)Air solar collectors integrated in south façade.	Lucernaires; Air collectors integrated in façade are used as a ventilated façade in summer. Cross ventilation is used through grilles inside the building	Mechanical ventilation is used to take and mix air from the different sources, as a function of the natural temperature obtained through the different subsystems. When needed, active systems provide cooled air to the system. The cooling system is a solar thermal-driven absorption pump combined with a geothermal heat pump.
4	Police office Schoten	Thermal mass, Natural ventilation, night ventilation	1. Supply: motorised bottom hung windows. The same bottom hung windows are used for hygienic ventilation and maximally opened for 25% by day. 2. Exhaust: motorised bottom hung windows	The supply openings for night ventilation are automatically controlled. Night ventilation is in operation between 10 pm and 6 am, The day ventilation is

			3. Internal: grilles (passive and motorised) 4. Building management system, including sensors (temperature, weather station,…)	controlled by occupancy in the individual offices and by CO2-concentration in the landscaped offices
5	Mellomhagen	A hybrid ventilation system	1. Top hinged, motorized windows with smart control. 2. Exhaust air damper controlled together with the window. 3. Exhaust air fan.	The ventilation system is mixed mode type based on natural ventilation which promotes air exchange, but without a heat recovery mechanism. It combines the controlled opening of motorised windows and the use of an extraction fan during periods when natural ventilation is either inadequate or inadvisable due to too low outdoor temperatures
6	Solstad	Hybrid mixed-mode ventilation combining motor controlled operable windows with balanced mechanical ventilation	1. Top hinged, motorized windows with smart control. 2. Interior hatches. 3. Energy efficient fan.	(1) During winter, window operation is limited in order to prevent cold draught and large heating demands;(2)During summer, the zone set point for window operation is an indoor temperature exceeding 21 °C.
7	Home for Life	Natural ventilation and thermal mass	Integrated design of the building according to the needs of the inhabitants; Operable windows; External solar shadings; Thermal mass; Automatic control	a combination of controlled solar protection, natural ventilation through automated window openings and moderate thermal mass in the building secures that a cooling demand is avoided despite the large window area and the very well insulated building envelope.
8	Maison Air et Lumière	A hybrid ventilation system	1. Integrated design of the building according to the needs of the inhabitants; 2. Operable windows; 3. External solar shadings; 4. Thermal mass; 5. Automatic control.	In the summer, the automatically controlled natural ventilation is used to air the rooms providing good air quality and natural ventilative cooling. During the heating season, mechanical ventilation with heat recovery is used for air quality and natural ventilative cooling is used in case of over-heating.

9	CHH - Christophorushaus	Mechanical ventilation and night-time natural stack ventilation	1. High level of insulation and limited glazing area. 2. Airflow enhancing ventilation components: atrium 3. Mechanical ventilation system with heat recover. 4. High thermal mass in the interior of the building and night-time natural ventilation.	The building has a mechanical system to provide heating and cooling. Additional cooling is provided at night by natural stack ventilation through automatically controlled vents. In combination with the internal thermal mass, this assists in reducing the cooling load.
10	Edifício Solar XXI	(1) Natural ventilation; (2) Assisted ventilation due to convection phenomena from the photovoltaic panels heat losses (3) Fan driven air drawn through a system of buried pipes	1. 5 cm expanded polystyrene external insulation to both walls and roof slab. Façade design to incorporate daylighting, shading and natural ventilation. 2. Airflow guiding ventilation components: openings in the façade and between internal spaces, openable clerestory windows at roof level, gap behind photovoltaic panels. 3. Airflow enhancing ventilation components: small fans and buried pipes to pre-cool air.	In addition to natural ventilation system, combined with high thermal mass, air is drawn through the buried pipe system. This is achieved by fans situated in each room on the south façade. Flow is adjusted by regulating the fan speed and the use of moveable doors. The main control is done manually, this is one of the possible methods of improvement commented below.
11	Frederick Lanchester Library	Natural ventilation	1. Ventilation towers; 2. Airflow guiding ventilation components: 3. windows and dampers controlled by the BEM system, 4. light-wells to provide light and extract ventilation, 5. plenum under the ground floor for air entry.	The BEM system controls dampers and openable windows depending upon indoor and outdoor temperatures, wind speed and direction and internal carbon dioxide concentrations. The system incorporates a self-learning algorithm to estimate the need for overnight cooling. Over-cooling is prevented by monitoring slab temperature.
12	Poikkilaakso School	Mechanicalventilation district heating and a small A/C system for cooling computer rooms	1. Air handling unit on the roof, two vertical ducts for each classroom terminating in displacement diffusers, dampers for each classroom. 2. speed-controlled fan. Management system with temperature, CO_2 and occupancy sensors in classrooms.	Control of the ventilation is based on temperature, CO_2 and occupancy sensors. There are supply airflow dampers for each classroom and a speed-controlled fan keeps constant 50 Pa pressure in the main supply duct on the roof. Design ventilation flow rates were 3 l/s per m2 in classrooms, 5 l/s per m^2 in the dining room and 2 l/s per m^2 in offices.

13	Bournemouth University	Ventilative cooling with natural driving force and night ventilation, using Phase Change Materials (PCM) and a low energy fan.	Airflow guiding ventilation components: Two Cool-phase system units, consisting of an air supply duct, the air handling unit and the thermal battery module. Airflow enhancing ventilation components: Phase Change Materials used as Thermal Batteries and a controlled fan.	The units are controlled to provide good air quality and comfortable temperatures during the year. A wall mounted user control with room temperature, humidity and CO_2 sensors is installed.PCM changes state from solid to liquid when exposed to temperature. During the day as warm air is passed over the PCM it absorbs thermal energy from the air to turn from a solid to a liquid thus cooling the air. Overnight as cooler air is passed across the PCM it releases the thermal energy it absorbed from the warm air during the day returning to its solid state. Thus providing a cooling cycle using only a low energy fan that is automatically controlled.
14	CIT Zero 2020 Building	Single sided natural ventilation, night cooling	In the retrofit space the ventilation module uses a flush faced external louvre with individual air inlet sections. Inside this louvre ventilation is supplied using side hung, inward opening, dedicated insulated doors controlled either manually or automated based on conditions in the enclosed spaces.	here is one open and one closed position setting for the high level automated ventilation doors. The opening is activated on internal air temperature of 21°C within the zone being serviced. There are also actuation overrides based on external temperature conditions (< 15°C) to avoid over cooling during shoulder seasons.
15	Energy Flex House	Demand-controlled mechanical ventilation with heat recovery, demand-controlled natural ventilation with night cooling and mechanical free night-time cooling with cold recovery during the daytime.	1. Automatically openable windows in hallway (east and west facing) and manually openable windows in all rooms for air inlet. 2. Automatic openable skylights in living room for air outlet. 3. Mechanical exhaust in kitchen and bathroom 4. External solar shading. 5. Weather station monitoring outside air temperature, wind speed and wind direction to control degree of window opening. 6. Temperature and CO_2 sensor in all rooms	Natural ventilation is activated, when the indoor temperature reaches 24C in summer and 25C in winter and if the outdoor temperature is lower than the indoor. The night cooling is activated in summer if the indoor temperature is above 24C and is stopped again, when the temperature becomes below 18C.

16	Spirehuset	Naturally ventilated; mechanical exhaust	1. Automatic openable windows in all rooms for air inlet. 2. Automatic openable skylights in central room for air outlet. 3. Internal roller blinds for solar shading. 4. Weather station monitoring outside air temperature, wind speed and wind direction to control degree of window opening. 5. Temperature and CO_2 sensor in all rooms	Natural ventilation is automatically controlled, but users have a possibility for manual control (opening windows) and can change the control strategy in the building, if needed. If the air temperature in a smaller zone exceeds the set point, then the roof openings in the centre zone are also activated to provide exhaust openings.
17	Rijkswaterstaat building	Naturally ventilated, using a system with electronically-controlled inlet openings	1. Sustainable materials providing a high level of insulation. Thermal mass in the walls and ceilings. 2. Airflow guiding ventilation components: manual windows, sound-proofed openings in the internal walls. 3. Atrium with chimney. 4. Management system with actuators to control vents in order to achieve a constant air flow.	An advanced natural ventilation system provides fresh air and assists in controlling thermal comfort in summer. In winter, the building management system controls the vents in the external wall to ensure a constant flow rate during occupied hours and to close the vents overnight.
18	The library of Shandong Jiaotong University	Natural ventilation	1. The draught chimney. 2. Electronically controlled shutter grille. 3. Tunnel	(1) In transition season: the inside and outside doors and windows are opened, the atrium top draught chimney from 1st to 4th floor is used to introduce outdoor air, creating a good indoor thermal and humidity environment.(2) In summer: the doors and windows are closed, the low temperature wind tunnel introduced into indoor in 1st to 3rd floors, hot air gathered in top atrium of 1st to 3rd floors is derived by the chimney, and the 4th to the top floor adopts air conditioner.(3) In winter: chimney opening of top atrium is closed; wind tunnel is used to preheat fresh air of 1st to 3rd floors.

19	Franshion Exhibition Centre of Green Building	Natural or mechanical driving forces	1. The concave balcony. The building shape coefficient will be changed in different seasons by opening or closing the windows to reduce the energy demand of building; 2. The electric sunshade glass louver with thermal insulation function; 3. Lots of windows install in front and back of the building; 4. Energy efficient fan.	The electric sunshade glass louver with thermal insulation function is designed for the concave balcony. It makes the building shape coefficient variable. The electric sunshade glass louver interlinks with air-conditioning system. The louvers automatically shut down as air-conditionings system turn on.
20	Vanke Center Shenzhen	Natural or mechanical driving forces	1. Natural ventilation of ground open floor. 2. Underfloor air distribution. 3. Sunshade system. 4. Cooling pond and reclaimed water system was installed for cooling the environment; 5. Green roof can cool the environment and increase the humidity of the atmosphere environment by creating a microclimate.	Based on the solar heat absorption of each facade, the louver system was designed. In order to save energy, the automatic louvers can be adjusted according to the direction of the solar. When the porous louvers are closed, the system is mainly used to provide enough natural light. The fresh air system of the underfloor air distribution is controlled by the concentration of CO_2.
21	Shanghai Eco-Housing	Night ventilation; wind cooling by ambient water surface; natural or mechanical driving forces	1. Green roof and vertical greening. 2. Wind inducing wall. 3. The electrical sunshade double window. 4. Ecological nuclear atrium. 5. The roof with opening and closing functions	The natural ventilation has mainly been used during summer night (20:00~7:00) and transition season. In the transition season, the controllable windows would be opened when outdoor temperature is in 16~28℃ and the dew point temperature above 16℃, also the weather is not rainy or snowy. Similarly, in summer night the windows would be opened as outdoor temperature is below 28℃ and the weather is fine.

22	Cork Country Hall	Single sided ventilation night ventilation	1. Automated external glass louvers; 2. Actuation devices; 3. Manual and automated Window components	The control strategy relies on monitoring of external wind speeds, rain precipitation & air temperature. When conditions are acceptable the internal temperature then determines the level of cooling ventilation. Night cooling is also implemented and is controlled on air temperature.
23	CasaClima in Bernate	Night ventilation with mechanical driving forces	1. Natural ventilation and a high thermal wave shift (>12 hours) thanks to the thick walls. 2. A green roof at the upper floor helps cooling down the building by evaporate transpiration. 3. A fan coil dehumidification system is used during the cooling season.	Several windows installed at the southern façade for the exploitation of solar gains in the winter time and windows on all sides to enable cross-ventilation in the summer time.
24	Basisschool KA Etterbeek	Night ventilation with mechanical driving forces	1. Air handling unit (balanced mechanical ventilation system) with summer bypass 2. Building management system, including sensors (temperature, weather station,…)	The summer bypass is activated if indoor temperature exceeds 23°C and outdoor temperature is smaller than the indoor temperature. Night ventilation is activated when indoor temperature at night exceeds 22°C and indoor-outdoor temperature difference is larger than 2°C.
25	LIXIL Passive first Pavilion (Gallery)	Cross ventilation; natural or mechanical driving forces	1. The balcony with sidewalls. The walls take external wind into living room. 2. Large windows on the windward wall. 3. Windows on the monitor roof. 4. Windows whose bottom is set on the floor of downstairs.	In cooling and intermediate seasons, the side walls of balcony catch various direction of external wind and take the wind into living room. The jalousie windows on monitor roof can be opened and closed automatically, but basically, HEMS system displays current condition (internal and external) on monitor, tablet computers or smart phones, and suggests opening or closing of

				windows to occupants. The sliding windows and projection windows are operated manually.
26	M-smart city Kumagaya	natural or mechanical driving forces	1. Ventilative cooling control system: The system controls the status of the openings, air-conditioner and the ceiling fan according to the outdoor and indoor temperature. 2. Passive Cooling Items: Greenery, sprinklers, water retentive pavement, and evaporating cooled fences. 3. Air passage opening at the top of each room door. 4. Room air-conditioner. 5. Sky window and air intake opening. 6. Ceiling fan.	Cool air may be taken in from the air intake opening in the morning. Internal heat of the house may be exhausted from the sky window. When the outdoor temperature becomes high, air intake opening and the sky window is closed. Interconnected air-conditioner turns on to keep the indoor climate comfortable. As the outdoor temperature becomes lower in the afternoon, the air-conditioner may be turned off automatically and the openings are opened again so that the ventilative cooling may become even effective than ever.

5 Available Building Components and Control Strategies for Ventilative Cooling

5.1 Introduction

This chapter gives an overview on available building components and control strategies of ventilative cooling, closely linked to natural ventilation.

Building Components of ventilative cooling are applied on all three levels of climate-sensitive building design, i.e. site design, architectural design and technical interventions. A grouping of these components is suggested in Figure 5.1 which is followed in the structure of this chapter.

Airflow Guiding Ventilation Components
Windows, Rooflights, Doors | Dampers, Flaps, Louvres | Special Effect Vents

Airflow Enhancing Ventilation Building Components
Chimneys | Atria | Venturi Ventilators | Wind Towers, Wind Scoops

Passive Cooling Building Components
Convective Cooling Comp. | Evaporative Cooling Comp.| Phase Change Cooling Comp.

Actuators
Chain Actuators | Linear Actuators | Rotary Actuators

Sensors

Figure 5.1. Structure of Ventilative Cooling Components and Building Elements

The chapter only very briefly addresses relevant landscaping and architectural components, such as

All sections are, if applicable, loosely sub structured as follows:

a) the component's physical principle, background and possible application
b) its capacity and limitations, fields of possible improvement and innovation
c) figures of exemplary products
d) outlook on fields of further development

At the end of the chapter there are indicative lists of

a) Literature
b) Manufacturers

5.2 Air flow Guiding Ventilation Components

5.2.1 Windows, rooflights, doors

Windows, rooflights and doors are the most widely used ventilation openings. Initially designed solely for manual control, they may be controlled by mechanical actuators, too. As regards ventilation a main distinction of windows is their opening mechanism. An overview of the most common mechanisms, except sliding windows, is shown by the Figure 5.2. Source [23].

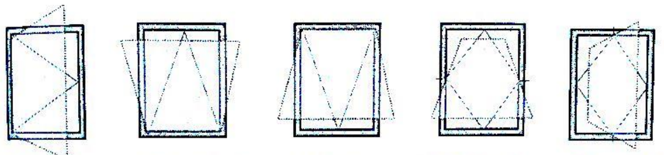


Figure 5.2. Various types of operable windows

As a major advantage in comparison with louvres or dampers they are familiar to occupants and they can be made to shut tight relatively easily, with effective seals relatively easy to provide and with robustness against higher closing forces.

Another major advantage of choosing simply windows and doors as the main air flow inlets and outlets is their high ventilation capacity potential: For effective ventilative cooling, especially night flush ventilation, air change rates in the range of 5 and higher are necessary. In most cases these high air flows can be supplied best via windows or façade-integrated flaps, usually mechanically actuated.

$$\dot{V} = C_d \times \sqrt{(2/\rho)} \times \sqrt{(\Delta p)} \times A = C_F \times \sqrt{(\Delta p)}$$ according to [8]

(5.1)

with C_d … Discharge Coefficient of the aperture
C_d typical for windows = 0.6-0.7
with $(C_d)^2 = 1/k$, with k … Flow Resistance
thus k typical for windows = 2,1

with C_F… Flow Coefficient of the aperture ($m^3/s.Pa^{1/2}$), depending from size and form of the aperture

with ρ … air density, equaling 1,21 kg/m³ at 20°C and standard pressure

with A … surface area

Thus, a pressure drop of only 1 Pa may drive an air flow through a window of 1 m² open area of an air flow rate magnitude up to 2.800 m³/h. This is a magnitude that cannot easily be beaten by any other type of air flow guiding or air flow enhancing measures.

Assessment criteria for different window and interior design might be:

- **Ventilation Capacity**, depending clearly from the effective opening area, itself depending from the way the window opens, the surrounding head, sill and jamb details, finally determining the interrelation between structural opening, throw and effective opening.
- **Controllability**, mainly being an issue of manual controllability, including optional mechanical operation. Qualities may include robustness against wind pressure, proportionality of opening angle and effective opening.
- **Comfort.** Comfort aspects include operability, occupants' control and, draft risk and increasingly issues of particles and noise. Low level openings under manual operation and high level openings under automatic control might be a good solution as regards avoiding draft risk.
- **Security.** Open windows may cause security problems at ground or first floor levels. Restricting the length of throws of stays or actuator arms or locking the opening vents in a secure position may be sufficient in many situations.
- **Sealing.** Sealing of windows usually is achieved at high levels by EPDM expanded rubber gaskets. Challenges to sealing only occur together with special window types, such as Pivot or Sush Windows. Attention has to be paid to sealing in case of automatic vent gears.
- **Integration of actuators or blinds.** Careful consideration is needed for conflict free integration of actuator options or blinds.

Ventilation strategies based on windows basically can be generally structured in a) single-sided ventilation, b) cross-ventilation and c) buoyancy-driven-ventilation and combinations.

Ventilation via windows, rooflights and doors is substantial issue not only in new buildings but in renovations as well. Renovation process is always a chance for significantly improving the ventilative cooling options by adding, withdrawing windows, by changing their dimension and their opening mechanics, and finally by adding actuators for automated window-operation.

5.2.2 Dampers, Flaps, Louvres, Grilles

Motorized dampers and louvres are widely used in mechanical ventilation systems, where they are usually effective and reliable both within the ventilation-system and at the air inlets and outlets. In natural ventilation systems they are widely and successfully used inside buildings to control air flows between rooms and within the building. When being used in facades one has to cope with their disadvantage not shutting as tight as most windows, which might cause excessive air infiltration together with draft problems in winter and heat losses in winter. Finally, both in natural and mechanical ventilation systems grilles are widely used as air inlets and outlets, offering protection against weather, burglary, animals down to size of insects and partly noise. In contrast to louvres, standard grilles aren't movable but offer fixed openings.

Dampers, flaps, louvres and grilles are offered in a significant variety of sizes, qualities and fields of application. Figures Figure 5.3 to Figure 5.7 show a few examples out of this variety. The possible air flow through dampers, flaps, louvres and grilles significantly differs with the construction types. Manufacturers, who deliberately address the application of their products in natural ventilation systems, usually give the magnitude of the air flow at pressure drops of 1 Pa and 2 Pa, which are typical values for well-designed natural ventilation layouts. Within mechanically driven systems pressure fixtures and control components are usually designed starting from pressure drops of 5 Pa.

Beside the air flow at a given pressure drop, manufacturers should give:

- the discharge coefficient (C_d) or the k factor exhaust, linked by $(C_d)^2 = 1/\text{k-exhaust}$
- the coefficient of entry (C_e) or the k factor intake, again linked by $(C_e)^2 = 1/\text{k-entry}$
- the physical free area A

Allowing calculating the air flow through the grille:

- $\dot{V}_{exhaust} = C_d \times A \times (2/\rho)^{1/2} \times (\Delta p)^{1/2}$ (m³/s)
- $\dot{V}_{inlet} = C_e \times A \times (2/\rho)^{1/2} \times (\Delta p)^{1/2}$ (m³/s) (5.2)

Figure 5.3. Glazed Louvre, SE Controls, GB, Source: www.secontrols.com (20.04.2014)

Figure 5.4. Motorized ventilation damper, TROX, Germany, www.trox.de (29.12.2014)

Figure 5.5. Butterfly ventilation damper, HiTech Enterprise, India, www.hitechenterprises.net (29.07.2014)

Figure 5.6. Frost free ventilation flap, Gaugele, Germany, www.gaugele.com (29.07.2014)

Figure 5.7. Acoustic Grille, DUCO, Belgium, www.duco.com (29.12.2014)

5.2.3 Slot Vents

Slot Vents, also addressed as trickle vents, are designed to provide a minimum fresh air rate during room occupation and, at higher airspeed, also provide the external air flow for ventilative cooling outside occupation time. They may be integrated in the window frame or be placed independently within the outside walls.

Most slot vents are passively working, with the air flow driven by external pressure drop, often being generated by a central exhaust fan. There are also slot vents available equipped with a fan, serving as exhaust vents for kitchens and bathrooms. As regards construction, there are versions of slot vents available either being mounted between window lintel and frame, or being surface mounted at the window frame or sash, or being glazed in. In order to prevent draft, slot-vents are usually controllable and closable and should preferably be mounted at high level, i.e. above 1.75m.

Figure 5.8 andFigure 5.8 Figure 5.9 show examples of commercially available slot vents.

Figure 5.8. Sash mounted trickle vent, Titon, UK, www.titon.co.uk (29.12.2014)

Figure 5.9. Trickle Exhaust vent with fan, Titon, UK, www.titon.co.uk (29.07.2014)

If used for hygienic external air supply, the core challenges of slot vents are minimizing the draft risk during periods of cold outside temperatures and preventing from excessive air flow in connection with wind occurrence.

If used for night flush ventilation the core concern is providing a high air flow at low pressure drops, equaling offering a high coefficient of entry equaling offering a low flow resistance. In both cases there are the additional challenges of noise protection, of fire resistance and of reasonable U-values.

All those challenges are already addressed or solved by well tested commercially available products, targeting the balance of costs, robustness and simplicity of the technology, favorably going along without electronic parts and without auxiliary energy demand.

- Draft risk is addressed by mounting the slot vents always at the upper edge of the glazing and in some cases additionally by directing the incoming air upwards.
- Self-regulating ventilation flaps provide from excessive air flow in case of wind pressure.
- Airflows at 2 Pa reach values in the range of 50 to 150 m³/h per meter of extension.
- Thermally broken constructions offer U-values down to 1.8 W/m²K
- Acoustic fillings provide noise protection in the range of an weighted element normalised level difference according to ISO 12354;2000 of up to $D_{ne,W}$ (C;Ctr) = 51 (-2;-5) dB(A)

Figure 5.10 and Figure 5.11 show examples of trickle vents with self-regulation against wind pressure, with thermal insulation and with noise protection.

Figure 5.10. Glazed-in, self-regulating, thermally broken trickle vent, Renson, BE, www.renson.eu (29.12.2014)

Figure 5.11. Self-regulating, fire- +noise-protective trickle vent for high-rise buildings, DUCO, BE, www.duco.eu (29.12.2014)

Another special applications of trickle vents are products which self-regulate the air flow dependent on the indoor air's relative humidity: Closing to a minimum below 30% RH. Those elements are tempting solutions for demand-controlled hygienic ventilation but do not offer options for ventilative cooling.

5.3 Air flow Enhancing Ventilation Components and Building Elements

5.3.1 Ventilation Chimneys

Ventilation Chimneys are a widespread and historically anchored element of enhancing air flow, especially for ventilative cooling purposes. Chimneys make use of the hydrostatic buoyancy of air being warmer than its surrounding. Thus, chimneys are independent from wind, but rely on height and temperature difference. The latter may be raised by additional heating, e.g. solar radiation (→ solar chimney), and may be secured additional heat insulation.

The thermal buoyancy driving force of air roughly results in

$$\Delta p = \left(\frac{1}{30}\right) \times \Delta T \times h \qquad (5.3)$$

with Δp … buoyancy driven static pressure difference

with ΔT … difference between room temperature and mean air temperature in the chimney

with h … static height between room and chimney exhaust

This rule of the thumb is valid for a given mixing ratio of 10g/kg and at a range of temperature between 15°C and 40°C, e.g. equaling 2 Pa at 6 m height and 10 K temperature difference. Thus, buoyancy driven chimneys only perform in combination with lowest flow resistance ventilation systems. Furthermore they may be combined with wind driven elements such as Venturi shaped capping or may be effectively empowered by supportive electric exhaust ventilators. Ventilation chimneys may be added at the roofs of buildings but as well may be constructed as internal ventilation shafts, what can form a favorable solution in high-rise buildings.

A special form of ventilation chimneys are the solar chimneys, making additional use of solar radiation to enforce buoyancy. Solar force may double or triple the effect of a solely buoyancy chimney. In cool climates the balance between the desirable effect of solar heat gains and the undesirable effect of transmittive heat loss has to be watched carefully. As a special form of solar chimneys there are double skin facades, exposed to solar radiation and causing negative pressure to the adjacent rooms. Most ventilation chimneys used in buildings are tailor made, with numerous fields of improvement left:

- Ensuring buoyancy for the majority of timespans of interest
- Properly designing the ventilation system in every level of the adjacent building
- Dynamically controlling the air flows in space and time, possibly enhancing night ventilation by making use of heat storage effects within the chimney
- Developing modular off-the-shelve solutions for combined solar + buoyancy chimneys
- Developing design guidelines for erection and operation plus best practice examples

Figures 5.12, 5.13 and 5.14 show examples of modern solar chimneys.

Figure 5.12. Solar ventilation chimneys, Sidwell Friends School, Washington D.C., USA. Addition and extensive renovation finished in 2008. Designed by Kieran Timberlake Associates.   Source: www.solaripedia.com (29.12.2014).

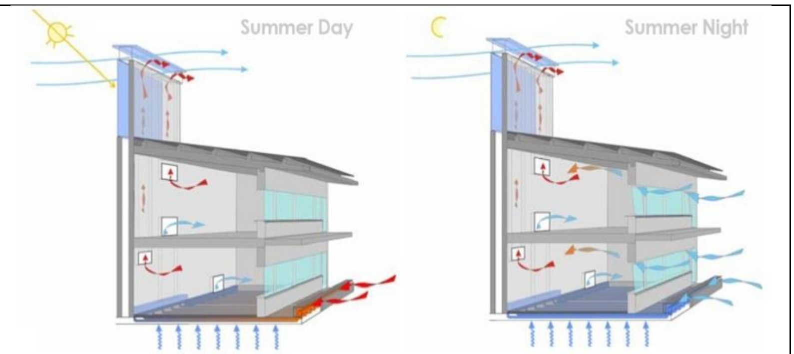


Figure 5.13. Solar ventilation chimneys at French school, Damascus, Syria. Erected 2008. Designed by TRANSOLAR (Germany), bombed and partly destroyed in Dec 2013.

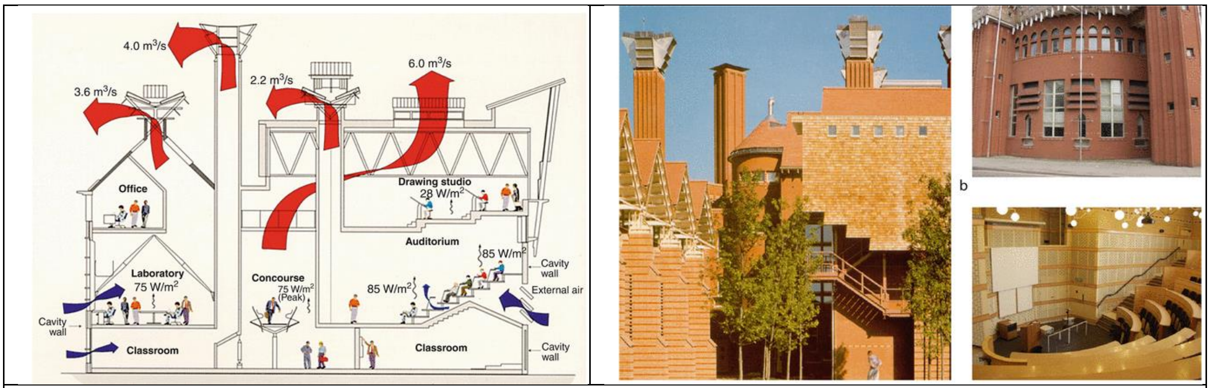


Figure 5.14. Natural and chimney ventilation at Queens Building, de Montfort University, Leicester, UK. Designed by architect Short Ford associates with Max Fordham Associates as the services consultant. Source: link.springer.com (29.12.2014)

5.3.2 Atria

The nomen of "atrium" in its historic meaning originally refers to the central room of an ancient Roman house, being fully surrounded by adjacent rooms and having been at least partly uncovered. In Renaissance Architecture it was the Patio which developed out of the Atrium. In today's meaning of the word, an Atrium indicates a glazed courtyard, still being fully or at least partly surrounded by the building. Depending from the ambient climate and the building's usage an atrium may offer a climatic buffer zone between inside and outside and may effectively support ventilative cooling, usually in the function of an exhaust air zone, with air flow driven both by thermal buoyancy and wind suction. Atria are always tailor-made. Their desired positive effect to indoor environmental quality therefore depends on a very careful design approach regards form, material and operational parameters.

Characteristic challenges of climate related atria design are:

- If extensively glazed, atria easily suffer from overheating. This can be counteracted by effective sun protection (movable, fixed or sun protection glass), by thermal mass, by using light colors and – last not least - by significant ventilation. If designed decently, the risk of overheating within atriums can be controlled quite satisfyingly, way easier than in a double skin façade.
- In glazed atria the nightly unloading of thermal masses has to be supplied fully by means of convection, since the effect of radiative heat transfer towards the cool sky is blocked by the glazing. Thus, especially in hot and dry climates, atria should be designed without a gazed cover but only with removable and preferably ventilated sunscreens.
  It has to be taken into account that an atrium experiences significant temperature stratification, what has direct effect on the magnitude and even the direction of air flow from or to the adjacent rooms. When designed as an exhaust atrium, the roof of the atrium should be significantly above the windows of the highest adjacent floor.

Fields of research are their design and the optimization of their contribution to ventilative cooling in different climates. Development seems possible towards combining the ventilative effect of an atrium with deliberately shaped radiative qualities of its surfaces, such as cool pavement, cool plaster and low-E sunblinds.

Figures 5.15 – 5.20 show examples of modern ventilation atria.

Figure 5.15. Office building with exhaust atrium: "Bayrisches Landesamt für Statik und Datenverarbeitung", Schweinfurt, Germany. Buit 1998. Architect kuntzundbrück. Building services engineer G. Hausladen.
Source: http://kuntzundbrueck.de/project/landesamt-fur-statistik-und-datenverarbeitung-schweinfurt/ (29.12.2014)

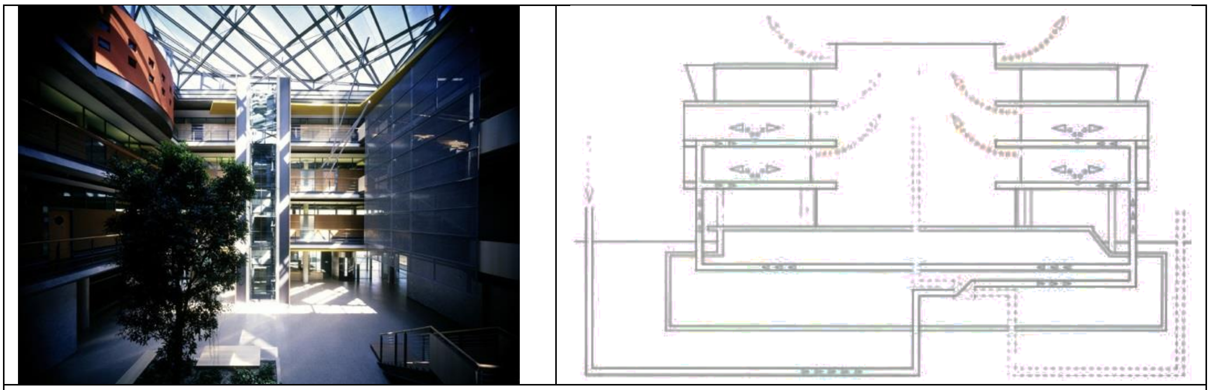


Figure 5.16. Office building with exhaust atria „Landesamt für Statik", Schweinfurt, Germany

Figure 5.17. UNILEVER central administration building with exhaust atria, Hamburg, Germany. Finished June 2009. [109]

[109] Architect: Behnisch Architects (Stuttgart), Building Service Engeneers: HKP Ingenieure (Hamburg), Klima Engineering: TRANSSOLAR Energietechnik (Stuttgart). Sources:

http://www.detail.de/daily/?attachment_id=2201
http://www.bau-immobilien-trends.de/behnisch-entwurf-zentrale-des-unilever-konzerns/
http://www.hochtief.de/hochtief/3810.jhtml (29.12.2014)

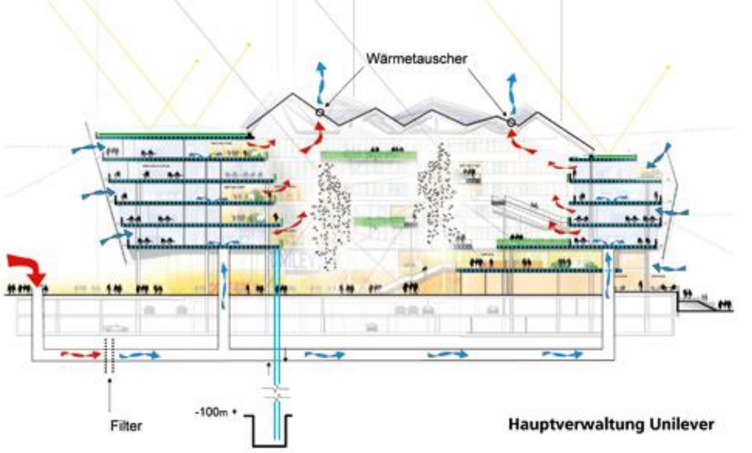


Figure 5.18. UNILEVER central administration building with exhaust atria, Hamburg, Germany

Figure 5.19. Atrium in Corps de Logies wing of Vienna Hofburg Palace, Austria. Finished 1913. [110]

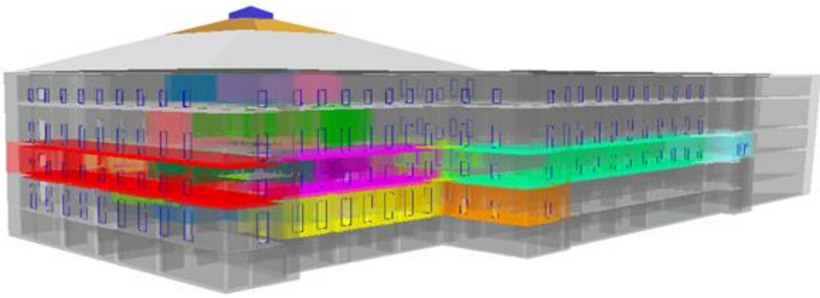


Figure 5.20. Atrium in Corps de Logies wing of Vienna Hofburg Palace, Austria

[110] Currently under reconstruction including re-implementation of the exhaust atrium, fed by inlet air from brick masonry earth tube heat exchangers. Architect: Gareth Hoskins Architects, Glasgow-Berlin, UK. Klima-Rngineering: IPJ Ingenieurbüro P. Jung, Colgne-Vienna. Sources: www.weltmuseum.at www.khm.at (29.12.2014)

5.3.3 Venturi and powerless rotating exhaust ventilators

The Venturi effect is the phenomenon that occurs when a fluid flowing through a pipe or similar is forced through a narrow section, resulting in a pressure decrease and a velocity increase. The physical phenomenon was named after Italian physicist, Giovanni Battista Venturi, 1746-1822.

The Venturi effect may be utilized for providing a negative pressure at exhaust vents and thus enhancing ventilation. Venturi elements for ventilative cooling may be shaped as Venturi roofs or Venturi roof ventilators.

The driving ventilation force can be significant, depending from the air velocity to the power of two.

$$p_{wind} = C_p \times {}^{\rho}/_{2} \times v^2 \qquad (5.4)$$

with p_{wind} ... wind pressure, additive to static pressure of the free stream

with ρ ... density of air (1,21 kg/m³) at normal condition

with v ... flow speed of the free stream

with C_p ... pressure coefficient

Pressure coefficients up to -1.0 have been proven, leading to negative pressure of up to

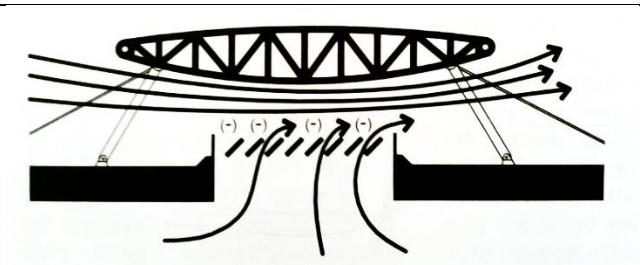
60 Pa at an undisturbed wind speed of 10 m/s

15 Pa at an undisturbed wind speed of 5 m/s

4 Pa at an undisturbed wind speed of 2.5 m/s

Not only Venturi roofs but also Venturi Roof Ventilators and Venturi chimney caps are offered throughout the world as robust and effective air flow enhancing exhaust devices, both for exhaust air and flue gas. Beside Venturi ventilators there are powerless rotating ventilators, again making use of wind speed for creating negative pressure and enhancing exhaust air flow.

Figures 5.21 – 5.27 show examples of Venturi ventilators.

	
Figure 5.21. Venturi effect chimney hat, Master Services, Denton, Texas, USA, https://mastersservices.com (29.07.2014)	**Figure 5.22. Principle of Venturi ventilator with adjustable louvres system. Source: [21]**

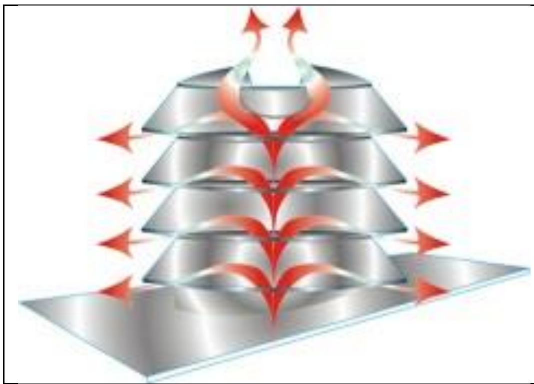


Figure 5.23. Prefab Venturi roof ventilator. Condor Kinetic, Queensland, Australia. Source: www.condorkinetic.com.au

Figure 5.24. Prefab Airstract Ventilator utilizing Venturi effect. The casing is similar to the one of the windcatcher, but without inner sections. Passivent, GB. Source: http://www.passivent.com/downloads/airstract_vents.pdf

Figure 5.25. Prefab Airstract Ventilator utilizing Venturi effect. Passivent, GB

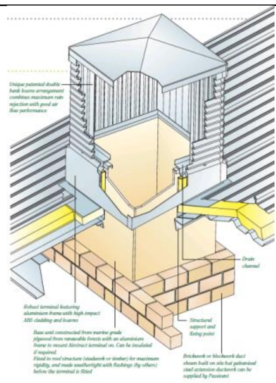


Figure 5.26. Powerless wind turbine ventilator. Airier Natura Pvt. Ltd., Bangalore, India. Source: http://www.industrialairventilator.com/ (31.12.2014)

Figure 5.27. Powerless roof ventilator, Airier Natura Pvt. Ltd., Bangalore,

5.3.4 Windcatchers and Windscoops

Wind catchers are traditional elements of especially Arabic architecture, particularly in the Persian Gulf region, i.e. Iran, Iraq, Dubai, Qatar, and other Arab countries in one hand and north of Africa region, i.e. Algeria, Egypt and other North African countries in another hand – ie in dry climates. Over the past three thousand years they have been the major cooling technology of buildings in those regions.

Wind catchers utilize the wind speed in elevated levels above ground, by special construction of the hood forcing the wind down into the chimney. In several cases, the effect is enforced by evaporative elements within the wind catcher. Traditionally the cooling effect from wind catchers is used to support local zones/places within the building or within the building's courtyard.

There are mono-directional and bi-directional windcatchers, the latter ones introducing downward air driven by wind pressure at the windward side of the windcatcher.This is possibly assisted by buoyancy from evaporative cooling, and introducing upward air flow by wind suction at the leeward side of the windcatcher, possible assisted by buoyancy if indoor temperature exceeds outdoor temperature.

There is significant amount of scientific literature available, studying the function of vernacular windcatchers, such as Roaf [24]]. There are also recent developments of modern, prefabricated windcatchers, some of them replacing the traditional form of the wind tower by the new form of windscoops, them with only mono-directional function for either supply or extract air. Still, wind catchers are very much tailor made and have to be, since their function is intrinsically linked to the local building site, the prevailing wind conditions in space and time, and last not least to the building itself.

The proper function windcatchers depends on the sensitive balance of the air flow driving forces, which are wind and temperature differences, and the air flow network within the building, including components of heat storage and evaporative cooling. There is three thousand years of experience, but still there's a lack of written design guidelines to integrate windcatchers in today's architecture.

Finally the challenge of hybrid ventilation is a relevant one for application of windcatchers in today's buildings, meeting today's comfort expectations. Thus, fields of development needed, are derivation and documentation of design guidelines and of control strategies in line with hybrid ventilation concepts.

Figures 5.29 – 5.35 show some examples of both vernacular and modern windcatchers and windscoops.

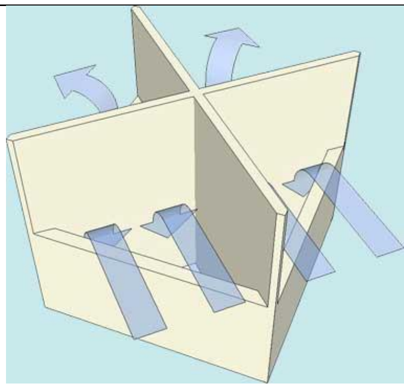


Figure 5.29. Traditional windcatcher at Qatar and sketch of functional principle Figure 5.28. Traditional windcatcher at Qatar and sketch of the functional principle of a square bidirectional windcatcher with four sections. Sorces: www.trekearth.com and http://catnaps.org/islamic/gulfarch4.html (29.07.2014)

Figure 5.29. Traditional windcatcher at Qatar and sketch of functional principle

Figure 5.30. Modern windcatcher Sola-Boost by Monodraught, UK. It is devided into four sections, working bidirectional at all wind directions. Integrated there’s a 10W monocrystalline photovoltaic solar module, linked to an assisting fan (2W at nominal power), adding up to 35l/s in addition to 110l/s ventilation calculated at between 2 and 3 m/s external wind speed. Source: http://www.monodraught.com (20.04.2014)

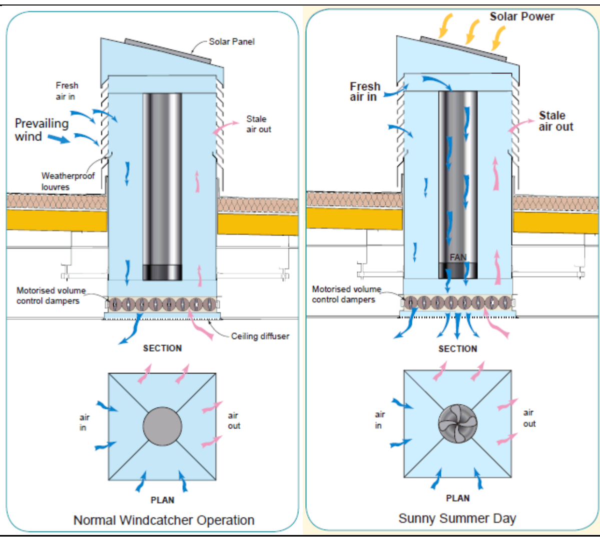


Figure 5.31. Modern fan-assisted, PV-integrated, bi-directional windcatcher by Monodraught, UK

Figure 5.32. Modern bi-directional windcatcher with option for ducted air dispersal by Passivent, UK. Source: http://www.passivent.com/wind_driven_ventilation.html

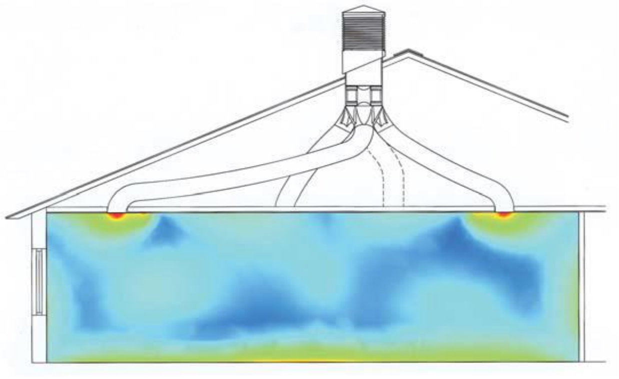


Figure 5.33. Modern bi-directional windcatcher with option for ducted air dispersal by Passivent, UK

Figure 5.34. Two examples of windscoops

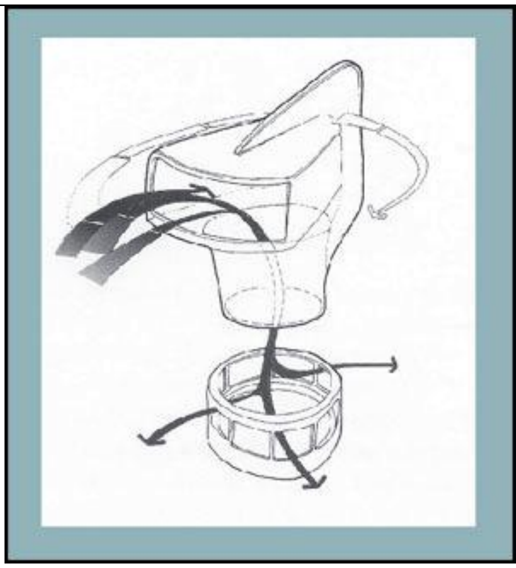


Figure 5.35. Two examples of windscoops, first one: Exhaust windscoop system Kaufman (also addressed as deflector), USA, Source: www.scoopsandrakes.com, second one: scematic sketch of a modern intake windscoop. Source: http://www.canadianarchitect.com/asf/principles_of_enclosure/environmental_mediation/environmental_mediation.htm (29.07.2014)

5.3.5 Double Facades, Ventilated Walls

Double facades, also addressed as curtain walls or ventilated walls, are a frequent element of modern architecture, especially applied at high rise office buildings. Core element is a second layer of façade which is usually ventilated, but forming a barrier against wind and rain, while the thermal boundary still is kept in the primary façade.

Amongst architects double facades are appreciated for allowing three-dimensional architectural expression while still keeping the load-bearing building structure itself simple and affordable.

Amongst indoor-climate-engineers they are regarded for their potential of offering a protected space usable for effective movable sunblinds, both fabric and lamella. Furthermore they are meant offering the chance of natural window ventilation even in high-rise buildings. But practical issues like noise reflection, fire protection and thermal stratification form significant limitations of this option. Numerous double skin facades didn't meet the expectations. It had to be learned that the buffer space of curtain walls during summer is necessarily and very often significantly warmer than the ambient air, contradicting the idea of nice window ventilation.

Amongst investors and facility managers double facades are known as notably costly features, raising the price of a façade by 200 to 700,- EUR/m², that is 30 to 100% (cost estimations from Austria, 2014) plus raising the maintenance-costs.

Still, regarding ventilative cooling, double facades offer an effective exhaust shaft, being very much suitable to significantly enhance cross-ventilation at night. Used for this, they offer the strength of making the ventilation independent from wind pressure at the façade or even offer the chance of making deliberately use of the wind suction at the top of the façade or at the leeward side.

These abilities in ventilative cooling do make double facades a worthwhile field of further investigation, with still a vast field of possible improvements open, regarding functionality and cost effectivity.

New developments toward facades out of transparent ETFE-foils nowadays somewhat re-boost the topic of double skin facades, offering strengths in fire protection, noise reflection, load optimization and, thus, cost reduction.

Figures 5.36 and 5.37 show examples of double skin facades, serving, amongst others, the ventilative cooling.

Figure 5.36. High-rise office building GSW-headquaters in Berlin. [111] Arch. Sauerbruch-Hutton, Berlin

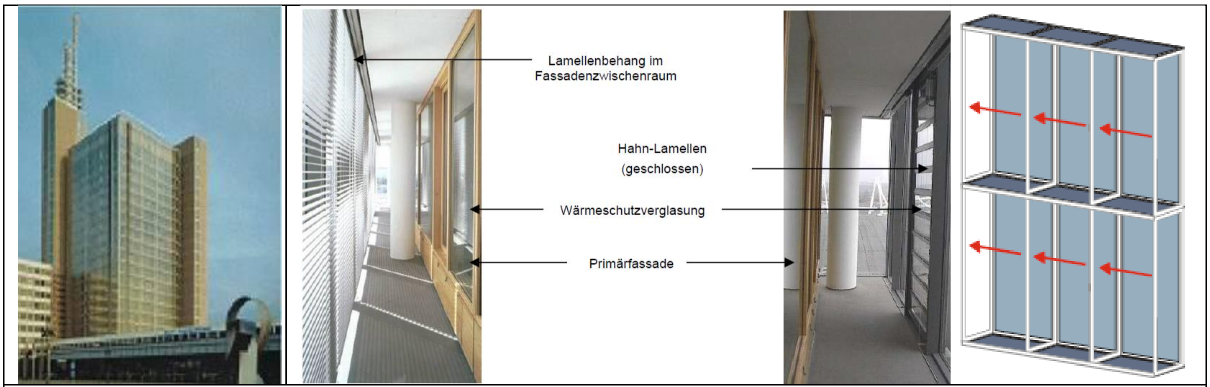


Figure 5.37. Double-skin high-rise office building Deutsche Messe Hannover, Arch. Herzog & Partner, Munich. Double-skin corridor façade. 1,32 m deep, double pane insulating glass in both façade layers, venetian blinds in between, openable windows in the inner skin, ventilation louvres in the outer skin.

5.4 Passive Cooling Components and Building Elements

5.4.1 Convective Cooling Components

Convective effects may strongly support ventilative cooling. They are traditional means of cooling especially in warm and humid climates. The effect of moving air enhancing the transpiration rate of the skin may cause an effect of lowering the individual operative temperature by up to four degrees. Being well based in scientific literature this effect already found its way into international standardization, namely ISO 7730.

Figure 5.38 indicates this effect, showing the acceptable increase of indoor air-temperature at the horizontal axis, over the mean air speed at the vertical axis, for different temperature differences between moving air and still air.

[111] Architect Sauerbruch-Hutton. Double-skin shaft-façade to the West, 71 m high, 1,15 m deep, inner skin made of double pane insulating glass with mechanically openable exhaust windows, outer skin made of single pane safety glass, colored sunblind-panels in between. Erected 1993.

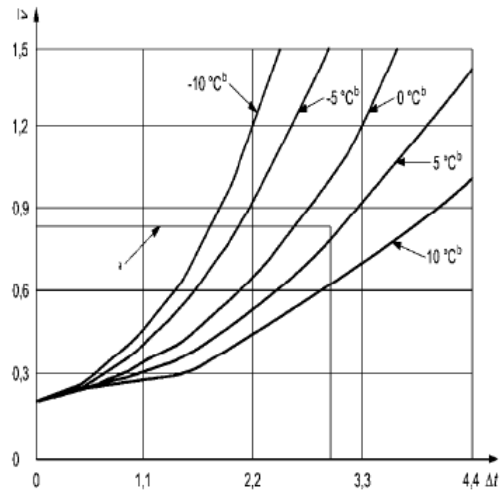


Figure 5.38. Chart of cooling effect from moving air, according to EN ISO 7730 [Source: ISO 7730:2005 Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria].

Though this ventilative cooling effect is well proven and practically tested over thousands of years, convective cooling today is regarded very much as a significant draft risk. Not at least influenced by from the comfort model of Fanger, with its criteria of local discomfort from draft, modern building design is eager to keep air velocity within occupation zones lower than 0,15 m/s or even less.

Thus, the design of convective cooling has to carefully balance the cooling effect against the draft risk. Adaptive comfort research revealed the effect that the perception of draft is unlikely to occur as long people have individual options to immediately influence the air movement. Thus, convective cooling has to be designed as an individual effect. It won’t be accepted if applied in a centralized way.

Box fans, oscillating or ceiling fans are well known and proven for increasing the interior air speed and improve comfort. Higher air speeds permit the buildings to be operated at a higher set-point temperature and thus to reduce its cooling needs. Researchers report a decrease of cooling load by 7 -10% for every degree Fahrenheit increase of the thermostat during the summer. With air circulation fans allowing the thermostat to increase by 4 °F; thus, fans can contribute up to 40% of the cooling need of buildings under the assumption that the occupants are always close to the fan. Research has shown that the additional use of ceiling fans in air conditioned buildings contributes to substantial savings of energy if the air conditioning set point is lowered.

Ceiling fans have dominated the US market, according to a study by ECOS Consulting and the Natural Resourses Defence Council of the USA (2001), two out of three homes in the US have at least one ceiling fan. In total, there are almost 193 million ceiling fans in the US.

Ceiling fans can save energy when users raise air conditioning thermostats. Research as far as in 1980s has shown that ceiling fan can extend the comfort zone, outside the typical ASHRAE comfort zone. In particular, at an air velocity of 1.02 m/sec, comfort may be achieved at 27.7 °C for 73% RH, 29.6 °C for 50% RH and 31 °C for 39% RH. Fairey in 1986 has shown that the use of ceiling or oscillating fans may significantly contribute to reducing the cooling load of buildings in the southern US if the thermostat settings are raised accordingly. As reported, energy savings of about 30% are calculated for typical frame buildings in Orlando and Atlanda by increasing the thermostat setting from 25.56 °C to 27.78 °C. The energy savings may increase by up to 50% for heavy mass buildings.

Error! Reference source not found.5.39 show different examples of ceiling fans. From left to right: Modern 3-blade industrial ceiling fan, modern bladeless ceiling fan, kindly folkloric ceiling fan on a stand. Sources: http://exhalefans.com/, http://freshome.com/2012/12/06/a-revolutionary-bladeless-ceiling-fan-by-exhale-fans/, http://www.farreys.com/ (02.01.2015)

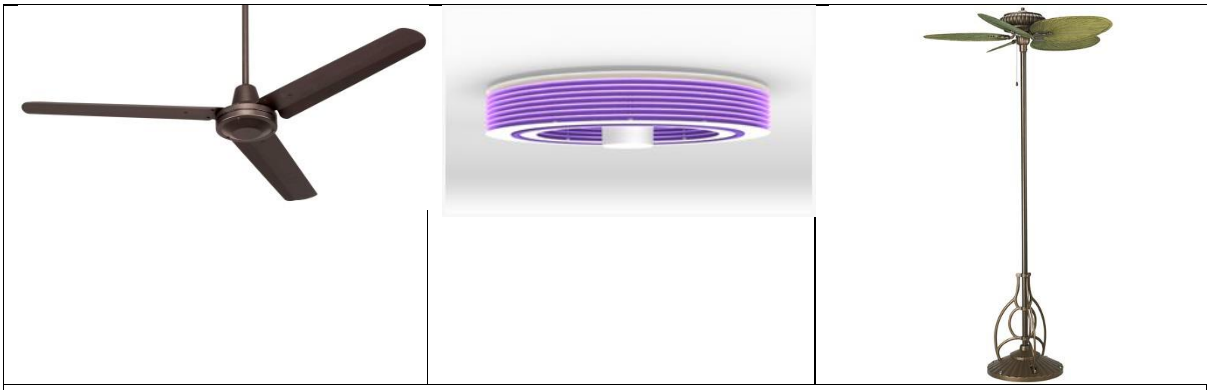


Figure 5.39. Examples of ceiling fans

Recent developments, being part of Subtask B of Annex 62, target at personal convective cooling devices e.g. ventilated chairs personal desk-fans.

5.4.2 Evaporative Cooling Components and Building Elements

Evaporative cooling utilizes the adiabatic cooling effect of humidifying the air. This can be done directly in the room or in the inlet air, or indirectly in the exhaust air by use of an additional heat-exchanger. Such components and building elements have been utilized extensively in buildings located in regions with dry climates.

Direct evaporative cooling components, commonly called swamp-cooler, are wide-spread in hot and arid regions, as long there's sufficient water supply. They are known as robust, cheap and effective cooling devices, with the only systematic shortcoming of causing a substantial rise of relative humidity.

Example: Figure 5.40 shows a characteristic evaporative cooling process within the psychometric chart: Starting from T = 32°C at a.H. = 5 g/kg and r.H. ≈ 17%, leading to T = 24°C at a.H. = 8 g/kg and r.H. ≈ 40%. If applied to an air-flow of 100 m^3/h this causes a need of water in the range of $^1/_3$ l/h.

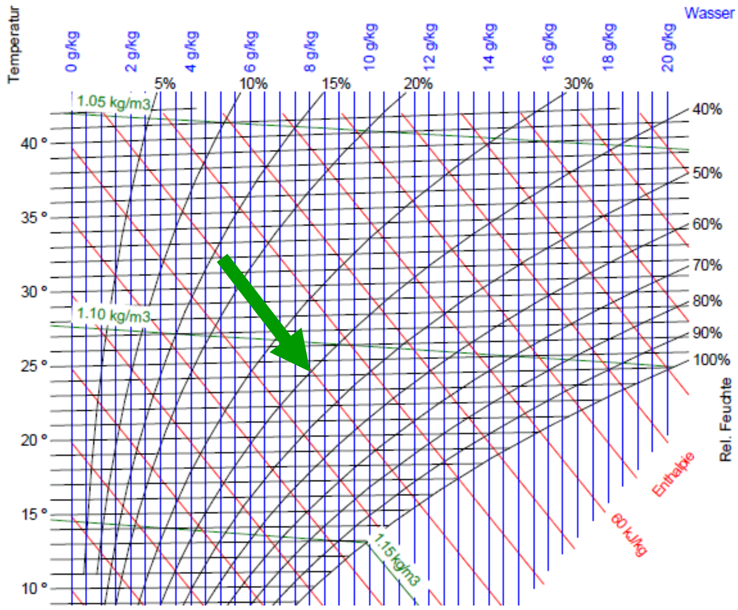


Figure 5.40. Process of evaporiative cooling within the psychrometric chart

Swamp coolers are offered for residential homes and for industrial applications, the latter ones up to air-flows of 50,000 m³/h,there are even outdoor components available. Besides, due to their technical simplicity, there self-made swamp coolers have even been constructed for cars, simply using the wind blast during driving.

Beyond swamp coolers there's a wide field of evaporative cooling appliances integrated in bioclimatic landscaping and architecture, both traditional and new, such as fountains, water ponds and plants.

Figures 5.41 and 5.42 show principle and exemplary products of swamp cooler, including a somewhat crazy prototype for vintage cars.

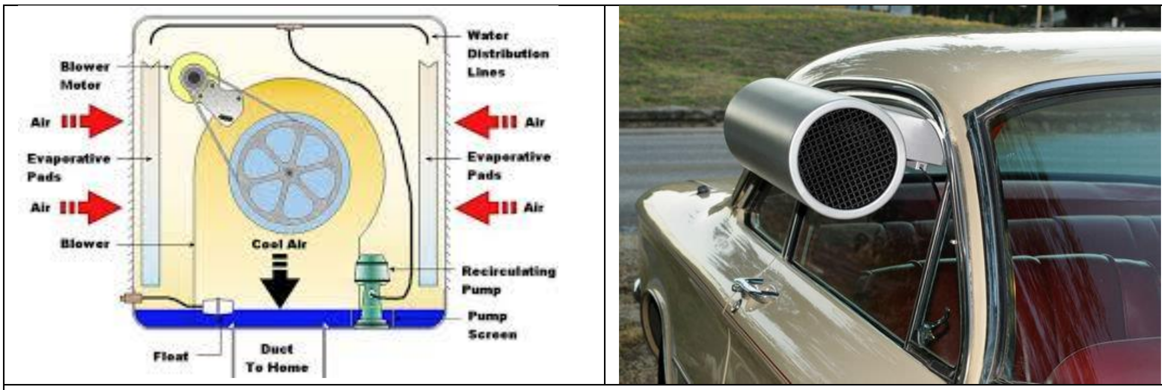


Figure 5.41. Principle of a swamp cooler and example of a historic car swamp cooler . Source: www.teachengineering.org (04.01.2015) and historic example of a car swamp cooler. Source: www.etsy.com/de/listing/115395443/swamp-cooler-vintage-fenster-ac (05.01.2015)

Figure 5.42. Example of a residential and industrial swamp cooler. BONAIR (AU). Source: www.bonaire.com.au (04.01.2015)

5.4.3 Phase Change Material (PCM) Cooling Components

The following text passage, written in Talic, is cited from Santamouris and Wouters [30]]:

Phase change materials can be used to store energy during the night and to recover it during the day. In PCM-based ventilative cooling components cool air is circulated during the night at the PCM store and is stored under the form of latent heat. During the following day, the high temperature ambient air is circulated through the PCM, where the latent heat offered to the material cools the air. The efficiency of the system deals primarily with the phase change temperature of the material, the temperature of the ambient air during the night period and the air flow rate. Phase change materials can be paraffin, eutectic salts etc., and can be embedded in microcapsules, thin heat exchangers, plaster, gypsum, board or other wall covering materials.

During recent years, many research studies and experimental applications have been carried out. Kang Yanbing et al. (2003) studied the use of an external PCM store associated with night ventilation techniques. A fatty acid was used as a phase change material. They found that the use of a PCM store decreases the maximum room temperature of the next day by almost 2 °C, compared to a commonly night ventilated building.

Turpenny et al. (2000) have proposed and tested a PCM storage with embedded heat pipes, coupled with night ventilation. A high heat transfer rate was measured and it was concluded that the system can ameliorate the performance of night cooling techniques.

The use of PCM wallboard coupled with mechanical night ventilation in office building has been studied by Stetiu and Feustel (1996). They concluded that PCM storage associated with night ventilation techniques offers the opportunity for system downsizing in climates where the outside air temperature drops below 18 °C at night. Calculations for a prototype IEA building located in California show that PCM wallboard could reduce the peak cooling load by 28%.

A newly developed PCM-based ventilative cooling component is “cool-phase” by Monodraught (GB) (Figure 5.43). It is a modular ventilation device, ceiling mounted or integrated within the suspended ceiling, guiding ventilation air through thermal battery modules, filled with paraffin PCM. Source: http://www.cool-phase.net/ (20.04.2014)

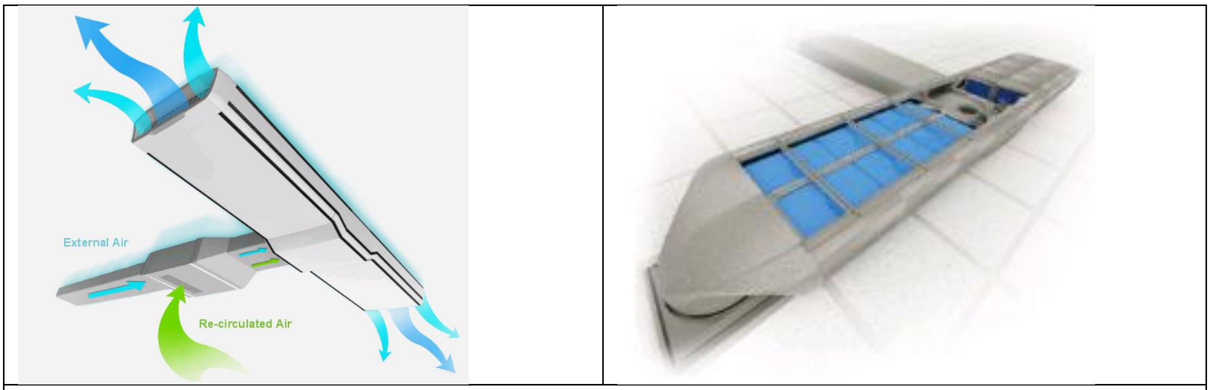


Figure 5.43. PCM cooling and ventilation system by cool phase by Monodraught (GB)

Outlook: PCM-based applications of ventilative cooling offer a very promising field of development.

5.5 Actuators

The core issue regarding actuation in ventilative cooling is opening and closing ventilation elements, such as windows, doors, flaps, dampers and louvres. There's an immense variety of actuators available. Roughly they may be structured in linear actuators, chain (including folding) actuators and rotary actuators.

5.5.1 Linear Actuators

Linear actuators (Figure 5.44) consist of solid tubes ore prisma, with a push rod, driven by a 230 V or 24 V electric motor via a spindle. They are robust; allow high opening strokes up to 1.000 mm and more and offer significantly high forces up to 1.000 N each.

Linear actuators are commonly used for domes, outside opening top hung windows, smoke exhaust flaps and similar applications.

Their limiting factor is only their special form, occupying significant areas of the room in front of the window and causing danger of injury if used in occupied zones.

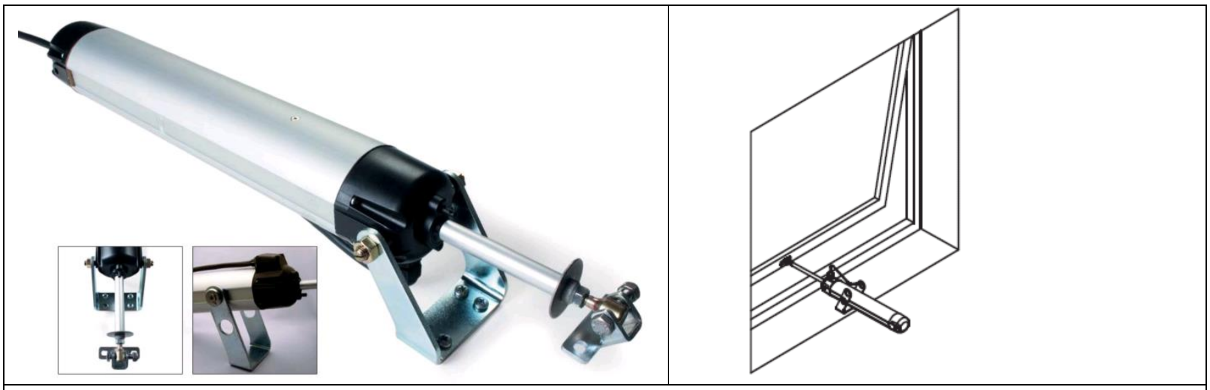


Figure 5.44. Linear spindle actuator. MAX (UK). Source: http://www.window-openers.com/linear_window_actuators.html (04.01.2015)

5.5.2 Chain Actuators

Chain actuators (Figure 5.45 and 5.46) deliver a pushing steel chain instead of the pushing rod, driven by a 230 V or 24 V electric motor via a sprocket. Chain activators are commonly used for Top Hung, Side Hung or Roof Vent Windows, and all kinds of applications in occupied zones.

In comparison to linear actuators chain actuators offer the big advantage of small dimensions but are comparably limited in stroke and force. Typical strokes reach 400 mm, while typical push and pull forces reach 300 N. Heavy duty chain actuators are constructed with a double chain for higher stability, offering strokes up to 800 mm and forces up to 600 N.

Beside chain actuators there's big number of folding actuators, again widely used for all kinds of applications with limited space at limited ranges of stroke and force.

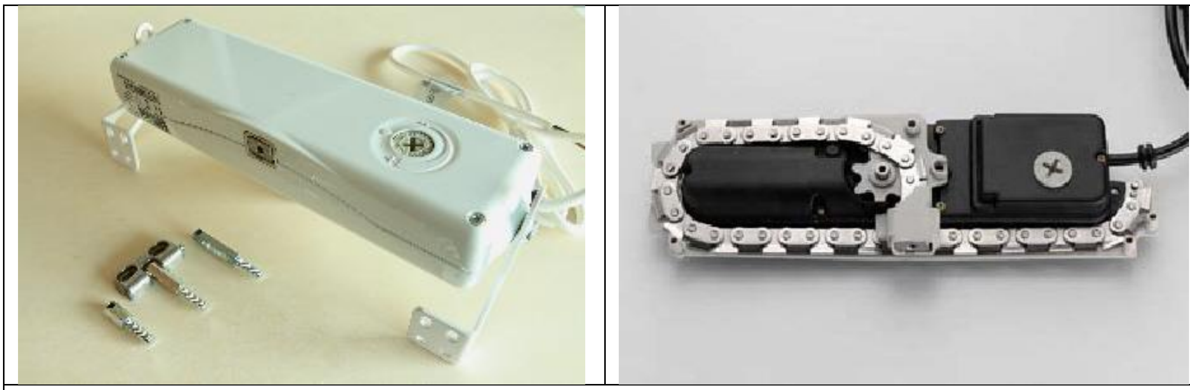


Figure 5.45. typical chain actuator. ACK4 (IT)
Source: http://www.window-openers.com/ack4_electric_chain_actuator.html (04.01.2015)

Figure 5.46. Heavy duty chain actuator with double chain. SE controls (UK)
Source: http://www.secontrols.com/product-catalogue/actuator/tgco-24-600/features/ (04.01.2015)

5.5.3 Rotary Actuators

Rotary Actuators are driven by electric motors, in most cases including a reduction gear.

They are standard element of every motorized louvre or damper, being distributed in an enormous variety.

5.6 Sensors

Effective Ventilative Cooling very much relies on effective control, needing accurate sensors and adequate control strategies.

Typical phenomena to be measured, amongst others, are temperature, radiation, humidity, CO_2-concentration, air-velocity, presence of users.

Challenges regarding sensor-technology are high robustness, cost-effectivity, adequate accuracy (especially robustness against long-time drift).

5.6.1 Temperature Sensors

Temperature sensors are standard equipment of Ventilative Cooling controls.

Temperature sensors for building control applications are predominantly equipped with NTC- or with Pt100-Sensor-technology. Pt100 is the more accurate one, but already NTC-technology offers accuracies in the range of ± 0.5 K being reliable and robust and free from long-time drift.

Since Ventilative Cooling control typically deals with low temperature differences, sensors have to offer an accuracy of ± 0.5 K or better. Concern has to be given to protecting the temperature sensors against influence from radiation, both solar and terrestric.

Room temperature sensors should be placed with care, depending on their purpose: If measuring the temperature within the operational zone, they should be mounted on a height between 1.2 and 1.8 m, at a well ventilated place, secure from direct solar-beam radiation and secure from influences from possible thermal heat loads within the room. If controlling the opening of exhaust vents in case of ventilative cooling, the sensors should be placed at a height accordingly to the position of the exhaust vents.

Outlook: New developments address combined air- and surface-temperature measuring, leading to measurement of resultant or operative temperature and to measuring surface temperatures via infrared sensors. Both developments offer promising perspectives towards improved hybrid ventilation solutions, with a better basis for managing the adequate change-over-point from natural to mechanical ventilation.

5.6.2 Air Flow Sensors

Air Flow Sensors are used to measure the air flow rate in ducts as well as the air speed in free flow.

As for physical principles there are thermal and mechanical anemometers available. Both sensor types are costly and sensitive against mechanical damage. They are used for control measurements, but rarely for constant control applications.

For constant air flow measurements in free flow applications see Wind Sensors.

For constant air flow measurements in ducts usually Prandtl-tubes or measuring orifices are used, both being exceptionally robust and comparably cheap.

5.6.3 Radiation Sensors

Radiation sensors are part of Ventilative Cooling control in case of both solar radiation and longwave radiation, i.e. surface temperatures.

Solar radiation sensors are especially important for controlling sunblind operation. Accuracies in the range of ± 10% or better are acceptable. As regards to positioning its favourable having at least one sensor mounted at the upper third of each façade, specifically controlling the sunblinds of this area. Experiments have been carried out with having only one solar radiation sensor, horizontally mounted at the roof and recalculating the radiation to specifically oriented facades. This method is theoretically tempting but suffers from low robustness and weak sensitivity of local shading effects.

Infrared sensors are used for both presence sensors and radiant temperature sensors.

In case of presence sensors they are reliable and cheap. They are easy to test and are widely used for control of artificial light and, rarely, ventilation. Radiant sensors measuring surface temperatures are so far rarely used for indoor environmental control, since they are significantly costly and suffer from their physically based sensitivity towards the emissivity of the specific surfaces.

Outlook: In case of solar radiation sensors and sunblind-control there's a field for improvement of control-algorithms, securing an accurate but "relaxed" sunblind-operation, what is highly important for its user-acceptance-level. In case of presence-sensors a field of steady development is the magnitude of the observed area and the control algorithm to form the signal, decently balancing the sensor's sensitivity towards desirable signals and robustness against undesirable disturbances.

5.6.4 Humidity Sensors

Humidity sensors are standard equipment of HVAC controls. They use capacitive sensor technology, robust if protected against mechanical damage and cheap. They are always combined with temperature sensors, usually Pt100, calculating the relative and the absolute humidity plus all other qualities of air, according to the psychometric chart, out of the combination of both signals. Satisfactory accuracy is in the range of ± 2 % r.H. One has to take care of the longtime drift which ranges around 1 % r.F./a. As regards sensor-positioning the same aspects are relevant like with temperature sensors. Combined humidity plus temperature sensors, with 0-10V output are offered for <100 EUR.

5.6.5 CO_2 Sensors

CO2 is an IAQ indicator of body odour but is not harmful to people in the concentrations normally found in buildings. In case of hygienic air change CO_2 is a first choice control parameter, ways better than relative humidity. CO2 sensors have been quite expensive and needed regular calibration, see Willem et al. 2002. Recent developments brought prices down to 100 – 200, - EUR/# and successfully introduced an Automatic self-adjusting calibration.

Outlook: Fields of improvement are still price, robustness, energy demand and durability.

5.6.6 Rain sensors

Rain sensors are of increasing importance since ventilative cooling, especially night ventilation has to work without personal occupancy control and since modern furniture and office equipment is strictly incapable withstanding temporary wetting. Precipitation sensors are small, reliable and cheap, usually less than 100 EUR. They normally only need to produce an on/off signal for overrule purposes. No significant field of improvement.

5.6.7 Wind Sensors

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 the Doppler Effect in two directions.

5.7 Control Strategies

Control Strategies in Ventilative Cooling solutions have to control the magnitude, sometimes even the direction, of air flows in space and time.

Main control parameters are zone air temperature, ambient temperature (both peak, actual or average), presence of users, CO_2 concentration level and humidity levels.

Another control parameter could be pressure difference. Its applicability is de facto limited to mechanically assisted ventilation; since only there pressure drops within the ductwork occur significant enough to for a control parameter.

Questions of specific control strategies are increasingly discussed, since Ventilative Cooling is emerging from traditional vernacular architecture and is introduced to modern buildings in urban surroundings, occupied by inhabitants with high level comfort expectations.

There's an open discussion whether ventilative cooling should be fully automatically controlled or if it should be – alternatively or additionally – be handed over to the personal control of inhabitants/users.

On one hand side, automation of summer-comfort-control, including ventilative cooling, in many cases has proven being significantly more effective than personal control. Especially in climate regions which haven't been trained for cooling traditionally, there seem to be a lack of intuition towards measurements to prevent from overheating.

On the other hand side, personal user control and/or manual override of automatic control are very important as it affects user acceptance of the indoor climate positively, (Rowe 2003 and others). Many studies and practical experiences reveal a high inhabitants' appreciation of user control over ventilation components, which is coherent to the development of adaptive comfort (Humphreys, Nicol, Roaf, de Dear, et al), indicating a "forgiveness factor" as soon as personal adaptive options are available.

A third option of control strategy is presently discussed, which is automated user-feedback: Operation of windows, fans, sunblinds, etc. is left to personal control of the inhabitants, but the building automation system gives active feedback and specific advise how to optimally use the specific components. Automated windows would increase the reliability of performance predictions, but manually controlled windows reduce costs and enhance workspace quality from a psychological point of view. Signaling systems that advise building occupants when to open and close windows represent a compromise between the two solutions. Even though prior studies found that occupants were not very active in intervening in the windows Ackerly et al. [1] make recommendations to maximize the potential of this solution. Such manual control with automated feedback is a promising field of development, being challenged by hard-to-fight human habits like laziness and habituation.

Still, if natural ventilation elements such as windows or flaps are controlled mechanically, it is worthwhile investigating, if - as regards comfort - defined airing periods with significant air change are preferable against constant ventilation with low air change rates.

Another challenge with need for further research is the practical balance of natural ventilation periods and of AC-periods in hybrid ventilation solutions.

Outlook: The development of adequate control strategies of ventilative cooling is a crucial issue and will be a key issue of research in this Annex 62. Many questions are open, as indicated above, very much dealing with the balancing full building automation and personal control.

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Earthscan, 2009

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5.8.2 Manufacturers

(1) Aralco
Natural Ventilation Systems.
Textielstraat 18A - B-8790 Waregem, Belgium
http://www.aralco.nl/

(2) Azbil Corporation
building automation products, industrial automation products, related services
19F Tokyo Building, 2-7-3 Marunouchi, Chiyoda-ku, 100-6419 Tokyo, Japan
http://www.azbil.com/index.html

(3) Condor Kinetic
Kinetic Ventilation Solutions
52 Overlord Place, Acacia Ridge, Queensland 4110, Australia
http://www.condorkinetic.com.au/

(4) Duco
Ventilation & Sun Control.
Handelsstraat 19, B-8630 Veurne, Belgium
http://www.duco.eu

(5) LIXIL Corporation
building materials and housing equipment, related services

36F, Kasumigaseki Building, 3-2-5 Kasumigaseki, Chiyoda-ku, 100-6036 Tokyo, Japan
http://global.lixil.co.jp/

(6) Misawa Homes Institute of Research and Development Co.,Ltd
Industrialized housing company
1-1-19 Takaido-nishi Suginamiku, 168-0071 Tokyo, Japan
http://www.misawa.co.jp/en/info/

(7) Monodraught Ltd
Natural ventilation, daylighting and cooling
Halifax House, Cressex Business Park, High Wycombe, Bucks HP12 3SE, United Kingdom
http://www.monodraught.com/

(8) Nikken Sekkei Ltd
Urban Planning, Architectural Design, Structural Design, Civil Engineering, Work Place Design, Interior Design, Landscape Design, etc.
2-18-3 Lidabashi, Chiyoda-ku, Tokyo, Japan
http://www.nikken.co.jp/en/index.html

(9) Passivent Limited
Natural Ventilation & Daylighting Solutions
North Frith Oasts, Ashes Lane, Hadlow, Kent TN11 9QU, United Kingdom
http://www.passivent.com/

(10) Renson Ventilation nv
Solutions-for-ventilation-and-sun-protection.
Industriezone 2 Vijverdam, Maalbeekstraat 10, 8790 WAREGEM, Belgium
http://www.renson.eu

(11) VELUX A/S
Skylights, Roof Windows, Blinds and Roller shutters, Home Automation.
Ådalsvej 99, 2970 Hørsholm, Denmark
http://www.velux.com

(12) SE Controls
Smoke and Natural Ventilation Solutions.
Lancaster House, Wellington Crescent, Fradley Park, Lichfield, Staffs WS13 8RZ, UK
http://www.secontrols.com/

(13) Sekisui House, Ltd.
Design and construction of pre-fabricated houses and residential buildings
1-1-88 Oyodonaka, Kita-ku, 531-0076 Osaka, Japan
http://www.sekisuihouse.co.jp/

(14) YKK AP Inc.
Manufacturer of building materials that specializes in windows and doors
Kanda Izumi-cho Chiyoda-ku, 101-8642 Tokyo, Japan
https://www.ykkap.co.jp/

6 Existing Methods and Tools

This chapter aims at documenting existing modelling methods and tools by assessing capabilities, gaps, needs and limitations in the context of ventilative cooling performance prediction. Existing tools range from simple empirical formulas to complex dynamic simulation environments. Their applicability at a certain design stage depends on the required input data detail level and output data accuracy.

Until very recently, natural ventilation systems were designed based on local or regional traditions, empirical studies, and fundamental but incomplete theoretical models.

As building design is characterized by different detailed design levels, airflow models with different resolution are used to support the decision-making process.

The available airflow models can be divided into two categories according to the detail resolution required:

- Early stage modelling tools: empirical models, monozone model, bidimensional airflow network models;
- Detailed modelling tools: airflow network models, coupled BES-AFN models, zonal models, Computational Fluid Dynamic, coupled CFD-BES-AFN models.

A review of the available methods for airflow modelling can be found in existing literature [1] [2] [3] [4] [5] [6] [7]. The following paragraphs try to summarize these findings.

6.1 Empirical models

Empirical models are basically static correlations derived analytically or experimentally to predict ventilation airflow rates for simple opening configuration. Because of their easy application, they are used in early-design-stages to pre-size components. In literature empirical methods are grouped in two categories, depending on their output results: air flow rate and opening sizes and air speed into the building. As they refer to a limited number of case studies or to more detailed model simplifications, they are based on specific assumptions.

The following empirical models (Table 6.1) can be applied to steady state calculations to assess the air flow rate at defined conditions or to transient state calculations. In both cases indoor building temperatures are required. The building temperature can be estimated through different ways:

1) Building temperature can be assumed constant and equal to cooling setpoint;
2) Building temperature can be assumed to oscillate harmonically according to a predefined function ((6.1 as example) to simulate the dynamic effect of heat storage in the structure materials [8];

$$T_{b,h} = 24.5 + \cos\left(2\pi\frac{(h-h_i)}{24}\right) \qquad (6.1)$$

Where

$T_{b,h}$ = building temperature at a certain hour h [°C]

h_i = initial time of night ventilation

3) Building temperature can be estimated using the simplified calculation method described in EN13792:2005 or the complex method in EN13791:2005.

As already pointed out in chapter 3, the standard calculation procedure is very complex, time consuming and might require expertise to be performed.

Table 6-1. Existing empirical model to estimate airflow rates. W=wind driven, B= buoyancy driven, W&B = Wind and buoyancy driven.

Openings nr	Configuration	Equation	Reference
1	W	$$Q = \pm c_D A \sqrt{\left\lvert U^2 - \left(\frac{2\gamma P_a}{\rho V}\right)\omega \right\rvert}$$ where Q = ventilation flow rate C_D = discharge coefficient γ = polytrophic exponent, 1.4 for adiabatic flows and 1.0 for isothermal flows	pulsation theory derived through wind tunnel testing by Cockroft J.P. and Robertson P. [9]
1	B	$$q_B = \frac{1}{3} A C_d \sqrt{\frac{\lvert T_{in} - T_{out}\rvert H g}{(T_{in} + T_{out})/2}}$$	derived analytically by Warren P.R. [10]
1	W	$$q_w = 0.025 A v_{w,ref}$$	wind tunnel tests and full-scale experiments in 2 real buildings by Warren P.R. [10]
1	W&B	$$q_{bw} = \frac{1}{2} A \sqrt{C_1 + \left(C_2 v_{w,ref}^2\right) + \left(C_3 H \lvert T_{in} - T_{out}\rvert\right)}$$	33 measurements on a full-scale building by Phaff H. and De Gids W. [11]
1	W&B	$$\mathrm{q_{bw}} = \mathrm{A}\sqrt{\mathrm{C_1 \lvert C_P \rvert v_{w,ref}^2 + C_2 H \Delta T + C_3 \frac{\Delta C_{P,opening} \Delta T}{v_{w,ref}^2}}}$$ with $$\Delta C_{p,opening} = 9.1894 \cdot 10^{-9} \cdot \varphi^3 - 2.626 \cdot 10^{-6} \cdot \varphi^2 - 0.0002354 \cdot \varphi + 0.113$$ where C_1, C_2 and C_3 are empirical coefficients	wind tunnel test and 48 full-scale measurements on real buildings by Larsen T.S. [12]
1	W	$$Q = CAU$$ where C = airflow coefficient varies depending on geometry and wind incidence direction A = opening area	ASHRAE handbook [13] and Yamanaca T. et al. [14]

		U = wind speed	
1	B	$$Q = \frac{C_d A}{3}\sqrt{gh\frac{\Delta T}{T_{out}}}$$ where h = height of the opening	semi-analytical model ASHRAE Handbook [13]
1	W&B	$$U_m = \sqrt{C_1 U_{10}^2 + C_2 h \Delta T + C_3}$$ where U_{10} = reference wind speed measured at the height of 10 m C_1 = wind constant (0.001) C_2 = buoyancy constant (0.0035) C_3 = turbolence constant (0.01) $$Q = \frac{1}{2} A U_m$$	Phaff J.C. et al. [15]
4*	W&B	$$q_w = C_d \cdot A_w \cdot v_w \cdot \left\lvert C_{p,1} - C_{p,2} \right\rvert^{0.5}$$ $$q_B = C_d \cdot A_B \cdot \left(\frac{2 \cdot \lvert T_{in} - T_{out} \rvert \cdot hg}{[(T_{in} + T_{out})/2]} \right)^{0.5}$$ where $$\frac{1}{A_w^2} = \frac{1}{(A_1 + A_2)^2} + \frac{1}{(A_3 + A_4)^2}$$ $$\frac{1}{A_B^2} = \frac{1}{(A_1 + A_3)^2} + \frac{1}{(A_2 + A_4)^2}$$	*two openings on each side – CIBSE guide [16]
2	B	$$q = C_d \sqrt{A^* \frac{\rho_o - \rho_i}{\rho} gh}$$ $$A^* = \sqrt{2} A_t A_b \Big/ \sqrt{A_t^2 + A_b^2}$$ where A_t = area at the top of the stack A_b = area at the bottom of the stack	fully mixed model by Andersen K. T. [17]
2	B	$$q = C_d A^* \sqrt{\frac{T_i - T_o}{T_o} g(h - h_c)}$$	emptying water-filling box model by Linden P.F. [18]
2	B	$$q = C_d A^* \sqrt{\left[\frac{T_b - T_o}{T_o} g h_c + \frac{T_t - T_o}{T_o} g(h - h_c) \right]}$$ $$T_t = \frac{E}{\rho c_P q} + T_o$$ $$T_b = \lambda (T_t - T_o) + T_o$$ where	emptying air filling box model I by Li Y. [19]

		$$\lambda = \left[\frac{q\rho c_P}{A_t}\left(\frac{1}{\alpha_f}+\frac{1}{\alpha_r}+\frac{1}{\alpha_c}\right)+1\right]^{-1}$$ α_f = convective heat transfer coefficient at floor α_r = radiative heat transfer coefficient α_c = convective heat transfer coefficient at ceiling	
2	B	$$q = C_d A^* \sqrt{\left(\frac{1}{2}gh\frac{T_b - T_o}{T_o} + \frac{1}{2}gh\frac{T_t - T_o}{T_o}\right)}$$	emptying air filling box model II by Li Y. [19]
2+	B	$$Q = C_d A\sqrt{2g\Delta H_{NPL}\,(T_i - T_o)/T_i}$$ where ΔH_{NPL} = height from midpoint of lower opening to neutral pressure level [m]	ASHRAE handbook [13]

Other analytical models that take into account buoyancy sources' geometry and position are:

- Buoyancy driven natural ventilation induced by two buoyancy sources [20];
- Buoyancy driven natural ventilation induced by a heat source distributed uniformly over a vertical wall [21];
- Buoyancy driven natural ventilation in an enclosure with two stacks and a heat source uniformly distributed over the floor [22];
- Natural ventilation of a room with distributed based heating and vents at multiple levels [23].

Non-dimensional methods allow quick and easy manual calculation avoiding the need of detailed and time-consuming numerical simulations; they can be used to identify important parameters and check the sensitivity of the design to possible changes. Li Y. and Delsante A. [24] present non-dimensional graphs to calculate ventilation flow rates and air temperatures, and for sizing ventilation openings in a single-zone building with two openings when no thermal mass is present. Both fully assisting and fully opposite wind solutions are taken into account. The model also incorporates solar radiation and heat conduction loss through the building envelope. Etheridge D.W. [25] also proposes the use of non-dimensional graphs to determine the size and the position of openings and estimate air flow rates. The graphs are generated from both theoretical models and experimental methods.

ASHRAE method defines a more general equation to estimate the bulk air flow rate in a single zone building ((6.2).

$$Q = A\sqrt{a\Delta T + b v_{met}^2} \tag{6.2}$$

where

Q = bulk airflow rate [m^3/h];
A = total effective leakage area [cm^2];
a = stack coefficient [m^6/h^{2}cm^{4}K];
ΔT = indoor-outdoor temperature difference [K];
b = wind coefficient [m^{4}s^2/h^{2}cm^4];
v_{met} = meteorological wind speed [m/s].

The stack coefficient *a* is defined depending on the number of building storeys, as in Table 6-2.

Table 6-2. Stack coefficients a. Source: ASHRAE Handbook [13]

Number of building storeys	*a [m^6/h^2cm^4K]*
1	0.00188
2	0.00376
3	0.00564

The wind coefficient *b* depends on the number of stories and the shielding class, as in Table 6-3.

Table 6-3. Wind coefficient b. Source: ASHRAE Handbook [13]

Shielding class	*1 storey*	*2 storeys*	*3 storeys*
No obstructions	0.00413	0.00544	0.00640
Light local shielding	0.00319	0.00421	0.00495
Moderate local shielding	0.00226	0.00299	0.00351
Heavy shielding	0.00135	0.00178	0.00209
Very heavy shielding	0.00041	0.00054	0.00063

Indoor air velocity is important to verify comfort conditions as air velocity increases body's convective heat exchange improving comfort conditions at high indoor temperatures. The Givoni method allows one to estimate the indoor air speed. The correlation in (6.3 is given by experimental results on a square floor zone with the same opening area on the upwind and on the downwind façade.

$$v_i = 0.45 \cdot (1 - e^{-3.48x}) \cdot v_{ref} \tag{6.3}$$

where

v_i = average indoor air velocity [m/s];

x = opening to wall ratio [ ];

v_{ref} = reference external wind speed [m/s].

Graca G.C. [26] developed a model to calculate indoor air speed in the jet and the recirculation zone in cross ventilated rooms while knowing the inlet air flow rates. Considering the maximum air velocity in front of the opening calculated as in (6.4.

$$v_{max} = \frac{q_{in}}{A_{inlet} c_d} \tag{6.4}$$

The air velocity of the main air jet is calculated as in (6.5.

$$v_{jet} = 1.56 \cdot v_{max} \cdot c_d \cdot \sqrt{\frac{A_{inlet}}{A_{cross}}} \quad \text{for } 1/3 < C_L < 11 \tag{6.5}$$

where

$$C_L = \frac{2L_{room}}{W_{room} - W_{inlet}}$$

The air velocity in the recirculation area is calculated as in (6.6.

$$v_{rec} = v_{jet} \cdot C_{RJ} \cdot \sqrt{\frac{D_{room}}{A_{inlet}}} \tag{6.6}$$

where

$$C_{RJ} = \begin{cases} 0.191\, for\ 1/3 < C_L < 4 \\ 0.104\, for\ 4 < C_L < 11 \end{cases}$$

As regards ventilative cooling, natural ventilation performance is related also to cooling load prediction. Thermal mass directly influences cooling loads and therefore more complicated methods such as frequency domain thermal network models are needed to develop simplified methods and tools.

Balaras C.A. [27] identified 16 simplified design methods for calculating cooling loads and indoor air temperature of a building taking into account thermal mass effects. The paper categorizes the models in terms of inputs, outputs and restrictions on their level of accuracy or other design limitations. Some of these models have been used to develop a software package.

6.2 Detailed modeling tools

Detailed models were developed to calculate airflows throughout a building taking into account variable climatic conditions and pressure distributions in and around the building. Most of these models can be coupled with building energy simulation tools to model interactions between thermal behavior and airflows within the building.

6.2.1 Airflow network models

Airflow network models have been developed to more quickly solve airflows throughout a building. They represent the building as one or more well-mixed zones, assumed to have a uniform temperature and a pressure varying hydrostatically, connected by one or more airflow paths. Air momentum effect is neglected. Each airflow path is mathematically described using the Bernoulli equation. Airflow paths form a network of “nodes” (zones) and “resistances” (linkages). The network can be solved by specifying external climate conditions (temperature, humidity, wind velocity and directions), climate-envelope interactions (wind pressure on the facade) and engineering models for resistances. A matrix consisting of a set of equations is constructed and numerically solved. Convergence is reached when the sum of all mass flow rates through all components approaches zero within the tolerance band specified [1].
Figure 6-1 and Figure 6-2 represent a sketch of a network example using building energy simulations thermal zones and lumped models.

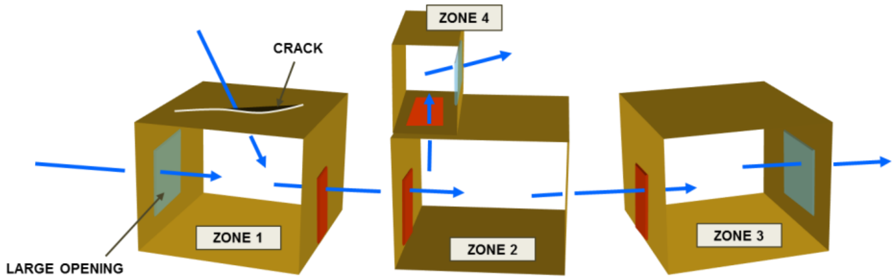


Figure 6-1. Airflow network schematic representation. Source: IBPSA-USA

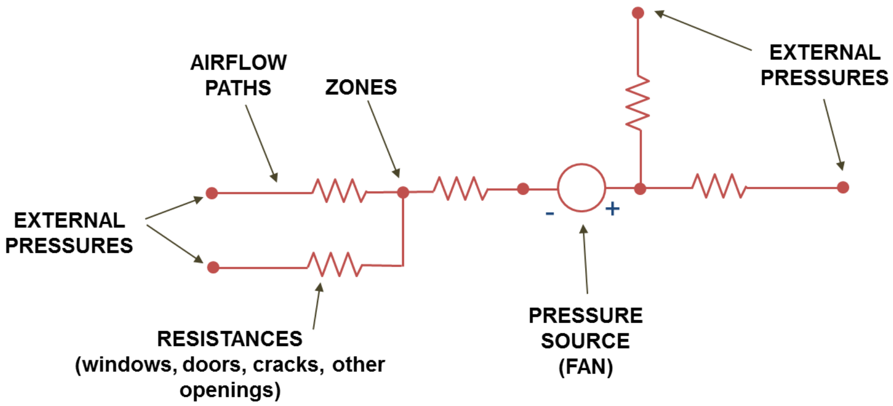


Figure 6-2. Schematic representation of relationship between zones and air paths. Source: IBPSA-USA

The most widely used airflow network modelling tools are COMIS [28] and CONTAM [29]. As both tools are based on the same theoretical model, no significant difference has been noted among them.
Airflow network models can be coupled to dynamic simulation models to evaluate the whole building performance, taking into account the thermal mass effect as well.

Because of their simplicity, airflow network models have some important limitations, which are:

- heavily dependency on coefficients like wind profile exponent, wind pressure coefficients and discharge coefficients;
- temperature distribution within air volumes (e.g. stratification) cannot be determined;
- local surface convection determination is limited by the insufficient resolution;
- turbulent fluctuations of wind pressures are neglected;
- air momentum effect is neglected;
- air speed in rooms cannot be calculated.

According to Wang L. and Chen Q. studies [30], the assumption of uniform air temperature distribution is acceptable when the dimensionless temperature gradient is less than 0.03 and the assumption of neglecting air momentum effect is reasonable when the jet momentum effect is dissipated before reaching an opening in downstream.

6.2.2 Zonal models

Zonal models are considered intermediate models between airflow networks and CFD, as they divide the bounded space into a number of smaller control volumes to calculate velocity and temperature field within the zone. These models have been initially developed for mechanical systems to study the interaction between the terminal unit and the rest of the room. Later they were used to detail

indoor environment and to estimate thermal comfort in a fast way. Zonal models are of particular interest to obtain information as temperature stratification, thermal interaction with cold façade, draft and thermal radiation performances.
A review of the zonal models developed can be found in Megri et al. 2007 [31]. To date, there is no commercial program based on the zonal modelling approach, limiting the possibility to use this kind of models for design purposes.

6.2.3 Computational Fluid Dynamics

CFD aims at solving the Navier-Stokes equations which are based on treating the fluid as a continuum. Navier-Stokes equations are based on conservation of mass, momentum and energy for viscous, incompressible fluid. They describe the unsteady three-dimensional motion of air in terms of instantaneous velocities, temperature (or density) and pressure at a point. The building is divided into control volumes and the equations are solved for every mesh element, using iterative solutions.

The primary applications of CFD to design natural ventilation are:

- the calculation of velocity and temperature fields in rooms and buildings;
- the calculation of envelope flows;
- the calculation of surface wind pressure distributions;
- calculations of parameters within the space;
- the calculation of the flow characteristics of openings.

Important modelling issues are the choice of calculation domain and the associated grid, the boundary conditions settings and the convergence requirements. Equally important is the choice of the turbulence model. Simplified zero equation models are questionable for geometries where they have not been validated. Standard k-epsilon models are the first choice for many flows excluding separated flows. Large eddy simulations yield more accuracy but require higher computation resources.

Grid density, shape and orientation have to be defined carefully. Regions of high spatial gradient need higher density of the grids. The orientation of the grids has to be set considering the local flow direction. In case of external CFD, the external flow domain needs to be large enough, such that the results are nominally independent of its size. Modeller should be experienced enough to decide how to refine the mesh for solving local gradients.

Boundary conditions have to be specified at the surfaces of the domain and at the internal solid surfaces. The accuracy of results depends strongly on the accuracy of boundary conditions. External CFD is easier to set, because boundary conditions regard only wind characteristics. Detailed information about the domain is needed otherwise even mediocre results might not be reached after the long calculation time.

CFD simulations provide the users with a large amount of information that can be handled with the desired spatial and temporal resolution. Given the long calculation time and the high dependency on boundary condition, CFD simulations are commonly used in the later stages of design. Due to the high effort both from computational than from output post-processing point of view, it is often counter-productive to use transient CFD to predict natural ventilation strategies within the whole building.

Most of the CFD codes used in practice are commercial programs where the source code is not available to the users and with many more applications than natural ventilation design. ANSYS Fluent [32] is the most widely used software.

6.2.4 Coupled AFN - BES models

Common dynamic simulation tools (EnergyPlus, TRNSYS, ESP-r, IES, TAS, CoolVent) allow users to couple the thermal analysis with the airflow model in order to:

- consider interactions between airflow and thermal calculations;
- assess infiltration rates;
- evaluate hybrid ventilation systems.

The coupling becomes fundamental to predict passive cooling performance, where a higher ventilation rate can avoid overheating [33] and improve thermal comfort. Although for winter ventilation design the airflow can be considered uncoupled from the thermal behaviour of the building, for summer natural ventilation a coupled model become fundamental [2].

Different ways exist to avoid computationally intractable fully coupled models [33]: in the ping-pong approach, the thermal model uses the results of the airflow model at the previous time step and vice versa; in the onion approach thermal and airflow model iterate within one time step until satisfactory small error estimates are achieved. In some instances there are multiple solutions to the coupled equations. Care must be exercised in the initial conditions to produce stable, realistic solutions.

Hensen [33] found out that the ping-pong approach may lead to substantial errors if combined with a large time step (equal or more than an hour), and the onion approach will have implications on computation time if combined with a short time step (less than an hour).

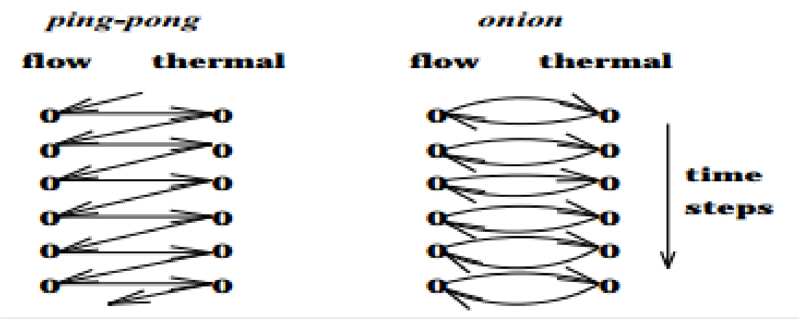


Figure 6-3. Ping-pong (left) and onion (right) coupling approach. Source: Hensen [33]

EnergyPlus is coupled to the COMIS airflow model [34] through a ping-pong approach [35]. Current version (8.x) of EnergyPlus uses Air Flow Network (from CONTAM) models to calculate zonal air flows. Trnsys adopts an onion approach with both COMIS and CONTAM airflow models [36], whereas in ESP-r different coupling approaches are available to be selected by the user [33].

Trnsys also recently released a plugin (Trnflow [37]) to perform multizone airflow simulation coupled with Type 56.

ESP-r has a built-in network model [38] developed by the Energy System Research Unit at the University of Strathclyde. It allows various way of coupling and also outputs the air velocity through an opening.

Although the coupling allows to consider interactions between airflows and building thermal behaviour, the convection heat transfer modelling is still too simplified for night cooling effect predictions. Furthermore, models for components like wind catchers or solar chimneys are not included in the airflow network models.

6.2.4.1 Convection heat transfer coefficient

Compared to the current state of modelling of radiation and conduction, surface convection is modelled in a simplified way by the most common building energy simulation tools. Past research works [39] [40] [41] revealed that convection heat transfer coefficient strongly affect thermal comfort and energy predictions by building energy simulations. In particular when night cooling is applied, larger differences occur in predicted night cooling performances, because of the larger temperature differences. Compared to EN ISO 13791 correlations for convective heat transfer coefficients, yearly cooling demand might deviate up to 200% for correlations used in building energy simulations in case of night cooling strategies [39].

CHTC correlations depend on the mechanism of fluid flow (natural, forced or mixed), the flow regime (laminar or turbulent), the properties of the fluid and the geometry of the specific system of interest.

CHTC correlations based on flat plate measurements can be found in literature [42] [43] [44] [45] [46] [47] and are used in the most common BES tools. Figure 6.4 shows a comparison of exterior vertical wall exterior convection models while Figure 6.5 shows a comparison of interior vertical wall convection models [49].

The CHTC correlations for internal surfaces are related to the difference between air temperature and surface temperature.

The CHTC correlations for external surfaces take into account also local wind velocity, surface roughness and whether surface is directed windward or not.

CHTC correlations for windows can be referenced to ISO 15099: 2003 or to measurements taken at the Mobile Window Thermal Test (MoWiTT) facility [48].

Beausoleil – Morrison I. [40] developed an adaptive convection algorithm which assigns default equations to external surfaces depending on their outside face classification, heat flow direction and wind direction and to internal surfaces depending on the zone airflow regime, the surface orientation and heat flow direction.

As a consequence of lumped parameter model assumptions, the enclosure volume is considered well mixed and therefore the air temperature refers to average air temperature of the thermal zone. Also locally surface temperature differences and flow regimes are neglected. A more detailed estimation of CHTC can be performed using CFD simulations.

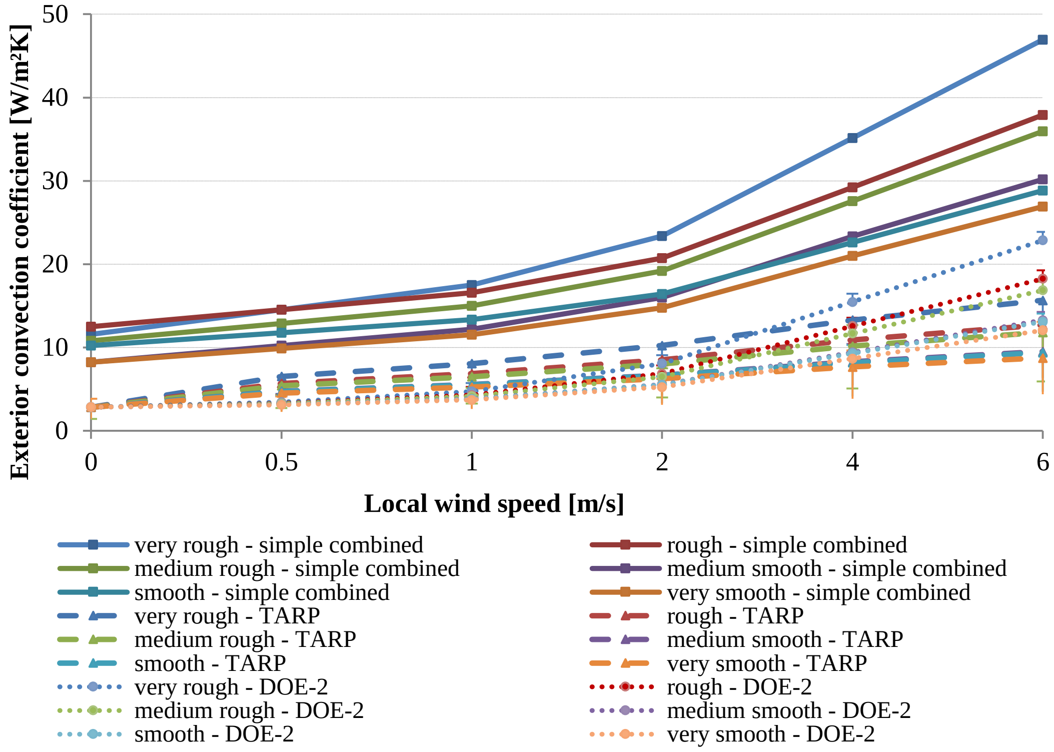


Figure 6-4. Vertical wall exterior convection model comparison depending on wind speed and surface roughness at a temperature difference of 10K between outdoor air and external wall surface when the façade is directed windward. Source: Belleri A. [49]

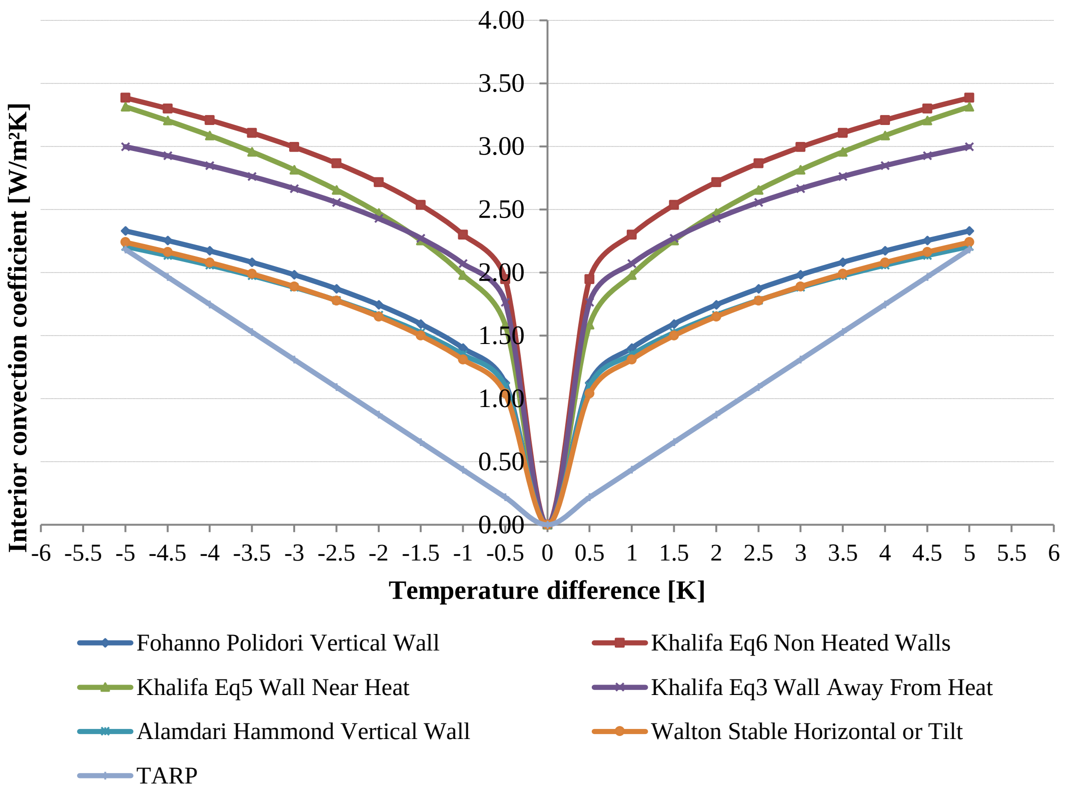


Figure 6-5. Vertical wall interior convection model comparison at different temperature differences between air and wall interior surface. Source: Belleri A. [49]

6.2.5 Coupled CFD – BES – AFN models

Investigation on BES and CFD coupling is still ongoing, enforced by the rapid development of computation power.

CONTAM was recently enhanced to incorporate CFD capabilities for both internal and external environmental analysis [50] by coupling with CFD0, a CFD software tool with an indoor zero-turbulence model [51]. The external link to CFD0 calculates wind pressure coefficients for each building leakage path and for a defined range of wind directions. The link to CFD0 allows to embed a CFD zone in a CONTAM network model by iteratively exchanging boundary conditions such as airflow rate, air pressure and contaminant concentrations. The internal CFD zone enables the detailed calculation of air and contaminant concentrations within a space of a building for which the well-mixed assumption is insufficient, handling the remaining rooms with the well-mixed assumption. The external CFD link predicts distributions of wind pressures and contaminant concentrations outside a building to simulate their effect on indoor air flows.

Thermal domain and detailed airflow domain can also be coupled to achieve better results because the two can exchange boundary conditions [52].

DesignBuilder software [53] performs both internal and external steady CFD analysis. Temperatures, heat flows and flow rates previously calculated by EnergyPlus can be seamlessly used to provide boundary conditions simply by specifying the time/date of the CFD analysis. Grids are automatically generated from model geometry and boundary conditions to promote optimal solution convergence.

Studies conducted by Srinivas T. [54], Yuan J. [55] and Jayaraman B. [56] showed that coupling a CFD model with a multi zone model allows to obtain more realistic predictions of airflow and contaminant transport in buildings with large spaces.

Zhai J. and Chen Q. [57] [58] revealed the advantages of the integrated building simulation over the separated building energy and CFD applications, which are:

- CFD receives more precise and real-time thermal boundary conditions and can predict the dynamic indoor environment conditions that are important for the assessment of indoor air quality and thermal comfort.
- BES obtains more accurate convection heat from enclosures and can provide more accurate estimation of building energy consumption and dynamic thermal behaviours of building envelopes.

Zang R. et al. [59] presented a new coupling approach via open source platform of BCVTB (Building Control Virtual Test Bed). EnergyPlus (nodal model) and coupled EnergyPlus (nodal model)-Fluent (CFD model) simulation results showed that airflow network model generally predict smaller airflow rates for the openings. They also compared heat transfer coefficients computed from the empirical methods to that computed from the coupled CFD simulations under natural ventilation conditions. Up to 80% differences between the two have been encountered.
ESP-r has automated coupling capabilities to a CFD module able to predict non-stable mixed (turbulent, laminar and transitional) flows within 2D/3D domains [60]. Boundary conditions are automatically defined at each time step by interaction with the building and airflow network.

Menchaca [61] has carried out a series of CFD simulations of zones with varying geometries. She was able to develop a dimensionless correlation of the resulting vertical temperature gradient in the zone as function of the Archimedes number with suitably defined dimensions that is used in the coupled model, CoolVent. Ray [62] carried out CFD simulations and experimental confirmation of momentum effects on flow in vertical ducts that is also included in CoolVent.

6.3 Early stage modelling tools

Some simplified tools have been developed to support natural ventilation design within the early design stages, defined as the initial concept phase of an architectural project, during which the design team explores alternative design solutions.

6.3.1 Monozone models

Monozone models represent the entire building as one single zone which has one temperature and one internal pressure. In case of small residential buildings the whole building can be considered as a single zone. In case of more complex buildings, only part of the building can be meaningful analyzed. These models are able to evaluate thermal behaviour and airflow interactions of the building with the outdoor environment through different paths (windows, vents, ducts, cracks), but do not take into account air movements within building zones.

NatVent [63] is the first simple design tool for office type buildings which integrates a monozone heat balance model with an airflow model. The software has been developed with the NatVent project and is compatible only with Windows 3.11 and Windows 95. Users can determine whether the building is ventilated by passive stacks and/or ducted air supply, but they cannot input the control strategy. The software calculates indoor temperature trend and airflow rates for the selected period. All internal structures and surfaces are assumed to have the same temperature.

More recently, Estia SA in collaboration with the Laboratory of Urban Architecture and Energy Reflexion (LAURE/EPFL) developed a suite of software modules (DIAL+suite [64]) aiming at optimizing room design by assessing daylighting autonomy, natural ventilation throughout windows and thermal dynamic behaviour. DIAL+ventilation module calculates airflow through windows taking into account temperature difference between inside and outside, windows dimensions, respective positions of the different openings and openings type. Some basic window control strategies are implemented and allow to assess cooling plant operating hours and cooling needs, as well as overheating hours. Outputs (temperature and airflow rates) are calculated over a period of 24 hours.

6.3.2 Multizone models

Multizone airflow models represent the building as a group of zones connected through airflow paths which allows to perform preliminary assessment of ventilation and infiltration rates in a building. Calculations can be performed both in transient or steady state mode. They usually do not handle heat transfer phenomena but indoor temperatures can be scheduled or input through the coupling with other software.

CONTAM [29] is a multizone airflow model developed by the National Institute of Science and Technology (NIST) to perform preliminary assessment of the adequacy of ventilation rates in a building, the variation in ventilation rates over time, the distribution of ventilation air within a building, the impact of envelope air tightening efforts on infiltration rates, the contaminant concentrations and the level of exposure of building occupants to contaminants. The complementary software tool LoopDA [65] applies the loop equation design method developed by Axley J. [66] to the CONTAM multi zone airflow model. Compared to the airflow network model, the equations are reversed. Equations are written for the changes of pressure along airflow paths within the building, defined as loops from the inlet to the exhaust and back to the inlet again. The sum of the pressure changes around any loop must equal zero at every time step. The resulting loop equations define combinations of system component sizes that will provide desired ventilation flow rates given specific environmental design conditions. Therefore, instead of defining the physical characteristics of the flow components (opening area and position) and calculate airflow through them, the loop equation method requires the user to define the design airflow rates through the components and determines the physical characteristics of the components to provide the required flow rates.

Recently more user-friendly interfaces have been developed to perform coupled thermal and airflow simulations on simplified building models.

CoolVent [67] is a natural ventilation design tool developed by MIT which allows to compare different natural ventilation strategies by means of steady and transient simulations. It has a user-friendly interface which couples multi-zone airflow network with thermal analysis to predict indoor temperatures and airflow rates. Transient simulations give an overview of the airflow and thermal dynamics behavior of the building over 24 hours or for as long as one year. The model includes wind, buoyancy and fan driven flows. It allows the user to define a wide range of generic residential and commercial building types with user input of building and window dimensions, number of floors, atria, etc. The model also simulates the energy use for dual mode natural ventilation and air conditioning systems based on user specified comfort conditions. It includes a prediction of vertical temperature gradients in internal zones based on a correlation of extensive CFD simulations as well as momentum effects on air flow in vertical shafts. Different control algorithms can be employed for night cooling. Solar gains through glazed surfaces are included although solar radiation through roof openings is not taken into account.

SUNREL [68] is an hourly building energy simulation tool developed by NREL which integrates a simple multizone airflow model. The simple graphical user interface allows to be applied in early design stages. SUNREL only models idealized HVAC equipment. Fans can be used to move a schedulable fixed amount of air between zones or from outside.

6.4 Validity of methods and tools

Several previous studies attempted to evaluate airflow models reliability by comparing AFN-BES predicted and measured performances.

Zhai J. et al. [5] performed airflow models evaluations by comparing predicted airflow from EnergyPlus, CONTAM and ESP-r airflow network models with measured airflow in laboratory experiments across 8 defined scenarios at steady conditions. They concluded that all the models yielded similar airflow predictions, which are within 30% error for the simple cases evaluated. The worst results were obtained for buoyancy driven single-sided, wind driven cross ventilation and combined buoyancy and wind driven natural ventilation configuration, whereas buoyancy driven cross ventilation error is less than 10%. It is well known that airflow network models cannot generally well represent single-sided ventilation, as it is mainly driven by turbulent fluctuations of wind pressures, neglected in nodal models [2].

Zhai et al. [69] [70] also compared measured indoor temperatures of three naturally ventilated buildings with detailed EnergyPlus model output data. The EnergyPlus model performed excellently for simple and well defined cases, but less accuracy is observed in cases with complex geometry. Due to the lack of available information (on site measured weather data, measured volume flow rats, level of thermal mass, effective area and discharge coefficient of openings, wind pressure coefficient data), it was not possible to assess the accuracy of model coupling.

Belleri et al. [71] compared early-design-stage natural ventilation performance predictions from an EnergyPlus model with measured data including on-site weather and measured air change rates. Airflow predictions were highly sensitive to input parameters like internal gains, occupancy profile and of course to window opening control. With sufficient input data about window control, employing EnergyPlus in combination with an airflow network can provide informative predictions of natural ventilation performance.

Zhai J. and Chen Q. [57] [58] also validated the coupling between EnergyPlus and Fluent with experimental/empirical data about natural convection in a room without radiator, natural convection in a room with a radiator, convective heat transfer coefficients in a room with a radiator and mixed convection in a glazed atrium. The validations verified that the program developed can provide reasonable and reliable predictions on building performance. In general, the coupled simulation produces more accurate and detailed results than the separate simulations.

6.5 Performance of methods and tools

This section offers a comparison of the performance of the different tools (computing times, errors, etc); and provides suitable simplifications and/or enhancements to actual tools.

Few studies offer a comparison of the performance of the previously described airflow network tools in terms of prediction reliability, computing time and applicability.

Haghighat F. and Megri A. C. [72] performed a comprehensive validation of the two most commonly used airflow network models: COMIS and CONTAM. The validation process was carried out at three different levels; inter-program comparison; validation with experimental data which was collected in a controlled environment; and finally, validation with field measurement data. The results showed good agreement between the two software programs' predictions and gas tracer measurements carried out in a residential building but some differences between predictions and experimental data.

Wang J. et al. [73] performed a comparison of BREEZE, COMIS and CONTAM in terms of both model predictions and computation time. All the three models use similar algorithms to solve non-linear equations. BREEZE and CONTAM provide the user with a graphical user interface for input, while for COMIS is not available. The three models predicted both the airflow rates and the contaminant profiles equally well for the analyzed case study (a five stores building). The simulation time taken by COMIS was greater than the other two programs. Computation time is mainly due to the contaminant timestep.

Dutton S. et al. [74] compared EnergyPlus airflow network and CONTAM at steady state conditions. Both models predict similar CO_2 concentrations with a RMS of 0.89 in a classroom when internal gains are neglected.

PhD work of Srinivas T. [75] validated and evaluated the capabilities of CONTAM and PHOENICS, a CFD model. Comparing the two models in terms of airflow predictions and contaminant distributions, he found out that CONTAM generates erroneous results in interzonal flow calculations.

6.6 Discussion: applicability to design stages

This section analyzes early design stage predictions from simplified tools and coupled BES_AFN models and compare them with detailed tools results.

Because of the recent advancement in hardware and software, building simulation tools are increasingly used within the design process to analyse newer and cost effective design solutions, to improve the energy efficiency of HVAC system and to perform statistical analysis. In airflow simulation, Hensen et al. [76] identified three approaches representing different resolution level:

- Building energy simulation with guessed or estimated airflow
- BES-AFN coupled models
- CFD

The choice of the tool and so the level of resolution depend on the performance indicators required, the resources available (computing capacity, manpower and time) and the ventilative cooling solution to be modelled. Table 6-4 reports the generally required targets and performance indicators to be assessed within the three main design steps of building.

During schematic design phase, the architect typically works with the client and other design team members to explore alternative concepts for addressing the client's needs. The design phase typically ends with a presentation of the proposed design including a description of the energy concept and how the design meets the client's project program and goals. Depending on the defined targets, alternative design concepts can be compared in terms of cooling demand reduction, achievable ventilation rates and thermal comfort improvement.

Design development phase aims at proving standard and building regulation accomplishment. Therefore, simulation tools are used to efficiently size building components in order to guarantee the standard requirements typically identified as minimum required ACR to guarantee indoor air quality or maximum number of overheating hours.

Construction documents describe in detail the components of a project that need to be fabricated and assembled in order for it to be built. Building components specification has to be guided and proven by relating simulations parameter settings to product characteristics.

Table 6-4. Design stages and generally required performance indicators.

Design stage	Schematic design	Design development	Constructive documents
Target	To explore design solutions	To size building components for standard accomplishment	To detail the description of building components
Performance indicators	cooling demand reduction thermal comfort improvement achievable ventilation rates fan electricity primary energy	Min required ACR guaranteed Max number of overheating hours Max heating/cooling load Max/min temperature in the zone PPD Contaminant distribution	conformity of building components to simulation components local discomfort

Djunaedy E. [77] (Figure 6.6) proposes a guideline to select the most appropriate and convenient level of resolution and complexity for airflow simulations depending on simulation objectives and the ventilative cooling strategy to be modeled.

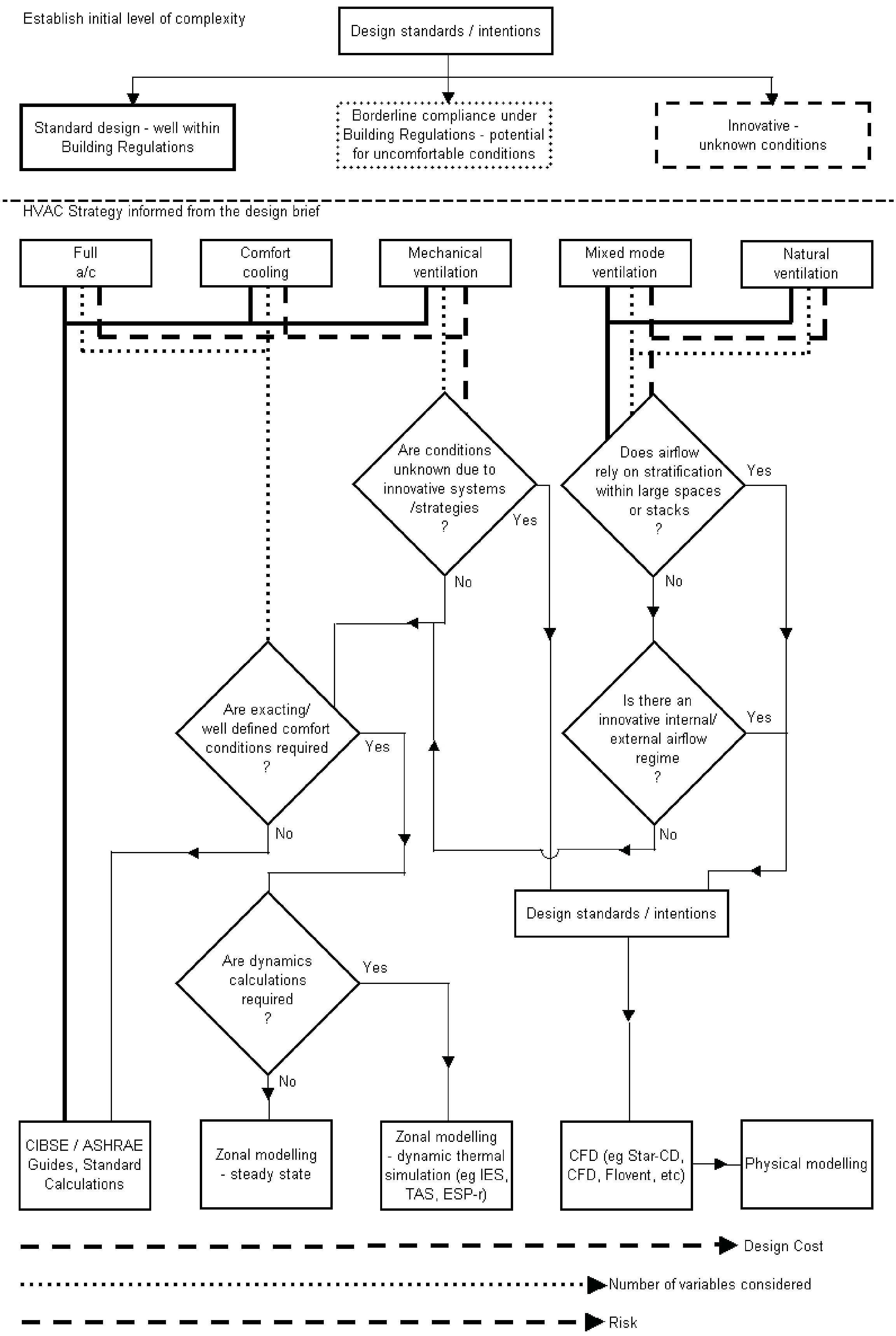


Figure 6.6. Early assessment design strategies. Source: [77]

The scheme in Figure 6.6 support the modeller in the model resolution choice. Model resolution choice should be based on the outcome request for example:

- if energy consumption is needed, then BES would be sufficient;
- if temperature gradient is required then at least AFN is needed;
- if local discomfort is in question, CFD is necessary.

Ideally, early design stage simulations can inform key design decisions that affect natural ventilation performance. However, the performance prediction of natural ventilation is affected by a significant number of input parameters which cannot be precisely addressed at early design stages (i.e. internal gains). Therefore, statistical analysis can be applied to building simulation:

- Uncertainty analysis enables to estimate the probability distribution of possible outcomes from the model, given input parameters' probability distributions.
- Sensitivity analysis enables to determine how the uncertainty in a model's output can be apportioned to different sources of uncertainty in the model's inputs.

Uncertainty and sensitivity analysis on key input parameters (Belleri A. et al. [78]) which cannot be addressed at schematic design stage showed that an accurate assessment of the input parameters affecting solar heat gains and internal loads, like the solar heat gain coefficient, the lighting and the electric equipment power density, significantly reduces the results uncertainty. Figure 6.7 and Figure 6.8 give an overview of the sensitivity analysis and uncertainty analysis procedure. In the analysed case study, uncertainty analysis showed that the percentage of hours when minimum ACR requirements were met might vary between 60% and 95%. In case no detailed information about internal loads is available, different internal loads scenario must be defined to evaluate natural ventilation performance at different internal loads levels.

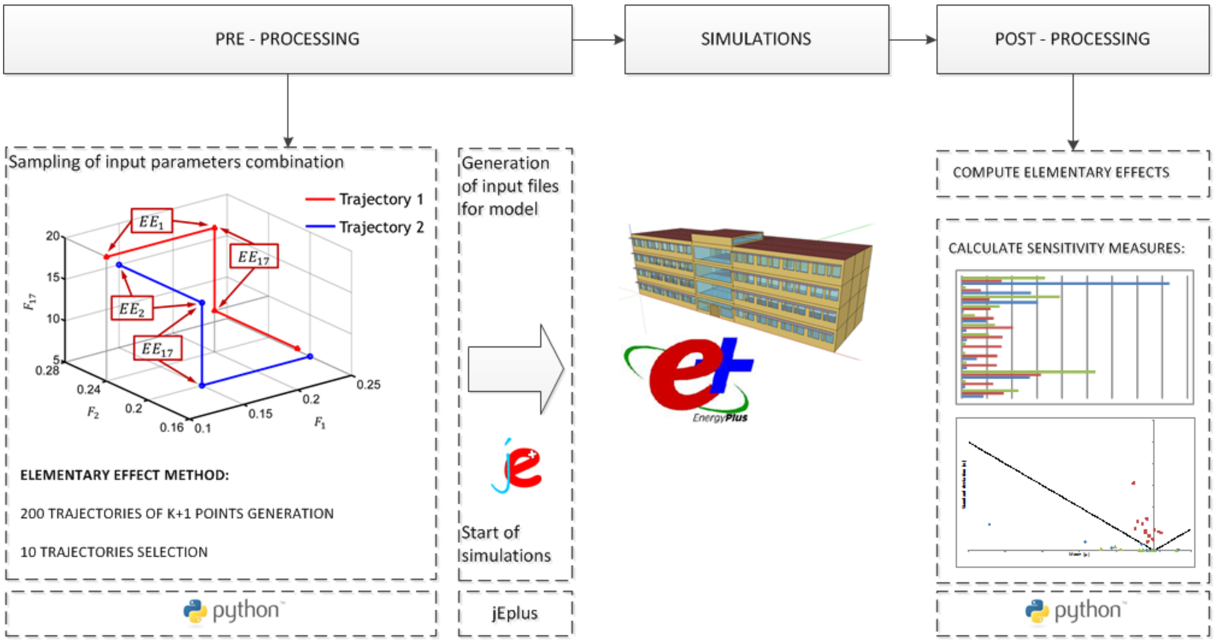


Figure 6.7. Sensitivity analysis procedure from sampling of input combinations by means of the elementary effect method to post-processing and sensitivity measures calculation. Source: Belleri A. [49]

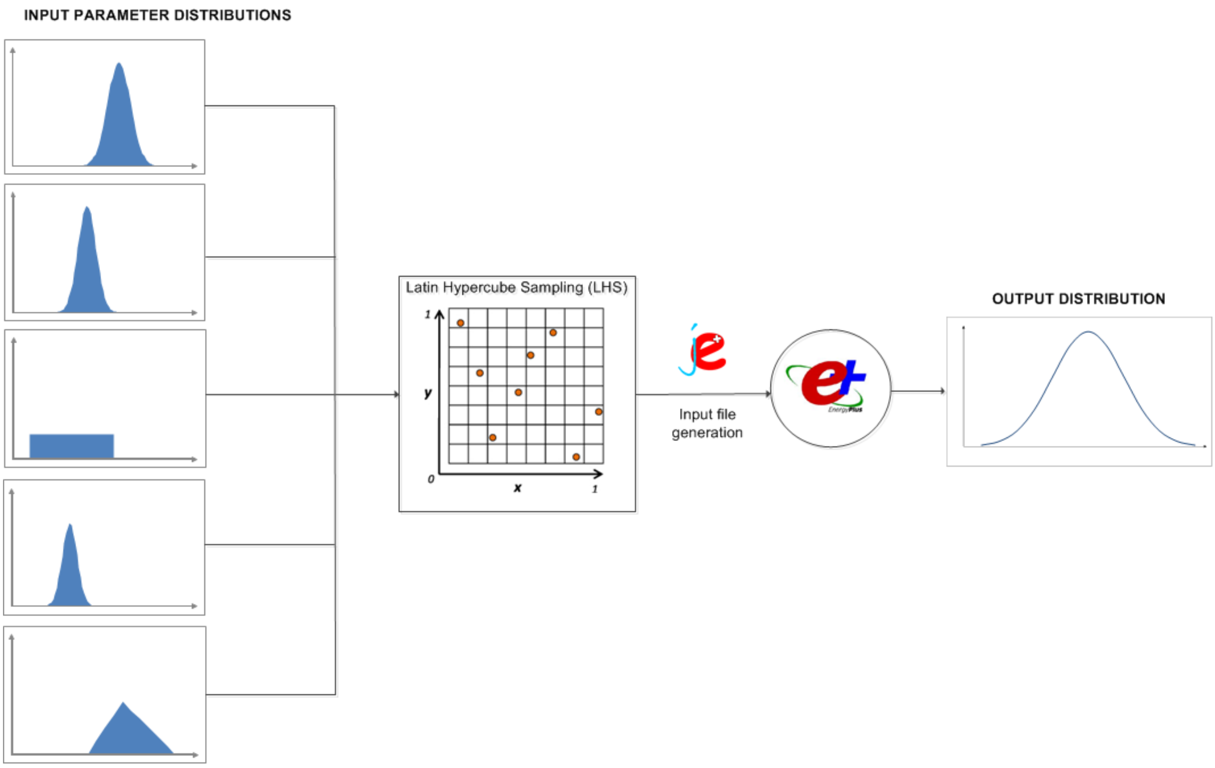


Figure 6.8. Uncertainty analysis procedure from input parameters probability distribution assignment, to sampling by mean of the Latin Hypercube method to post-processing and output probability distribution. Source: Belleri A. [49]

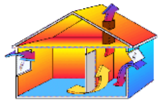
No prior study explored the reliability of the early stage modelling tools described in section 6.3.

6.7 Conclusion

The following aspects have been identified for software improvement.

- Airflow network models coupled with the most commonly used building energy simulation tools allow to predict natural ventilation strategies performance. Although the coupling allows to consider interactions between airflows and building thermal behaviour, the convection heat transfer modelling is still too simplified for night cooling effect predictions. Furthermore, new features/types to model new solutions and technologies like wind catchers and solar chimneys are needed.
- Airflow predictions are obviously highly sensitive to window opening controls. In case of manual controls, it is necessary to include more detailed occupant comfort based stochastic window control algorithm. In case of automatic controls, the integration of predefined control strategies would support designers in choosing the most effective control for a particular climate and/or design.
- The recent developments in BES-CFD-AFN coupling are very promising and revealed the advantages of the integrated building simulation over the separated building energy and CFD applications, which are:
    - CFD receives more precise and real-time thermal boundary conditions and can predict the dynamic indoor environment conditions that are important for the assessment of indoor air quality and thermal comfort.
    - BES obtains more accurate convection heat from enclosures and can provide more accurate estimation of building energy consumption and dynamic thermal behaviours of building envelopes.
- Designers need clearer guidance regarding sources of uncertainty in natural ventilation performance predictions and ways to improve the reliability of these predictions and the model robustness. Simulation tools should be combined with stochastic models to develop statistical analysis in a more automatized way.

Table 6.5. Summary table of available tools for airflows prediction.

Tool	Type of airflow model	Developer	Coupling with other tools	Coupling approach	Output	Particular features
COMIS 	Airflow network	LBNL IEA Annex 23	EnergyPlus Trnsys (Trnflow)	Ping-pong coupling with EnergyPlus Onion coupling with Trnsys	– airflows due to infiltration or natural ventilation; – interactions of the HVAC system, ducts, and exhaust hoods and fans.	Variable air density model allowable. Ability to apply a density gradient on each side of the opening.
CONTAM	Airflow network	NIST	Trnsys	Onion coupling with Trnsys. It could either be integrated in Type 56 or be included in the model as a separate Type.	– airflows due to infiltration or natural ventilation; – interactions of the HVAC system, ducts, and exhaust hoods and fans; – air contaminant concentration; – user exposure.	Graphical interface for data input and result viewer. Fully coupled multizone CFD model CONTAM does not allow the user to modify the wind speed reference height.
mfs	Airflow network	ESRU	ESP-r	Various way of coupling possible	– airflows due to infiltration or natural ventilation; – velocity at connections; – air contaminant concentration;	Poor representation of single-sided ventilation. Bidirectional flow can be approximated with a pair of airflow openings. Different wind profile options available. It has a built-in pressure coefficient database.

Tool	Type of airflow model	Developer	Coupling with other tools	Coupling approach	Output	Particular features
LoopDA Natural Ventilation Opening Sizing Tool	Loop equation method	NIST			size ventilation airflow components of natural and hybrid ventilation systems	The equations are re-written to form physical closed loops around which the sum of the pressure changes must equal zero. They can be used also as "reverse" method.
DIAL+	Monozone model	EPFL			Time variation over a typical day of: – Neutral pressure level visualization – Air flow rate common to all zones – Mean zone air temperatures – mean zone surface temperatures – Ventilation cooling rate for each zone	It cannot: – calculate multi path air movement, simulate periods much longer than 1 day; – include interactions with neighbouring zones other than by the ventilation rate of the common flow path; – directly take into account solar gains (they has to be scheduled); – directly simulate wind induced natural ventilation (it is assumed that the worst case for cooling purposes is the case without wind); – model multi-layer wall elements (it is assumed that the thermal effect of the surface layer dominates),; – model thin walls (the thermal storage effect of thin walls may be overestimated).
NatVent	Monozone model integrated to a monozone heat balance model for	Danish Building Research Institute SBI			– Hourly indoor temperature – Maximum and minimum airflow rate during working hours	The thermal model is only used in the summer for the calculation of the indoor air temperature and the internal surface temperature in the building. In winter the temperatures are set to 20°. No heat losses through ground floor.

Tool	Type of airflow model	Developer	Coupling with other tools	Coupling approach	Output	Particular features
	office type buildings					All internal structures and surfaces have the same temperature.
EDSL Tas	Multizone airflow model	Environmental Design Solutions Ltd			– airflows due to infiltration or natural ventilation; – indoor temperatures	It automatically generates airflow network. It can import/export from CAD models.
CoolVent	Multizone airflow model	MIT		Ping pong	– airflows due to infiltration or natural ventilation; – internal temperatures – comfort conditions – energy use for dual mode systems – vertical temperature gradient in interior zones	User friendly interface The model allows time-varying thermal conditions for a typical day , month or year of a month (based on weather data), accounting for the effects of thermal mass, and night cooling. With different control algorithms for night cooling Solar gains included but solar radiation through roof openings is not taken into account.
Buildings Research SUNREL®	Multizone model	NREL			–	
IDA - ICE	Multizone model	Equa (Sweden)	EIC- Energy and Indoor Visualizer (Velux)		– internal temperature (mean and operative) – internal surface temperature – air flow rates inside the building zone due to infiltration and natural ventilation – mechanical air flow (AHU) – energy flows	The software works modulating systems and controllers, optimizing energy consumption and occupant comfort. The main feature of this software is the use of a general-purpose variable time step solver that allows identifying the exact moment in which a change is occurring (e.g. opening or closing of the windows).

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Chapter 3	*Jie Han assisted by the contributors to review of existing buildings*
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15	Energy Flex House	Per Heiselberg
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17	Rijkswaterstaat building	Per Heiselberg
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The effort of the ExCo reviewers is highly appreciated.

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9 Annex Description

IEA EBC Annex 62 "Ventilative Cooling"

Ventilative Cooling is application of ventilation flow rates to reduce the cooling loads in buildings. Ventilative Cooling utilizes the cooling and thermal perception potential of outdoor air. The air driving force can be natural, mechanical or a combination.

Ventilative cooling can be an attractive and energy efficient solution to reduce the cooling load and avoid overheating of both new and renovated buildings. Ventilation is already present in buildings through mechanical and/or natural systems and it can remove both excess heat gains as well as increase air velocities and thereby widen the thermal comfort range. The Annex will address the challenges and devise recommendations through development of design methods and compliance tools related to predicting, evaluating and eliminating the cooling need and the risk of overheating in buildings and through the development of new attractive energy efficient ventilative cooling solutions.

Background and Justification

The current development in building energy efficiency towards nearly-zero energy buildings represents a number of new challenges to design and construction. One of the major new challenges is the increased need for cooling arising in these highly insulated and airtight buildings, which is not only present in the summer period but also in the shoulder seasons and in offices even in midwinter during periods of occupation. In most post-occupancy studies of high performance buildings elevated temperature levels are the most frequently reported problem. Also conventional buildings can experience high temperatures resulting in a high need for cooling e.g. commercial buildings with too high internal gains. Especially office building have experienced an increase in internal gains due to the increased use of office equipment.

There are a number of different reasons to why we presently are facing this situation in high performance buildings. For residential buildings the design process is much more simplified than for commercial buildings and is to a very large extent based on experiences and rules of thumb. To reach a low energy need for heating designers apply guidelines for passive solar buildings developed in the past where insulation and airtightness levels were far from the levels of today. And as they have no previous experience with overheating problems in their previous designs (especially in the colder climates), they underestimate the need for cooling and might not even take it into account. Prediction of energy use in residential buildings is often based on simplified monthly methods and is estimated for the residence as a whole. Averaging the need for cooling in both time and space underestimates the need for cooling. Excess heat in spaces exposed to solar radiation is considered to be distributed fully to other spaces and excess solar radiation during daytime is partly distributed to night-time. Due to these simplifications the need for cooling to ensure acceptable temperature levels in all spaces will be higher in reality. The analysis of the risk of overheating is typically based on the calculated cooling need and typical compliance tools used do not facilitate a calculation of the cooling effects together with the thermal evaluation of the building. Unfortunately, there is no correlation between the calculated cooling need with these simplified methods and the actual number of hours with elevated temperature levels. So, even if no cooling need is predicted and designers do not expect overheating problems, the number of hours with elevated temperature levels can be considerable.

Cooling and overheating in residences have so far not been considered as a design challenge. Therefore, the developed solutions available for application in residences to address the cooling issue are very limited and often too simplified. In the few cases, where the cooling challenge is addressed by a “one-of-a-kind” design, it has led to solutions which are expensive and need careful commissioning to function. Finally, also to especially owners of high performance buildings in cold climate countries cooling might be an unknown challenge that they have not experienced before. They do not know how to reduce the overheating problem efficiently and their behaviour might instead actually increase the problem. Or as many home owners are used to air-conditioned cars can even result in the purchase and installation of air conditioning units, resulting in an increased energy use, which in many situations depending on climatic zone and internal loads could be avoided by appropriate use of ventilative cooling and passive cooling techniques.

For offices and other commercial buildings the challenges are different and mainly related to the development of new approaches towards reduction of the existing energy use for cooling. Sometimes the cooling potential of outdoor air is already utilised in mechanical ventilation systems. However, due to thermal comfort issues and the risk of draught limited temperature differences between air supply and room air can be utilized making heat recovery or air preheating necessary. The result of this is a reduction of the cooling capacity and an increased airflow rate - sometimes with a factor of more than 5. In mechanical ventilation systems this leads to increasing energy use for air transport and increasing investment in equipment. Thus, the energy and cost advantage of utilising the free cooling potential of outdoor air compared to a mechanical cooling solution might become very limited. These limitations do not apply to the same extend when utilizing the cooling potential of outdoor air in a free-running building (naturally ventilated building) and thus the appropriate use of ventilative cooling in connection with natural ventilation in non-residential buildings could contribute significantly to a reduction of the energy consumption. Secondly, as the buildings are heavily insulated and airtight the variations in excess heat load will significantly vary between occupied and unoccupied hours and between cloudy and sunny days. The dynamic thermal characteristics will have a relatively higher influence on energy use and exploitation of building thermal mass as heat storage for reduction of cooling demand in combination with night cooling will become more important for energy optimization.

Previous annexes have dealt with these issues. Annex 27 dealt with domestic ventilation systems, but focused mainly on air quality issues as cooling was not an important issue in residences 10-20 years ago. Annex 28 dealt with low energy cooling systems and a lot of the ideas and principles from this annex can be built upon in this project. However since the performance characteristics of up-to-date high performance buildings are much different many of the results and conclusions are no longer valid. The project will also draw on results from Annex 35 hybrid ventilation, from Annex 44 in relation to utilization of building construction elements and from Annex 53 in relation to occupant behaviour. The work will be closely coordinated with Annex 59, which deals with optimization of HVAC systems (mainly water-based systems).

9.1 Research issues

In order to address the cooling challenges of buildings the research focus of the annex will be on development of design methods and compliance tools related to predicting, evaluating and eliminating the cooling need and the risk of overheating in buildings and to develop new attractive energy efficient ventilative cooling solutions. Before ventilative cooling is considered the internal gains from equipment and solar radiation are assumed to be reduced to a reasonable level.

Objectives and Limitations

Ventilative cooling can be an attractive and energy efficient solution to avoid overheating of both new and renovated buildings. Ventilation is already present in buildings through mechanical and/or natural systems and it can remove both excess heat gains as well as increase air velocities and thereby widen the thermal comfort range. As cooling recently becomes a need not only in the summer period the possibilities of utilizing the free cooling potential of low temperature outdoor air increases considerably.

Objectives

To fulfil the scope of the Annex and to make energy-efficient use of ventilative cooling (air-based systems) the preferred solution the Annex focuses on the following specific objectives:

- To analyse, develop and evaluate suitable methods and tools for prediction of cooling need, ventilative cooling performance and risk of overheating in buildings that are suitable for design purposes (Subtask A).
- To give guidelines for integration of ventilative cooling in energy performance calculation methods and regulations including specification and verification of key performance indicators (Subtask A).
- To extend the boundaries of existing ventilation solutions and their control strategies and to develop recommendations for flexible and reliable ventilative cooling solutions that can create comfortable conditions under a wide range of climatic conditions (Subtask B).
- To demonstrate the performance of ventilative cooling solutions through analysis and evaluation of well-documented case studies. (Subtask C).

Scope and Demarcation

Ventilative Cooling is the application (distribution in time and space) of ventilation flow rates to reduce or even eliminate cooling loads. The air driving force can be natural, mechanical or a combination.

The Annex will focus on analysis and development of ventilative cooling solutions from the perspective of utilization of the cooling and thermal perception potential of outdoor air.

The Annex will address both residential and non-residential buildings, however, these two sectors will be treated separately because the issues, challenges and possible solutions are very distinct. The

Annex will address both new constructions and renovation of buildings and the technical conditions needed to make ventilation cooling possible

Developed solutions should be able to create comfortable conditions under both “large flow rate/high temperature” and “small flow rate/low temperature” conditions, i.e. able to provide comfort under a wide range of climatic conditions.

The Annex research focus will not be on solutions to increase the cooling potential of outdoor air by lowering its temperature through exploitation of heat exchange in earth ducts, ground water heat exchangers and similar technologies. The research focus will be is on the exploitation of the cooling potential of untreated outdoor air.

The Annex will address the impact of elevated air velocities on thermal comfort due to increased ventilation flow rates. The Annex will address the interaction of ventilative cooling with other measures to improve thermal comfort and cool buildings like the use of thermal mass, solar shading, desk and ceiling fans, water based cooling systems, etc.

Means

Methodology

To address the specific Annex objectives the research and development work in the Annex will be divided in three subtasks, which is further divided in a number of research activities.

Subtasks

The Annex will comprise of the following main subtasks:

Subtask A: Methods and Tools

Subtask B: Solutions

Subtask C: Case studies

The main part of the activities will operate in parallel.

Subtask A: Methods and Tools

This subtask will analyse, develop and evaluate suitable design methods and tools for prediction of cooling need, ventilative cooling performance and risk of overheating in buildings. The subtask will also give guidelines for integration of ventilative cooling in energy performance calculation methods and regulation including specification and verification of key performance indicators.

The subtask will be divided into the following research activities:

Activity A.1. Development of key performance indicators for ventilative cooling solutions including verification methods to be used in energy performance calculations (compliance tools). Special focus will be on performance indicators for high indoor temperature conditions.

Activity A.2. Identification of existing methods and tools for prediction of cooling needs, ventilative cooling capacity and risk of overheating including analysis and evaluation of their performance and functionality based on inter-method comparison. Development of design methodologies for prediction of cooling need, ventilative cooling capacity and overheating risk, including guidelines for their fidelity and usefulness as well as definition of suitable boundary conditions and prediction assumptions.

Activity A.3. Development of recommendations for integration of ventilative cooling in legislation, standards, design briefs as well as on energy performance calculation and verification methods.

Subtask B: Solutions

This subtask will investigate the cooling performance of existing mechanical, natural and hybrid ventilation systems and technologies and typical comfort control solutions as a starting point for extending the boundaries for their use. Based upon these investigations the subtask will also develop recommendations for new kinds of flexible and reliable ventilative cooling solutions that can create comfort under a wide range of climatic conditions.

The subtask will be divided into the following research activities:

Activity B.1. Analysis of the performance of existing ventilation systems and technologies from the perspective of utilization of the cooling potential of outdoor air, of their cooling capacity and of their ability to reduce energy use and support a high quality indoor environment (comfort, health, productivity).

Activity B.2.Extention of the ability of existing ventilation system solutions to provide acceptable thermal comfort conditions in high temperature and inhomogeneous environments and to provide ventilative cooling with low energy use.

Activity B.3. Development of recommendations for new ventilative cooling solutions and control strategies and their design that in an energy-efficient way can create comfortable conditions under both “large flow rate/high temperature” and “small flow rate/low temperature” conditions.

Subtask C: Case studies

The subtask will demonstrate the performance of ventilative cooling through analysis and evaluation of well-documented case studies.

The subtask will be divided into the following research activities:

Activity C.1. Analysis and evaluation of performance of ventilative cooling solutions and of used design methods and tools using similar criteria and methods

Activity C.2. Lessons learned and development of recommendations for design and operation of ventilative cooling as well as identification of barriers for application and functioning.

Results and deliverables

The outcome of the annex will be guidelines for an energy-efficient reduction of the risk of overheating by ventilative cooling solutions and for design and operation of ventilative cooling in both residential and commercial buildings. It will also include recommendation for the integration of ventilative cooling in legislation, standards and design briefs as well as on energy performance calculation and verification methods.

The main products will include instructions for improvement of the ventilative cooling capacity of existing systems and for development of new ventilative cooling solutions and including their control strategies. The performance of ventilative cooling solutions will be documented by case studies.

The results from the Annex will facilitate better possibilities for prediction and estimation of heat removal and overheating risk – for both design purposes and for energy performance calculation. The documented performance of ventilative cooling systems through analysis of case studies will promote the use of this technology in future high performance and conventional buildings

Official deliverables

The deliverables are listed below:

	Official deliverables	***Target group***	***Related subtask***
D1	Overview and state-of-the art of Ventilative Cooling	Research community and associates. Policy makers	STA, STB, STC
D2	Ventilative Cooling Source Book	Building component and ventilation system developers and manufacturers. Architects, and design companies, engineering offices and consultants	STA, STB, STC
D3	Ventilative Cooling case studies	Architects, consulting engineers	STC
D4	Guidelines for Ventilative Cooling Design and Operation	Architects and design companies, engineering offices and consultants	STA, STB, STC
D5	Recommendations for legislation and standards	Policy makers and experts involved in building energy performance standards and regulation	STA
D6	Project Summary Report	Research community and associates + EBC Programme	STA, STB, STC

All reports will be published electronically.

Annex beneficiaries and outreach activities

The Annex beneficiaries will be:

- The building research community and associated specialists
- Architects and design companies, engineering offices and consultants in building physics, energy, HVAC and sustainable construction
- Building component and HVAC-system developers and manufacturers with an interest in high performance systems
- Policy makers and experts involved in building energy performance standards and regulation
- Educational institutions

Outreach activities will be planned and carried out in cooperation with the Ventilative Cooling Platform

	Outreach activities	***Target group***
O1	Internet site and Annex newsletter	Research community and associates, EBC Programme
	Social Media (Build Up, Linked-in, ...)	Building Sector, often specific target groups
	Active internet seminars	Building Sector, but most events will have specific target groups
O3	Conferences and seminars	Building Sector, but most events will have specific target groups
	Proceedings of international events	Building Sector, but most events will have specific target groups

Management of the Annex

The Annex is managed by the Operating Agent assisted by subtask leaders and co-leaders.

Operating agent

The Operating Agent is responsible for the overall performance and the time schedule of the Annex, for reporting, and for information dissemination activities. The operating agent is Aalborg University, Denmark

Subtask leaders

The Subtask leaders shall be participants who bring a high level of expertise to the subtask they manage and who undertake substantial research and development in the field of the subtask. They are elected by the Annex participants. Duties of the subtask leaders are:

- Co-ordinate the work performed under the subtask;
- Assist the Operating Agent in preparing the detailed work plans and editing the final reports of the Annex;
- Direct the technical workshops of the subtask and provide the Operating Agent with the workshop results;
- Coordinate the technical reports resulting from the Subtask;

Subtask leaders are:

Subtask A Switzerland, represented by ESTIA

Subtask B: Austria, represented by IBRI

Subtask C: China, represented by Hunan University

Time schedule

The duration of the Annex in the working phase will be three years (planned to start in the beginning of 2014), with the preparation phase beginning in spring 2013. Two meetings will be held every year. The Operating Agent will organize semi-annual plenary Annex meetings at varying locations, each time hosted by one of the participating countries. In connection with the plenary Annex meetings, a semi-annual subtask leaders meeting will be organized. If needed, the participants and subtask leaders of each subtask may decide to organize separate meetings. In such cases, they must inform the Operating Agent of the meeting and its results. A fourth year will be used to finish reports.

Funding and commitment

The work is divided into three subtasks. Each participant shall work in at least one of the subtasks. All participants are also required to deliver information and written material to the final reports. Each participant shall individually bear their own costs incurred in the Annex activities. Funding is expected to cover labour costs, consumables and investments (including eventual overhead costs) associated with the execution of activities defined in paragraph 3 and 4, and to cover traveling costs for participating in at least two expert meetings per year during the four-year working phase of the Annex. The working meetings shall be hosted by one of the participants. The costs of organizing and hosting the meeting shall be borne by the host participant.

All participating countries have access to the workshops and results of all subtasks. Each participating country must designate at least one individual (an active researcher, scientist or engineer, here called the expert) for each subtask in which they decide to participate. It is expected that the same expert attends all meetings and acts as technical contact regarding the national subtask contribution. A minimum commitment of six person-months of labor for each year of the Annex term will be required for participation. For the subtask coordinators funding shall allow for six person-months and an extra two person-months per year for Annex activities. For the Operating Agent, funding shall allow for six person-months and an extra four person-months per year for Annex activities including the attendance at the two ExCo meetings per year.

Intellectual Property

The Operating Agent will hold all intellectual property rights arising from the Annex on behalf of the participants in accordance with the EBC Implementing Agreement.