International Energy Agency

Ventilative Cooling Design Guide

Energy in Buildings and Communities Programme

March 2018

EBC is a programme of the International Energy Agency (IEA)

Front cover picture:

CML Kindergarten, Lisbon, Portugal
Photo: Appleton Domingos - Architects

International Energy Agency

Ventilative Cooling Design Guide

Energy in Buildings and Communities Programme
March 2018

Editor

Per Heiselberg, Aalborg University, Denmark (ph@civil.aau.dk)

Authors

Adam O'Donnavan, Cork Institute of Technology, Ireland
Annamaria Belleri, Eurac Research, Italy
Flourentzos Flourentzou, Estia SA, Switzerland
Gou-Qiang Zhang, Hunan University, China
Guilherme Carrilho da Graca, University of Lissabon, Portugal
Hilde Breesch, KU Leuven, Belgium
Maria Justo-Alonso, SINTEF Byggforsk, Norway
Maria Kolokotroni, Brunel University, United Kingdom
Michal Pomianowski, Aalborg University, Denmark
Paul O'Sullivan, Cork Institute of Technology, Ireland
Per Heiselberg, Aalborg University, Denmark
Peter Holzer, Institute of Building Research & Innovation, Austria
Theofanis Psomas, Aalborg University, Denmark

© Copyright Aalborg University 2018

All property rights, including copyright, are vested in Department of Civil Engineering, Aalborg University , Operating Agent for EBC Annex 62, on behalf of the Contracting Parties of the International Energy Agency Implementing Agreement for a Programme of Research and Development on Energy in Buildings and Communities.

In particular, no part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior written permission of Department of Civil Engineering, Aalborg University.

Published by Department of Civil Engineering. Aalborg University, Thomas Manns Vej 23, 9220 Aalborg EAST, Denmark

Disclaimer Notice: This publication has been compiled with reasonable skill and care. However, neither Department of Civil Engineering, Aalborg University nor the EBC Contracting Parties (of the International Energy Agency Implementing Agreement for a Programme of Research and Development on Energy in Buildings and Communities) make any representation as to the adequacy or accuracy of the information contained herein, or as to its suitability for any particular application, and accept no responsibility or liability arising out of the use of this publication. The information contained herein does not supersede the requirements given in any national codes, regulations or standards, and should not be regarded as a substitute for the need to obtain specific professional advice for any particular application.

ISBN 87-91606-38-1

Participating countries in EBC: Australia, Austria, Belgium, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

Additional copies of this report may be obtained from:
EBC Bookshop
C/o AECOM Ltd
Colmore Plaza
Colmore Circus Queensway
Birmingham B4 6AT
United Kingdom
Web: www.iea-ebc.org
Email: essu@iea-ebc.org

Preface

The 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 international co-operation among the 29 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the Energy in Buildings and Communities (EBC) 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 IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas for 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 IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects 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 Exergy 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 & CO2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO2 Equivalent Emissions for Building Construction
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings
Annex 60: New Generation Computational Tools for Building & Community Energy Systems
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings
Annex 62: Ventilative Cooling
Annex 63: Implementation of Energy Strategies in Communities
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behavior in Buildings
Annex 67: Energy Flexible Buildings
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Public Communities
Annex 74: Energy Endeavour
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables

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 (*)
Working Group - Survey on HVAC Energy Calculation Methodologies for Non-residential Buildings

Abbreviations

Abbreviations	Meaning
ADV	Ventilative Cooling Advantage
AHU	Air Handling Unit
AT	Austria
BEMS	Building Energy Management System
BIM	Building Information Modelling
CH	Switzerland
CRR	Cooling Requirement Reduction
DEC	Direct Evaporative Cooling
DhC	Degree hours Cooling
DHW	Domestic hot water
DK	Denmark
EN	European Norm
EPBD	Energy Performance of Buildings Directive
GWP	
HP	Heat pump
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEA-EBC	Energy in Buildings and Communities Programme of the International Energy Agency
KPI	Key Performance Indicator
kWh	Kilowatt hours: 1 kWh = 3.6 MJ
LCC	Lift Cycle Cost
LPD	Long-term Percentage of Dissatisfied
MPC	Model Predictive Control
NCP	Night-time Cooling Potential
NO	Norway
NRE	
NZEB	Nearly zero energy building or nearly zero emissions building
OH	Overheating Hours
PCM	Phase Change Materials
PE	Primary energy
PMV	Predicted Mean Vote
POF	Proportional of maximum net openable area of a natural ventilation system as a function of the floor area
POR	Percentage Outside of Range
PT	Portugal

Abbreviations	Meaning
PV	Photovoltaic (cell or panel)
QA	Quality Assurance
Ref	Reference
RES	Renewable energy sources
SEER	Seasonal Energy Efficiency Ratio
SFP	Specific Fan Power
SPI	Specific Power Input
VAV	Variable Air Volume
VC	Ventilative Cooling
VOC	Volatile Organic Compounds

Foreword

This design guide is based on the work of IEA-EBC Annex 62 “Ventilative Cooling” and the research findings of the participating countries.

The publication is an official Annex report. Beside this guide the Annex has produced the following official reports:

- Ventilative Cooling Case Studies
- Ventilative Cooling Source Book
- Ventilative Cooling Recommendations for Standards and Legislation
- Ventilative Cooling Summary Report

All reports can be found on the website of IEA-EBC, www.iea-ebc.org

This guide is designed for both architects and engineers to support the design of ventilative cooling systems especially in the early design stages.

The guide provides an introduction to the principles of the ventilative cooling technology as well as methods to express and evaluate its potential and performance. The guide focuses on the design process and how calculation and simulation tools can be used for design, for design evaluation and for risk analysis. It also describes how to control ventilative cooling in the operation phase. By summarizing the outcome of the use of ventilative cooling in a number of case studies, it also illustrates typical designs, performance expectations and lessons learned.

It is the hope, that these guidelines will be helpful for both architects, engineers and professional building owners in their search for innovative and energy-efficient ventilative cooling solutions.

Per Heiselberg

Operating Agent, Aalborg University, Denmark

Acknowledgement

The material presented in this publication has been collected and developed within an Annex of the IEA Technology Collaboration Programme: Energy in Buildings and Communities, Annex 62 “Ventilative Cooling”.

The publication is the result of an international joint effort conducted in 15 countries. All those who have contributed to the project are gratefully acknowledged. A list of participating institutes can be found on page 119.

Thanks to the two internal reviewers of the guide: Hilde Breesch, KU Leuven, Belgium and Massimo Fiorentini, University of Wollongong, Australia

On behalf of all participants, the members of the Executive Committee of the IEA Technology Collaboration Programme Energy in Buildings and Communities as well as the funding bodies are gratefully acknowledged.

Executive Summary

The current development in building energy efficiency towards nearly-zero energy buildings lead to increased need for cooling and in most post-occupancy studies of high performance buildings elevated temperature levels are the most frequently reported problem.

We are presently facing this situation in high performance residential buildings because the design process is too simplified and to a very large extent based on experiences and rules of thumb. To reach a low energy need for heating designers typically apply guidelines for passive solar buildings developed in the past, where insulation and airtightness levels were far from the levels of today, and they underestimate the need for cooling or might not even take it into account. 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 to meet high performance requirements. In high performance buildings the cooling demands depend less on the outdoor temperature, and more on solar radiation and internal heat gains. This naturally gives better potential for the use of ventilative cooling, because the cooling need is not only in the summertime, but actually all year round.

These guidelines are designed for architects and engineers involved in the design of buildings and HVAC systems. The guide focuses on the design process and how calculation and simulation tools can be used for design, for design evaluation and for risk analysis. Case studies include both new build and retrofit designs.

Chapter 1 gives an introduction to and defines ventilative cooling. It also shows that ventilative cooling can have considerable impact on the risk of overheating in all climates. In cold and moderate climate, the risk of overheating can be eliminated completely, while in warm and hot climates supplementary cooling solutions will be needed to ensure acceptable comfort levels.

Chapter 2 contains a description of the wide range of ventilative cooling principles and shows how their application depends on climate and microclimate, building type, ventilation approach and user expectations. It focuses on the main principles and describes how typical design challenges can be met. The chapter also describes typical strategies, system solutions and components used for temperature control. It gives an overview of the principles used in all of the case study buildings in this project and three examples are selected to illustrate the different principles and possible ventilation strategies.

Chapter 3 gives an introduction to the key performance indicators that can be used in the design process and to evaluate compliance with regulations and standards. These include among others: The Cooling Requirement Reduction (CRR), which is defined as the percentage of cooling requirements saved in a ventilative cooling scenario compared to the reference scenario; The Seasonal Energy Efficiency Ratio (SEER), which is defined as the cooling requirement saving divided by the electrical consumption of the ventilation system; and the Ventilative Cooling Advantage (ADV_{VC}), which is defined as the benefit of the ventilative cooling, i.e. the cooling energy difference divided by the energy for ventilation.

Chapter 4 describes the design approach for ventilative cooling systems. A design procedure adapted to ventilative cooling design is presented. The design procedure ensures a thermal environment where every important issue is considered, where the process is efficient and where the final design is allowed to evolve in a logical way from idea to construction. The procedure aims at achieving a good thermal indoor environment at a low energy use and a seamless integration of the ventilative cooling solution with the building design and the environment. The tight integration results in many parameters to consider in an organized way, especially at an early stage.

Chapter 5 describes a methodology to analyse the climate and to evaluate the ventilative cooling potential prior to the conceptual design phase. It presents a ventilative cooling potential tool (VC tool) that is able to assess the potential effectiveness of ventilative cooling strategies by taking into account both building envelope thermal properties, occupancy patterns, internal gains, ventilation needs and the outdoor climate. The tool is useful in the conceptual design phase where decisions about application of ventilative cooling in buildings is made.

Chapter 6 contains a description of methods for performance calculation and simulation applied in the detailed design and the design evaluation phase to assess ventilative cooling strategies combined with other passive and natural technologies. The chapter also includes guidance on methods to be used to evaluate the performance of a ventilative cooling design and to ensure that the performance targets are achieved.

Chapter 7 contains an overview of control strategies, control parameters and algorithms. It presents how the ventilative cooling control strategy is significantly influenced by the general climatic conditions in the area where the building is located. It also includes a description of the main challenges in designing control systems for ventilative cooling in order to obtain the right balance between (1) installation cost, (2) operating cost, (3) energy consumption, (4) indoor climate and comfort, (5) user satisfaction and (6) robustness.

Chapter 8 concludes the design guide with an overview of the characteristics and lessons learned from the investigated case studies. Well documented case studies using ventilative cooling from across the world are summarised. From the case studies a number of key lessons learned are reported. A number of these relate to that the design of a building incorporating ventilative cooling can be challenging and may require a lot of detailed building information.

Content

Preface i

Abbreviations iii

Foreword v

Acknowledgement vi

Executive Summary vii

Content ix

1. Introduction 12

1.1. Definition of Ventilative Cooling 13

1.2. Rationale for Ventilative Cooling 14

1.3. Design Philosophy 18

1.4. Scope of the guidelines 19

2. Principles 20

2.1. Ventilative Cooling Principles 20

2.1.1. Ventilative cooling during cold outdoor conditions 21

2.1.2. Ventilative cooling during temperate outdoor conditions 21

2.1.3. Ventilative cooling during hot outdoor conditions 22

2.1.4. Application of hybrid solutions 22

2.2. Type of components and system integration 23

2.2.1. Airflow guiding components 24

2.2.2. Airflow enhancing components 24

2.2.3. Passive and natural cooling components 24

2.2.4. Control and automation components 25

2.3. Ventilative cooling principles and components in case studies 25

Example 1: Natural ventilative cooling, CML Kindergarten, Portugal 28

Example 2: Mechanical ventilative cooling with increased air supply and energy storage, Bristol University, United Kingdom 29

‘Example 3: Natural night time ventilative cooling, Nexus Hayama, Japan 30

3. Key Performance Indicators 32

3.1. Thermal comfort 33

3.2. Energy 34

3.3. Application example 36

3.4. Component indicators 41

4. Design Process 43

4.1. The Ventilative Cooling Design Process 43
4.2. Conceptual Design Phase 46
4.2.1. Initial Considerations 46
4.2.2. Basic conditions feasibility study 46
Application example CML Kindergarten, Portugal 50
Application example Seminar Room, Bristol University, UK 51
4.3. Ventilative cooling concept feasibility study 53
Application example CML Kindergarten, Portugal 53
4.4. Basic Design Phase 54
4.4.1. Initial integration of building and ventilative cooling system 54
4.5. Detailed design phase 57
4.6. Design Evaluation 57
5. Ventilative Cooling Potential 58
5.1. Methodology 59
5.2. Evaluation criteria 59
5.3. Examples based on the case studies 60
6. Design Calculations and Performance Evaluation 63
6.1. Performance evaluation 63
6.1.1. The use and validation of evaluation methods in design 65
6.2. Design Strategy 67
6.3. Estimation of air flow rates 70
6.4. Selecting relevant outdoor conditions 71
6.5. Selecting the ventilative cooling strategy 71
6.6. Determining possible airflow paths for systems driven by natural forces 74
6.7. Dimensions and positions of windows for natural driving forces. 76
6.7.1. Calculation of opening sizes for single sided ventilation 78
6.7.2. Calculation of opening sizes for stack ventilation 81
6.7.3. Calculation of opening sizes for cross ventilation 83
6.8. Airflow rate, control strategy and energy use for mechanical systems. 84
6.9. Sensibility analysis of key parameters and risk factors. 90
7. Control Strategies 93
7.1. Control Strategies and Systems 93
7.1.1. Control systems limitation 95
7.1.2. Dynamic or static control 95
7.1.3. Sensitivity to Occupancy 96

7.2. Level of possibility of user intervention 97
7.3. Controls Strategies in Case Studies 98
7.3.1. Example of ventilation and control strategies for different climate zones 100
8. Case Studies 103
8.1. Building design 104
8.1.1. Design Influences 104
8.1.1. Morphology 105
8.1.2. Thermal Properties 107
8.2. VC strategies, components & control 107
8.2.1. Strategies & components 107
8.2.2. VC system control 108
8.3. Sizing and simulation of VC Systems 110
8.3.1. Sizing of VC systems 110
8.3.2. Simulation of VC systems 111
8.4. Performance evaluation 111
8.5. Lessons Learned 112
8.5.1. Lessons from design and construction 113
8.5.2. Lessons from operation and post occupancy 113
9. References 115
Participants 117

1. Introduction

The current development in building energy efficiency towards nearly-zero energy buildings (nZEB) 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. The cooling demand depends less on the outdoor temperature, and more on solar radiation and internal heat gains. This naturally gives better potential for the use of ventilative cooling technologies, because the cooling need is not only in summer, but actually all year round.

In most post-occupancy studies of high performance buildings, elevated temperatures 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). There is 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 typically apply guidelines for passive solar buildings developed in the past, where insulation and airtightness levels were far from the levels of today, and they underestimate the need for cooling or might not even take it into account.

Prediction of energy use in residential buildings is often based on simplified monthly methods and it is estimated for the residence as a whole. Averaging the need for cooling in both time and space underestimates the total cooling demand. 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 real need for cooling to ensure acceptable temperature levels in all spaces will be higher than the predicted one. 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 temperatures. 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 a design challenge, especially in colder climates. Therefore, the developed solutions to address cooling issues available for residential application are very limited, often too simplified and might not be well adapted for practical application. In the few cases, where the cooling challenge is addressed by a “one-of-a-kind” design, the solutions were expensive and needed careful commissioning to function.

Finally, especially to 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 effectively reduce the overheating in their building and their behaviour might instead actually increase the problem. If technologies such as solar shading and ventilative cooling are applied, it is critical to use an appropriate control and operation strategy, taking into account occupant behaviour, to make sure that they operate successfully. Otherwise, as many home owners are used to air-conditioned cars, it may 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 like solar shading.

For **offices and other non-residential 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 supply air and room can be utilized making heat recovery or air preheating necessary. The result of this is a cooling capacity reduction and an increased airflow rate - sometimes with a factor of more than five. In mechanical ventilation systems, this leads to an increase in energy use for air distribution and an increased investment in equipment. As a results, the energy and cost advantage of utilising the free cooling potential of the outdoor air in a mechanical ventilation system compared to a mechanical cooling solution might become very limited.

These limitations do not apply to the same extent when the outdoor air cooling potential is applied to 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.

1.1. Definition of Ventilative Cooling

Ventilative Cooling (VC) is defined as the application of the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads and/or the energy use by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment.

Ventilative Cooling utilizes the cooling and thermal perception potential of cool outdoor air and the air driving force can be either natural, mechanical or a combination of the two. The most common technique is the use of increased daytime ventilation airflow rates and/or nighttime ventilation.

1.2. Rationale for Ventilative Cooling

Ventilative cooling can be an attractive and energy efficient natural cooling solution to reduce cooling loads and to avoid overheating in buildings. Ventilation is already present in most buildings through mechanical and/or natural systems and by adapting them for cooling purposes, cooling can be provided in a cost-effective way (the prospect of lower investment and operation costs). Ventilative cooling can both remove excess heat gains as well as increase air velocities and thereby widen the thermal comfort range.

As cooling becomes a need not only in the summer period, the possibilities of utilizing the cooling potential of low temperature outdoor air increases considerably. However, it is most effective to address the cooling challenge through a combination of measures including utilization of the potential of other passive measures like solar shading and thermal mass activation.

Naturally, expectations of ventilative cooling performance will vary between different countries because of climate variations, energy prices and other factors. In countries with cold climate, ventilative cooling can avoid the trend to use air conditioning in new buildings, which has occurred in response to the heavily insulated and air tight building designs, higher occupant expectations and the requirements of building regulations, codes and standards. In countries with warm climate, it can reduce the reliance on air conditioning and reduce the cost, the energy penalty and the consequential environmental effects of full year-round air conditioning.

To illustrate potential expectations for ventilative cooling performance in different climates the predictions of expected thermal comfort and cooling requirements reduction by utilization of ventilative cooling have been calculated for the same building configuration located in different climates. Figure 1 and Table 1 show the building case and key characteristics used and Figure 2 shows the impact of ventilative cooling in the form of cooling requirement reduction (CRR, see definition in Chapter 3) and expected reduction in overheating hours in different climates. Ventilative cooling can have considerable impact on the risk of overheating in all climates. In cold and moderate climates the risk of overheating can be eliminated completely, while in warm and hot climates supplementary cooling solutions will be needed to ensure acceptable comfort levels. In cold climate (e.g. Oslo) daytime ventilative cooling is sufficient to remove the heating loads, while in most other climates it is essential to apply night cooling strategies to efficiently remove excess heat loads. In warm and hot climates daytime ventilative cooling strategies have very limited effect, while night cooling strategies are more efficient.

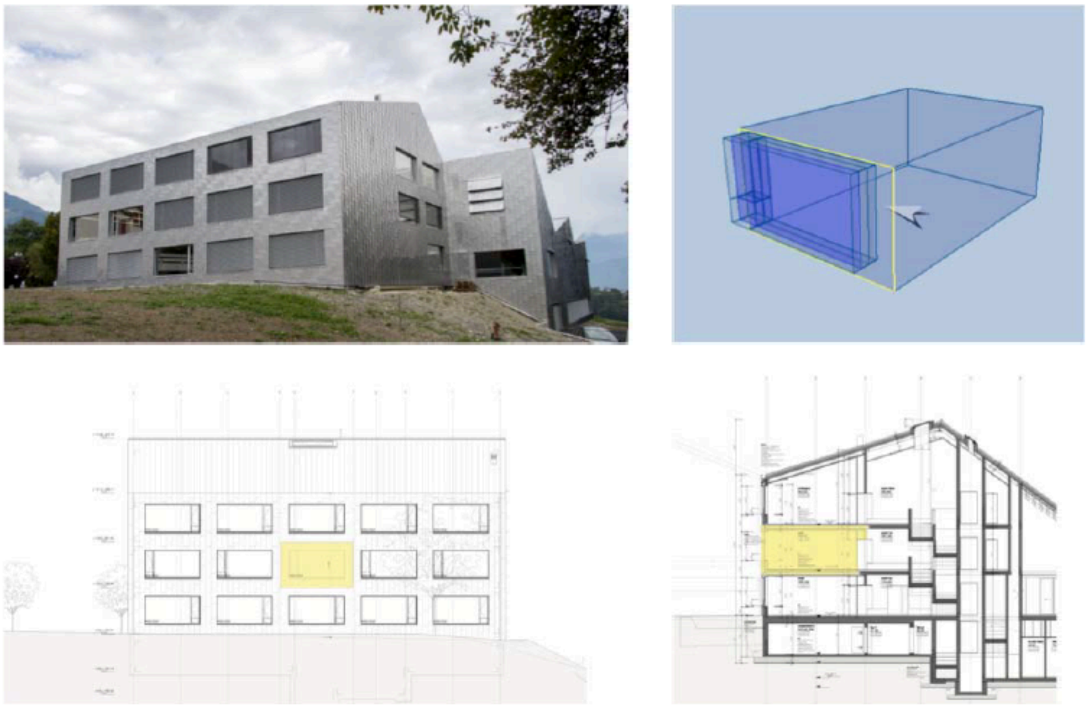


Figure 1. Illustration of Saviese primary school, St-Germain (Switzerland) used as a test case for investigation of ventilative cooling performance in different climates. The Saviese primary school was built in 2014 and was designed to get a Minergie® label[1], [2].

Table 1. Thermal transmittance of building elements of the Saviese primary school, St-Germain (Switzerland).

Building element	U-value [W/m²K]
External wall	0.16
Internal wall	2.90
Internal floor/ceiling	0.32
Window: glazing system	0.60
Window: frame	1.35
Door	1.10

---

[1] The Minergie is a Swiss low energy building label (www.minergie.ch)

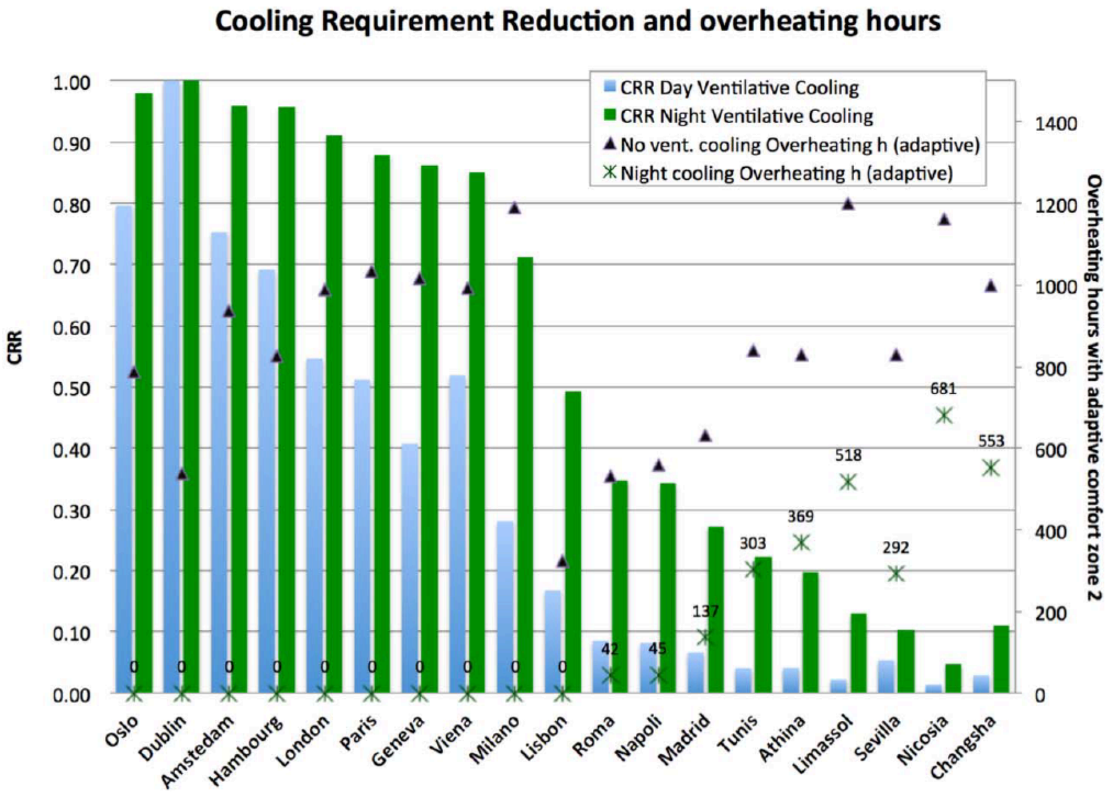
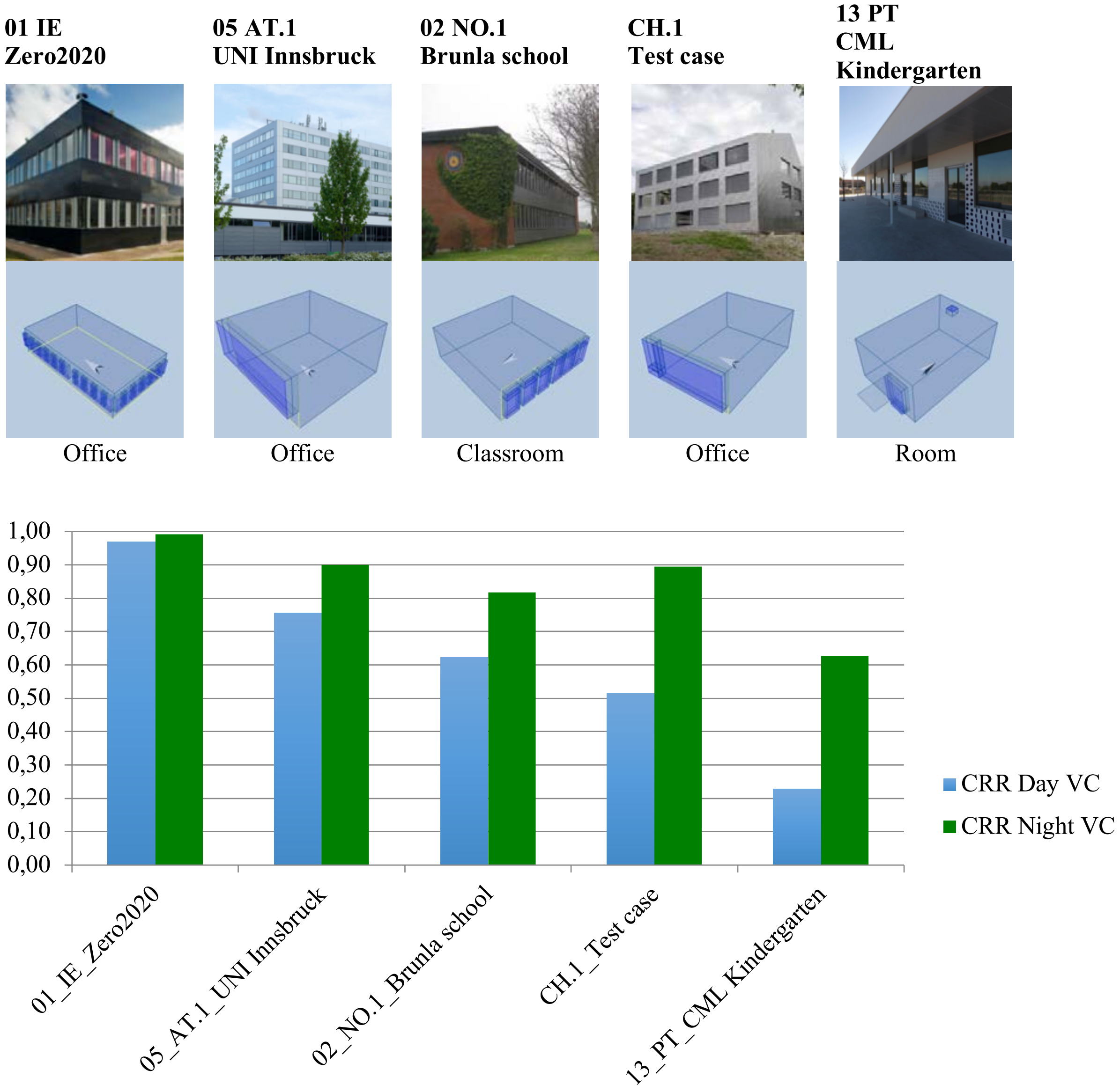


Figure 2. Expected cooling requirement reduction for day and night ventilative cooling strategy and overheating hours according to class 2 adaptive comfort indicator for a standard scenario without ventilative cooling and a scenario with night cooling.

The focus on the environmental impacts of energy production and consumption has provided an increased awareness of the energy used by fans, heating/cooling coils and other equipment in ventilation and air conditioning systems. The expectations of a reduction in annual energy costs has also been an important driving force for the development of ventilative cooling strategies in many of the case study buildings. Figure 3 shows the expected reduction in cooling requirement in five case studies in Annex 62 for two different ventilative cooling strategies; 1) Ventilative cooling during daytime, 2) Additional ventilative cooling during nighttime.



Case Study no.	Building	Type	Hours >25°C	Hours >26°C	Hours >28°C
01 IE	Zero2020	Office	5.5%	-	0.7%
02 NO.1	Brunla school	Classroom	2.0%	-	1.0%
05 AT.1	University, Innsbruck	Office	32%	-	1.1%
13 PT	CML Kindergarten	Room	16%	10%	-
CH.1	BestTest Case	Office	-	1.0%	-

Figure 3. Expected cooling requirement reduction and measured overheating hours during occupation in selected Annex 62 Case studies and the Swiss Besttest Case. For more detailed information see the case study reports for each building, [1]

Besides cooling requirement reduction and improved thermal comfort, the degree of user control has also an influence on the perceived indoor environmental quality and productivity.

Allowing occupants to adapt to their thermal environment can expand the comfort range in buildings. This adaption can be important in guaranteeing the thermal satisfaction of building occupants, but some consideration must be given when allowing occupants to adapt freely. In the Annex 62 case studies, the approach can vary and some limitations or constraints on the use of natural ventilation may be necessary to prevent overheating or overcooling. Adopting user control into design can use a purely manual approach or mix of manual and automated openings. In systems that are purely manual, training of building occupants may be necessary to guarantee comfortable conditions. While in countries with large cooling potentials purely limiting the time manual interactions last, may suffice. The following examples convey the range of user control available in the case studies:

- Case study no.13 (CML Kindergarten, Portugal) has a high level of user control allowed in the building, and there is no automated control system. In this instance, the users were educated on how to use the ventilation system in the building.
- Case study no.1 (zero2020, Ireland) has a combination of manual and automated openings incorporated in a natural ventilation system. The bottom openings are purpose provided and occupants can interact with them freely. The top openings are automated but have a manual override switch that can allow occupants to interact with them, but they will close after 30 minutes.
- Case study no.2 (Brunla School, Norway) has a combination of mechanical and natural ventilation systems. However, there is a large proportion of openings which can be manually overridden for 30 minutes, but they are rarely opened fully even in a manual override scenario due to constraints based on wind and rain.

1.3. Design Philosophy

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

The ventilative cooling process is very dependent on the outdoor climate, the microclimate around the building as well as the thermal behaviour of the building. Therefore, it is essential that these factors are taken into consideration from the very beginning of the design. It is also important that issues like night cooling potential, noise and air pollution in the surroundings as well as fire safety and security are taken into consideration.

In the design the location and size of openings in the building, as well as features to enhance the driving forces as solar chimneys and passive stacks must be co-ordinated with the selected strategy for both day and night time ventilation.

Appropriate control strategies must be determined and decisions made regarding the level of automatic and/or manual control and user interaction. Finally, necessary mechanical systems to fulfil comfort and energy requirements are designed.

1.4. Scope of the guidelines

These guidelines are designed for architects and engineers involved in the design of buildings and HVAC systems. The guide focuses on the design process and how calculation and simulation tools can be used for design, for design evaluation and for risk analysis. Case studies include both new build and retrofit designs.

Chapter 2 contains a description of the primary ventilative cooling principles and the typical strategies, system solutions and components used for temperature control. Chapter 3 gives an introduction to the key performance indicators that can be used in the design process and to evaluate compliance with regulations and standards. Chapter 4 describes the design approach for ventilative cooling systems with focus on barriers, requirements and design targets in the conceptual design phase. Chapter 5 describes a methodology to analyse the climate and to evaluate the ventilative cooling potential prior to the conceptual design phase. Chapter 6 contains a description of methods to be used for design calculations and performance evaluation in terms of energy use and thermal comfort. Chapter 6 also gives guidance on methods to be used to evaluate the performance of a ventilative cooling design and to ensure that the performance targets are achieved. Chapter 7 contains an overview of control strategies, control parameters and algorithms. Chapter 8 concludes with an overview of the characteristics and lessons learned from the investigated case studies.

2. Principles

There is a wide range of ventilative cooling principles and their application depends on climate and microclimate, building type, ventilation approach and user expectations. Ventilative cooling can be combined with other natural cooling solutions utilizing other natural heat sinks in the environment or with mechanical cooling solutions under unfavourable weather conditions.

This chapter focuses on the main principles and describes how typical design challenges can be met. It gives an overview of the principles used in all of the case study buildings in this project, while the Case Study report [1] includes descriptions of each building, the ventilative cooling strategy applied and the monitored performance. Three examples are selected to illustrate the different principles and possible ventilation strategies.

2.1. Ventilative Cooling Principles

The appropriate ventilative cooling principles for different outdoor climatic conditions and building ventilation systems are summarized in Table 2.

Table 2. Overview of typical ventilative cooling strategies applied depending on outdoor climatic conditions and type of ventilation system.

Temperature Difference[1]	Ventilative Cooling	Supplementary cooling options
Cold (ΔT more than 10ºC)	Minimize air flow rate - draught free air supply	-
Temperate (2-10ºC lower than comfort zone)	Increasing air flow rate from minimum to maximum	Strategies for enhancement of natural driving forces to increase air flow rates Natural cooling strategies like evaporative cooling, earth to air heat exchange to reduce air intake temperature during daytime
Hot and dry (ΔT between -2ºC and +2ºC)	Minimum air flow rate during daytime Maximum air flow rate during night time	Natural cooling strategies like evaporative cooling, earth to air heat exchange, thermal mass and PCM storage to reduce air intake temperature during daytime. Mechanical cooling strategies like ground source heat pump, mechanical cooling
Hot and humid	Natural or mechanical ventilation should provide minimum outdoor air supply	Mechanical cooling/ dehumidification

---

[1] Temperature difference between indoor comfort temperature and mean outdoor air temperature.

2.1.1. Ventilative cooling during cold outdoor conditions

In winter time when the outdoor air temperature can be very cold, the main challenge is to introduce outdoor air to the space without creating a high risk of draught and with a minimum use of electricity use for air transport.

One of the solutions that has been used in Annex 62 to overcome this challenge is to supply outdoor air through diffuse ceilings, see [3, page 76]. This technology can supply cold outdoor air with temperatures as low as -8°C without creating any risk of draught to the occupants in spaces of normal room height and with a cooling demand less than 90 W/m^2. The air supply system has a very low pressure loss and can be driven by natural forces or by a low pressure fan minimizing the energy use for air transport.

For ventilation systems driven by natural forces, another challenge is the balance between required air flow rate to ensure an acceptable indoor air quality and to remove the excess heat load. If the heat load in the building is relatively small, the required air flow rate for indoor air quality might remove more heat than needed. This will increase the heating system energy use, as effective heat recovery is difficult to be applied to naturally driven systems. Accurate control of the air flow rate is important to minimize the energy use for heating. The system should only be implemented, if the additional energy use for heating in winter associated with natural ventilation is compensated by larger energy savings in the rest of the year. Internal heat loads of more than 20-30 W/m^2 will typically benefit from natural ventilation.

For mechanically driven ventilation systems, the main challenge in exploiting outdoor air for cooling is to minimize the energy use for air transport. Typical mechanical systems cannot provide cold outdoor air to the building without increasing the risk of draught of the occupants. Supply air temperature is therefore increased by efficient heat recovery. This reduction in cooling capacity is compensated by an increased air flow rate up to 4-5 times the required for indoor air quality purposes. Increased pressure loss for heat recovery and in the air distribution system, increases the energy use for air transport considerably and in some cases outweighs the benefit of the “free cooling capacity” of the outdoor air. Solutions that can provide low temperature air supply without creating a draught risk for the occupants are therefore essential for mechanical ventilation system, especially in winter.

2.1.2. Ventilative cooling during temperate outdoor conditions

Under temperate conditions, outdoor air can be provided to the building and the occupied zone without creating a risk of draught. The air flow rate should be controlled according to the temperature and will typically be higher than required to ensure an acceptable indoor air quality. As in naturally driven systems there is no energy use for heating, cooling or air transport, the control requirements for the air flow rate are not very strict and technically relatively simple systems (like manual or automatic window opening in the façade) can handle the ventilative cooling appropriately. However, in periods with small temperature differences between indoor and outdoor air, where the naturally driving buoyancy forces are limited, it might be necessary to enhance them by implementing additional technical solutions to the building. In windy climates, solutions that can enhance wind forces are typically suitable (wind catchers, high positioned roof openings, etc.) while in sunny climates enhancement of buoyancy forces by solar chimneys might be useful.

For mechanically driven system, the cooling capacity can be kept constant at increasing outdoor air temperature by reducing the heat recovery efficiency. Not until outdoor air temperatures is above 18-19 °C, the cooling capacity will drop as increase in air flow rates is not possible or only to a very limited extend.

To enhance the ventilative cooling capacity, it is important to position the air intakes in a cool environment (shaded side of the building). It might also be necessary to further reduce the outdoor air intake temperature by supplementary natural cooling solutions like ground cooling (earth to air heat exchange) or evaporative cooling.

2.1.3. Ventilative cooling during hot outdoor conditions

In summer, in dry climates with high outdoor air temperatures during daytime, the air flow rates should be controlled to a minimum to ensure an acceptable indoor air quality and minimum additional heat load on the building. Effective night-time ventilation should be applied to remove the absorbed heat during daytime by cooling the building thermal mass. If the night-time cooling capacity is high enough and the building is well-designed with well-balanced glass area in the facades, efficient solar shading and exposed thermal mass, the next day's indoor temperature profile will be lower than outdoor temperature. Otherwise, supplementary natural cooling solutions and/or mechanical cooling will be required to reduce daytime outdoor air intake temperatures in the warmest periods.

In hot and humid climates, naturally driven ventilative cooling will not be useful in the warm period. Mechanical ventilation systems are required to be supplemented by mechanical cooling to ensure a constant high cooling capacity regardless of the outdoor temperature and humidity.

2.1.4. Application of hybrid solutions

As aforementioned, adopting naturally or mechanically driven ventilation systems for ventilative cooling presents different challenges.

Naturally driven ventilation systems are most effective in buildings with high heat loads in winter, in buildings with low heat loads in summer and in periods of the year where the outdoor temperatures are temperate, while mechanical systems are more suitable in buildings with relative low heat loads in winter, in buildings with high heat loads in summer and in periods of the year where the outdoor temperature is either very cold (utilization of heat recovery to decrease energy use) or very warm (mechanical cooling can be applied to ensure thermal comfort).

In many cases it can be beneficial from both an energy and a thermal comfort point of view to combine the two different types of ventilation systems to exploit their different strengths and avoid their weaknesses. The most appropriate strategy for the combination of systems will depend on the outdoor temperature (climate) as well as the building type and the overall cooling demand.

In cold climates, the typical combination is the use of mechanically driven ventilation in the winter season and naturally driven ventilation during intermediate and summer seasons. In temperate climates, naturally driven ventilation can be used during the whole year. In cold and hot climates, mechanically driven ventilation is used in winter and summer, while naturally driven ventilation is used in the intermediate seasons. In warm climates, naturally driven ventilation is used in the winter period, while mechanically driven ventilation is preferable in the rest of the year.

Different systems can also be used at different times of the day. Generally, mechanically driven ventilation is used during occupancy hours and naturally driven ventilation is activated at night time to increase the cooling capacity at night.

2.2. Type of components and system integration

As such, there are no ventilative cooling components. Ventilative cooling systems in nearly all cases consist of a combination of components, which can be used in purely naturally driven or in purely mechanically driven ventilation systems. However, in order to allow a correct design and functioning of a ventilative cooling system the availability of appropriate components is essential. Figure 4 shows a way to characterise typical components used in ventilative cooling systems.

Functionality	Component
Air Flow Guiding	Windows, Rooflights, Doors, Dampers, Flaps, Louvres, Special Effect Vents
Air Flow Enhancing	Chimneys, Atria, Venturi Ventilators, Wind Towers, Wind Scoops
Passive and Natural Cooling	Convective Cooling, Evaporative Cooling, Phase Change Cooling
Control and Automation	Chain Actuators, Linear Actuators, Rotary Actuators, Sensors

Figure 4. Characterization of functionality of typical components in ventilative cooling systems.

2.2.1. Airflow guiding components

The most widespread airflow guiding components in ventilative cooling applications are the classical façade elements (architectural apertures): windows, doors and roof lights. These components are already in place for the purpose of daylight supply, view or connection to the exterior or other spaces. They are very effective in terms of providing high air flow rates and ventilative cooling also under minimum pressure difference (driving force). Special attention has to be paid to positioning, sizing and opening mechanism.

Beside the façade elements, special ventilation components that belong to this category are dampers, flaps, louvres and grilles. These components offer extended possibilities of control and protection against the environment (sound, rain, particles, burglary, etc.).

Finally, air terminals also belong to this category. Air terminals are technical openings which guide air into or out the ventilated space. They can be connected either to a ductwork or directly to the outside air or air in the space. Air terminals are divided further in window ventilators, trickle vents, slot or circular diffusers and disc valves.

2.2.2. Airflow enhancing components

The airflow enhancing components are fans (powerless or mechanical) and chimneys. Powerless fans generally make use of the wind pressure to generate either excess pressure driving supply air flow or - more often - generate negative pressure driving extract air. Powerless fans are mainly venturi fans, rotating fans, windcatchers and windscoops.

Chimneys make use of the hydrostatic buoyancy differences of the air. Chimneys can be designed independent from the wind direction, but they rely on the vertical extension of the construction and on the established temperature difference.

Ventilative cooling may be supported by mechanical fans, such as axial fans. Fans offer high airflow at low pressure drop, wide control range, low noise and free flow capability.

2.2.3. Passive and natural cooling components

The most widely used passive cooling components are solar shading, comfort fans and thermal energy storage in the building construction or in phase change material (PCM) storages. The typical natural cooling components include evaporative coolers and earth to air heat exchangers.

Evaporative cooling utilizes the adiabatic cooling effect for humidifying the air exploiting water's large enthalpy of vaporization. These components (swamp coolers, fountains, water ponds and others) have been utilized extensively in buildings located in regions with dry climates.

In PCM-based passive cooling components, cool air is circulated during the night and the stored latent heat is then released during daytime. The efficiency of the system depends primarily on the phase change temperature of the material, the temperature of the ambient air during the night period and the air flow rate. Modular ventilation devices can be ceiling mounted or integrated within the suspended ceiling.

2.2.4. Control and automation components

The core issue regarding actuation in ventilative cooling is opening and closing ventilation elements. There is a large variety of actuators available worldwide. Linear, chain (including folding) and rotary actuators are the most commonly employed for the operation of ventilation elements.

Secondary ventilative cooling components, especially important for automated opening control, are the sensors. Typical environmental parameters and other phenomena that are measured to provide a feedback to controllers are, amongst others, temperature, radiation, humidity, CO_2 (VOC)-concentration, air-wind velocity (air flow), rain and occupancy. Actuators and sensor are in many cases integrated in an embedded controller.

Modern controllers can integrate sophisticated heuristic control strategies and can be accessed remotely, for example via mobile applications.

2.3. Ventilative cooling principles and components in case studies

Different ventilative cooling principles are demonstrated in the case studies analysed in Annex 62. Table 3 and Table 4 give, respectively an overview of the principles, and an overview of the components and supplementary technologies used in every case study. More information can be found in [1].

Table 3. Ventilative cooling principles applied in the investigated case studies, [1].

Ventilative Cooling Principle **Case Study** **No.**		**Type and location**	**Day time air supply**	**Night time air supply**	**Natural ventilation combined with mechanical exhaust**	**Mechanical ventilation in winter, natural ventilation in summer**	**Mechanical ventilation with natural night time ventilation**	**Mechanical ventilation with increased flow rate**
01	IE	Zero2020	x	x				
02	NO.1	Brunla school			x			
03	NO.2	Solstad Kindergarten				x		
04	CN	Wanguo MOMA						x
05	AT.1	UNI Innsbruck	x	x				
06	AT.2	wkSimonsfeld			x			
07	BE.1	Renson	x	x				
08	BE.2	KU Leuven, Ghent					x	
09	FR	Maison air et lumiere				x		
10	IT	Mascalucia ZEB				x		
11	JP.1	Nexus Hayama	x	x				
12	JP.2	GFO	x	x	x			
13	PT	CML Kindergarten	x	x				
14	UK	Bristol University						x
15	NO.3	Living Lab	x		x			x

Table 4. Ventilative cooling components and supplementary technologies applied in the investigated case studies, [1].

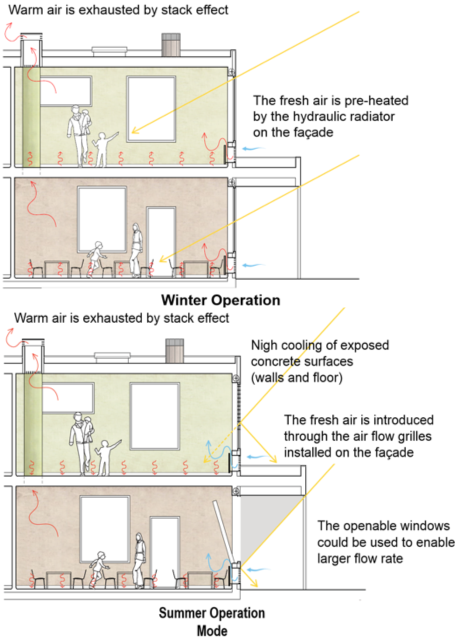
Ventilative Cooling Components and Technologies			**Air Flow Guiding components**					**Air Flow Enhancing Components**				**Supplementary Cooling Technologies**			
Case Study No.		**Type and location**	Windows	Insulated louvre	Overflow vents between rooms	Air pipes and air supply devices	Roof vents	Chimney	Fan	Ground cooling	Evaporative cooling	Ground Source heat pump	Earth to air Heat Exchanger	Radiant solar heat and cooling	PCM storage
01	IE	Zero2020		x											
02	NO.1	Brunla school	x						x						
03	NO.2	Solstad Kindergarten	x			x			x						
04	CN	Wanguo MOMA				x			x			x			
05	AT.1	UNI Innsbruck	x		x					x					
06	AT.2	wkSimonsfeld	x				x			x					
07	BE.1	Renson	x					x							
08	BE.2	KU Leuven, Ghent	x								x				
09	FR	Maison air et lumiere	x			x			x						
10	IT	Mascalucia ZEB	x						x				x		
11	JP.1	Nexus Hayama	x				x							x	
12	JP.2	GFO		x		x			x						
13	PT	CML Kindergarten	x	x				x							
14	UK	Bristol University				x			x						x
15	NO.3	Living Lab	x												

In these case studies, naturally driven ventilative cooling is mainly used in temperate climates and in several different building types. Naturally driven ventilation is both used during daytime for indoor air quality and cooling purposes as well as for night-time cooling of the buildings. Windows and/or louvres are typically used as air supply devices providing outdoor air directly to the occupied zones, while in some buildings roof vents or chimneys are used to enhance air flow. In some cases exhaust ventilation is also used to ensure a satisfactory air flow rate through the building at all times or natural cooling solutions are applied to improve the cooling capacity in warmer periods.

In cold climates and/or in buildings with a low heat load or very limited cooling need during winter, hybrid ventilation systems are typically used. Balanced mechanical ventilation with heat recovery is used in winter (the heating season), while natural ventilation is used in summer (outside the heating season), when outside temperatures are higher and direct supply of outdoor air does not result in draught risks. In some cases, mechanical ventilation is used during occupied hours during the whole year to ensure a controlled and satisfactory air flow rate at all times and combined with natural ventilation for night cooling in the warm periods. In many cases ventilative cooling is supplemented by natural cooling solutions.

Ventilative cooling solutions based on mechanical ventilation with increased flow rates are also among the demonstrated solutions in the case studies. These solutions offer the possibility for better distribution of air inside the buildings and are also used in combination with natural cooling solutions and energy storage/modulation.

Example 1: Natural ventilative cooling, CML Kindergarten, Portugal

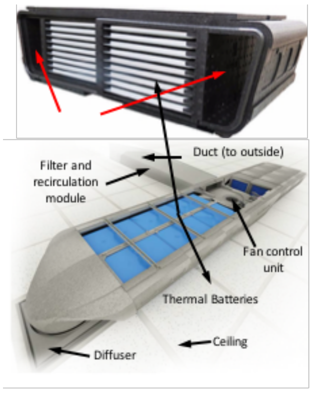


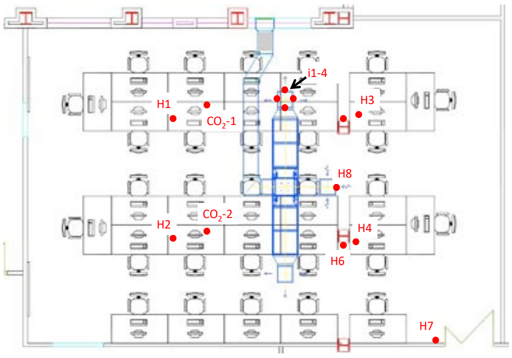
The ventilative cooling system consists of two different naturally driven ventilation and air distribution strategies: Displacement ventilation and single-sided ventilation. In the displacement ventilation system, air is introduced in the room near the floor with low air velocity. In order for the buoyancy forces to be more effective, the displacement ventilation system includes chimneys to increase the height difference between in and outflow. The single-sided ventilation system is mainly driven by wind pressure, but is also affected by local buoyancy effects, to induce air currents through the openings in the façade. Single-sided ventilation is used during the cooling period in order to enable larger flow rates to remove the higher heat gains.

The implemented ventilative cooling solution consists of a high-level openable window plus low-level grilles installed on the façade of each classroom for control of inflow of air. During the colder months a hydraulic radiator installed in front of the grilles can be used to increase the air intake temperature and reduce the draught risk. The air is exhausted in the back of the room, through one or two thermal chimneys. For optimal performance of the ventilative cooling, the system is designed with two operation modes: winter and summer. The system is implemented in the case study “CML Kindergarten” situated in the mild Subtropical-Mediterranean climate of Lisbon, Portugal. The use of the ventilative cooling system eliminated the energy use for cooling of the building and created acceptable thermal comfort and IAQ conditions. Long term measurements have shown that the indoor temperature only exceeds 26 °C for 10% of the time during occupied hours.

The stack driven natural ventilation proved to be very effective, self-regulating and was able to meet the airflow rate goals in spring and winter. The most significant problem encountered was related to control and user training. The users were convinced that the chimneys were poorly designed skylights [1].

Example 2: Mechanical ventilative cooling with increased air supply and energy storage, Bristol University, United Kingdom



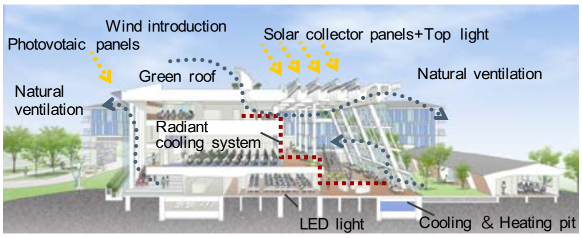


The ventilative cooling system consists of a balanced mechanical ventilation system with a thermal storage of Phase Change Material (PCM) plates within the ventilation path to capture and store heat. Air is drawn from outside or the room using a variable speed fan. During operational hours and depending on internal air quality, the air is mixed with recirculated air from the room to conserve energy. The air is then directed through the PCM thermal storage to be cooled if necessary or by-passed if cooling is not needed. Outside operational hours, ambient air is used to recharge the PCM thermal storage, the duration of which is determined by air temperature sensors and control rules according to the season.

The mechanical ventilation system consist of a G4 filter, recirculation damper, fan, thermal batteries and diffusers. An electronic system controls the damper and directs the airflow through thermal storage or bypasses it through an EPP Expanded Polypropylene duct. The fan provides 260 L/s maximum during cooling mode and 300 L/s during charging mode.

This ventilative cooling system is implemented in classroom and offices in the case study “Bristol University” situated in West England. The use of the system reduces the energy use for cooling of the building considerably. The electricity use for air transport was 0.78 kWh/(m^2 a) in 2014 and 0.67 kWh/(m^2 a) in 2015, which is only a fraction of what a normal air conditioning system would use. Acceptable thermal comfort and IAQ conditions were achieved. The system was able to cool the space, so no overheating was monitored, but a few periods with overcooling were identified [1].

‘Example 3: Natural night time ventilative cooling, Nexus Hayama, Japan



	2011	2012	2013	2014	2015
NV operating time [h/a]	102	146	816	680	1282
AHU operating time [h/a]	1641	467	177	98	128

The ventilative cooling system consists of a naturally driven ventilation system that combines large space thermal buoyancy and wind-driven ventilation, taking advantage of the strong south wind of the site. The outside air is introduced in the occupied zone at the first floor and at the top floor and together with exhaust windows in the upper non-occupied zone the occupied area is efficiently cooled. In order to prevent that the thermal environment on the top floor deteriorates a wind catching window is installed and the outside air is captured on the top floor by using the wind pressure of the relatively strong wind originating from the ocean. The outside air is introduced from the cooling and heating pit and enters through perforated metal sheets installed on the stairs, designed to introduce the outside air directly into the occupied zone of the room. In the intermediate seasons, a ventilation opening via a folding door to the courtyard creates a comfortable semi-outdoor space. While in, summer and winter, an efficient below-floor heating and air conditioning system operates, creating a comfortable space throughout the year. The exhaust openings in the building use the H-type chimney principle, designed to always have negative pressure regardless of the direction of the outside air. The wind capture opening installed on the top floor is a backflow preventing window designed with a streamlined ventilation path to minimize its pressure drop. Insulation panels instead of glass are used for a higher heat-insulating capacity, when the ventilation window is closed.

This system is implemented in the case study “NEXUS HAYAMA” building situated in Syonan International Village in Kanagawa, Japan. It serves as a training environment and accommodation for employees of a Japanese pharmaceutical company. In 2011 and 2012, mechanical air conditioning was mainly used based on the safety considerations by the operator. However, after consultations between the designer, the owner, and the operator, the operation changed to include the use of natural ventilation in 2013. The operator gained an understanding of the system and a comparison of 2012 and 2013 indicates that the average room temperature did not change considerably. Acceptable thermal comfort and IAQ conditions were achieved. The number of hours where the temperature exceeded 28 °C was less than 2% [1].

3. Key Performance Indicators

Key Performance Indicators (KPIs) are quantifiable measures used to evaluate design goals and to provide means for the measurement and monitoring of the progress of the design towards those goals. KPIs are used in building regulations and standards to evaluate and compare performance. KPIs are defined in Statement-of-Requirements for a building, which guide design development. In every design phase, KPIs are applied to compare design solutions supporting the decision-making process.

So far, no framework for ventilative cooling performance evaluation has been developed. This is a major barrier for the application and the further development of the technologies related to ventilative cooling.

In IEA EBC Annex 62 national experts have discussed and developed KPIs to represent the performance of ventilation cooling and they have identified four different categories of KPIs:

- SYSTEM INDICATORS: ‘system’ refers to all the components which together allow the functioning of the ventilative cooling strategy. Therefore, system indicators reflect building performance in both energy and thermal comfort terms;
- COMPONENT INDICATORS: component indicators represent the performance of each component of the ventilative cooling system (i.e. opening efficiency, ventilation unit, SPF of cooling system, etc.). Component indicators are complimentary indicators to be used for component design and selection, compliance verification and in Statement-of-Requirements for a building;
- BOUNDARY CONDITIONS INDICATORS: boundary conditions indicators represent the assumptions on input data or building operating conditions (i.e. level of internal gains, solar gains, thermal mass, window surface area, solar transmission, airflow - natural or mechanical, ventilation and occupation schedules, weather data) under which the system indicators are calculated. Boundary condition indicators aim at easing the control of assumptions on input data and the identifying tricky projects or errors;
- SENSITIVITY INDICATORS: sensitivity indicators communicate the uncertainty on predicted/expected performance (design phase) due to assumptions and boundary conditions. They also indicate the risk of divergence of real performance to the predicted one (compliance phase) due to building use, occupant behaviour, weather condition as well as in relation to the varying capacity of passive solutions.

In these guidelines only selected KPIs related to the performance of ventilative cooling systems (system indicators) are presented.

3.1. Thermal comfort

Thermal comfort performance cannot be represented well by a single indicator [5]. A set of indicators is needed, combined with effective graphical representation, to support the building design and operation. During the design phase, it is necessary to compare different design solutions both in relation to overheating frequency and its severity.

The standard EN 15251:2007 proposes methods for long-term evaluation of general thermal comfort conditions, where the combination of the “Percentage Outside the Range Index” (method A) and the “Degree-hours Criterion” (method B) enable the evaluation of both frequency and severity of overheating and overcooling occurrences. The reference comfort temperature can be derived from the Fanger model, the adaptive comfort model or briefed by the building owner/occupants.

The Percentage Outside the Range (POR) index [%] (Equation 1) calculates the percentage of occupied hours, when the PMV or the operative temperature is outside a specified range.

$$POR = \frac{\sum_{i=1}^{Oh}(wf_i \cdot h_i)}{\sum_{i=1}^{Oh} h_i} \qquad \text{Equation 1}$$

where wf is a weighting factor which depends on the comfort range. The comfort range can be expressed in terms of PMV, when referring to the Fanger model or in terms of operative temperature, when referring to the adaptive comfort model.

According to the Degree-hours criterion (DhC) [Kh] (Equation 2) the time during which the actual operative temperature exceeds the specified range during the occupied hours is weighted by a factor which is a function of how many degrees the range has been exceeded.

$$DhC = \sum_{i=1}^{Oh}(wf_i \cdot h_i) \qquad \text{Equation 2}$$

Where weighting factor wf is here calculated as 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. In case the comfort range is expressed in terms of PMV, the comfort operative temperature range has to be estimated by making assumptions on clothing and metabolic activity.

Ideally, the thermal comfort evaluation within design phases can be supported with a carpet plot displaying discomfort degrees within each hours of the year, as shown in Figure 6. This graphical representation gives a good picture of the thermal conditions within the building or part of the building throughout the year, easing the identification of critical time frames or periods along the year.

In case of compliance demonstration, it is recommended to use a concise indicator able to summarize the building performance in terms of thermal comfort. Previous studies [6,7], identified the long-term percentage of dissatisfied (LPD) index [%] (Equation 3) as the optimal index to evaluate comfort conditions.

$$LPD\ (LD) = \frac{\sum_{t=1}^{T}\sum_{z=1}^{Z}\left(p_{z,t} \cdot LD_{z,t} \cdot h_t\right)}{\sum_{t=1}^{T}\sum_{z=1}^{Z}\left(p_{z,t} \cdot h_t\right)} \qquad \text{Equation 3}$$

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 can be formulated in different ways depending on the reference comfort model [6]. This indicator is concise, symmetric, robust and can be derived from building energy simulation outputs or long-term monitoring and can be used to compare the performance of different buildings as it is expressed in terms of percentage.

3.2. Energy

Existing energy indicators suit to all building typologies and evaluate active systems only. Energy indicators only implicitly consider the benefits of passive solutions, as energy need reduction, or the side effects, as the increase of heating need due to cold draughts or higher infiltrations or the increase of auxiliary energy consumption for control and automation. Passive systems are implicitly taken into account in the energy need calculation but the related energy savings are not explicitly shown. These calculation methods do not allow fair comparison between passive and active design options and other competitive measures.

Furthermore, most of the existing indicators consider either cooling or ventilation energy use, but not the total energy use for cooling and ventilation. Free cooling is meant to reduce or to avoid active cooling. Energy consumption of the fans is used to reduce or substitute the active cooling energy. The energy use for hygienic ventilation is usually not disaggregated from the overall energy consumption for ventilation.

From these considerations arose the need for an energy indicator or a set of indicators able to tackle the following aspects:

- cooling need and/or energy savings related to ventilative cooling;
- ventilation need and/or savings related to ventilative cooling only, possibly excluding the energy needed by hygienic ventilation;
- possible drawbacks on energy behaviour during heating season, i.e. increase of heating need due to cold draughts or higher infiltrations, auxiliary energy consumption for control and automation;
- ventilative cooling effectiveness as the match of cooling need and ventilative cooling potential.

In Annex 62 a new set of energy indicators have been developed and tested for the evaluation of ventilative cooling system performances. These are presented in the following.

The first indicator, the Specific Primary Energy Consumption (Equation 4) of a ventilative cooling system, is meant to express the primary energy consumed by the ventilative cooling system per heated floor area.

$$Q_{pe,vc} = Q_{pe,v} + Q_{pe,h} + Q_{pe,c} - Q_{pe,v\_hyg} \qquad \text{Equation 4}$$

where $Q_{pe,v}$ is the annual primary energy consumption of the fan, $Q_{pe,h}$ and $Q_{pe,c}$ are the annual primary energy consumption for space heating and cooling respectively and Q_{pe,v_hyg} is the annual primary energy consumption of the fan when operating for hygienic ventilation.

The second indicator, the Cooling Requirements Reduction (CRR), is meant to express the percentage of reduction of the cooling demand of a scenario in respect to the cooling demand of the reference scenario (Equation 5). It can be easily calculated by post processing outcomes of building energy simulation runs of a reference scenario (e.g. mechanically cooled building) and a ventilative cooling scenario (e.g. natural night cooling and daytime mechanical cooling). Therefore, it is particularly suitable to compare different design scenarios and drive design decisions.

$$CRR = \frac{Q_{t,c}^{ref} - Q_{t,c}^{scen}}{Q_{t,c}^{ref}} \qquad \text{Equation 5}$$

where $Q_{t,c}^{ref}$ is the cooling demand of the reference scenario and $Q_{t,c}^{scen}$ is the cooling demand of the ventilative cooling scenario.

This indicator can range between -1 and +1. If CRR is positive, it means that the ventilative cooling system reduces the cooling need of the building. If CRR is equal to 1, the ventilative cooling scenario has no cooling requirement. If CRR is zero or negative, the ventilative cooling scenario does not reduce the cooling need of the building.

CRR can also be applied on a natural ventilation scenario, calculating the cooling need by means of dynamic energy simulations in ideal loads/unlimited power mode.

In the case of mechanical ventilation systems, it is worth noting that this indicator does not take into account the energy required for air distribution. Therefore, in case of mechanical ventilation, the design decision cannot be taken regardless of the ventilative cooling effectiveness, including fan energy use in the rating.

3.3. Application example

One of the meeting rooms of the Saviese primary school (Figure 5), located in St-Germain (Switzerland) is used as case study. The meeting room is 5.12 m wide, 6.45 m long and 2.81 m high and has a total air volume of 92.79 m³. The Saviese primary school was built in 2014 and was designed to get a Minergie® label (Flourentzou, Pantet et al. 2015). Therefore, the building envelope is highly air tight and insulated. Table 1 reports the thermal transmittance of each envelope component.

Figure 5. Saviese primary school (St-Germain, Switzerland). The meeting room is the one highlighted.

The meeting room has only one window that is 4.00 m wide and 2.02 m high. The glazed area consists of a side-hung window of 1 m² (0.64 m wide per 1.56 m high) and fixed window of 7.9 m². An exterior blind with adjustable slats shades both the side hung window and the fixed window.

The blind has a standard positioning each day of the week (from Monday to Friday) as:

- Blind is totally open (i.e. it covers none of the glazed surface) at 07:00;
- Blind is closed (i.e. it covers all the glazed surface) at 14:00 with the slats at a tilt angle of 45°;

- Blinds are totally closed at 18:00.

During the weekends, the blind is totally closed (i.e. it covers the entire glazed surface and slats have a tilt angle of 90°).

We assume the room occupied by 4 persons from Monday to Friday between 08:00 and 17:00. Lighting power is 300 W and the lighting can be activated between 8:00 - 12:00 and 13:00 - 17:00 during working days. A daylight sensor is set in the middle of the zone and activates the lights only if the illuminance is below 300 lx. No additional electric equipment is taken into account.

Infiltration is set using the basic equation of [9] with default coefficients suggested by EnergyPlus Engineering reference [8].

The following ventilative cooling strategies were tested:

- Balanced mechanical ventilation (Specific Fan Power is 0.45 Wh/m^3) with inlet airflow and inlet air temperature as in Table 5;
- Direct natural ventilation with window control based on indoor-outdoor temperature difference: this strategy assumes that there is no mechanical ventilation and windows are opened (opening factor = 62%), when the building is occupied, if the zone air temperature is higher than the outdoor air temperature and the cooling set-point temperature (26°C);
- Direct ventilation with window control based on indoor thermal comfort: this strategy assumes that there is no mechanical ventilation and windows are opened (opening factor = 62%), when the building is occupied, if the zone operative temperature is higher than the comfort temperature (central line) calculated from EN 15251:2007 standard;
- Passive night ventilation: This strategy assumes there is no mechanical ventilation and windows are opened (opening factor = 62%) during both daytime and night-time if the zone air temperature is higher than the outdoor air temperature and the cooling set-point temperature (26°C).

Simulations are run during the cooling season (15/04 to 15/10) in both ideal loads mode (unlimited power) and free floating mode. Temperature setpoints are set as in Table 5. Heating season refers to the period from October 15th until April 15th

Table 5. Mechanical ventilation and air temperature setpoints.

Day	Time [hh:mm]	Inlet airflow [m³/hr]	Inlet air temperature [°C] during cooling season	Inlet air temperature [°C] during heating season	Cooling setpoint	Heating setpoint
Mon-Fri	07:00 – 17:00	150	26	20	26	20
	17:00 – 23:00	62	26	20	-	--
	23:00 – 07:00	0	-	-	-	-
Sat-Sun holidays	00:00 – 24:00	0	-	-	-	-

The performance of the above described ventilation strategies were compared in terms of energy consumption and thermal comfort.

Table 6 reports the calculated indicators for thermal comfort. Both percentage outside the range (POR) and Degree hours Criteria (DhC) are calculated considering 20 – 26°C as comfort range for the operative temperature of the zone.

The percentage outside the range indicators is easy to calculate and provides the designers with basic information about the thermal comfort situation within the building zone. The degree-hours criteria, supported by the carpet plot in Figure 6, allow to identify whether the discomfort is due to cold indoor temperatures or hot indoor temperatures and to detect high risk of overheating times of the day. The histogram in Figure 7 also classifies the occupied hours by overheating or overcooling severity.

Both POR and DhC refer to fixed comfort ranges and therefore thermal comfort evaluation is in favour of security.

The Long Term Percentage of Dissatisfied (LPD) indexes refer instead to thermal comfort models compliant with international standards and can be used in later proof of concept phases.

The comparison among the ventilation strategies shows how natural ventilation with window control based on indoor/outdoor temperature difference during occupied time can reduce the POR from 48% to 17-20%. Extending the use of natural ventilation 24 hours, reduces the POR to 2%. The overcooling situation highlighted by DhC indicators is caused by the window opening control being based on the adaptive comfort temperature while DhC is based on a fixed comfort temperature range (20-26°C).

Table 6. Thermal comfort indicators cased on simulation outcomes, with controlled and with free-floating indoor temperatures, for the four ventilation strategies.

Index	**Description**	**Ventilation strategy (with controlled indoor temperature)**				**Ventilation strategy (with free-floating indoor temperature)**			
		1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
POR	Percentage outside the range	39%	14%	17%	0%	48%	17%	20%	2%
DhC (warm)	Degree hours Criterion (warm period)	124	45	33	0	478	176	148	5
DhC (cold)	Degree hours Criterion (cold period)	66	0	16	0	66	0	16	0
LPD (LD$_{fanger}$)	long term percentage of dissatisfied based on Fanger model	2%	2%	1%	1%	2%	2%	1%	1%
LPD (LD$_{adaptive}$)	long term percentage of dissatisfied based on adaptive comfort model	2%	1%	2%	1%	2%	1%	2%	1%

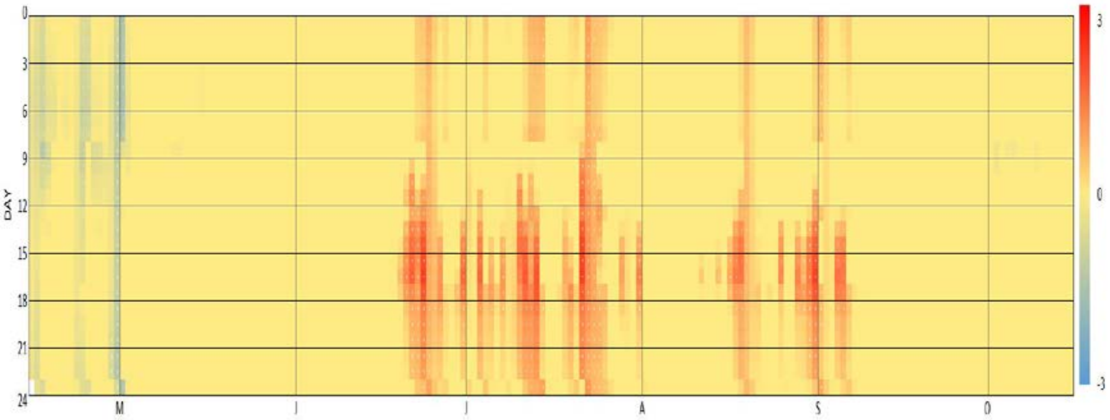


Figure 6. Carpet plot displaying discomfort degrees resulting from free floating simulation of BES test case with ventilation strategy nr 3.

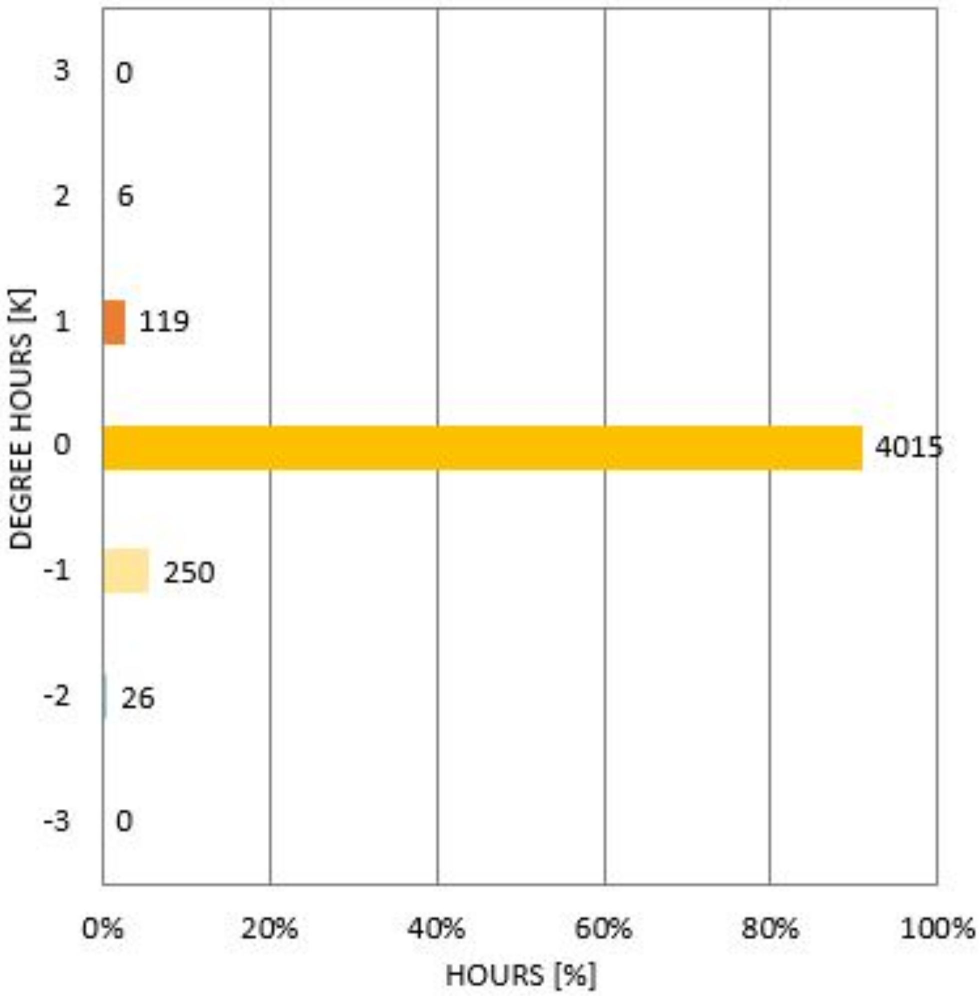


Figure 7. Histogram displaying the frequency of discomfort from free floating simulation of BES test case with ventilation strategy nr 3.

The Cooling Reduction Requirement, over the simulation period (15/04 to 15/10), is 0.4 and 0.5 for strategies 2 and 3 with daytime natural ventilation and 0.9 for strategy 4 with day and night natural ventilation. The CRR uses ventilation strategy 1 as reference scenario (mechanical ventilation) and compares it with the ideal cooling demand of the building zone with ventilation strategy 2, 3 and 4.

The primary energy for heating, cooling and ventilation is reduced by 86%-97% thanks to natural ventilation strategies.

Table 7. Energy indicators cased on simulation outcomes, with controlled indoor temperatures, for the four ventilation strategies.

Index	**Description**	**Metric**	**Ventilation strategy (with controlled indoor temperature)**			
			1	**2**	**3**	**4**
Qpe, heating	Primary energy for heating	kWhpe	0	0	0	0
Qpe, cooling	Primary energy for cooling	kWhpe	78	45	40	10
Qpe, v	Primary energy consumption of the fans	kWhpe	268	0	0	0
Qpe,v_hyg	Primary energy consumption of the fans when operating for hygienic ventilation	kWhpe	0	0	0	0
$Q_{pe,\,vc}$	Primary energy for ventilative cooling	kWhpe	346	45	40	10
CRR	Cooling Requirement Reduction	%	-	0.4	0.5	0.9

3.4. Component indicators

Component indicators refer to the performance of a particular part of the ventilative cooling system. The ventilation effectiveness of a window or a set of windows is a component indicator. It can be expressed as the window airflow at 2°C and at 5°C indoor-outdoor temperature difference without wind presence.

Concerning energy performance indicators 2 component indicators of a mechanical ventilation system are defined and tested:

- Ventilative Cooling Seasonal Energy Efficiency Ratio (SEERvc).
- Ventilative Cooling Advantage of a passive component compared to conventional air conditioning.

The Seasonal Energy Efficiency Ratio [-] of the ventilative cooling system expresses the energy efficiency of the whole system. The SEER rating of a system is the reduction in cooling demand during a typical cooling season divided by the electrical consumption of the ventilative cooling system, in case ventilation rates are provided mechanically.

$$SEER_{VC} = \frac{Q_{t,c}^{ref} - Q_{t,c}^{scen}}{Q_{el,v}} \qquad \text{Equation 6}$$

where $Q_{el,v}$ is the electrical consumption of the ventilation system. If $SEER_{VC}$ is lower than 1, the reduction in cooling demand is lower than the energy use for ventilation. If $SEER_{VC}$ is equal to 1, the reduction in cooling demand is equal to the energy use for ventilation. If $SEER_{VC}$ is higher than 1, the reduction in cooling demand is higher than the energy use for ventilation.

The ventilative cooling advantage [-] (ADV_{VC}) indicator defines the benefit of the ventilative cooling in case ventilation rates are provided mechanically, i.e. the difference cooling energy use divided by the energy use for ventilation.

$$ADV_{VC} = \frac{Q_{el,c}^{ref}\text{-}Q_{el,c}^{scen}}{Q_{el,v}} \qquad \text{Equation 7}$$

where $Q_{el.c}^{ref}$ is the electrical energy use of the cooling system in the reference case, $Q_{el,c}^{scen}$ is the electrical energy use of the cooling system in the ventilative cooling scenario and $Q_{el,v}$ is the electrical energy use of the ventilation system.

If ADV_{VC} is lower than 1, the electrical energy use of the scenario is higher than the reference scenario. If ADV_{VC} is equal to 1, the electrical energy use of the scenario is the same as in the reference scenario. If ADV_{VC} is higher than 1, the electrical energy use of the scenario is lower than the reference scenario.

4. Design Process

In design and optimization of ventilative cooling the challenge is to sequentially minimize the cooling load, maximize the ventilative (VC) capacity to remove the load and, as a last step, minimize the electricity consumption of the supplementary cooling systems (if needed).

First of all, the design process aims at a reduction of internal and external heat loads by application of low energy equipment, by utilization of daylight and effective solar shading. Secondly, it evaluates a possible application of thermal mass of the building, which absorbs and stores heat during occupied hours and can be cooled during unoccupied hours with night ventilation. Finally, it focuses on energy reduction for air transport by using low pressure duct work and other components and/or optimization of natural driving forces from stack effect and wind.

The major issues of concern with regard to thermal comfort are avoidance of too low temperatures at the start of the working hours (appropriate night cooling strategy) and achieving an acceptable temperature increase during working hours (solar shading and thermal mass). Second the risk of draught at low outdoor air temperatures needs to be managed by choosing an appropriate air distribution strategy to reduce the required air flow rates in the cool season to a similar level as the ones needed for indoor air quality purposes. The ventilation air flow rate needed for natural cooling is in the warm period generally much higher than the necessary ventilation air flow rate for indoor air quality control.

4.1. The Ventilative Cooling Design Process

Ventilative cooling has the best chance of success when the design process is carried out in a logical, sequential manner with increasing detail richness towards the final design and in the framework of a design procedure.

Depending on possibilities and limitations in the actual case, the ventilative cooling system may come out as mechanical, hybrid or natural ventilation and may also be supplemented by other natural cooling technologies like ground cooling, earth-to-air heat exchangers or evaporative cooling.

A design procedure adapted to ventilative cooling design is shown in Figure 8. Phases for construction, commissioning and operation are also included to achieve a holistic approach. The design procedure for ventilative cooling ensures a thermal environment where every important issue is considered, where the process is efficient and where the final design is allowed to evolve in a logical way from idea to construction. The procedure aims at achieving a good thermal indoor environment at a low energy use and a seamless integration of the ventilative cooling solution with the building design and the environment. The tight integration results in many parameters to consider in an organized way, especially at an early stage.

A ventilation design procedure consists of different phases: conceptual design phase, basic design phase, detailed design phase and design evaluation. The conceptual design phase for ventilative cooling sets off by setting targets for indoor environment, energy use and cost and by performing an analysis of the ventilative cooling potential of the site taking into account both the climate, the surroundings, as well as overall building characteristics. If applicable, the ventilative cooling principle to be used is decided together with any supplementary passive and natural cooling solutions.

In the basic design phase, the internal heat, solar and contaminant loads are estimated on room level and the ventilative cooling system layout is designed. The necessary air flow rates as well as the expected temperature levels are calculated. A coarse annual energy use is calculated together with the necessary peak power demands. If the results do not meet the targets, the building and its systems will have to be redesigned and/or other supplementary passive or natural cooling solutions need to be considered before entering the next phase.

In the detailed design phase, thermal loads are re-evaluated and source control options are considered and/or optimized. The type and location of ventilative cooling system components are selected as well as the control strategy and sensor location. If needed other natural cooling solutions are designed and their operation integrated with the ventilative cooling solution.

Based on hourly calculations through a design year, the whole system (building and technical systems) is optimized with regard to indoor environment, energy use and costs. Finally, in the design evaluation phase, detailed predictions of thermal comfort can be performed to ensure that the design fulfils the targets of the project.

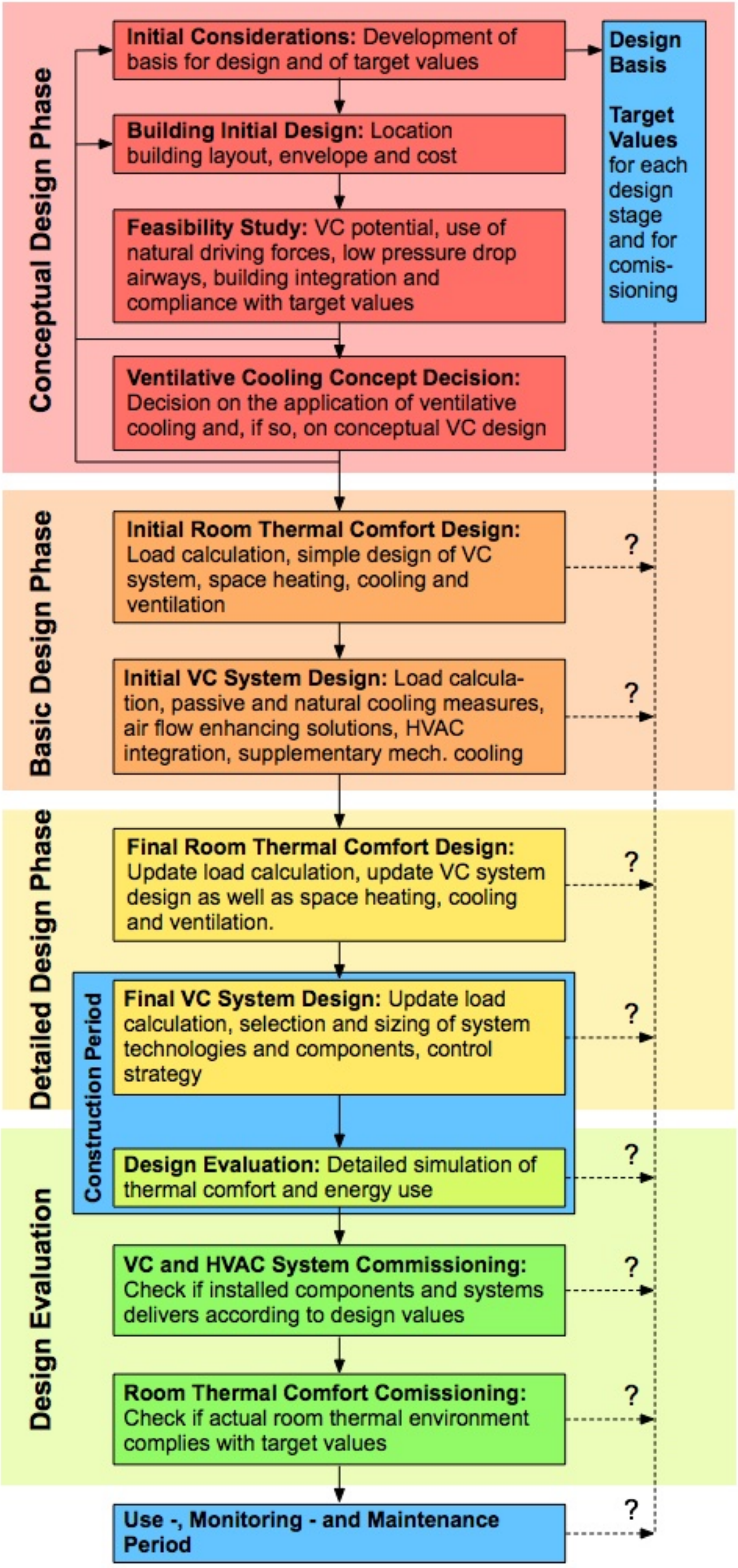


Figure 8. Design procedure for ventilation and ventilative cooling.

4.2. Conceptual Design Phase

4.2.1. Initial Considerations

The builder or his representative (building project manager) will normally be responsible for setting performance targets and other requirements. It is extremely important that the builder is aware of this responsibility, and put time and effort into the early stages of the design process to define goals and limits together with consultants, architects and engineers.

A set of thermal comfort target values should be defined to check if the suggested design is going in the right direction. The target values may need to be specified at different levels of detail for use at different stages of design. Goals for energy use, initial costs and operational costs (preferable Life Cycle Cost) should also be set.

Parameters chosen as target values should be measurable and as far as possible monitored during building operation. Annex 62 has developed a number of key performance indicators, see chapter 3, that can used to set targets for ventilative cooling performance.

The set of target values decided should be included in the contract document for design of the building and for maintenance until a possible reconstruction or refurbishment.

4.2.2. Basic conditions feasibility study

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

Initially, an analysis of the climate potential should be carried out both in relation to the cooling potential of the outdoor air, but also in relation to the potential use of natural driving forces for ventilation. As buildings with different use patterns, envelope characteristics and internal load levels react differently to the external climate conditions, the climate analysis cannot abstract from building characteristics and use.

In Annex 62, a ventilative cooling potential tool (VC tool) has been developed, which assesses the potential effectiveness of ventilative cooling strategies by taking into account not only climate conditions, but also building envelope thermal properties, internal gains and ventilation needs (see chapter 5 for further explanation). The output of the tool supports the decision making process by evaluating the ventilative cooling potential for a given climate and for a given building typology, by identifying the most efficient ventilative cooling strategy and by providing a rough estimation of the airflow rates needed to cool down the building in relation to internal gains, comfort requirements and envelope characteristics.

In many cases ventilative cooling needs to be based partly or fully on mechanical driving forces for air distribution. Therefore, it is very important to assess the availability and strength of the natural driving forces in the early design phases in a simplified way, as presented in chapter 6, to be able to decide on the need for mechanical assistance. It might also be necessary to introduce supplementary natural or mechanical cooling solutions to ensure that the thermal comfort requirements are fulfilled.

Table 8 and Table 9 can guide a first evaluation of the need for mechanical assistance and/or the need for supplementary cooling solutions in a ventilative cooling concept.

It is required that users of this procedure, firstly use data from the building programme to find the distribution of No’s, M(aybe)’s and Yes’s and evaluate options. Secondly they should settle on one or two ventilative cooling concepts for further evaluation or consider changes to the building program to decrease the need for mechanical assistance and/or decrease the need of supplementary natural or mechanical cooling solutions. The process going through Table 8 and Table 9 may be iterated a few times before a ventilative cooling concept is chosen. Design concepts that will involve “Yes’s” should be avoided to ensure that a certain ventilative cooling concept will be possible to carry out without extra costs and delays. Extra costs, delay or other problems should be accounted for if the actual design involves an “Yes”. More Yes’s means more challenges, and risks are involved. This must be considered when building contracts are discussed. Design guides and special advisors should be studied and consulted. It is also advisable that well documented case study building with similar outdoor conditions and use are taken as a reference.

Table 8. Evaluation of the need for mechanical assistance in driving the air flow.

Ventilative cooling: Need for fan assistance?						
Outdoor environment		**N**		**M**		**Y**
Cold	Winter (heat recovery needed)			■	■	■
	Summer	■	■			
Moderate		■				
Hot and dry	Winter	■	■			
	Summer (low temp. difference)			■	■	
Hot and humid	Winter	■	■	■		
	Summer (mechanical cooling needed)			■	■	■
Dense urban area with low wind speeds (low natural driving force)				■	■	■
Dense urban area with high night temperatures (heat island)				■	■	■
High pollution level in the area (air filtration needed)				■	■	■
Noisy surroundings (high noise insulation needed)			■	■	■	
Building heat load level		**N**		**M**		**Y**
Low heat loads < 20 W/m^2 during occupation	Cold (> 10°C from comfort zone) (heat recovery needed)			■	■	■
	Temperate (2-10°C from comfort zone)	■	■	■		
	Hot and dry (-2°C …. +2°C from comfort zone)		■	■	■	
	Hot and humid				■	■
Medium heat loads 20 -30 W/m^2 during occupation	Cold (> 10°C from comfort zone) (heat recovery needed)		■	■	■	
	Temperate (2-10°C from comfort zone)	■	■			
	Hot and dry (-2°C …. +2°C from comfort zone)			■	■	■
	Hot and humid					■
High heat loads > 30 W/m^2 during occuation	Cold (> 10°C from comfort zone) (heat recovery needed)	■	■	■		
	Temperate (2-10°C from comfort zone)	■	■			
	Hot and dry (-2°C …. +2°C from comfort zone)				■	■
	Hot and humid					■
Thermal comfort		**N**		**M**		**Y**
High requirements for 95% of occupancy hours						■
Normal requirements for 90% of occupancy hours			■	■	■	
Normal requirements for 80% of occupancy hours		■	■	■		
Requirements adaptive to outdoor conditions		■	■			
Integration with other natural cooling solutions		**N**		**M**		**Y**
Chilled slab by ground water exchange		■	■			
Earth to air heat exchanger			■	■	■	
Evaporative cooling		■	■			
Building and system		**N**		**M**		**Y**
Low level of exposed building thermal mass				■	■	■
Moderate level of exposed building thermal mass			■	■	■	
High level of exposed building thermal mass		■	■			
High space- and use-flexibility				■	■	■

Interpretation of abbreviations: N(o): Mechanical air flow assistance is not needed and/or will lead to unnessary high energy use or cost. M(aybe): Mechanical air flow assistance might be needed and/or might be more energy efficient and less costly with conscious design. Y(es): Mechanical air flow assistance is required and/or is the most energy efficient solution to apply.

Table 9. Evaluation of the need of supplementary natural or mechanical cooling solutions.

<table>
<tr><th colspan="7">Ventilative cooling System: Need for supplementary cooling?</th></tr>
<tr><th colspan="2">Outdoor environment</th><th>N</th><th></th><th>M</th><th></th><th>Y</th></tr>
<tr><td colspan="2">Cold (> 10ºC from comfort zone)</td><td>▨</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Temperate (2-10ºC from comfort zone)</td><td></td><td>▨</td><td>▨</td><td>▨</td><td></td></tr>
<tr><td colspan="2">Hot and dry (-2ºC …. +2ºC from comfort zone)</td><td></td><td></td><td>▨</td><td>▨</td><td>▨</td></tr>
<tr><td colspan="2">Hot and humid</td><td></td><td></td><td></td><td></td><td>▨</td></tr>
<tr><td colspan="2">Dense urban area with low wind speeds (low natural driving force)</td><td></td><td>▨</td><td>▨</td><td>▨</td><td></td></tr>
<tr><td colspan="2">Dense urban area with high night temperatures (heat island)</td><td></td><td>▨</td><td>▨</td><td>▨</td><td></td></tr>
<tr><td colspan="2">High pollution level in the area</td><td></td><td></td><td>▨</td><td>▨</td><td>▨</td></tr>
<tr><td colspan="2">Noisy surroundings</td><td></td><td></td><td>▨</td><td>▨</td><td>▨</td></tr>
<tr><th colspan="2">Building heat load level:</th><th>N</th><th></th><th>M</th><th></th><th>Y</th></tr>
<tr><td rowspan="4">Low heat loads < 20 W/m² during occupation</td><td>Cold (> 10ºC from comfort zone) (heat recovery needed)</td><td>▨</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Temperate (2-10ºC from comfort zone)</td><td>▨</td><td>▨</td><td>▨</td><td></td><td></td></tr>
<tr><td>Hot and dry (-2ºC …. +2ºC from comfort zone)</td><td></td><td></td><td>▨</td><td>▨</td><td>▨</td></tr>
<tr><td>Hot and humid</td><td></td><td></td><td></td><td></td><td>▨</td></tr>
<tr><td rowspan="4">Medium heat loads 20 -30 W/m² during occupation</td><td>Cold (> 10ºC from comfort zone) (heat recovery needed)</td><td>▨</td><td>▨</td><td></td><td></td><td></td></tr>
<tr><td>Temperate (2-10ºC from comfort zone)</td><td></td><td>▨</td><td>▨</td><td>▨</td><td></td></tr>
<tr><td>Hot and dry (-2ºC …. +2ºC from comfort zone)</td><td></td><td></td><td></td><td>▨</td><td>▨</td></tr>
<tr><td>Hot and humid</td><td></td><td></td><td></td><td></td><td>▨</td></tr>
<tr><td rowspan="4">High heat loads > 30 W/m² during occuation</td><td>Cold (> 10ºC from comfort zone) (heat recovery needed)</td><td></td><td>▨</td><td>▨</td><td>▨</td><td></td></tr>
<tr><td>Temperate (2-10ºC from comfort zone)</td><td></td><td></td><td>▨</td><td>▨</td><td>▨</td></tr>
<tr><td>Hot and dry (-2ºC …. +2ºC from comfort zone)</td><td></td><td></td><td></td><td></td><td>▨</td></tr>
<tr><td>Hot and humid</td><td></td><td></td><td></td><td></td><td>▨</td></tr>
<tr><th colspan="2">Thermal comfort:</th><th>N</th><th></th><th>M</th><th></th><th>Y</th></tr>
<tr><td colspan="2">High requirements for 95% of occupancy hours</td><td></td><td></td><td>▨</td><td>▨</td><td>▨</td></tr>
<tr><td colspan="2">Normal requirements for 95% of occupancy hours</td><td></td><td>▨</td><td>▨</td><td>▨</td><td></td></tr>
<tr><td colspan="2">Normal requirements for 80% of occupancy hours</td><td>▨</td><td>▨</td><td>▨</td><td></td><td></td></tr>
<tr><td colspan="2">Requirements adaptive to outdoor conditions</td><td>▨</td><td>▨</td><td></td><td></td><td></td></tr>
<tr><th colspan="2">Building and system:</th><th>N</th><th></th><th>M</th><th></th><th>Y</th></tr>
<tr><td colspan="2">Low level of exposed building thermal mass</td><td></td><td>▨</td><td>▨</td><td>▨</td><td></td></tr>
<tr><td colspan="2">Moderate level of exposed building thermal mass</td><td>▨</td><td>▨</td><td>▨</td><td></td><td></td></tr>
<tr><td colspan="2">High level of exposed building thermal mass</td><td>▨</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">High space- and use-flexibility</td><td></td><td>▨</td><td>▨</td><td>▨</td><td></td></tr>
</table>

Interpretation of abbreviations: N(o): Supplementary cooling will not be needed. M(aybe): Supplementary cooling will probably be needed and/or is a more energy efficient or less costly solution with conscious design; Y(es): Supplementary cooling will be needed and/or is the most energy efficient and cost-effective solution.

Application example CML Kindergarten, Portugal

To clarify the application of these principles we present here an analysis of Example 1 in chapter 2 (Lisbon Kindergarten). More detailed information about this project can be found in the Annex 62 case study report [1].

The climate, site and project characteristics evaluation is carried out using the two tables shown in the previous section. The goal of these tables is to guide designers and identify design challenges. When the indication is clear, they prevent the use of solutions that are not feasible.

Not all fields in the tables apply to a given project. In this example, only the lines that apply are shown. In each line the answer (marked by an "O") to each question is included, and in some cases an upper-script number for clarification comments below.

Ventilative cooling: Need for fan assistance?						
Outdoor environment		**N**		**M**		**Y**
Hot and dry	Winter	O	▨			
	Summer (low temp. difference)			O[1]	▨	
Dense urban area with low wind speeds (low natural driving force)				▨	O	▨
Noisy surroundings (high noise insulation needed)			▨	O[2]	▨	
Building heat load level:		**N**		**M**		**Y**
High internal loads > 30 W/m^2 during occuation	Cold (> 10ºC from comfort zone) (heat recovery needed)	O[3]	▨	▨		
	Temperate (2-10ºC from comfort zone)	O[3]	▨			
	Hot and dry (-2ºC …. +2ºC from comfort zone)				O[1]	▨
Thermal comfort:		**N**		**M**		**Y**
Normal requirements for 90% of occupancy hours			▨	▨	O[3]	
Building and system:		**N**		**M**		**Y**
High level of exposed building thermal mass		O[4]	▨			

Notes on ratings used above:

1. Although the Lisbon climate is warm in the summer the kindergartens are closed in August. For this reason, we chose "Maybe".
2. This project included eleven kindergartens in different locations in the Lisbon urban area. In two cases, there were noisy surroundings. Cost constraints for all the buildings did not allow for the use of advanced acoustic insulation solutions.
3. The Portuguese building code mentions an indoor temperature range of 19-27°C with no proposed % of time outside this range. EN15251 proposes a requirement of no more than 5% of occupied hours outside this range. The project used these two criteria.
4. The buildings have exposed concrete internal and external walls (with exterior insulation) and exposed concrete floors

A simple quantitative interpretation of the table “need for fan assistance” can be done by attributing a value to each line (No=1, Maybe=3, Yes=5). In this case, the average value is 2.4: the project may need fan assistance. In fact, it was decided in the project to use chimneys to obtain the required assistance effect.

Ventilative cooling System: Need for supplementary cooling?						
Outdoor environment		**N**		**M**		**Y**
Temperate (2-10°C from comfort zone)			▨	O	▨	
Dense urban area with low wind speeds (low natural driving force)			▨	O	▨	
Dense urban area with high night temperatures (heat island)			O	▨	▨	
Noisy surroundings				O	▨	▨
Building heat load level:		**N**		**M**		**Y**
High internal loads > 30 W/m^2 during occuation	Temperate (2-10°C from comfort zone)			O	▨	▨
Thermal comfort:		**N**		**M**		**Y**
Normal requirements for 90% of occupancy hours			▨	O	▨	
Building and system:		**N**		**M**		**Y**
High level of exposed building thermal mass		O				
High space- and use-flexibility			O	▨	▨	

A simple quantitative interpretation of the table “need for supplementary cooling” can be done in the same way as the table before to identify the need for fan assistance. In this case, the average value is 2.1. This value is between “No” and “Maybe”. The project uses night cooling and a ventilative cooling system that is assisted by chimneys. A monitoring campaign during the spring and early summer of 2016 showed that adequate thermal comfort can be achieved with 5-10% overheating hours. This is consistent with the results of the quantitative analysis of this table.

Application example Seminar Room, Bristol University, UK

As a second example is also presented an analysis of Example 2 in chapter 2 (Bristol University, United Kingdom). More detailed information about this project can be found in the Annex 62 case study report [1].

Ventilative cooling: Need for fan assistance?						
Outdoor environment		**N**		**M**		**Y**
Moderate		O[5]				
Dense urban area with low wind speeds (low natural driving force)				▨	▨	O[5]
Building heat load level		**N**		**M**		**Y**
High heat loads > 30 W/m^2 during occupation	Cold (> 10°C from comfort zone) (heat recovery needed)	O[6]	▨	▨		
	Temperate (2-10°C from comfort zone)	▨	▨	O		
	Hot and humid					O
Thermal comfort		**N**		**M**		**Y**
Normal requirements for 90% of occupancy hours			▨	▨	▨	O[7]
Building and system		**N**		**M**		**Y**
Moderate level of exposed building thermal mass			▨	O[8]	▨	

Notes on ratings used above:

5. The seminar room is on the ground floor of a building within a university campus surrounded by other buildings mostly 3-4 storeys high. It has only one external wall so single sided natural ventilation is the only option. This is the reason "No" is chosen for the climate but "Yes" for the surroundings, which give us an average of 3 "Maybe" for this category.
6. Internal heat gains are relatively high (60W/m^2) due to occupancy density and computers. Considering the different seasons, this category give is a "Maybe".
7. Being a seminar room, thermal comfort should be ensured for most occupancy hours, so the rating here is "Yes".
8. The buildings have some exposed thermal mass in the walls (brick with plaster).

The assessment gives us an average score of 3.3 – which is a "Maybe".

Ventilative cooling System: Need for supplementary cooling?						
Outdoor environment		**N**		**M**		**Y**
Cold (> 10°C from comfort zone)		O				
Temperate (2-10°C from comfort zone)			▨	O[1]	▨	
Hot and humid						O[2]
Dense urban area with low wind speeds (low natural driving force)			▨	▨	▨	O
Building heat load level:		**N**		**M**		**Y**
High heat loads > 30 W/m^2 during occupation	Cold (> 10°C from comfort zone) (heat recovery needed)		▨	▨	▨	
	Temperate (2-10°C from comfort zone) but humid			▨	▨	O[3]
Thermal comfort:		**N**		**M**		**Y**
Normal requirements for 90% of occupancy hours			▨	▨	▨	O

Building and system:	N		M		Y
Moderate level of exposed building thermal mass			O[4]		

Notes on ratings used above:

1. In this case the seasonal weather is considered so the rating is a "Maybe" but towards "Yes".
2. As the climate can be humid during the summer, a rating of "Yes" is selected here.
3. Being a seminar room, thermal comfort should be ensured for most occupancy hours, so the rating here is "Yes".
4. The buildings have some exposed thermal mass in the walls (bricks with plaster).

The assessment gives us an average score of 3.9, which moves the "Maybe" more towards "Yes".

The solution selected for this existing building was to install the CoolPhase system which is a mechanical ventilation system incorporating a latent thermal storage to provide cooling. The performance of the system is presented in one of the case studies in [1].

4.3. Ventilative cooling concept feasibility study

In the conceptual design phase, it is beneficial to develop a wide range of solutions to minimize the risk of overlooking good solutions. This work can be set off by a simple and fast analysis of the ventilative cooling potential of the site, using the ventilative cooling potential tool that was developed in this Annex (see chapter 5). This tool takes into account both the climate and the surroundings, as well as the overall building characteristics and targets for the indoor environment, energy use and cost. If applicable the ventilative cooling principles to be used can be selected together with any supplementary passive and natural cooling solutions as needed.

Application example CML Kindergarten, Portugal

For the same example as used above the results of the analysis of ventilative cooling potential are shown in Figure 9 below. The tool performs a 24h/day annual analysis, while the Kindergarten operates in approximately 50% of the hours of a day. In this context, this means that the number of residual discomfort hours predicted by the tool must be multiplied by two (all overheating hours occur during the day). The prediction of 2x8%=16% discomfort hours indicates, that the design must be carefully tuned. The results of this simple analysis are conservative since this model does not consider the beneficial effects of thermal mass, particularly in combination with night cooling, which can reduce the number of overheating hours. In the project a monitoring campaign during the spring and early summer of 2016 showed that adequate thermal comfort can be achieved with 5-10% overheating hours. This is consistent with the results of the quantitative analysis of the tool.

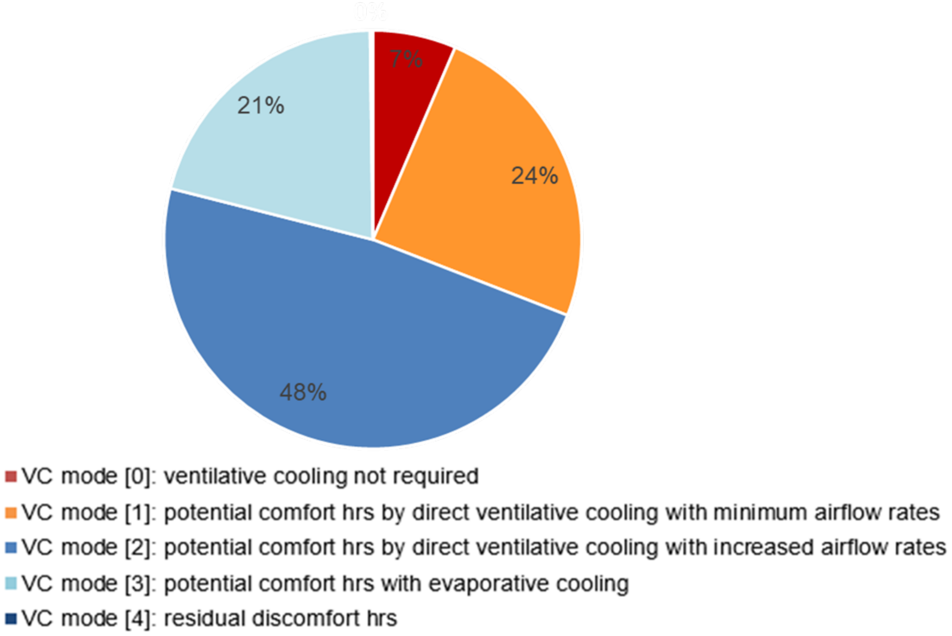


Figure 9. Results of the application of the VC cooling potencial tool to the Kindergarten case (Lisbon climate, average total gains of 53W/m^2, average natural ventilation flow rate 15l/s.m^2)

4.4. Basic Design Phase

4.4.1. Initial integration of building and ventilative cooling system

The conceptual design phase results in a few potential ventilative solutions that need to be developed into a single (and maybe an alternative) solution in the basic design phase.

The basic design of ventilative cooling of buildings can be accomplished in three separate steps. The first step is the design of the building itself i.e. to minimize and modulate building loads. Poor decisions at this point have a crucial influence on the heat loads and limit the number of the implementable potential ventilative cooling strategies.

The second step involves the climatic design where supplementary strategies to enhance air flow and/or natural cooling strategies to enhance the capacity of ventilative cooling can be considered. Proper decisions at this point can increase the ventilative cooling capacity and decrease or even eliminate the need for mechanical cooling solutions to meet the heat loads identified in the first step.

The third step consists of designing the mechanical cooling equipment to handle the loads that remain from the combined effect of the first and the second step, see Table 10.

Through all steps, expected temperatures at building level and in the most exposed rooms are evaluated continuously by simplified heat balances methods. Moreover, the possibility to provide required air flow rates by natural driving forces is considered (chapter 6). For more complicated building designs and/or if BIM-tools are used in the first design phases, more advanced simulation tools might be used instead. Cost of the design solutions is also evaluated in relation to their ability to reduce cooling loads and energy use.

Design Steps	
Step 1: Passive cooling solutions	Shading, Exterior colours, Insulation, Thermal mass, low energy lighting and equipment, …
Step 2: Air flow enhancing and natural cooling solutions	Solar chimney, air shafts, roof vents, fan, …. Night cooling, evaporative cooling, earth to air heat exchange, …..
Step 3: Mechanical Cooling system	Refrigeration machine, Supplementary water-based cooling in ceiling or floor.

Table 10. Typical design considerations at each basic design step.

The ventilative cooling process depends on the outdoor climate, the microclimate around the building as well as the internal layout of the building, the possible air flow paths through the building and the thermal behaviour of the building. Therefore, it is essential that these factors are taken into consideration in the basic design step. The output from the first step is a building orientation, design and internal layout that minimize the thermal loads on the building in warm periods. Together with the selected ventilation strategy, this make it possible to exploit the dominating driving forces (wind and/or buoyancy) at the specific location and to ensure a proper air distribution through the building. It is also important that issues like night cooling potential, noise and air pollution in the surroundings as well as fire safety and security are taken into consideration.

In the second step the ventilation mode of the ventilative cooling system is designed. In case of a naturally driven system, the location and size of openings in the building, air distribution strategy and air supply devices to reduce the risk of draft and improve cooling efficiency as well as features to enhance the driving forces are designed according to the selected strategy for both day and night-time ventilation. In case of a mechanically driven systems minimization of the pressure loss and reduction of required outdoor air flow rate are essential to decrease the energy use for air transport.

Natural cooling solutions of the outdoor air should also be considered. Appropriate control strategies are determined and decisions are made regarding the level of automatic and/or manual control and user interaction.

In the third step the necessary mechanical cooling systems to remove excess heat and fulfil the comfort requirements are designed. These can range from systems to cool outdoor air intake in warm period to cooling beams or supplementary water-based cooling systems for radiant cooling ceilings or floors.

There are many pitfalls on the way, and the checklists presented as Table 11 and Table 12 may be useful to ignite ideas for use in development of a design.

The investment costs for a design suggestion at this stage should be coarsely estimated to evaluate if the concept is realistic to build or not.

Table 11. Avoid the following when searching for solutions using ventialtive cooling.

÷ Direct solar exposure of occupants
÷ Solar heating of intake air
÷ Negative effects from wind on buoyancy driven air flow
÷ Building design with little thermal mass exposed in intake air flow paths and in rooms
÷ Noise transfer from outside and from other rooms of building
÷ Inefficient room air distribution
÷ Air flow paths which do not allow easy inspection and cleaning

Table 12. Look for the following when searching for good solutions applying ventilative cooling.

✓ Possibility to use outdoor air without filtering
✓ Possibility to use direct airflow from/to outside without a noise problem, a control problem, a burglary, insect and/or rain problem
✓ Use exposed thermal mass in the building structure
✓ Use heat recovery in cold climates and in buildings with relatively low heat loads
✓ Use a large height difference between ventilation intake and exhaust to maximize stack effect and vertical temperature differences
✓ Use overflow between rooms either for supply- or extract side of ventilation
✓ Minimize need for ducting of ventilation air
✓ Minimize airflow rate by air distribution design that can provide low supply air temperatures with risk of draught

4.5. Detailed design phase

In the detailed design phase the developed solution in the basic design phase is further developed and optimized. Information on boundary conditions and design assumptions are updated. Specific ventilative cooling components are selected, their exact size and location is determined. Chapter 6 include the description of method for the detailed design. The integrated function of the ventilative cooling system with building heating and cooling systems is determined including the development of integrated control strategies (chapter 8).

4.6. Design Evaluation

Finally, in the design evaluation phase detailed predictions of thermal comfort and energy use are performed to control if the design fulfils the targets of the project. The detail richness and complexity of design tools and methods increases as the design develops. The level of detail on information as well as expectations on accuracy of prediction results also increases, see chapter 7 for a detailed description of the design evaluation approach.

5. Ventilative Cooling Potential

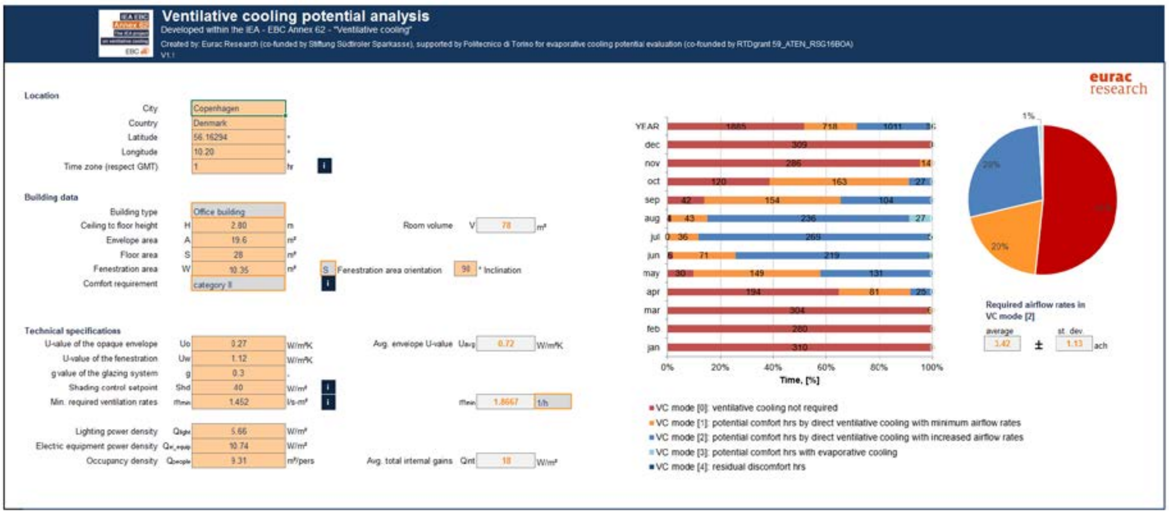
According to its definition (see chapter 1), ventilative cooling is dependent on the availability of suitable external conditions to provide cooling. As buildings with different use patterns, envelope characteristics and internal loads level react differently to the external climate condition, the ventilative cooling potential analysis cannot abstract from building characteristics and use. In an assessment of the potential it is important to limit the evaluation of the cooling potential to the period where cooling is needed. Therefore it is necessary, to look at the outdoor climate as well as the expected cooling need of the building.

In the conceptual design phase, where decisions about application of ventilative cooling are made, it is important to be able to assess the ventilative cooling potential without the need for rigorous analysis.

The ventilative cooling potential tool (VC Tool) was developed within the Annex 62 project. The aim of this VC Tool is to assess the potential effectiveness of ventilative cooling strategies by taking into account building envelope thermal properties, occupancy patterns, internal gains and ventilation needs.

The tool is freely accessible on the IEA EBC website including the user guide and examples to guide users through its use. Figure 10 reports the tool GUI with input and outputs visualization.

It has to be considered only as a preliminary analysis on the assumption that the thermal capacity of the building mass is sufficiently high and therefore does not limit the heat storage process.



Ventilative cooling potential analysis
Developed within the IEA - EBC Annex 62 - "Ventilative cooling"
Created by: Eurac Research (co-funded by Stiftung Südtiroler Sparkasse), supported by Politecnico di Torino for evaporative cooling potential evaluation (co-founded by RTDgrant 59_ATEN_RSG16BOA)
V1.1

Location
City Copenhagen
Country Denmark
Latitude 56.16294 °
Longitude 10.20 °
Time zone (respect GMT) 1 hr

Building data
Building type Office building
Ceiling to floor height H 2.80 m
Envelope area A 19.6 m²
Floor area S 28 m²
Fenestration area W 10.35 m²
Comfort requirement category II
Room volume V 78 m³
S Fenestration area orientation 90 ° Inclination

Technical specifications
U-value of the opaque envelope Uo 0.27 W/m²K
U-value of the fenestration Uw 1.12 W/m²K
g value of the glazing system g 0.3 -
Shading control setpoint Shd 40 W/m²
Min. required ventilation rates ṁmin 1.452 l/s-m²
Lighting power density Qlight 5.66 W/m²
Electric equipment power density Qel_equip 10.74 W/m²
Occupancy density Qpeople 9.31 m²/pers
Avg. envelope U-value Uavg 0.72 W/m²K
ṁmin 1.8667 1/h
Avg. total internal gains Qint 18 W/m²

Required airflow rates in VC mode [2]
average 1.42 ± st. dev 1.13 ach

Figure 10. Tool GUI with input data and output visualization.

5.1. Methodology

The ventilative cooling potential tool refers to the method proposed in [10] and is further developed within the IEA EBC Annex 62 activities.

This method derives from the energy balance of a well-mixed single-zone delimited by heat transfer surfaces. It assumes that a heating balance point outdoor air temperature can be determined below which heating must be provided to maintain indoor air temperatures at a defined internal heating set point temperature. Therefore, when outdoor dry bulb temperature exceeds the heating balance point temperature, direct ventilation is considered useful to maintain indoor conditions within the comfort zone. At or below the heating balance point temperature, ventilative cooling is no longer useful but heat recovery ventilation should be used to meet minimum air change rates for indoor air quality control and reduce heat losses.

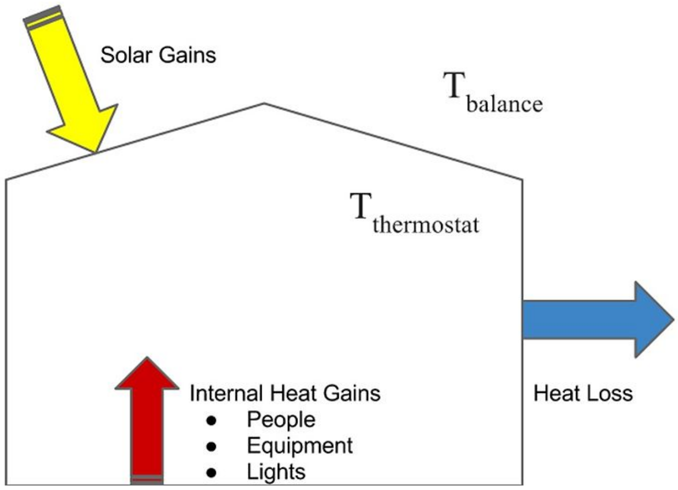


Figure 11. The heating balance point temperature is the outdoor temperature at which heat gains are equal to heat losses.

This relies on the assumption that the accumulation term of the energy balance is negligible. It is a reasonable assumption if either the thermal mass of the zone is negligibly small or the indoor temperature is regulated to be relatively constant. Under these conditions, the energy balance of the zone is steady-state and can provide an approximate measure to characterize the ventilative cooling potential of a climate [11].

5.2. Evaluation criteria

The analysis is based on a single-zone thermal model applied to user-input weather data on hourly basis. For each hour of the annual climatic record of the given location, an algorithm splits the total number of hours when the building is occupied into the following groups:

1) **Ventilative Cooling mode [0]**: when the outdoor temperature is below the heating balance point temperature, no ventilative cooling is required since heating is needed;
2) **Ventilative Cooling mode [1]:** Direct ventilation with airflow rate maintained at the minimum required for indoor air quality can potentially ensure thermal comfort when the outdoor temperature exceeds the balance point temperature, yet it falls below the lower temperature limit of the comfort zone;
3) **Ventilative Cooling mode [2]:** Direct ventilative cooling with increased airflow rate can potentially ensure comfort when the outdoor temperature is within the range of comfort zone temperatures. In this case, the tool calculates the airflow rate required to maintain the indoor air temperature within the comfort zone temperature ranges. Direct ventilative cooling is not considered useful if the temperature difference between indoor and outdoor is below 3 K;
4) **Ventilative Cooling mode [3]:** direct evaporative cooling (DEC) can potentially ensure comfort even if direct ventilation alone is not useful because the outdoor temperature exceeds the upper temperature limit. The evaporative cooling potential is considered when the expected temperature of the treated air is within the upper operative temperature limit minus 3 K. The expected outlet temperature of a DEC system is calculated according to [12, 13]. Moreover, an indirect limitation on DEC potential to prevent too high relative humidity values is also included, fixing a maximum reference for the outdoor wet bulb temperature – see [13] for residential buildings and [14] for offices;
5) **Ventilative Cooling mode [4]:** Direct ventilative cooling is not useful when the outdoor temperature exceeds the upper temperature limit of the comfort zone. Furthermore, this limit is also overtaken from the expected DEC outlet temperature;
6) If direct ventilative cooling is not useful for more than an hour during the occupied time, the night-time climatic cooling potential (NCP) over the following night is evaluated using the method described in [15]. Night-time ventilation is calculated by assuming that the thermal capacity of the building mass is sufficiently high and therefore all the exceeding internal gains can be stored in the building mass. Night-time cooling potential (NCP) over the following night is evaluated as the internal gains that may be offset for a nominal night-time air change rate.

5.3. Examples based on the case studies

As an example, the graph in Figure 12 shows the ventilative cooling potential of the case studies described in chapter 8. Table 13 reports the building characteristics used as input data. Room size is the same in all the cases and it has an area of 18 m², a height of 3 m and an envelope surface of 36 m². Weather data were derived from EnergyPlus weather format files available on the EnergyPlus website (https://energyplus.net/weather). Results look different even for buildings within the same climate because of their different use characteristics.

Renson office building located in Waregem (Belgium) has higher ventilative cooling potential than the Technology Campus in Ghent because of the lower required airflow rates of an office building (1.1 l/s-m²) compared to the one of a school building (4 l/s-m²). The hygienic airflow rates required prevent the building to overheat during heating and shoulder seasons, reducing the cooling need of the building.

The two case study schools in Norway have a lower cooling potential due to the cold climate where the minimum required airflow rate is enough to keep the building cool for more than 75% of the occupied time. On the contrary, the mild climate of Lisbon is particularly suitable for ventilative cooling, having the potential to work for over 70% of the occupied time.

Because of the low internal gains, detached houses have low ventilative cooling potential. In general, ventilative cooling can be exploited for at least 30% of the occupied time over the year.

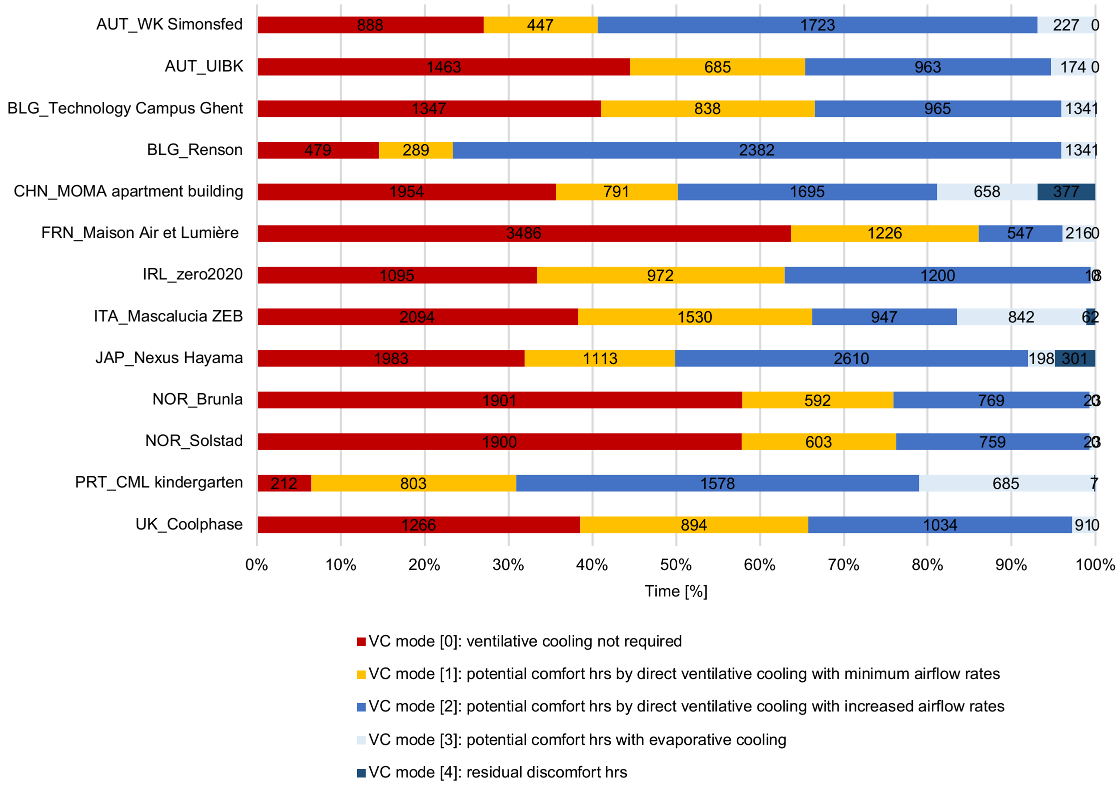


Figure 12. Ventilative cooling potential of the case studies.

Table 13. Overview of case studies features [1].

Case study name			City	Building type	Orientation	Internal gains [W/m^2]	WWR [%]	Window U-value [W/m^{2}K]	Window g-value [-]	U-value of the opaque envelope [W/m^{2}K]	Min. required ventilation rates [l/s-m^2]
01	IE	Zero2020	Cork	School	N	47	56	1.09	0.52	0.09	4.03
02	NO.1	Brunla school	Stavern	School	W	47	10	1	0.68	0.27	4.03
03	NO.2	Solstad Kindergarten	Larvik	School	S	47	8	0.92	0.68	0.18	4.03
04	CN	Wanguo MOMA	Changsha	Apartment	S	6	30	2	0.56	0.54	0.95
05	AT.1	UNI Innsbruck	Innsbruck	School	W	47	38	0.78	0.3	0.15	4.03
06	AT.2	wkSimonsfeld	Ernstbrunn	Office	N	18	22	0.88	0.41	0.15	1.11
07	BE.1	Renson	Waregem	Office	N	18	94	1.3	0.58	0.4	1.11
08	BE.2	KU Leuven	Ghent	School	NW	47	27	0.65	0.52	0.15	4.03
09	FR	Maison air et lumiere	Verrières-le-Buisson	Detached house	S	4	31	1.4	0.3	0.14	0.87
10	IT	Mascalucia ZEB	Catania	Detached house	SE	4	25	1	0.1	0.13	0.87
11	JP.1	Nexus Hayama	Kanagawa	Accommodation	W	13	55	1.6	0.52	0.86	1.34
12	JP.2	GFO	Osaka	Mixed use	N	35	70	1.7	0.33	0.9	1.34
13	PT	CML Kindergarten	Lisbon	School	W	47	18	3.5	0.75	0.59	4.03
14	UK	Bristol University	Bristol	School	W	47	50	1.82	0.43	0.56	4.03
15	NO.3	Living Lab	Trondheim	Detached house	S	-	6.8	0.83	0.52	0.11	4.03

6. Design Calculations and Performance Evaluation

6.1. Performance evaluation

The ultimate objective of the environmental control solution for a building is to ensure satisfactory thermal comfort and indoor air quality for the occupants. In addition to fulfilling these primary objectives, the environmental control solution should be energy-efficient and fulfil economic, safety, acoustic, aesthetic and other objectives. Consequently, the designer needs analytical methods that can assist, evaluate and, where possible, optimize the design of ventilative cooling of buildings. As the environmental and architectural design develops, more data becomes available to the designer, who should select a method with an appropriate level of detail for each stage of the design process.

This chapter describes simulation performance methods applied in the detailed design and the design evaluation phase to assess ventilative cooling strategies combined with other passive and natural technologies. New energy efficient buildings with a good indoor environment require a holistic design approach as the design of different technologies and aspects of the design needs to be coordinated to exploit synergies between design solution and an efficient operation of the building after construction.

Table 14 Characteristics and usefulness of different design methods for ventilative cooling.

	Combined air flow and thermal models
Design phase	Detailed design Evaluation
Purpose	Optimization of building and system performance through combined analysis of air flow rates, temperature conditions and energy use
Available models	TRNSYS, BSim, IES, EnergyPlus, IDA-ICE, ESP-r, Dial+, Other …
Outputs	Hour by hour variation in temperature, air flow rate, IAQ and energy use Optimized control strategy
Necessary equipment /computer	Personal computer/laptop Workstation
User	Researcher/Advanced designer
Required time for application	Depends on complexity of the model, input data
CPU time	< Few minutes

If the building is equipped with a ventilative cooling strategy, then the natural choice should be to use design and simulation tools that combine thermal and airflow models. Only tools with such combination of modelling options allow accurate insight into energy performance versus thermal comfort. Nowadays, there are several software tools that provide such combined functionality. Table 14 shows some examples of the most common tools used, including their key features and characteristics.

As naturally driven ventilative cooling relies on variable natural forces, air flow patterns have to be ensured over a wide range of outdoor and boundary conditions. Bulk airflow models seem to offer a reasonable compromise for evaluation of naturally driven ventilative cooling configurations and control rules in a quick and inexpensive way. Moreover, coupled thermal-airflow models are able to predict airflows within 30% error for single-sided ventilation and for wind driven ventilation, whereas the error of airflow prediction in case of buoyancy driven cross ventilation is less than 10%, [16]. Although the coupling allows considering interactions between airflows and building thermal behaviour, the model is very sensitive to input data related to solar and internal gains [17, 18]. Especially the latter ones are related to user behaviour. During energy design modelling, occupancy and occupant behaviour models as well as change in the control strategies should be performed using multiple scenarios that realistically represent a typical range of possible scenarios. This issue is discussed in chapter 6.2.

For design purposes, it is essential to value model and result credibility. Result credibility depends first of all on model credibility. A model is always a simplification of the reality. This simplification is credible, if the neglected aspects do not risk to affect design decisions. For illustration, the example of how to account for wind effects can the used. Wind affects the mean airflow and temperature sensation due to air movement. It is difficult to quantify the effect of wind on perceived temperature and design considerations remain mostly qualitative. On the other hand, wind has a non-negligible effect on the global mean airflow and as a consequence the extracted heat during day or night. However, wind is uncertain in magnitude and direction and the occupant actions affect its efficiency and limits windborn airflow. A simple approach is to design openings without considering wind effect to evaluate the minimum performance. A building should perform whatever the wind conditions are, and therefore designer would address the most pessimistic case. Another modelling solution is to take only single sided wind effect into account although there is a possibility for cross ventilation. If the model may take into account cross ventilation, it would be cautious to consider two scenarios, with and without cross wind ventilation and have a critical look on the results. However, when considering the controllability of the openings and the risk of having too high air flow rates and to avoid draught risk, it is also important to take scenarios with the most “favourable” wind conditions into consideration, where pressure differences can be quite high and required window areas are therefore at the minimum.

6.1.1. The use and validation of evaluation methods in design

In order to be able to use models properly and get reliable results several issues are important to consider as: specification of relevant boundary conditions, evaluate and justify model simplifications, decide on necessary time discretization, evaluate the risk associated with the use of detailed performance simulation.

The aim of detailed performance simulations is to tune and optimize the building design. For example, oversized ventilation systems will often fulfil design criteria but at a too high investment cost and will not necessarily operate in an optimum manner in relation to energy use, see example calculations presented in Figure 12-14. This is often the main drawback of systems designed based on steady-state assumptions for critical conditions. Moreover, optimum building performance is very often a trade-off between energy use and indoor environmental quality. Another aspect that has to be taken into account is that today’s buildings and technologies used are often operating dynamically and therefore dynamic simulation tools are needed.

Building performance simulation tools are usually significantly more detailed than compliance tools. Contrary to compliance tools, they are in the most of the cases not mandatory, but still are used to predict and gain trust in future building performance.

The aim of dynamic simulations is to receive reliable and trustworthy results. It must be checked if the building/room model is correct, systems are modelled as designed, controls and set-points are as planned and that boundary conditions represent realistically the surrounding environment. The quality assurance (QA) in use of energy and thermal comfort prediction software with respect to ventilative cooling is very similar to the one used for the other technologies/design aspects. Moreover, it would always be an advantage to create a robust design solution, which means that buildings will perform as intended, even if the real boundary conditions deviate from the reference boundary conditions or if the buildings real operation strategy deviate from the simulation assumptions, see more on that in section 6.2. Furthermore, models should be developed and tested gradually, from very simple to more complex. This ensures good quality of the final output and minimizes the risk of failure and errors.

The software features and characteristics should suit the purpose, therefore when selecting software for the task, it needs to be checked:

- If the software is capable to model the processes involved (Mechanical ventilation, natural ventilation: single/cross/stack, hybrid ventilation, etc. It has to be kept in mind that software models are only simplifications of the reality).

- If the software performs the calculation it is meant to do, and if the results sufficiently approximate the realworld performance.

(Software is never bug free, but usually the longer it lives and the more often it is updated, the fewer bugs are experienced. The degree of accuracy of the software is how accurate it is able to mimic the realworld process. Over the last 2-3 decades several validation procedures were developed for that purpose: BESTTEST, BRE/SERC, CIBSE validation for EPBD, several PhD projects, IEA Task 8, BRE/edf validation).

- If software support is available - commercial support, forums, users community.

The results obtained by a software model are only as good as the quality of input data and the expertise of the modeller. The quality of the input data is decisive for the quality of the output. It is crucial to have reliable input parameters such as, for example, pressure coefficients, discharge coefficients, weather data and others. It is also well known that, the model is only as good as the modeller's knowledge of the software. The task of the modeller in the entire modelling process is very significant. The key tasks standing in front of the modeller are: to translate the reality into a simulation model, to select representative input data, to enter the data correctly into the software interface, to make proper interpretation of the results and present them in an understandable way. As presented in Figure 13 the error initially is high and decreases as the level of the detail increases. However, at certain point total error begins to increase again, which is mainly due to modeller error. Therefore, in order to minimize error, it is recommended neither to use model that is too simple nor too detailed.

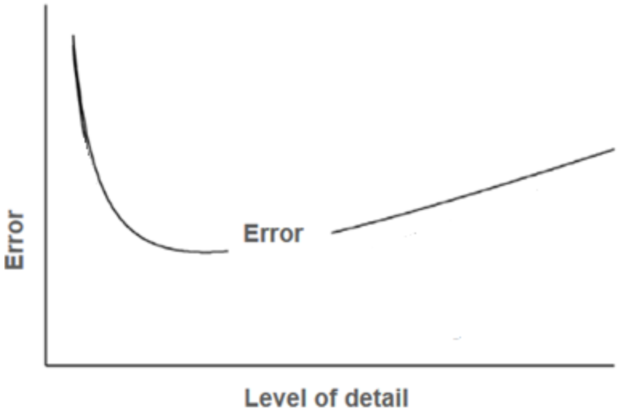


Figure 13. *Illustration of simulation error as the level of the detail increases.*

It is the modeller's responsibility to perform appropriate decisions, for example, simplify complicated geometries, specify boundary conditions, take user behaviour into account, recognize and implement air flow paths in the design, size and place openings in the facade.

At the detailed design stage using combined airflow and thermal models, it is impossible to separate air flow related issues from the rest of the building and its systems. At that stage, model verification has to include all aspects of model creation.

Quality assurance in the use of energy and environmental performance prediction software should as minimum include:

1. Orientation check
2. Geometry visual check
3. Location and weather data
4. Areas and volumes of spaces
5. System types entered as design specification
6. Thermal mass exposure /raised floors/suspended ceilings (as in design)
7. Construction specification, U values and material thermal properties
8. Air flow paths
9. Shading devices, properties and controls
10. Free cooling by air possibilities (natural ventilative cooling)
11. Infiltration and ventilation rates, outdoor air amount and schedules
12. Loads (external and internal heat and moisture gains)
13. Mechanical ventilation system details and controls
14. Heating and cooling systems

The quality assurance check list incorporates a broad range of issues, however, some of them are influencing more the performance of ventilative cooling than others, see Table 15 and Figure 14 in chapter 6.2. The quality assurance check list indicates that to cope with all of the aforementioned aspects of the design one should select a whole building simulation tool that combines thermal – airflow models.

The interaction between airflows and building thermal behaviour is particularly relevant for the evaluation of night cooling performance. However, the convection heat transfer modelling is still often too simplified for accurate prediction of night cooling effects. Furthermore, bulk airflow models do not consider the internal space layout. Internal semi-partitions and furniture may affect the ventilation performance. Designers should consider the impact this may have on limiting cross ventilation and access to thermal mass. On the other hand, furnishing and interior finishes represent additional thermal mass that would contribute to shifting peaks. This is important in buildings with lightweight constructions, but are seldom taken into account.

6.2. Design Strategy

This chapter includes a description of the methods that can be used in the detailed design and design evaluation phase. The aim is to:

1. Estimate required airflow rates and determine typical outdoor design conditions
2. Determine the ventilative cooling strategy

3. Determine possible airflow paths
4. Determine dimensions and position of openings in the envelope
5. Determine airflow rates of the mechanical ventilation system
6. Perform sensibility analysis, optimisation of relevant parameters and risk analysis.

The first four design aims address the ventilation strategy. They follow the typical design sequence of a) determining design conditions and required air flow rates, b) identifying the most appropriate ventilation strategy and possible air flow paths through the buildings and c) Determining the position of opening in the building envelope and calculate typical sizes required under different outdoor conditions during a typical year. In anyway a closed building, which is insulated according to the near zero energy standards, has no dissipative elements and is likely to overheat and the first design aims are to ensure that during summer, a maximum amount of interior heat can be extracted by the ventilation system before the use of mechanical air conditioning.

The last two design aims should verify the impact of the most influencing risk factor for ventilative cooling system performance, which is the solar gains, but also analyse the internal gains, if a variation from standard conditions of use might be expected. This will clarify the need for a mechanical ventilation or supplementary cooling solutions.

In designing a ventilative cooling system, it is very useful to know the impact that the various design parameters have on natural ventilation and cooling performance already in the early design phases. This can be clarified by a sensitivity analysis on key design parameters. Figure 14 shows an example of such analysis performed for two different ventilation strategies in three different climate types. The first strategy is based on night ventilation to reduce cooling needs (Strategy A) and the second strategy on wind driven cross ventilation during the day to improve thermal comfort (Strategy B).

In Strategy A, it is assumed that windows are closed during office hours, and that cooling loads are met using mechanical cooling. Windows and vents open autonomously if the indoor temperature exceeds 26°C, allowing night-time free cooling through the stairwell passive stack. The modelled strategy varies the opening area depending on the inside-outside temperature difference, in order to reduce the possibly large fluctuations in temperature. The stairwell passive stack is modelled as four vertically stacked zones connected to each other through horizontal openings and to the office floors through vents.

In Strategy B, it is assumed that windows are operated during normal office hours by occupants based on their thermal comfort. When windows are in use, ventilative cooling is provided by wind driven cross ventilation. The modelled control strategy is based on EN 12521 adaptive comfort model and allows window opening during the day, if the indoor operative temperature exceeds the adaptive comfort temperature.

Table 15 Input parameter variables

	Description	MIN	MAX
F1	Exterior wall insulation thickness [m]	0.1	0.25
F2	Exterior roof insulation thickness [m]	0.16	0.28
F3	Exterior window U-value [W/m²K]	0.5	1.7
F4	Exterior window Solar Heat Gain Coefficient (SHGC)	0.3	0.9
F5	Exterior wall density [kg/m^2]	230	430
F6	Slab density [kg/m^2]	150	415
F7	Overhang depth [m]	0.3	1.5
F8	Inside reveal depth [m]	0	0.24
F9	People fraction radiant	0.3	0.6
F10	Lights fraction radiant	0.18	0.72
F11	Effective Leakage Area	0.5	2
F12	Window opening factor	0.4	1
F13	Window discharge coefficient	0.3	0.9
F14	Vent discharge coefficient	0.3	0.9
F15	Number of people per Zone	7	16
F16	Lighting Watts per Zone Floor Area [W/m²]	5	20
F17	Electric equipment Watts per Zone Floor Area [W/m²]	5	20
F18	Wind velocity profile: Exponent α, Boundary layer thickness δ [m]	α=0.10 δ=210	α=0.33 δ=460

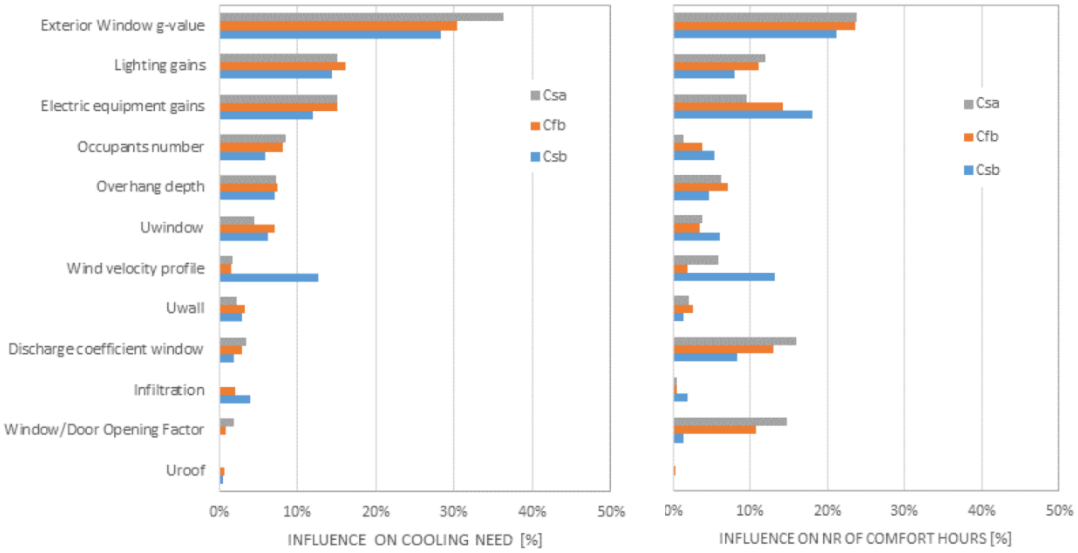


Figure 14. Influence of input parameters on the cooling need of an office building with night ventilation (left) and on the number of comfort hours of an office building with daytime wind driven cross ventilation (right). [18].

In this case, it is assumed that the building is in free-running mode with no mechanical heating or cooling. The sensitivity analysis is performed by varying input parameters equally within the ranges shown in Table 15 below and using three different weather files: Bolzano, Palermo and San Francisco.

The sensitivity analysis quantifies the influence of the factor on the objective (i.e. cooling need or thermal comfort). The graphs show similar trends in all the considered climate conditions and ventilation strategies. The parameters affecting solar and internal gains have a dominant influence on the reduction of cooling need while the window discharge coefficient and opening factor have a notably higher relative impact on the number of comfort hours. Climate type Csb has relative high wind velocities and plenty of driving force leading to less importance of large window openings for ventilation.

6.3. Estimation of air flow rates

The required airflow rate for ventilative cooling can initially be estimated by the VC tool described in chapter 5. The required air flow rate is very dependent on the outdoor temperature as presented in the tool by the different ventilative cooling modes:

Ventilative cooling mode [0]: In this mode, the outdoor temperature is lower than the heat balance point temperature and there is no need for ventilative cooling. The air flow rate is at the minimum value required for indoor air quality reasons. For temperatures decreasing below the heat balance temperature heat recovery and/or heating is required to maintain acceptable comfort temperatures. The typical minimum air flow rate for indoor air quality reasons corresponds to an airchange rate of about $n=0,5\ h^{-1}$ in residences, $n=1\text{-}2h^{-1}$ in offices and $n=2\text{-}4h^{-1}$ in schools and kindergartens.

Ventilative cooling mode [1]: In this mode, the airflow rate is maintained at the minimum required for indoor air quality reasons and even if the outdoor temperature exceeds the heat balance point temperature, this air flow rate can ensure comfortable conditions until the outdoor temperature exceeds the cooling balance point temperature, where the upper limit of the comfort temperature is exceeded in the space.

Ventilative cooling mode [2]: In this mode, the air flow rate is increasing from the minimum value to a maximum value as the outdoor temperature increases to a value close to the indoor comfort limit (2-3 K below). The typical maximum air flow rate to be used in the design of daytime ventilative cooling corresponds to an air change rate of about $n=4\text{-}6h^{-1}$. Air flow rates above this air change rate may induce a high risk of draught for occupants in the building unless special air distribution terminals are used.

Night ventilation mode: During night, where there is no risk of draught, the maximum air flow rate for design of night ventilation should be further increased corresponding to an air change rate of about $n=8\text{-}10h^{-1}$. However, limitations in opening sizes due to safety concerns may lead to lower flow rates that can still be effective. For night ventilation, it is very important to have large air flow rates to quickly cool down the building to ensure an efficient heat transfer between building fabric and room air.

6.4. Selecting relevant outdoor conditions

The necessary opening sizes depend on both the air flow rate required for ventilative cooling and the available driving forces, which are both dependent on the outdoor conditions. The difference in opening size required can be very large and it is often not possible to accommodate this difference in required opening size in just one opening. Therefore, the required opening size needs to be calculated for several different scenarios to be able to decide the optimum configuration of openings and their control.

These scenarios include the following:

Ventilative cooling mode [0]: Calculate opening sizes for the minimum air flow rate and typical weather conditions (outdoor temperature, wind direction and speed) in the heating season.

Ventilative cooling mode [1]: Calculate opening sizes for the minimum air flow rate and typical weather conditions (outdoor temperature, wind direction and speed) in the intermediate season (no heating or cooling need in building)

Ventilative Cooling mode [2]: Calculate opening sizes for the maximum air flow rate at an outdoor temperature 2-3 K below indoor temperature and at typical weather conditions for wind direction and speed. If the wind patterns are not stable and consistent it is advisable to size the openings in a no wind scenario (only buoyancy driving the flow).

Night ventilation mode: Calculate opening sizes for the maximum air flow rate for night ventilation at an outdoor temperature of 3-6 K below indoor temperature. Often wind speeds are quite low during night in the summer period and are not reliable to drive night ventilation.

The opening sizes that are calculated for the different scenarios described above will depend on the selected ventilation strategy and can often be grouped according to the different modes of the ventilative cooling system to define the VC operation modes.

6.5. Selecting the ventilative cooling strategy

The ventilative cooling strategy should be selected according to the building use, the ventilative cooling potential of the location and the building typology.

If there is a mechanical system in the building for indoor air quality (standard airflow rate q_{vs}), the designer has several questions to answer:

- is standard airflow rate q_{vs} sufficient for ventilative cooling during day / night
- is it desirable or necessary to rise q_{vs}? If yes, how much?
- is it desirable to combine hybrid mechanical and natural ventilation?
- is it possible to shift to pure natural ventilation for ventilative cooling?

The answers to these questions depend on qualitative characteristics of the project but also on quantitative results of design simulations. Using performance indicators and depending on the answer to these questions, designers should decide the ventilation strategy.

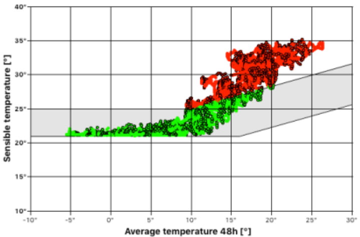
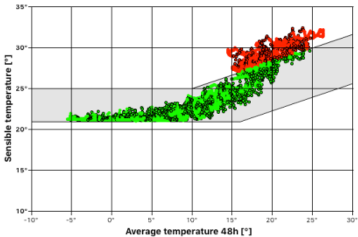
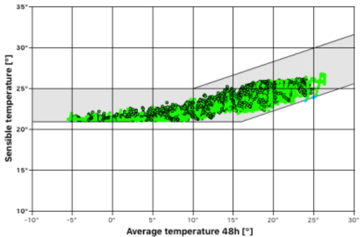
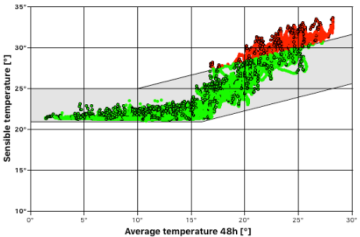
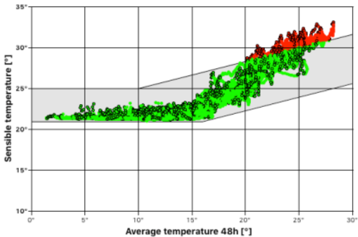
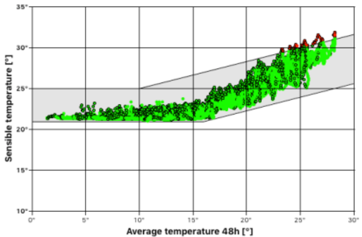
No extra ventilative cooling	Day ventilative cooling	Day/night ventilative cooling
Geneva		
		
Cool 8.2 kWh/m^2, oh 1017h, CRR 0%	Cool 4.8 kWh/m^2, oh 449h, CRR 41%	Cool 1.1 kWh/m^2, oh 0h, CRR 86%
Rome		
		
Cool 10.1 kWh/m^2, oh 532, CRR 0%	Cool 9.2 kWh/m^2, oh 338h, CRR 9%	Cool 6.6 kWh/m^2, oh 42h, CRR 35%

Figure 15. Performance indicators for 3 ventilative cooling strategies for Geneva and Rome: cooling requirements with set point 26°C, overheating hours and cooling requirement reduction.

Figure 15 shows design simulations for the test case office, previously described in chapter 5, for the climatic conditions of Geneva and Rome and for three different ventilation scenarios, using standard mechanical airflow during occupied hours, using day ventilative cooling through the window and using 24h ventilative cooling through the window. Overheating hours in relation to adaptive comfort limits and the cooling requirement reduction (CRR) are used as performance indicators. If the building use required windows to remain closed, we should use the Fanger comfort criterion and only mechanical ventilative cooling strategies.

The results in Figure 15 show that mechanical ventilation with standard airflow to ensure indoor air quality is not sufficient to cool the office (first column, 1017 and 532 hours of overheating). Overheating in Geneva, where the building has a higher degree of envelope insulation, is more severe although the climate is cooler. As shown in the second column, opening the windows during daytime use is still not a sufficient ventilative cooling strategy. Overheating hours are still considerable and CRR shows that the daytime ventilative cooling strategy in Rome does not even reduce the cooling requirements, while in Geneva this cooling strategy may be profitable reducing the cooling requirements by 41%. Figure 15 shows that a day and night ventilative cooling strategy may completely solve the problem in Geneva. For Rome, it may reduce cooling requirements by 35%. This reduction means shorter cooling season with night cooling able to provide comfort. Analysing another system performance indicator, the cooling and heating power of a typical room, confirms this conclusion, see Figure 16.

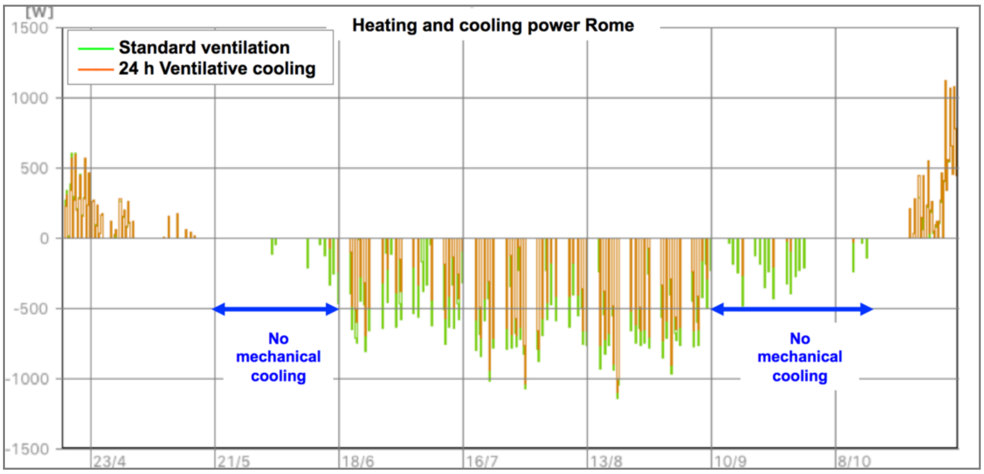


Figure 16 Heating and cooling power shows that with 24h ventilative cooling in Rome the months May, September and October does not need to run mechanical cooling system, while with standard ventilation strategy the room should be air conditioned

This example illustrates a basis on which the ventilative cooling strategy can be selected. In the specific case, it shows night cooling is needed to avoid air conditioning. The final decision whether the ventilative cooling strategy should be natural, mechanical or hybrid should be taken with a trade-off analysis considering the constraints for applying natural ventilation during night and economic analysis for increasing the hygienic ventilation rate to get sufficient cooling effect and the mechanical ventilation energy consumption.

6.6. Determining possible airflow paths for systems driven by natural forces

When considering natural forces to drive ventilative cooling, three critical factors influence the decisions regarding the airflow paths:

- The potential of the building shape for utilization of stack effect and its orientation in relation to the dominant wind direction during day and night.
- The limitations of window opening during day and night and the cost for automation.
- The minimum airflow rate for ventilative cooling.

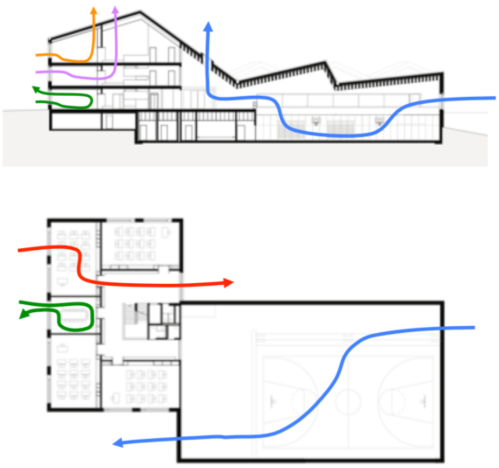


Figure 17 Illustration of possible airflow paths analysing the shape of the test case building.

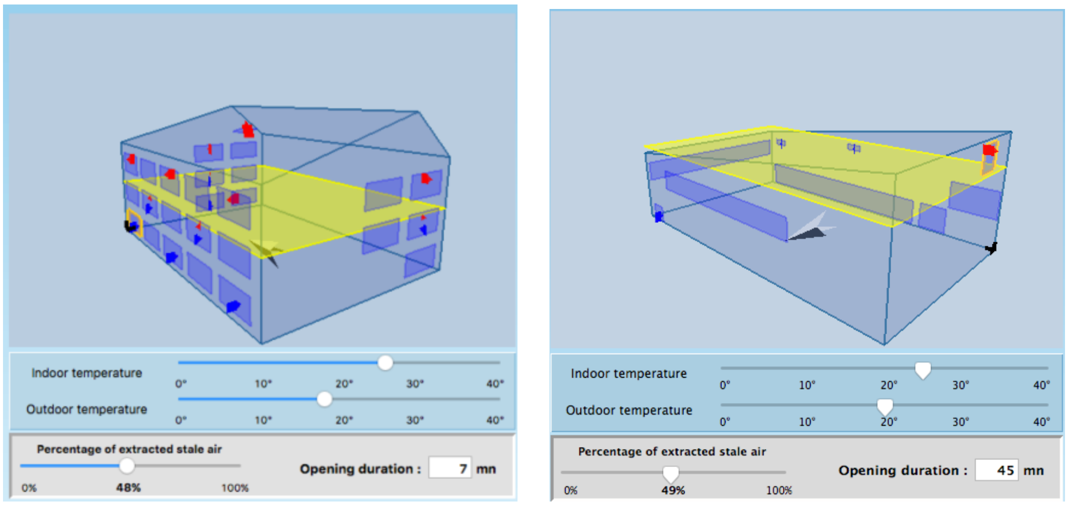
The importance of these factors is described using the test case from chapter 5 as an example. The analysis of possible natural ventilation airflow paths shows many possibilities, see Figure 17. However, these possibilities do not exist on the initial drawings and their creation may have a significant architectural or financial cost. In this building, there are 5 typologies of spaces to ventilate: offices, classrooms, a gym, staircases and landings, and toilets.

Green, purple, red and orange paths show that offices and classrooms may be ventilated in single sided or cross ventilation mode. The gym may function in single sided or cross ventilation. According to national fire regulations, cross ventilation mode may create serious problems to solve. Staircases and fire exit emergency corridors should be separated from the other spaces, called "fire compartments" with fire resistant walls and doors or openings that should always remain closed or equipped with an automatic closing mechanism in case of fire detection. This might increase the complexity of the project and increase the cost. When single sided ventilation is sufficient, it is preferable to count only on this in order to avoid passing from one fire compartment to another, implying automation of interior fire resistant openings. In general, fire evacuation ways (horizontal and vertical) are always a separate fire compartment, and this is a very strong constraint to cross ventilation, horizontal or vertical. In this case, single sided ventilation or mechanical ventilation for offices and classroom spaces would be the least expensive option, if it could ensure the necessary air flow rate.

On the other hand, fire regulations for smoke evacuation may also be a chance for applying natural forces for ventilative cooling. According to national regulations the gym and staircase should have a top and bottom opening representing 1% of the total floor surface area each. A preliminary simulation showed that these openings would be sufficient to provide the necessary air flow rates.

The pressure level in the building is crucial for the possible air flow paths. The neutral plane level of the building is a useful parameter to use, when determining the airflow path. Under the neutral plane level fresh air enters in the building, while the same amount of hot air is exhausted from the openings situated over the neutral plane level. In a building, where opening areas are evenly distributed, the neutral plane level is situated in the middle of the building. Figure 18 shows its position and the airflow direction in each opening for the two volumes of the test case building. In the main school building (left figure) the neutral plane level is situated higher than the middle of the building between storey 1 and 2. The relatively larger area of the roof window results in a higher neutral plane level, but not enough to ensure fresh air entering windows at the top storey. If the users of the top storey open their interior doors, they will not have fresh air entering from the windows but hot air from the staircase through the door opening that will be exhausted from the windows. This result obliges the designer either to make the roof window much bigger, to create a kind of chimney positioning the exhaust opening higher, or to dissociate the ventilation of the top storey from the air path of the rest of the building, ventilating it by single sided or stand-alone cross ventilation with air path not passing from the staircase. For the gym volume on the right of the figure, a big opening positioned on the top the building, brings the neutral level very high, making every opening under it a fresh air opening.

If the designer does not have access to software able to position the neutral plane level, it might be difficult to calculate it, because it often needs an iterative simulation, see following section.



48%

Opening duration : 7 mn

49%

Opening duration : 45 mn

Figure 18 Simulations of the two test case volumes with DIAL+ to evaluate the position of the neutral pressure level and the airflow rate of windows under it with income air and over it with exhaust air (when Ti>Te).

6.7. Dimensions and positions of windows for natural driving forces.

The calculation of opening sizes depends on the natural ventilation strategy selected.

These include:

Single-sided ventilation: In this strategy, the air flow is driven by both buoyancy and wind forces and is provided through a single opening or through multiple openings on the same façade. The driving forces and the air flow capacity is limited, so this strategy is most useful for smaller rooms with a relatively low cooling demand. The driving forces and the air flow rate can be enhanced by having openings at different levels in the room or by opening design to “catch” the wind driven air flow along the façade.

Stack ventilation: In this strategy, the air flow rate is driven by buoyancy forces and is provided by inlet openings in the façade and outlet openings in the roof. For multi-storey buildings, internal air flow from inlet to outlet is typically provided through stacks, light shafts or atriums. The driving forces are small, typically below 1-6 Pa, even for large temperature differences. The strategy is most useful for multi-storey building, where large height differences between inlet and outlet openings can be established. In tall and large rooms stack ventilation can significantly enhance the ventilative cooling capability of single sided ventilation. The driving forces can be enhanced by chimneys with outlet above roof height and solar chimneys.

Cross ventilation: In this strategy, the air flow rate is driven by wind forces and is provided by openings in two or more façades facing different directions and/or outlet openings in the roof. Possible internal air flows between different facades in required and/or through stacks, light shafts or atriums to roof outlets. The driving forces vary considerably from a few Pa at low wind speeds to more than 100 Pa at high wind speeds, which leads to the need for openings of very different sizes. The strategy is most useful for wind exposed buildings and for low rise buildings. In this strategy, draught control should be a major design concern.

In practical system operation, a combination of different strategies will typically be applied and it is important that for systems driven by both buoyancy and wind that the opening configuration always ensures that the wind forces assist the buoyancy forces (working together).

The proportional of maximum net openable area of natural ventilation system as a function of the floor area (POF) was considered to be a key metric when initially sizing natural ventilation systems in buildings. Typically, this value is around a POF of 5%. However, as different climates have different cooling requirements for natural ventilation and some national guidelines may focus on the need to provide cooling in the summer or night ventilation this value can vary. Table 16 highlights the potential range of POF that have been applied in the case study buildings, for more detail on this see chapter 8.

Table 16: POF values for three case study buildings

Building name			Climate	POF (%)
01	IE	Zero2020	Cfb	2.3
06	AT.2	wkSimonsfeld	Cfb	7.9
10	IT	Mascalucia ZEB	Csa	14.7

Table 16 indicates that the maximum net opening area can vary depending on the location in the range of 2.3 – 14.7%. This range could be as a result of the cooling potential of the climates involved. In Ireland, there is a large potential for both day-time and night-time cooling. In continental Europe, this value can be much higher perhaps as a response to the need for night ventilation. While in warmer European climates this value needs to be much higher to prevent overheating.

In the following, methodologies to calculate opening sizes for ventilative cooling driven by natural forces are presented. The methodologies are different from those that can be found in EN1698-7, as the objective in design is not only to ensure that opening areas are large enough for the critical situation, but also to ensure a suitable area variability for improved air flow control during operation.

6.7.1. Calculation of opening sizes for single sided ventilation

For single sided ventilation driven by thermal buoyancy the air flow as function of opening size can be calculated from:

$$q = \frac{1}{3}A\sqrt{\frac{g(T_i - T_u)(H_t - H_b)}{T_i}}$$ Equation 8

where *q* is the total air flow rate through the opening [m^3/s]; A is the effective opening area calculated as the geometrical opening area multiplied by the discharge coefficient, $A_{geo}C_d$ [m^2]; C_d is the discharge coefficient for the opening. For windows typically 0,6-0,7 [-]; H_t is the height of the top of the opening above the floor [m]; H_b is the height of the bottom of the opening above the floor [m]; *g* is gravitational acceleration [m/s^2]; T_u is external temperature [K]; T_i is internal temperature [K]

For single sided ventilation driven by a combination of thermal buoyancy and wind the air flow as function of opening size can be calculated from:

$$q = \frac{A}{2}\sqrt{0.001v_{ref}^2 + 0.0035(H_t - H_b)(T_i - T_u) + 0.01}$$ Equation 9

where v_{ref} is wind speed at a reference height (building height) [m/s]

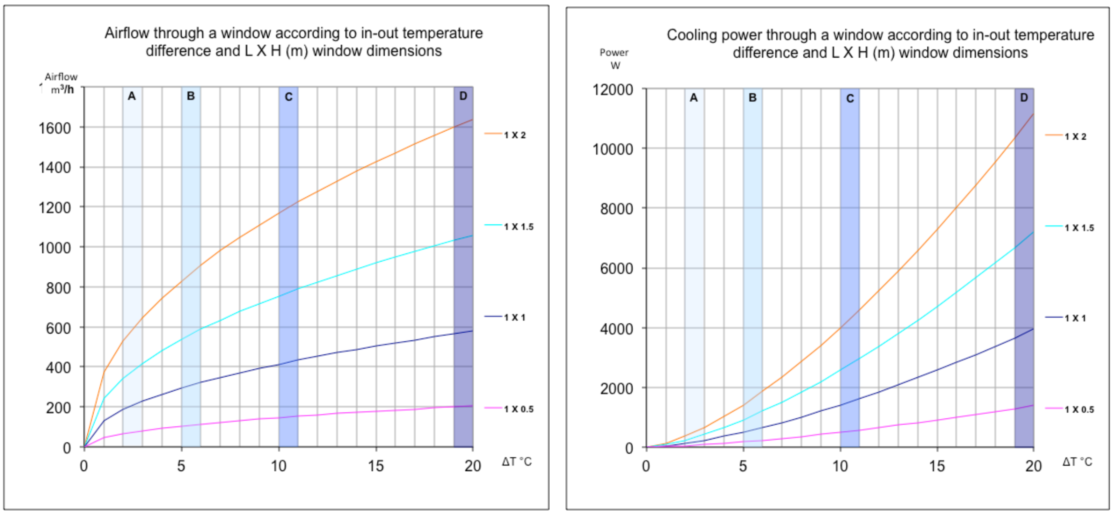
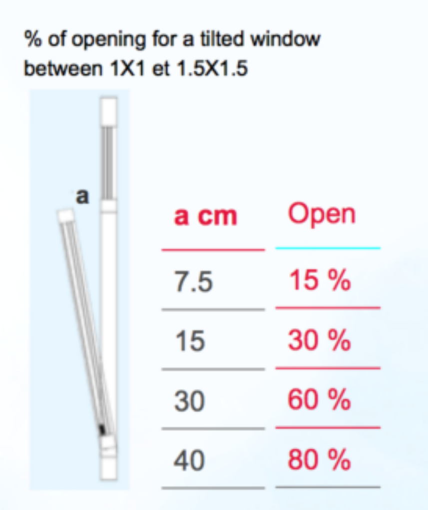


Figure 19. Airflow rate and cooling power of a window opening of different dimentions according to ΔT.

For single sided ventilation Figure 19 shows the airflow and cooling power of a window of four different L X H ratios. The values correspond to a completely open window without any obstacle (discharge coefficient is 0.63). For a partial opening, or for an obstacle of a certain additional discharge coefficient, the corresponding reduction ratio must be applied to the values calculated with an opening of 1m width. For different heights than those considered for each curve, an interpolation is needed because airflow and cooling power are not linear to window height. For two openings on the same height the airflow rate can be added. On Figure 19, it can be seen that an opening of 1 x 0.5 provides an air flow of 114 m^3/h at 6°C ΔT and a cooling power of 232 W while the same opening area turned 90° clockwise - 0.5 x 1 – gives an air flow rate of 160 m^3/h and a cooling power 328 W (+40%) (use the 1x1 curve and divide by 2). This illustrates and quantifies the advantage of narrow high openings compared to wide and low ones.

The calculation of the cooling power assumed that the air leaves the room at room air temperature. As the room is cooled down as a function of time, both the room air temperature and the airflow rate will be reduced and, as a consequence, also the cooling power. The cooling power will typically be reduced by 30-60% compared to the initial depending on the air change rate (most for large air change rates), [19,20].

For tilted windows, calculation is more complicated and must take into account the two lateral vertical triangles and the top rectangular opening W x a, where W is the window width and a the window opening. A first order of window area fraction as a percentage of W according to the opening a (in cm) is given in the Figure, corresponding for windows dimensions ranging from 1x1 - 1.5x1.5 to 2% per cm opening. A 10 cm opening correspond to 20% opening of the total or an additional discharge coefficient of 0.2.



% of opening for a tilted window between 1X1 et 1.5X1.5

a cm	Open
7.5	15 %
15	30 %
30	60 %
40	80 %

Figure 20. Percentage of opening according to the tilted opening a (in cm).

Evaluation of the window airflow rate at a certain temperature gives a first indication, if the opening dimensions are sufficient. But in the end, it depends on the climate and the ventilative cooling strategy. The most appropriate indicator to dimension the window opening area is the comfort indicator. Figure 21 shows in terms of comfort what was calculated in Figure 19 in terms of airflow rate. A one square meter window with dimensions WxH = 0.6 x 1.6 m with a tilted opening of 25% gives an air flow rate of approximately 80 m^3/h of at 5°C indoor-outdoor temperature difference according to Figure 19, while a wide and low window of the same surface area (dimensions WxH = 4 x 0.25 m) gives an air flow rate of approximately 40 m^3/h. The carpet diagram in Figure 21 shows that between July and August 61 hours are outside the comfort range when using the wide and low window opening. The combination of a carpet diagram with a comfort diagram gives a more spherical image of the thermal comfort. On the comfort diagram, the slope of the interior temperature according to the outside mean temperature can be found as well as any temperatures outside the comfort region. The comfort diagram is more synthetic and it is easy to compare two different strategies and easy to determine immediately if the room provides comfort or not. The carpet diagram gives more detailed information on when discomfort occurs. The second diagram shows that discomfort occurs in July - August, sometimes in late June and rather in the afternoon with peak discomfort hours around 16h.

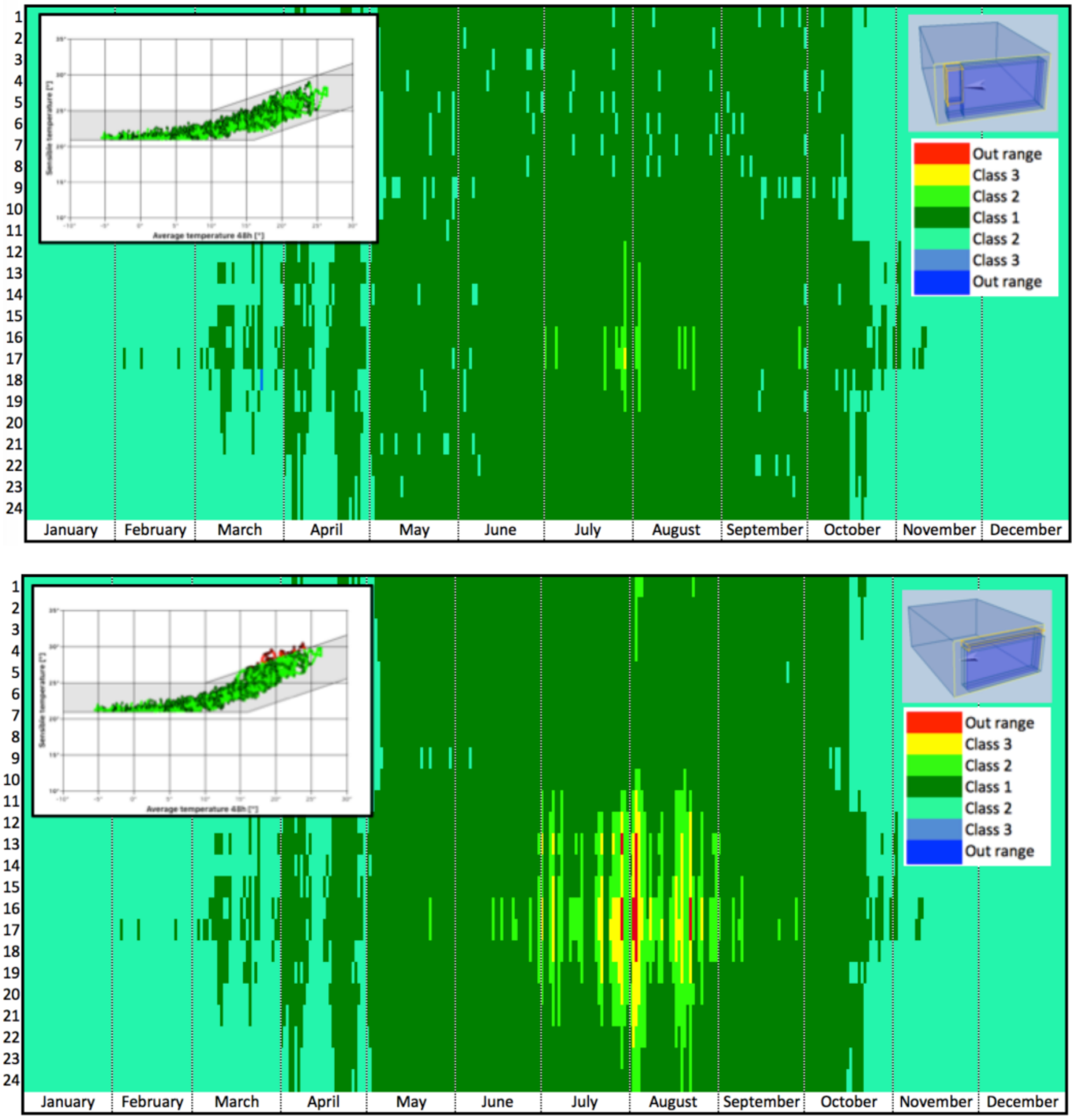


Figure 21 Two carpet and adaptive comfort diagrams showing the difference of thermal behaviour of a 1 m2 narrow and high window (0.6 x 1.6) on the top and wide and low window of the same surface area (4 x 0.25) on the bottom. The first window provides comfort with a night cooling strategy in Geneva climate, while the second presents 61 hours of overheating, outside of the class 2 adaptive comfort range.

The required window size depends not only on the climate, but also on other key design parameters like the control strategy and the solar and internal gains. Figure 22 shows that only daytime ventilation is not sufficient to provide comfort in the test office in Geneva climatic conditions although there is a perfect solar control. The 449 overheating hours occur between June and mid-September. On the carpet diagram, it is seen that during night the accumulated heat cannot be evacuated by the heat losses without a night ventilative cooling strategy. In the morning, most of the period, until 11 O'clock when the occupants open the window, there is comfort but during some days of the hot period in July - August, when there is not enough temperature difference, comfort cannot be provided event during the morning opening of the windows.

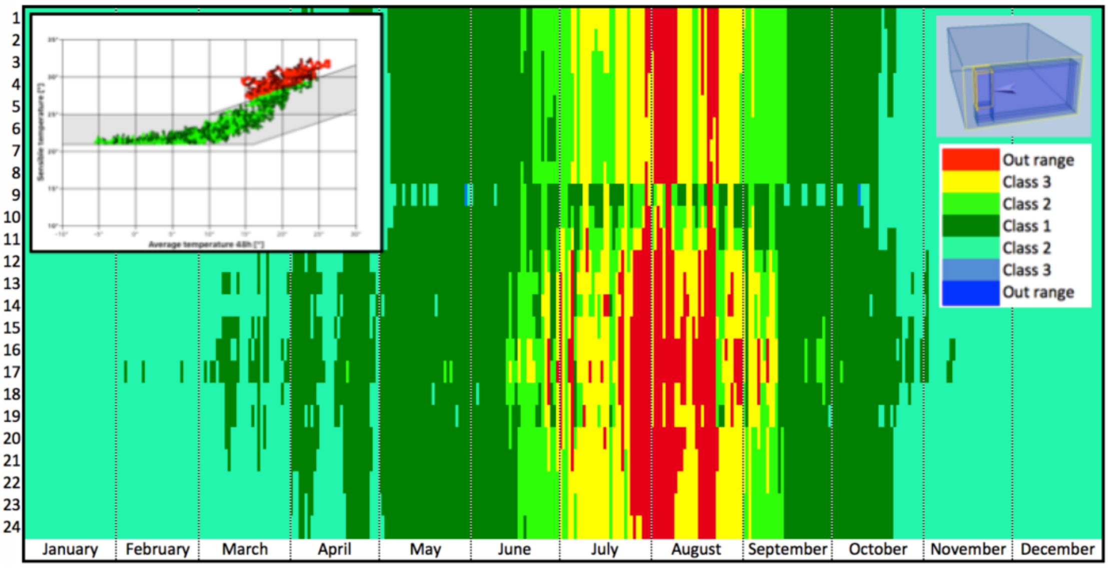


Figure 22 Carpet and comfort diagram of the test office with vertical 1 m2 window without night cooling strategy. In the combination of the two diagrams we can see when the 449 overheating hours occur.

6.7.2. Calculation of opening sizes for stack ventilation

For a zone with two openings the air flow rate as function of opening size can be calculated from:

$$q_v = C_d A^* \sqrt{\frac{2gh(T_i - T_o)}{T_o}} \qquad \text{Equation 10}$$

$$A^* = \frac{A_T \cdot A_B}{\sqrt{A_T^2 + A_B^2}} \qquad \text{Equation 11}$$

where q_v is the air flow rate [m^3/s]; A^* is the effective opening area [m^2]; A_T is the area of the top opening [m^2]; A_B is the area of the bottom opening [m^2]; g is the gravitational acceleration [m/s^2]; T_i is the inside temperature [K]; T_o is the outside temperature [K]; h is the vertical distance between the two openings [m]; C_d is the discharge coefficient of the openings.

The location of the neutral plan level can be calculated from:

$$H_0 = \frac{(C_{d,1}A_1)^2 H_1 + (C_{d,2}A_2)^2 H_2}{(C_{d,1}A_1)^2 + (C_{d,2}A_2)^2} \qquad \text{Equation 12}$$

where H_0, H_1 and H_2 is the height above a reference level of the neutral plane, the lower and the upper opening respectively [m]; A_1 and A_2 is the effective opening area of the lower and the upper opening respectively [m^2]; $C_{d,1}$ and $C_{d,2}$, is the discharge coefficients of the lower and the upper opening respectively [-].

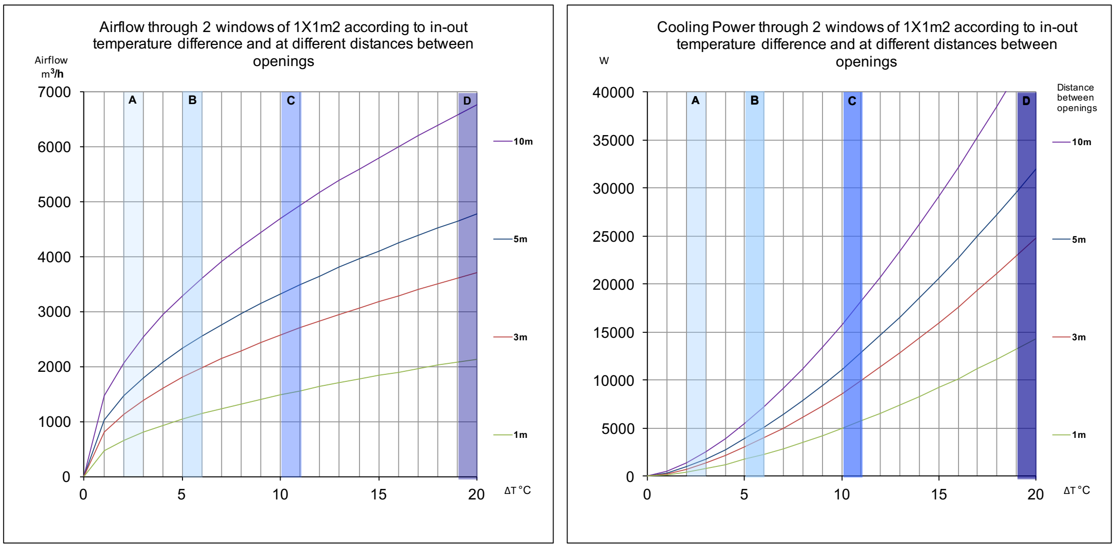


Figure 23 . Airflow rate and cooling power of two openings of 1 m^2 each in stack ventilation with different distances between the openings according to ΔT.

For stack ventilation with two window openings of the same size (1 m^2) Figure 23 shows the airflow and cooling power for different distances between the openings. For other opening areas, results can be found by multiplying by the actual opening area.

For a zone with multiple openings the air flow rate as function of opening size can be calculated by the zone mass balance:

$$\sum_{j=1}^{n} C_{d,j} A_j \rho_j \left(\frac{\left|\Delta p_j\right|}{\tfrac{1}{2}\rho_j}\right)^{\tfrac{1}{2}} \frac{\Delta p_j}{\left|\Delta p_j\right|} = 0$$

Equation 13

where n is the number of openings; Δp_j is the pressure difference across opening j [Pa]; ρ_j is the air density of the air flowing through the opening [kg/m^3]; A_j is the area of opening j [m^2]; $C_{d,j}$ is the discharge coefficient of opening j [-].

The pressure difference, Δp_j, across each opening is calculated from:

$$\Delta p_1 = \rho_u g (H_o - H_1) \frac{T_i - T_u}{T_i}$$

Equation 14

where Δp_j is the pressure difference across opening j [Pa]; ρ_j is the air density of the air flowing through the opening [kg/m^3]; g is the gravitational acceleration (m/s^2); T_u is external temperature [K]; T_i is internal temperature [K]; H_j is height of opening j (m); H_0 is height of the neutral plane [m].

The height of the neutral plane, H_o, is the unknown parameter that can be found by solving the mass balance equation by iteration. By multi-parameter iteration both the height of the neutral and openings area of individual openings can be calculated.

6.7.3. Calculation of opening sizes for cross ventilation

For a zone with two openings the air flow rate as function of opening size can be calculated from:

$$Q_1 = C_{d1} A_1 \sqrt{\frac{\left|C_{p1}\rho_u v_{ref}^2 - 2P_i\right|}{\rho_u}} \qquad \text{Equation 15}$$

where Q_1 is the air flow rate [m^3/s]; A_1 is the effective opening area [m^2]; C_{d1} is the discharge coefficient [-]; C_{p1} the wind pressure coefficient [-]; ρ_u is the outdoor air density [kg/m^3]; v_{ref} is the wind speed in the reference height (normally building height) [m/s]; P_i is the internal pressure [Pa].

The internal pressure level can be calculated from:

$$p_i = \tfrac{1}{2}\rho_u v_{ref}^2 \frac{C_{p,1}\left(C_{d,1}A_1\right)^2 + C_{p,2}\left(C_{d,2}A_2\right)^2}{\left(C_{d,1}A_1\right)^2 + \left(C_{d,2}A_2\right)^2} \qquad \text{Equation 16}$$

where A_1 and A_2 is the effective opening area of the wind and the leeward opening respectively [m^2]; $C_{d,1}$ and $C_{d,2}$, is the discharge coefficients of the wind and the leeward opening respectively [-];$C_{p,1}$ and $C_{p,2}$, is the pressure coefficients of the wind and the leeward opening respectively [-].

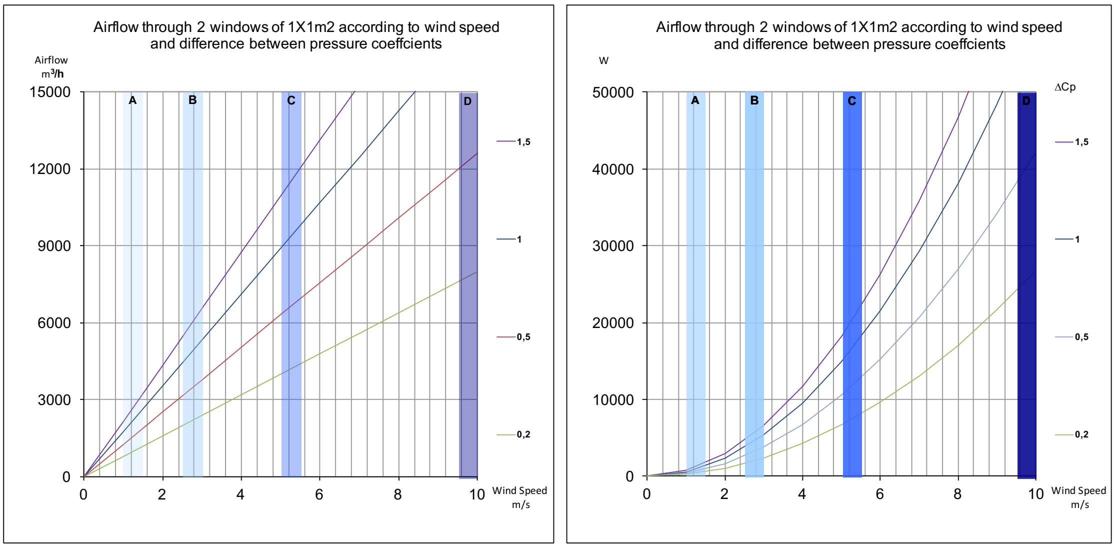


Figure 24 . Airflow rate and cooling power of two window openings for different wind pressure coefficients as a function of vind speed.

For cross ventilation with two window openings of the same size (1 m2) Figure 24 shows the airflow and cooling power for different pressure differences between the openings as a function of wind speed. For other opening areas results can be found by multiplying by the opening area.

For a zone with multiple openings the air flow rate as function of opening size can be calculated by the zone mass balance, see Equation 13. The pressure difference, Δp_j, across each opening is calculated from:

$$\Delta p_j = p_{v,j} - p_i = \tfrac{1}{2} C_{p,j} \rho_u v_{ref}^2 - p_i \qquad \text{Equation 17}$$

where Δp_j is the pressure difference across opening j [Pa]; $C_{p,j}$ is the wind pressure coefficient on the opening [-]; ρ_u is the outdoor air density [kg/m^3]; v_{ref} is the wind speed in the reference height (normally building height) [m/s]; p_i is the internal pressure [Pa].

The internal pressure, p_i, is the unknown parameter that can be found by solving the mass balance equation by iteration. By multi-parameter iteration both the internal pressure and openings area of individual openings can be calculated.

6.8. Airflow rate, control strategy and energy use for mechanical systems.

For mechanical ventilation, the first question to answer is whether the standard ventilation rate, q_{vs}, for hygienic reasons is sufficient for ventilative cooling. As mentioned before, the typical minimum air flow rate for indoor air quality reasons corresponds to an air change rate of about n=0,5 h^{-1} in residences, n=1-2h^{-1} in offices and n=2-4h^{-1} in schools, kindergartens and meeting rooms. In the last room category, existing mechanical ventilation may be sufficient to extract heat during night or during fresh summer days. If it is not sufficient, it is important to decide if it is pertinent to oversize the ventilation system. In general, an oversizing up to 2 times the standard ventilation rate can be acceptable. Space considerations and extra cost are parameters that may affect this decision.

The first simulation to perform is to evaluate the cooling effect of the standard ventilation rate. The key energy performance indicator CRR provides additional information to the comfort indicator. The questions to answer with dynamic simulation and performance indicators are the following:

- Is q_{vs} sufficient for summer comfort?
- What should be the value of time and temperature set-point parameters?
- Is ventilative cooling preferable to conventional air-conditioning?

The sufficiency of q_{vs} can be tested with similar analysis as for window dimensions.

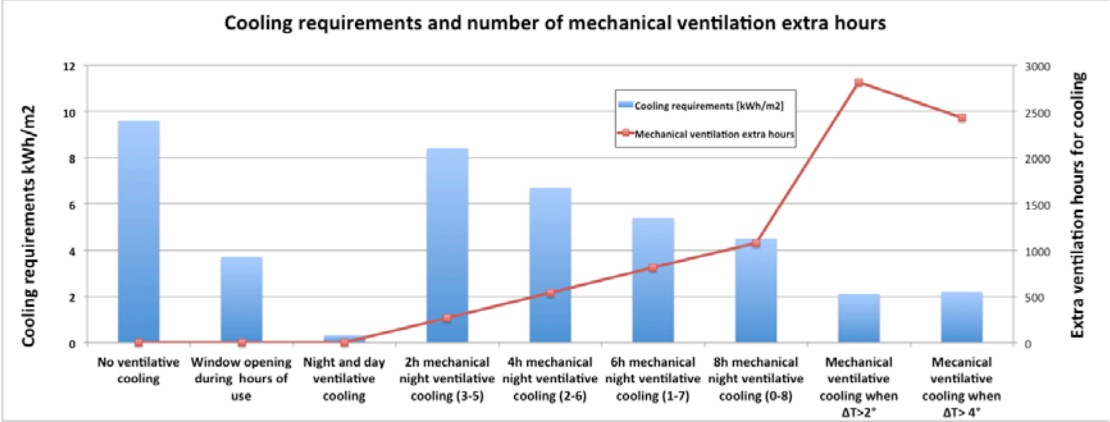


Figure 25: Cooling requirements and extra mechanical ventilation hours for ventilative cooling strategies for the test case climate in Switzerland (typical Central Europe climate) and a hygienic airflow rate of 2.6 m^3/m^2h corresponding to about $1h^{-1}$.

An example of such calculations is provided in Figure 25, where it is shown that the only really free cooling is the naturally driven ventilative cooling with no extra ventilation hours required. Ventilating only with hygienic airflow rate (first scenario with no ventilative cooling), does not provide sufficient comfort, and opening windows during hours of use, although it reduces cooling requirements, does not have a too significant impact on the demand. The only scenarios, where the cooling requirements are reduced by more than 60%, are the ones where night ventilative cooling was used. If mechanical ventilation is utilised, this comes at a cost, since extra ventilation hours and in the case a higher ventilation airflow rate are required, resulting in extra energy use. As presented in Figure 26, the intuitive ventilative cooling strategies that are very commonly used, are activating ventilation, when the outside temperature is lower than 2° or 4°C implying extra ventilation hours of more than 2000 hours. For more southern climates, these hours may reach 3000 hours. A simple calculation of the energy consumption with so many additional ventilation hours reveals a serious problem with energy use for the fan operation. There is an optimum to find between the ventilative cooling energy consumption and the extracted heat that reduce the cooling requirements to be covered by a conventional air conditioner. Performing a dynamic simulation to evaluate the cooling requirements reduction for each possible scenario and the calculation of mechanical ventilative cooling SEER are used to identify the best strategy that compromises between the cooling effect and the energy use. These indicators allow a comparison of the ventilative cooling energy performance with the performance of a conventional air conditioning system.

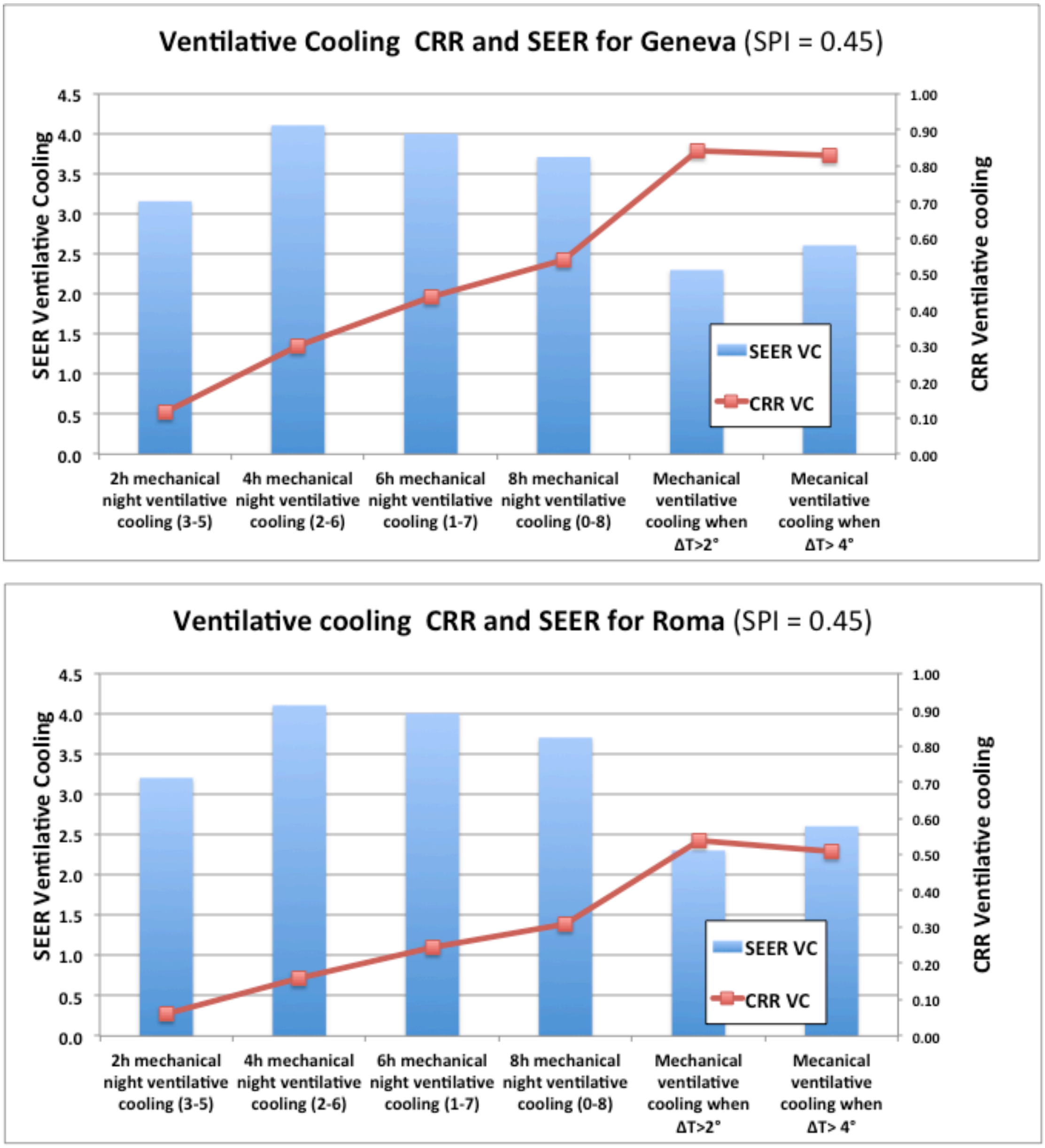


Figure 26: Mechanical ventilative cooling $SEER_{VC}$ of a ventilation system providing 2.6 m^3/m^2h of airflow with a Specific Power Input SPI of the system of 0.45 $W/(m^3/h)$ with blue bars on the left vertical axis, and Cooling Requirement Reduction ratio CRR_{VC} with red points on the right vertical axis. Although ventilative cooling for Geneva is more efficient with higher CRR_{VC}, the SEER is poor, <4 for the two climates. A continuous ventilative cooling without time limit show very poor $SEER_{VC}$ between 2.2 and 2.6.

The optimal time schedule and ventilation rate of mechanical ventilative cooling depends on the characteristics of the AHU As seen on Figure 26, a good dual flow ventilation system with SPI 0.45 $W/(m^3/h)$ offer a $SEER_{VC}$ between 2.2 and 4. A simple extraction systems with a lower pressure drop and a single ventilator would present a better $SEER_{VC}$.

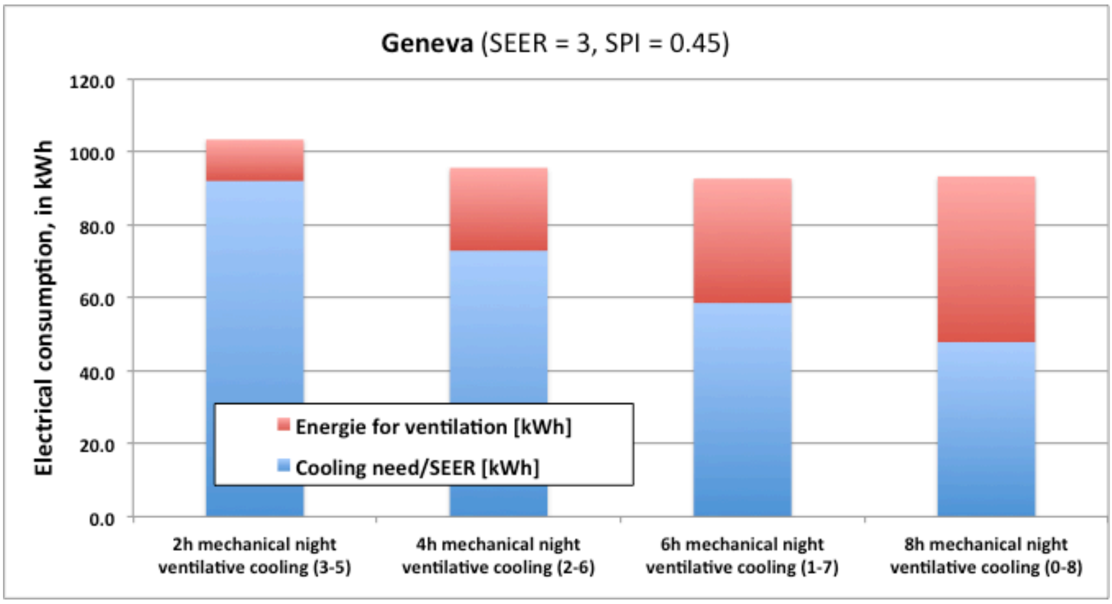


Figure 27: Total electrical consumption of a hybrid cooling system with air conditioning SEER 3 and a ventilation system SPI 0.45 W/(m^3/m^2) at different time schedules. Optimum energy consumption is situated at 6 hours duration mechanical cooling at the most cool hours of the night.

Analysis of these simulation results lead to an optimum of 6 hours ventilative cooling centred at 4:00 am when the outdoor air temperature is the lowest. This implies approximately 800 hours of night ventilative cooling in the period from mid-April to mid-October. This optimum is the same for all the climates with a significant night cooling potential.

Finding the best airflow rate for the ventilative cooling system depends on three parameters: the need for cooling requirement reduction, the energy use of the ventilation system and the air conditioning system SEER and cost. In climates where the cooling system can be avoided, designers may accept lower $SEER_{VC}$. When an air conditioning system is present in the building, ventilative cooling will be preferred, if its energy performance is better than the performance of the air conditioning system. When a balanced ventilation system is present, the $SEER_{VC}$ can be quite low (2.2-4), but when extraction systems with low pressure losses are utilised, a more extensive use of ventilative cooling may be attractive, since the $SEER_{VC}$ can be of the order of 5 -10.

The ADV_{VC} indicator helps to justify the outcome of the comparison between air conditioning and ventilative cooling. ADV_{VC} may also be the indicator shifting a hybrid cooling system to ventilative cooling or air conditioning.

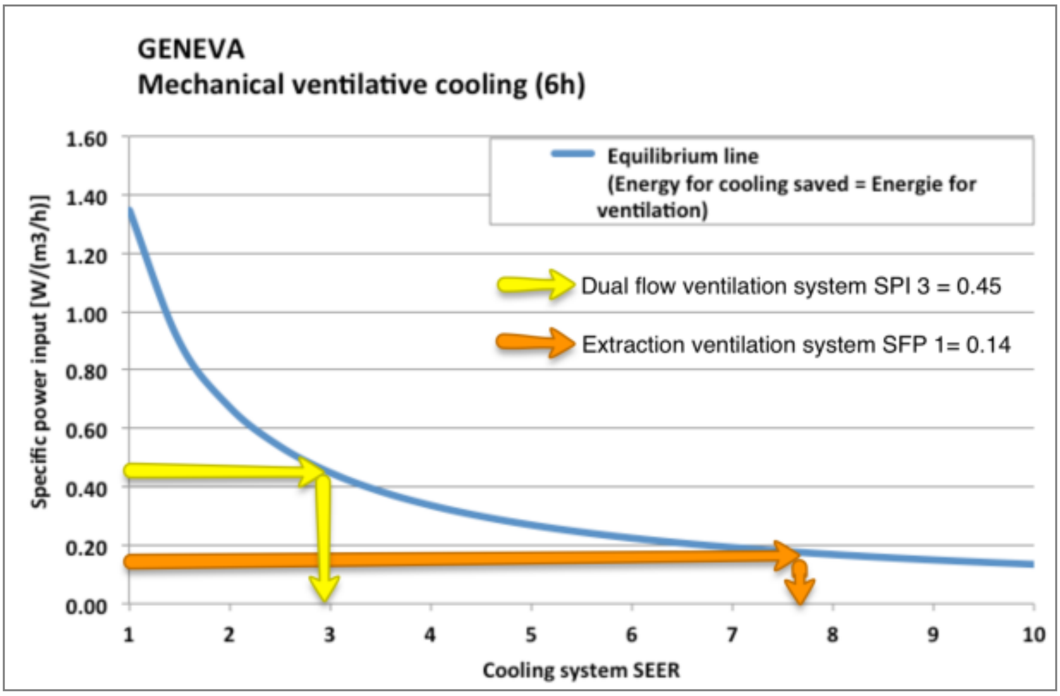
Two cities are considered in the following example, Geneva and Rome. It is assumed that the building has a cooling system with SEER=3 and a ventilation system with SPI=0.45 W/(m^3/h). In the reference scenario the entire cooling requirement is provided by mechanical cooling with a SEER=3. In the second scenario, mechanical ventilative cooling is limited only from 01:00 to 07:00 by doubling the hygienic ventilation flow rate 2.6 x 2 = 5.2 $m^3/h\ m^2$ and for the third scenario mechanical ventilative cooling is switched on whenever ΔT>4°C without time limitation.

Table 17: $SEER_{VC}$ and ADV_{VC} for Geneva and Rome

		Geneva							Roma					
		Cool. R. kWh	Cool. Energy	Ventil. Energy	Total Energy	$SEER_{VC}$	ADV_{VC}		Cool. R. kWh	Cool. Energy	Ventil. Energy	Total Energy	$SEER_{VC}$	ADV_{VC}
1. Reference		292	97	0	97				351	117	0	117		
2. Mech. 6h VC		90	30	67	97	3.01	1.0		244	81	67	148	1.60	0.53
3. Mech. ΔT> 4°		36	12	112	124	2.29	0.8		222	74	78	152	1.65	0.55

In scenario 3, ventilative cooling runs 1349 hours in Geneva and 940 hours in Rome. A reduction of the ventilative cooling hours can be seen for higher ventilation flow rate compared to the graphs on Figure 26. Increasing the flow rate and reducing the ventilative cooling hours, optimisation is not intuitive. It can be seen from the results that $SEER_{VC}$ are poor and in the most cases ADV_{VC} is lower than 1, compared to a conventional system of SEER=3. When there are no time limitations (as in scenario 3), the ventilation energy use is higher than for the scenario 2, with direct consequence of even lower $SEER_{VC}$. For Geneva ADV_{VC} is very near to 1 for the optimum case, meaning that ventilative cooling with a balanced ventilation system spends at least as much energy as an air-conditioning system of SEER = 3.

This analysis example shows that the optimum time for ventilative cooling when reduction of the hours of use is needed, is at 04:00 am in all climatic conditions. The optimum mechanical ventilative cooling duration is around 810 hours per cooling season (6 hours per night) with ventilative cooling switched on when ΔT>4°C. Even with these optimum operating conditions and with hot climates it is difficult to have a positive ADV_{VC} (i.e. a ventilative cooling SEER superior than the one of the mechanical cooling system). High performance balanced ventilation system have SPI>0.4 $W/(m^3/h)$ and single flow systems SFP>0.1 $W/(m^3/h)$.



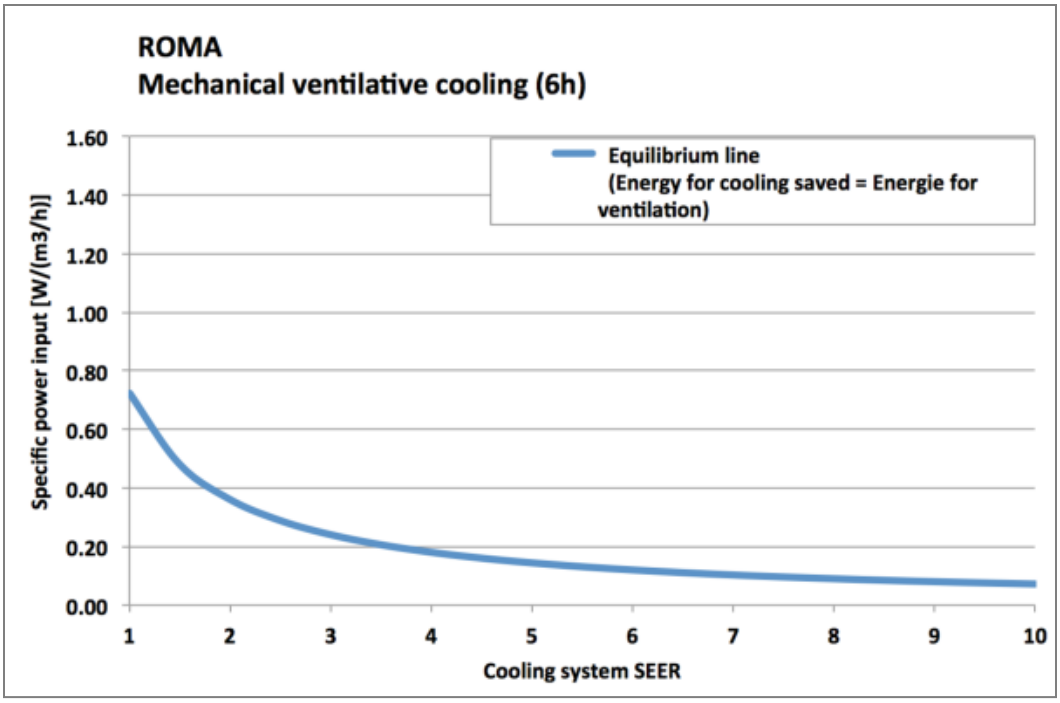


Figure 28: ADV_{VC} = 1 curves for Geneva and Rome.

The graphs of Figure 28 show the curve where ADV_{VC} = 1. These curves are calculated for a particular site and a particular scenario for a given building. The curves presented in Figure 28 represent the optimum mechanical ventilative cooling scenario 1:00-7:00 am with an airflow of 5.6 m^3/ m^2h.

On the graph of Geneva, it is seen that for a ventilation system with SPI = 0.45 W/(m^3/h) the maximum conventional cooling system SEER that can be replaced without losing energy is 3. For a single flow extraction system of SPI= 0.14 W/(m^3/h), ventilative cooling has the advantage over conventional cooling systems. The mechanical cooling system must have a SEER > 7.7 to be more advantageous than ventilative cooling.

6.9. Sensibility analysis of key parameters and risk factors.

The parametric analysis presented at the beginning of this chapter showed that solar gains (and internal gains) are the most influencing parameter for summer comfort and energy need for cooling. To simulate the overheating hours and the cooling requirements applying a ventilative cooling strategy and varying the shading use to 50% for several climates is a common practice with blinds not controlled automatically, [11], as the associated risk of such user behaviour is high.

The indicator that should be used to evaluate the influence of this risk depends on the context. In a naturally ventilated building without cooling system, the most appropriate indicator is the overheating hours. In a mechanically ventilated building the $SEER_{VC}$ and CRR_{VC} may be the appropriate indicators to assess this risk. Figure 29 shows the cooling requirements of the test case office with night ventilative cooling strategy with perfect blind control and with 50% parasite solar gains. The graph shows that an insulated building, even with the right ventilative cooling strategy, presents overheating even in cold climates like Oslo or Hamburg. For central Europe climates and for southern European climates, imperfect solar shading may cost 8 to 13 kWh/m2 of extra cooling requirements. This energy waste is higher without a ventilative cooling strategy. In terms of overheating hours, partially controlled solar shading may cost 170 extra overheating hours in Geneva or Vienna, and up to 350 extra hot hours in Madrid or in Athens. This risk is higher in cold climates, where solar protection is not very common in usual practice. Absence of solar shading control combined with well insulated envelope makes the overheating problem more distinct and eventually rooms in cold climates present similar thermal behaviours that is similar to rooms in southern climates.

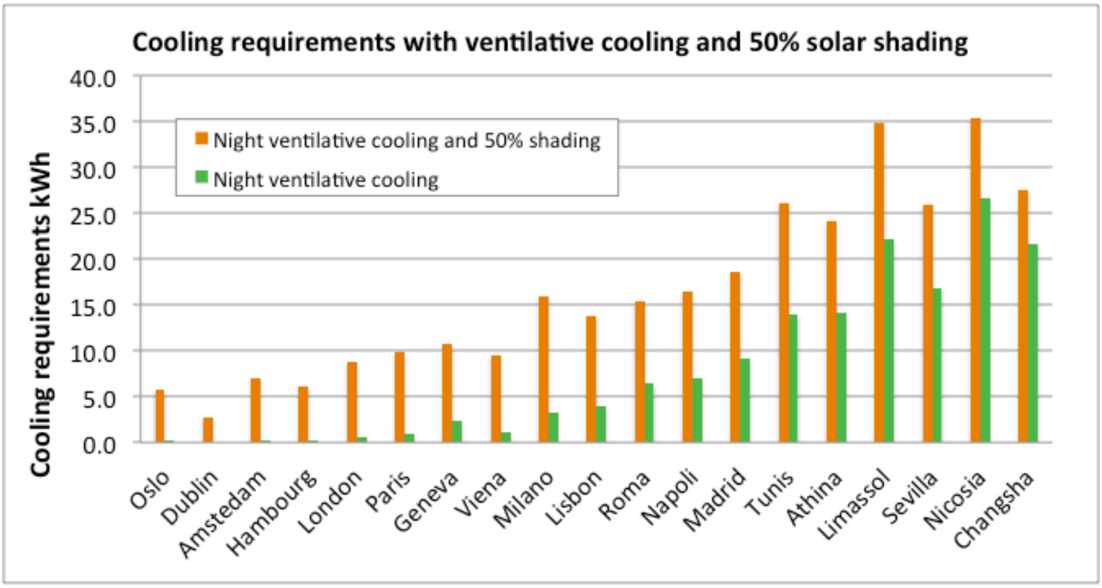


Figure 29: Comparison of cooling requirements of the test case with night ventilative cooling strategy with perfect solar control and with a solar control of 50% efficiency.

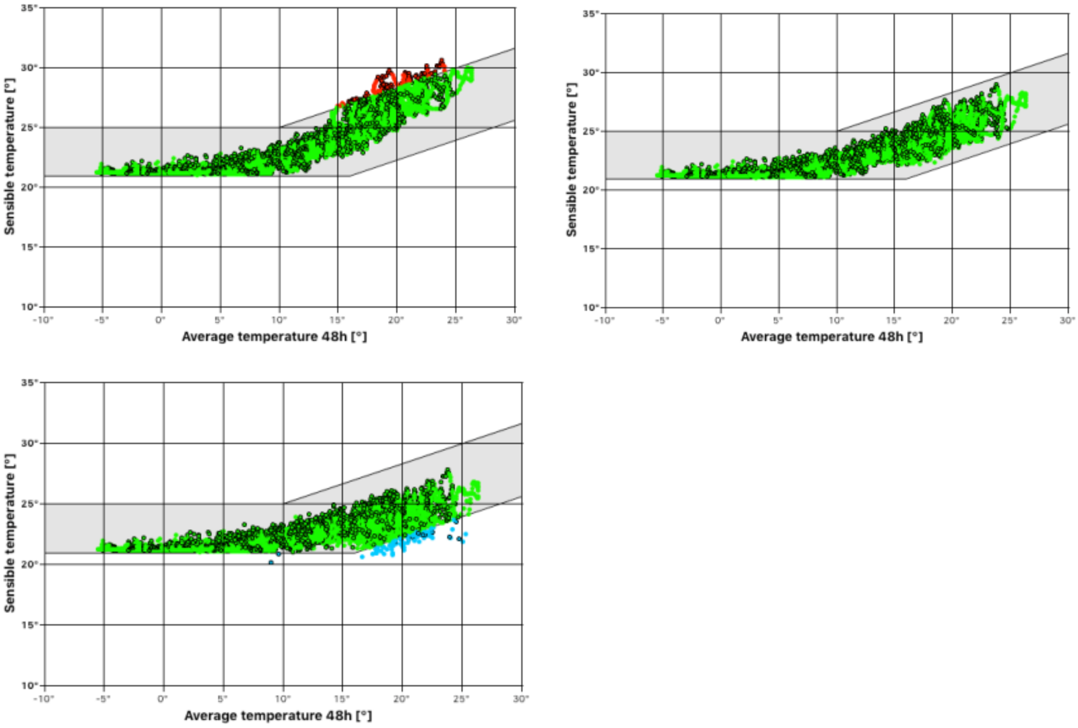


Figure 30: Interior thermal comfort of the test case with 10% window opening, 25% and 100% and night ventilative cooling strategy.

As can be seen in Figure 30, 10% of the window opening makes the building uncomfortable. This risk is not negligible. Sometimes it is prohibited to open windows more than 10% because of the security problems. Sometimes it is just due to bad design, with tilted windows opening in an unfavourable geometry.

A similar room as the test case has been simulated varying the thermal mass from 40 Wh/m^{2}K (light building with wood structure and interior thermal insulation) to 95 Wh/m^{2}K. A ventilative cooling strategy during hours of use in the climatic zone of Fribourg in Switzerland was used. Cooling requirement simulations were performed for five variations of input parameters: natural ventilation during occupancy, blinds partially used, openings partially used and a hot meteorological year weather data was used. The effect of changing individual parameters was evaluated and then the effect of all of them together. It can be seen from Figure 31 that the thermal mass has a little impact for a perfectly ventilated and controlled room (scenario with natural ventilation during occupancy). Although the cooling requirements are doubled, they are always low, less than 2 kWh/m^2. However, combined with the other risks, the effect of thermal mass is more significant and may play an important storage role that is able to absorb extra internal or solar gains.

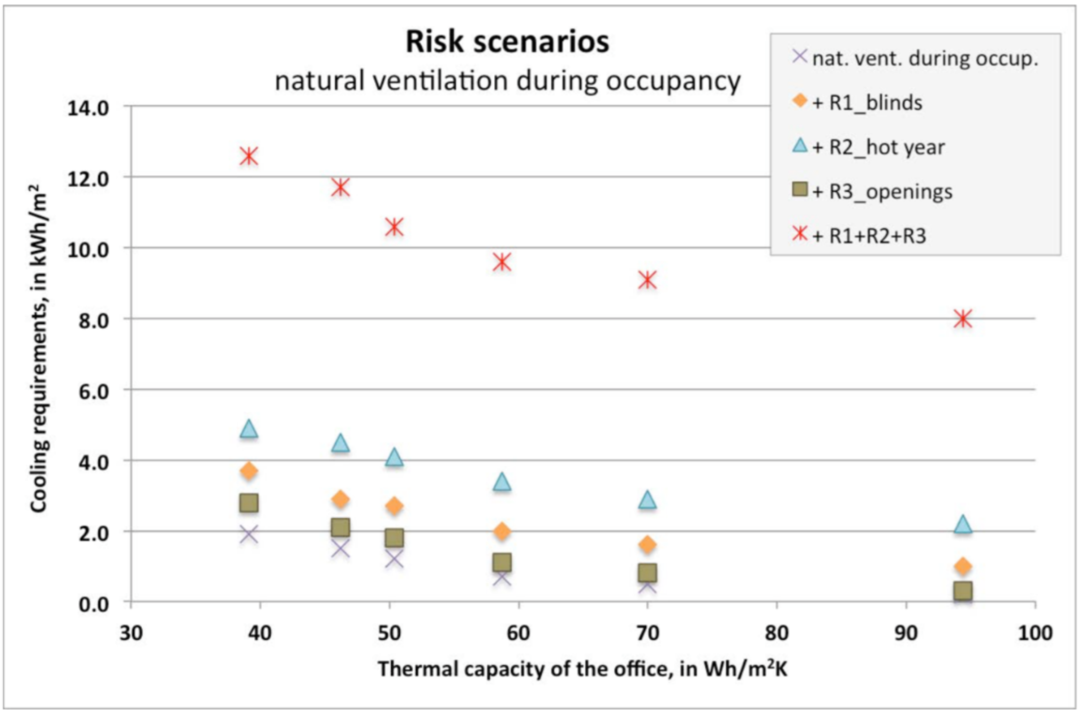


Figure 31: Cooling requirements for different risk scenarios and several thermal masses varying from 40 Wh/m^{2}K to 95 Wh/m^{2}K.

7. Control Strategies

The ventilative cooling control strategy is significantly influenced by the general climatic conditions in the area where the building is located. The developed strategies should assist strategies for indoor air quality through natural or mechanical systems. Cooling control strategies have to appropriately coordinate with the heating control strategy for the period of the year when there might occasionally be a heating demand as well as overheating incidents.

The purpose of ventilative cooling control is primarily to adapt the airflow rate to the actual cooling demand, without compromising the local thermal comfort and the air quality of the space. It is therefore important that the ventilation system and the control strategy are integrated and designed in parallel.

The main challenge in designing control systems for ventilative cooling is to obtain the right balance between (1) installation cost, (2) operating cost, (3) energy consumption, (4) indoor climate and comfort, (5) user satisfaction and (6) robustness.

7.1. Control Strategies and Systems

The design of a well applied control strategy for a given building depends on the following parameters:

1) building type and design
2) ventilation system
3) constraints (e.g. external noise, security, pollution and others)
4) solar shading
5) internal heat load
6) dress code
7) user expectations
8) user habits.

A satisfactory control algorithm aims to minimize energy consumption, ensure thermal comfort by using the knowledge of occupancy schedules, weather forecast, and system dynamics.

There are many different types of controllers based on how they react to variations of a parameter:

- The on/off controller is widely used in residential buildings. They control a set point temperature based on monitoring of the temperature of the room. When the temperature in the room is over the set point, it will send a signal to partly or fully open windows or run the selected ventilative cooling system. It is simple to install and therefore powerful in residential buildings as its cost is limited. However, the control is not "soft".

- The P, PI, PID controllers regulate to achieve a set point using error dynamics, relying only on the measured property, but not on any knowledge of the system. They use the same principle as the previous but the reaction of the cooling system is proportional to the deviation from the wished temperature (P). A PI considers in addition, the past values and the PID considers the possible trends of the error. A proportional control checks a single control element for each set point value, a PI control changes to accommodate load changes while keeping a control point very close to the set point. The PID compensates for system dynamics and allows faster control response. These controllers are more efficient than on/off but need of better tuning and several control points and therefore are more expensive.

The biggest drawbacks of these two types of control are that each one can only control one parameter at the time, for instance based on the temperature they control the window opening. In addition, each case is "tailor-made", the solutions need to be developed for each building. Finally, as a result of the single control, they are very affected by disturbances such as occupancy, solar radiation, etc.

Non-linear controllers are based on feedback linearization and adaptive control techniques; they are very much used in AHUs. Nonlinear controllers require complex mathematical analysis.

- Robust controls are used for supply air temperature and zone temperature control. They are used for controlling time dependent variations considering uncertainties.
- Adaptive controllers require self-regulation of the controller, so that they can learn from previous user behaviour or the environment. If users want the house to be at 25 degrees in the evening and 19 in the morning for example, the controller will learn from the actions to achieve these set points and mimic them on a normal basis. They are used more and more in AHU with VAVs.
- Model Predictive Control (MPC) controllers seek to combine the measurement of a property such as temperature and combine it with predictions of, among others, weather, occupancy, availability of renewable energy. MPC systematically learns with a goal such as ensuring comfort, decreasing costs, etc. The MPC sets up an optimal schedule over the prediction horizon at each single time step. It optimizes the schedule for a chosen parameter, for example minimum costs. MPC can handle nonlinear dynamics, time dependent system dynamics, disturbances and lack of maintaining control. Their use is being more and more widespread but they need of a lot of information about the ventilative cooling system and the building to achieve a good regulation. MPC need very accurate building models, occupancy models and therefore may be too complicated not being compensated by an increase in performance or cost. Therefore, until now their use is restricted.

Within these exist several types, among others position and control feedback. This type of controller is based on full knowledge of the position of the window, roof or other opening. They need a good data communication between the building energy management system (BEMS) and the actuators but can react very fast and consider a whole façade instead of only one room. These controllers are good in double façade solutions having similar openings and avoid many resets of the position of the window. Two speed operation controls are used for instance in schools allowing a silent automatic control of window opening during lectures and a faster opening when manually activated so that the user perceives a change

7.1.1. Control systems limitation

In maintaining comfort with low energy use, the control systems should consider a number of limitations which typically are introduced as "if" sentences in the control algorithms. The following are some of the limitations to consider.

Rain will limit window opening and, depending on the combination of wind and rain, the window opening may be compromised in order to avoid water penetration to the building. Extreme weather ought to be introduced in the same way. If there is high wind velocity or high amount of rain, windows are not to be opened and the regulation of the mechanical system has to account for that. Rain and wind sensors are therefore required to establish limitations on the opening control.

During pollen season, occupants with allergies may not want to open windows. Together with pollution such as traffic, this can be introduced in schedules of window opening (such as "if within rush hours than windows are not opening"). However, using a sensor which may increase accuracy, would also increase costs.

The position of the openings in the building and their control has to consider noise. In some cases, the window opening itself may represent a noise and users may not want the opening to happen in sleeping hours or in a frequent manner during school hours. In other cases, during rush hour, traffic noise may be a disturbance. In such cases, control systems need to be scheduled/controlled accordingly. Another factor to consider is security; people may not want to open windows during night or during absence as this may result in a breakthrough of a thief. For both noise and security, it is probably easier to introduce some kind of schedules instead of using sensors.

7.1.2. Dynamic or static control

A static control defines a goal, for example to keep a value at a fixed set-point, such as to keep the indoor temperature constant. The system will control admission variables to achieve this goal neglecting the dynamics of the system. To optimize comfort and minimize energy use dynamic controllers are more preferable. A static control may for instance have the goal of maintaining a set indoor temperature by controlling the window opening only. A dynamic system will take into consideration the total dynamics of the system like thermal mass. More advanced systems will consider several extra parameters like wind, outdoor temperature, thermal mass, etc. The static control will be cheaper to install, but an exhaustive tuning period has to be carried out. An advanced dynamic control system can increase the energy savings, by means of computer analyses and the use of sensors. The overall control will be better as the control is based on actual and historical measurements and not just on momentary values.

7.1.3. Sensitivity to Occupancy

In offices, the control system has to handle many different perceptions of comfort and the ventilation can be controlled either manually or automatically.

In single occupancy offices, it seems that manual control during occupancy hours is sufficient, as people have a clear perception of their comfort. In landscaped offices or other room types with many people or whenever the building is not occupied, automated strategies are more suitable to satisfy the larger amount of people.

A common window control will have the challenge of ensuring that as many occupants as possible are satisfied. For this reason, the control must be able to be overridden by the occupants. Depending on the type of room, single office or open landscaped, the control has to be adapted to respond robustly to changes.

The control of night ventilation is of great importance to achieve acceptable indoor environment during hot summer days in buildings without mechanical cooling and to diminish energy consumption for mechanical cooling.

Night-time ventilation should normally be automated to avoid overcooling. If the control for natural ventilation is based only on windows opening, it is possible to have independent user-controlled windows or hatches in individual rooms, but in warm countries, manual control requires users to know what to do and in cold climates it may result in overcooling and therefore should be avoided or limited. An automated control can be used locally for instance in landscaped offices or centrally based on measurements in representative rooms.

In large buildings where there is a switch between hybrid ventilation and mechanical cooling the risk is that, once activated, the system would stay in active cooling for a long period of time. The ability to switch automatically between natural and mechanical modes in order to optimize the balance between indoor thermal quality and energy use is very important. For fan-assisted systems, the fan can be controlled by the temperature, the pressure in the supply or exhaust ducts, or the airflow rate supplied by the fan. If the fan is in the natural ventilation flow path, the control can be either on or off, stepped or continuous, depending on the natural driving forces. Natural and mechanical ventilation may normally be controlled based on the external temperature and humidity. Alternatively, it can be controlled by a time schedule. In some classroom control the system regains control of windows 30 minutes after the system has been overridden.

7.2. Level of possibility of user intervention

Occupant behaviour affects building energy performance by influencing several variables such as: 1) set-points for heating and cooling, 2) window opening and natural ventilation, 3) building occupancy levels and profiles 4) lightning, equipment and other electrical loads and profiles [4]. It is proven that occupants exhibit a tendency to prefer operable systems that allow them to modify their environment. During interviews, occupants normally express their wish to have more information about the systems and their control. In such conditions, experience shows that they normally use heating and cooling systems in an energy efficient way. One of the challenges is that equally informed occupants react differently to the same level on information. To have a good user's satisfaction, users should get more information on how to modify their ventilative cooling control.

User's behaviour is proven to have a large effect on the energy consumption due to type and length of window opening schemes, use of air conditioning and the set-point temperatures choice. Occupant behaviour may vary based on external parameters such as: 1) outdoors weather conditions, 2) occupant personal background, expectations, clothing, etc. and 3) building properties such as ownership or availability of heating, ventilation and window opening capability.

One of the advantages of individually controlled natural ventilation systems is higher satisfaction and acceptability from the users. Recent research indicates that users are more tolerant to deviations in indoor environmental conditions, if the system is controlled by themselves. Occupants appear to have a ‘tolerance’ limit that varies from day to day. They have a very clear sense of their own thermal comfort, but typically, they react too late, when the temperature is already above their acceptable temperature limit. Even though occupants should have the possibility of controlling their own environment (windows, blinds, fans), automatic control is necessary to support them in achieving a comfortable indoor climate and to take over when manual control cannot improve the condition and during non-occupied hours. In spaces occupied by several and different users, a higher degree of automation is needed. In non-domestic buildings, it can be difficult to find an acceptable strategy for ventilation system control that satisfies all users. Automatic control is also needed during non-occupied hours to reduce energy use and to precondition rooms for occupation – that is, to provide and control night cooling.

The ventilation flow rate in natural or mechanical systems, in automated mode, is controlled by motorized actuators according to time, occupancy detection, set points for room temperature, CO_2 or VOC concentration and humidity levels. However, it is very important that the ventilative cooling control strategy is understandable for the users and can be easily operated. Simplicity and high transparency of the user/system interface is of the utmost importance. Users should have the possibility to modify their environment, but an automatic system should be able to modify the use of ventilative cooling whenever users do not react to changes or forget to take actions when leaving the space.

It is also very important to consider carefully how and when the automatic control regains control (if) after being overruled by the user. For systems with occupancy detection, the automatic control system usually takes over when the occupants are outside the room. For other systems, it can take over when the normal occupation period has ended or after certain adjusted time.

During summer, the small difference between indoor and ambient temperature on warm summer days has limited potential to reduce the room temperature, even if the flow rate is high. In many cases, the body cooling potential of air movement because of open ventilation systems might be the most important factor in relation to thermal comfort. It is important that occupants are carefully instructed on how to operate ventilation systems when outdoor air temperature is high or when mechanical cooling is on.

Manual control by occupants requires clear and easy-to-understand instructions. Users have some routines regarding window opening that are superimposed to the ventilative cooling strategy. These have to be compensated for. Some studies have depicted that window opening is highly dependent on the outdoor weather conditions. Users will normally open windows during warm periods and close them during cold or windy periods. Experience suggests that occupants with a limited understanding of how their ventilation system works often result in inadequate ventilation rates. It seems that window opening behaviour is also strongly linked to personal cultural background.

7.3. Controls Strategies in Case Studies

The control strategy applied in each case study are shown in Table 18. More than half (54%) of the case studied presented in IEA EBC Annex 62 use hybrid ventilation, 31% use natural ventilation only and 15% mechanical ventilation only. All case studies use the internal temperature as set point control; over 60 % use the external temperature as extra parameter for control, normally limiting the window opening. Wind speed, CO_2 and relative humidity are sometimes (~40%) used for control mostly in hybrid and natural ventilation. It is also interesting that mechanically ventilated systems do not consider precipitation or rain. Natural and hybrid systems seldom consider relative humidity in their control strategies.

In general, two control strategies are most often implemented in the case studies, one for occupied buildings and one for night ventilation. Again, during occupied periods, temperature in the occupied zone and external temperatures are the main measurements used by the control system. The internal temperatures are normally controlled to be maintained within the range of 20-24°C. The external temperature is used to limit the possibility to use windows allowing operation only for external temperatures between 10 and 18°C. 54 % of the cases allow users to override the control based on their preferences. No mechanical systems allowed for user interaction. The CO_2 level was the most used parameter for control of ventilation, followed by temperature. Mechanical ventilation systems typically have narrower ranges of allowed concentration levels (the CO_2 range was 900 to 1200 ppm) than natural ventilation systems (the CO_2 range was 900 to 1500 ppm). Night ventilation was used in 69% of the cases

Table 18. Control strategy applied in the investigated case studies. Man.: Manual control; Aut.: Automatic control; Con.: Constant ventilation; PIR: Demand control with presence detection; CO_2: Demand control with CO_2 sensors.

			Driving forces for ventilation	**Overheating criteria**	**Opening signal**	**Window opening parameters**	**Window opening control**	**Natural night ventilation T controlled**	**Mech. night ventilation**	**Mechanical cooling**
01	IE	Zero2020	Nat	28degC 1% occ hrs				X		
02	NO.1	Brunla school	Nat	T > 26	Temp+ CO_2	Temp+ wind+ rain	PIR	X		
03	NO.2	Solstad kindergarten	Nat+ Mech exh	T > 26				X	X	
04	CN	Wanguo MOMA	Mech supply & exh	Tz < 28 for 99% hrocc (check)					X	X
05	AT.1	UNI Innsbruck	Nat+ Mech exh	T < 26 for 95% hrocc				X		
06	AT.2	wk Simonsfeld	Nat+ Mech exh	T > 26 zone / T > 29 gallery						
07	BE.1	Renson	Nat					X		
08	BE.2	KU Leuven Ghent	Nat+ Mech exh					x		
09	FR	Maison Air et Lumiere	Nat							
10	IT	Mascalucia ZEB	Nat					X		X
11	JP.1	Nexus Hayama	Nat	Tz < 28 for 99% hrocc (check)						X
13	PT	CML Kindergarten	Nat	80% acceptibility limit for 99% hr occ				X		
14	UK	Bristol University							X	X
15	NO.3	Living Lab	Nat + Mech	T>26			Variable			

and in most of the cases the control system was based on set point temperatures for the zone and the properties of the air brought into the building. The range of internal set point temperatures was between 15 and 23°C, with an outdoor temperature limit for window opening between 10 -18°C. The wind speed should typically be below 10-14m/s and with no rain for allowing night ventilation systems to operate. Indoor air quality parameters were not considered for night ventilation.

7.3.1. Example of ventilation and control strategies for different climate zones

Three case studies are selected to illustrate the different ventilations and control strategies used in case studies depending on their location and climate zone. The following three climate zones were chosen:

Cfb, warm temperate, fully humid, warm summer

Dfc, Snow, fully humid, cool summer and cool winter

Cfa, warm temperate, fully humid, hot summer

Case Study No. 8: KU Leuven, Ghent, Belgium (Cfb)

The hybrid ventilation in the KU Leuven building has both an ventilation strategy for the occupied period as well as a night ventilation strategy. During the occupied hours mechanical ventilation is used with an internal room temperature set-point of 22°C. External air is used directly, unless the outside air temperature is higher than or equal to the room set-point, indirect evaporative cooling is used then. When the external air temperatures are between 14°C and 16°C 50% of outdoor air is used. When the external air temperatures are between 16°C and 22°C 100% outdoor air is used. Figure 32 shows an example of the control strategy for natural night ventilation in the building. The night ventilation strategy operates between 10pm and 6am. If the following criteria are fulfilled, then night ventilation is activated:

- Maximum zone temperature of the previous day > 23°C
- Zone temperature > heating set point = 22°C
- Zone temperature > outside air temperature + 2°C
- Outside air temperature > 12°C
- Internal relative humidity < 70%
- No rainfall
- Wind velocity < 10 m/s

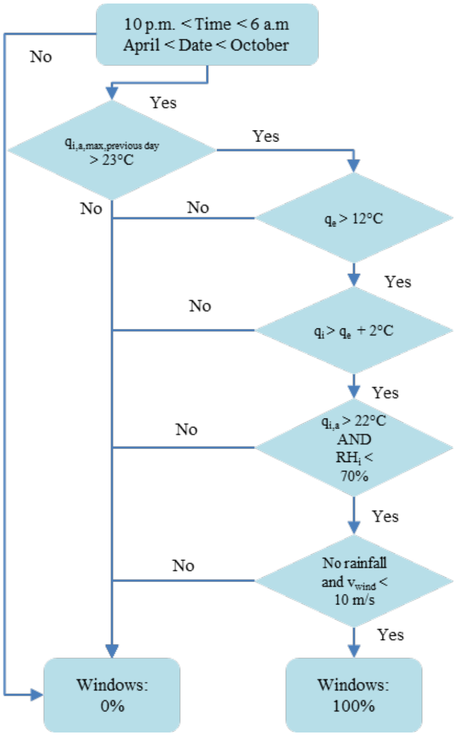


Figure 32: Control strategy for natural night ventilation

Case Study No. 3: Solstad Kindergarten, Larvik, Norway (Dfc)

The control strategy used in the Solstad Kindergarten uses both set-points for thermal comfort and air quality and the strategy incorporated also differs depending on the season. The hybrid ventilation system uses predominately mechanical ventilation in the winter. The system controls the CO_2 level to be between 900-1200ppm, while automated window operation is activated only if the zone temperature is above 19°C, and is limited to an opening percentage of 50% of maximum opening. Window operation may also occur, if the mechanical system cannot maintain the CO_2 level. The system controls the CO_2 level to be between 950-1500ppm, when windows are operated. During summertime, the zone temperature set-point is increased to 21°C. The mechanical ventilation is not utilized very often during the summer as the air flow rates needed in order to remove surplus heat often are larger than air flow rates needed for CO_2 control. A night ventilation strategy is also used during summer. If zone temperatures exceeds 23°C at the end of the occupied period, automated windows (limited to an opening percentage of 50%) are used to reach a temperature set-point of 18°C in each zone. The control strategy also considers rain and wind when determining opening percentages for the automated window system as is shown in Table 19.

.

Table 19: Opening percentage allowances as a function of rain and wind speed

With Rain		Without rain	
Wind below (m/s)	Maximum window opening degree (%)	Wind below (m/s)	Maximum window opening degree (%)
3	50	10	50
8	25	12	30
		14	10

Case Study No. 11: Nexus Hayama, Kanagawa, Japan (Cfa)

The control strategy used in the Nexus Hayama building uses a large amount of actuated high-level automated openings. The ventilation system also has a mechanical AHU backup. While occupants can manually operate the system, the control strategy follows Figure 33 in the automatic mode. Natural ventilation with these automated openings is only used if the following criteria are met:

- Outdoor enthalpy < room enthalpy
- Outdoor air temperature ≤ lowest zone air temperature
- Outdoor air temperature ≥15°C
- Outdoor dew point ≤ 20°C
- External wind speed < 10 m/s
- No rain

If the outside air is not considered suitable, the mechanical system is used and the AHU will operate in cooling mode. If zone air temperatures go above 28°C air conditioning aside from the AHU is automatically activated.

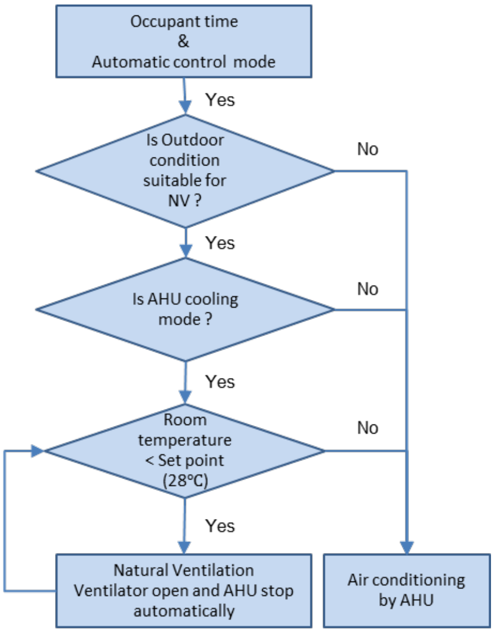


Figure 33: Automated ventilator and AHU control flowchart

8. Case Studies

Well documented case studies using ventilative cooling from across the world were collected together and are presented in specific case study brochures available on the IEA EBC Annex 62 website. These case studies are included because of the rich information available about their design, construction and operational performance.

This chapter gives an overview of the characteristics and lessons learned of the investigated case studies. It summarizes the features of the various case studies including the building characteristics, ventilative cooling strategies and systems, design criteria and approach and lessons learned. It also presents results from performance evaluations for selected case studies. The 15 case studies that are analysed in this chapter are located in 10 countries. Three were completed in 2014, four in 2013, two in 2012, four in 2011 with the two remaining case studies in 2003 and 2007. Over 85% of case studies were built after 2010. There are three office buildings, five educational buildings, four residential, one mixed use and one kindergarten. Eight of the case studies have rural surroundings and seven have urban surroundings. Four case studies were refurbishment projects. Table 20 shows the range of climate regions represented within the case studies while Table 21 summarises key categorical information about the case study buildings.

Table 20: Variation in climate regions for all case study buildings. (Please refer to the Koppen-Geiger climate classification system for details on KG abbreviations in column 1)

KG	General Description	Qty	Locations
Cfb	Temperate with warm summers and no dry season	6	Cork, IE; Ernstbrunn,AT; WaregemandGhent, BE;Verrieres-le-Buisson, FR; Bristol, UK
Cfa	Temperate, hot summers and no dry season	2	Changsha, CN; Hayama, JP
Dfb	Cold with warm summers and no dry season	3	Stavern, NO; Trondheim, NO; Innsbruck, AT
Dfc	Cold with no dry season and cold summer	1	Larvik, NO
Csa	Temperate with dry, hot summers	2	Sicily, IT; Lisbon PT

Table 21: Building Type, size and year of completion for all case studies

No	Country	Building	Type	Year (New or Refurb)	Floor Area m^2	Strategy
01	IE	Zero2020	Office	$2012^{(R)}$	223	Natural
02	NO.1	Brunla school	Education	$2011^{(R)}$	2500	Hybrid
03	NO.2	Solstad Kindergarten	Kindergarten	$2011^{(N)}$	788	Hybrid
04	CN	Wanguo MOMA	Residential	$2007^{(N)}$	1109	Mechanical
05	AT.1	UNI Innsbruck	Education	$2014^{(R)}$	12530	Hybrid
06	AT.2	wkSimonsfeld	Office	$2014^{(N)}$	967	Hybrid
07	BE.1	Renson	Office	$2003^{(N)}$	2107	Natural
08	BE.2	KU Leuven, Ghent	Education	$2012^{(N)}$	278	Hybrid
09	FR	Maison Air et Lumiere	House	$2011^{(N)}$	173	Natural
10	IT	Mascalucia ZEB	House	$2013^{(N)}$	144	Hybrid
11	JP.1	Nexus Hayama	Mixed Use	$2011^{(N)}$	12836	Natural
12	JP.2	GFO	Mixed Use	$2013^{(N)}$	399000	Hybrid
13	PT	CML Kindergarten	Education	$2013^{(N)}$	680	Natural
14	UK	Bristol University	Education	$2013^{(R)}$	117	Mechanical
15	NO.3	Living Lab	Residential	$2014^{(N)}$	100	Hybrid

8.1. Building design

The case studies demonstrate a range of different building characteristics. Some of these characteristics are developed in response to the decision to use VC while others are the reason VC was adopted. The following summarises design influences, building morphology and thermal properties of the case studies.

8.1.1. Design Influences

A range of factors can have varying levels of influence on building design when adopting ventilative cooling. From a review of the case studies, a list of those that will affect the type of strategies and components adopted for cooling is presented in Table 22. For each case study, the relative importance of different factors on the design of the building was ranked qualitatively using High, Medium or Low classifications. It can be noted that lower initial costs and lower energy costs were consistently important design influences across most case studies. Reducing solar loads and air leakage were also important factors for most case studies. However, even in urban case studies, external and internal noise did not appear to influence the building and ventilation designs. Avoiding rain ingress was however, relatively important in many locations. Finally, reducing internal loads were important in about half of the case designs. It is difficult to draw global conclusions from the matrix in Table 22 but lower energy and lower initial costs along with lower internal and lower solar loads are key factors when considering design solutions.

Table 22: Design Influences (R dentoes Rural; U denotes Urban; *dentoes residential)

Country		Building	Surroundings	Lower Initial costs	Lower Maintenance Costs	Lower Energy Costs	Reducing Solar Loads	Reducing Internal Loads	Reducing External Noise	High Internal noise	Elevated Air Pollution	Avoiding Rain Ingress	Insect Prevention	Burglary Prevention	Reduced Privacy	Air Leakage
01	IE	Zero2020	R	H	M	H	H	L	L	L	L	M	L	H	M	M
02	NO.1	Brunla School	R	H	H	H	L	M	L	L	H	M	L	L	L	H
03	NO.2	Solstad Kindergarten	R	L	L	H	L	L	L	M	H	L	L	L	L	H
04	CN	Wanguo MOMA*	U	H	M	H	H	L	L	L	L	M	L	M	L	H
05	AT.1	UNI Innsbruck	U	H	H	H	M	L	M	L	L	M	L	L	L	H
06	AT.2	wkSimonsfeld	R	H	H	H	M	L	L	L	L	L	L	L	L	M
07	BE.1	Renson	R	L	L	M	H	H	H	H	M	H	H	L	L	L
08	BE.2	KU Leuven, Ghent	U	H	L	H	H	H	L	L	L	M	L	L	L	H
09	FR	Maison Air et Lumiere*	U	M	M	L	H	M	L	L	H	L	L	M	L	M
10	IT	Mascalucia ZEB*	R	H	M	H	H	L	L	L	L	L	L	M	L	M
11	JP.1	Nexus Hayama	R	M	M	H	H	L	L	L	L	M	H	H	M	M
12	PT	CML Kindergarten	U	H	L	L	M	M	L	L	L	M	M	M	M	L
13	JP.2	GFO	U	H	M	L	L	L	L	L	L	L	L	L	L	L
14	UK	Bristol University	R	H	H	H	L	H	L	M	L	M	M	H	L	L
15	NO.3	Living Lab*	U	L	L	H	H	M	L	M	L	H	L	L	L	H

8.1.1. Morphology

Some of the case studies are small, dedicated research spaces or studies using small isolated parts of a building such as the lecture rooms in KU Leuven, Bristol University computer room and the zero2020 testbed in Ireland.

Others are grand in scale such as the GFO or Nexus Hayama buildings in Japan and The University of Innsbruck. In almost all cases, except arguably the Chinese case study in Changsha, the buildings can be classified as low rise with typically 2-4 floors. The average floor area for the buildings is 2,468m^2. However, when we remove Nexus Hayama in Japan (the largest case study at 12,836m^2) and University of Innsbruck this reduces to 765m^2. At 400,000 m^2 the GFO building is an outlier and is not included in these average floor areas. The smallest case study is the living lab in Trondheim at 100m^2, this is a research test facility for residential dwellings in cold climates. The shape coefficient, a measure of the building shape and efficiency of external building surface to floor area, is shown in Figure 34. We can see that the small Italian zero energy home has a disproportionately high shape coefficient compared with the other buildings. Excluding this we have a minimum shape coefficient of 8.3 and a maximum shape coefficient of 96, which is still a good spread. Figure 35 shows the window to wall area ratios for each case study. Five of the case studies have relatively high window to wall area ratios at or greater than 50% while the average is 37%.

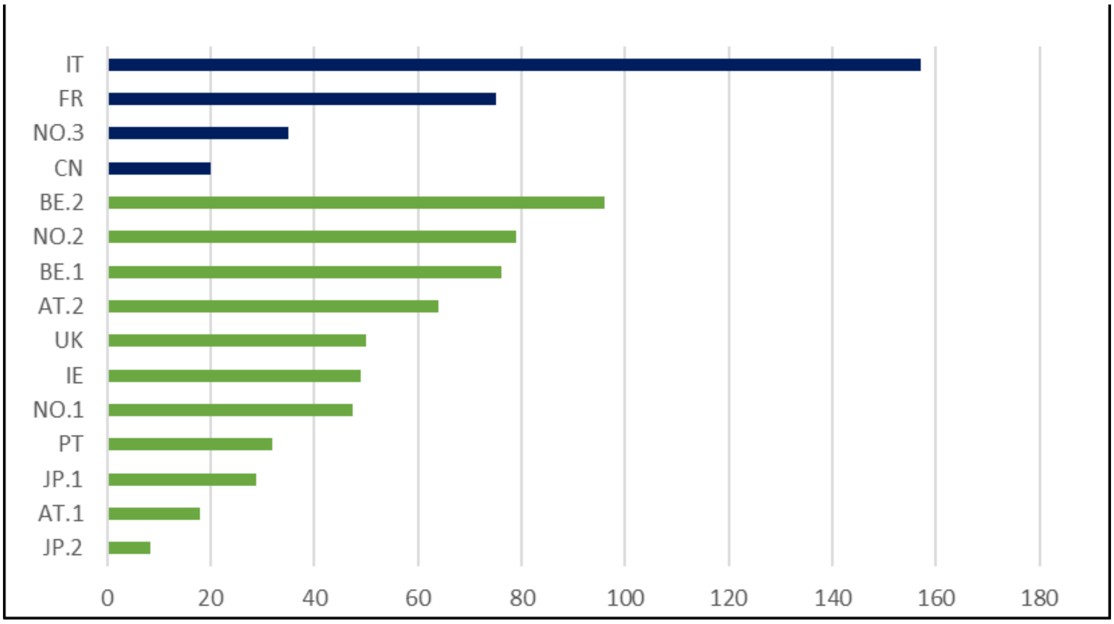


Figure 34: Building Shape Co-efficient for all Case Studies. (Residential shown in Blue)

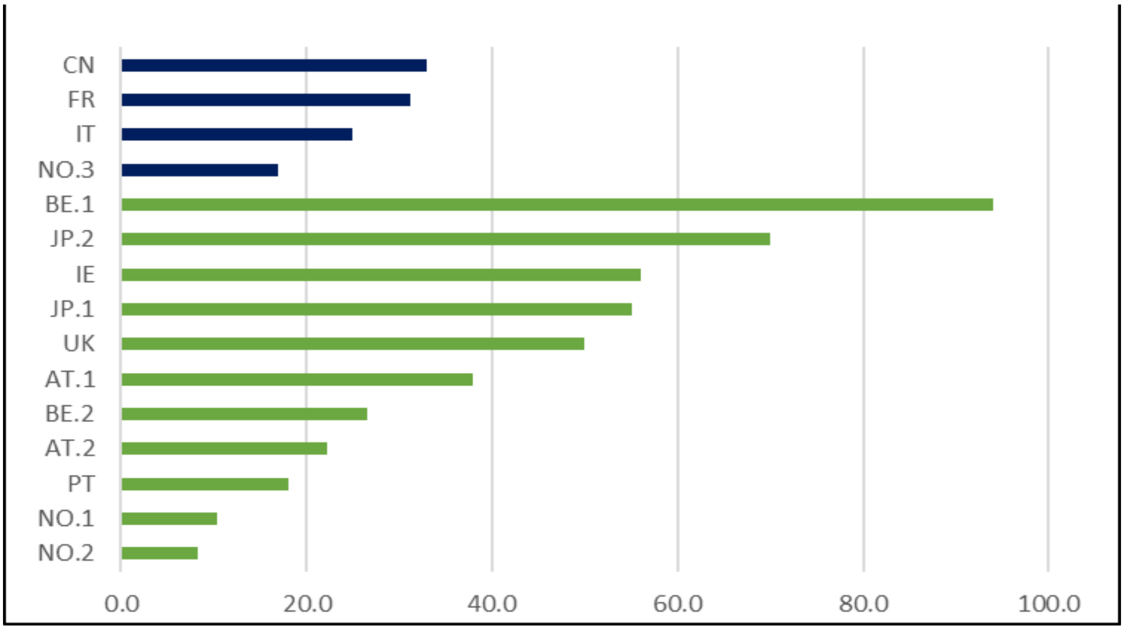


Figure 35: Window to Wall area ratio for all Case Studies. (Residential shown in Blue)

8.1.2. Thermal Properties

The case study buildings overall can be classified as high performant. Most buildings were designed as low energy or sustainable buildings. The average elemental U-value for all 15 case studies is 0.35 W/m^{2}K, which appears high but there is a large spread in individual values, with an average standard deviation across all elements of 0.27 W/m^{2}K. Some buildings such as the zero2020 testbed in Cork, have very high fabric performance (Wall U-value of 0.09 W/m^{2}K) while other buildings have lower performance, in part due to their respective national building regulations, such as the Nexus Hayama (wall U-value of 0.86 W/m^{2}K). This variation is in some part due to the different performance requirements and construction types for different climates. Six of the case studies can be classified as having heavy or very heavy thermal mass according to ISO13790. Good air tightness is a recurring feature of most case studies with the average Air Change Rate (ACR) from infiltration of 1.13 h^{-1}, ranging from 0.51 to 1.85 h^{-1}.

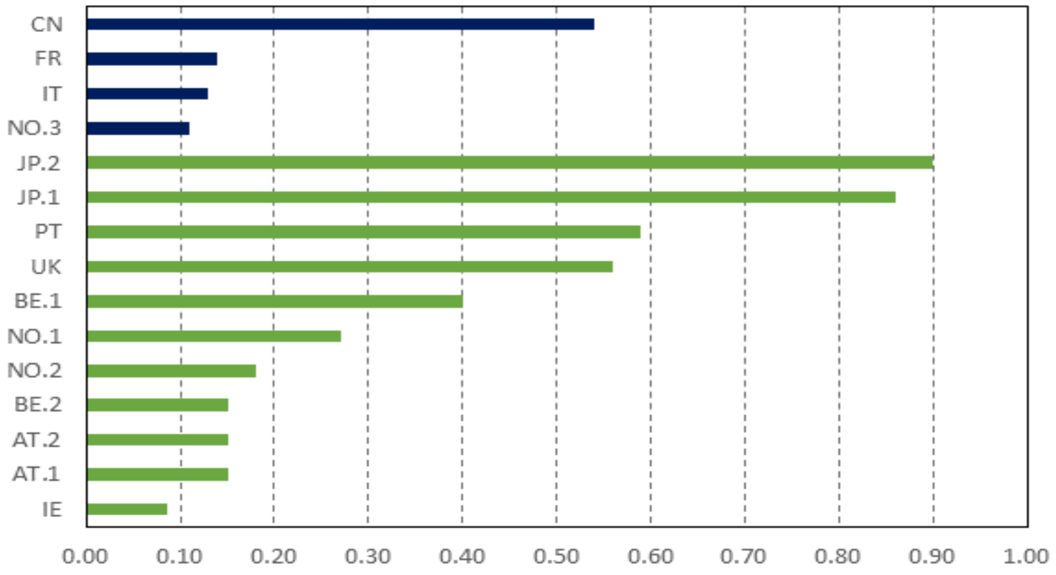


Figure 36: External Wall U-values for all Case Studies. (W/m^{2}K) (Residential shown in Blue)

8.2. VC strategies, components & control

8.2.1. Strategies & components

The case studies present a rich variety of ventilative cooling solutions across a range of building types, morphologies and climates. Table 2 in Chapter 2 summarises ventilative cooling concepts used in the case studies. The large majority, 86%, of the case studies use natural ventilation for ventilative cooling strategy. The sensible internal loads for these case studies are all below 30 W/m^2 except for the Kindergarten in Portugal. The average is 25 W/m^2. All the climates were temperate. The number of days with the maximum daily external temperature greater than 25°C ranged from 0 to 123 days and the cooling season humidity is also low throughout except in Japan. Figure 37 highlights values for all case studies.

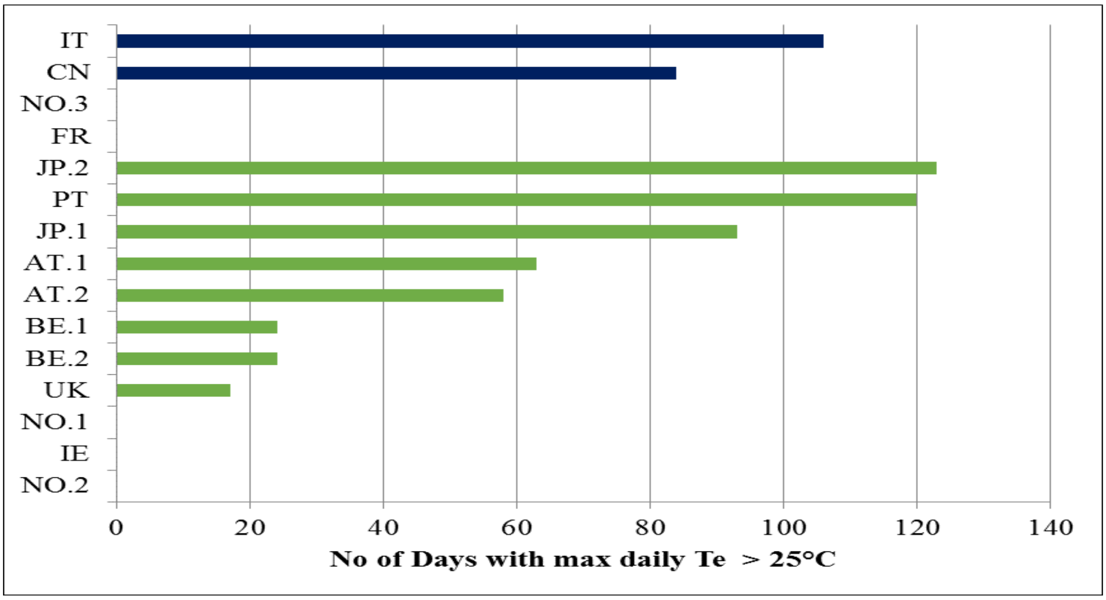


Figure 37: No of days with maximum daily external temperature above 25°C (Residential shown in Blue)

The most prevalent strategy is hybrid ventilation with 50% of buildings using this approach for ventilative cooling. Many of these systems used mechanical exhaust ventilation when conditions required an increased airflow through the building. The internal loads in these spaces are greater than 40 W/m^2 in Norway and Belgium, while in Austria and Italy they are less than 10 W/m^2. Two out of the 15 case studies use mechanical ventilation as a ventilative cooling strategy. A number of unique systems are employed in particular case studies such as, the integrated manual and automated slot louvres at zero2020 in Ireland, [21-23]; the displacement ventilation system at CML Kindergarten in Portugal, [24]; the earth to air heat exchanger at the ZEB Home in Italy, [25], and the PCM mechanical ventilation system in the UK, [26].

8.2.2. VC system control

The control strategies used vary depending on the ventilation strategy of each case study building. Figure 38 conveys which parameters are used depending on the ventilation strategy as a percentage of all case studies. Thermal comfort is the main driver for controlling all ventilation systems. Temperatures and relative humidity are the main parameters considered by control systems for comfort, while CO_2 is the main parameter considered when controlling the indoor air quality. Internal temperature was used by all cases studies with set-point control, one case study has a purely manual system. In addition, over 60% of case studies uses an external temperature as part of their control strategy, this is typically a low temperature limit where the outside air has to be below the zone internal air temperature. Another point to note is the fact that exclusively mechanical systems do not consider precipitation or wind, while natural and hybrid systems do not incorporate external relative humidity levels into their control strategies.

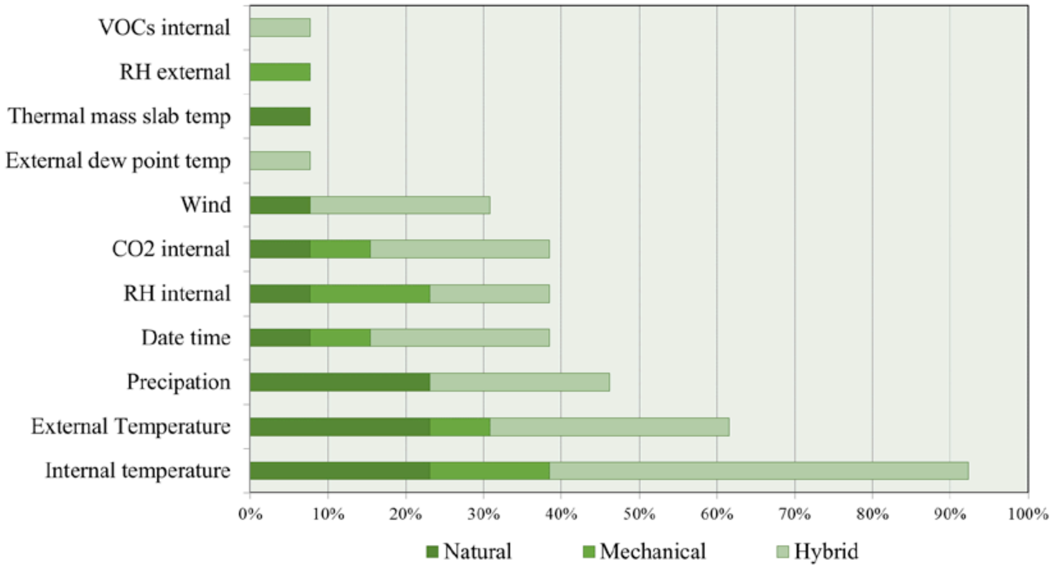


Figure 38: Summary of parameters used in VC control strategies for all case studies

Most control strategies for occupied periods use the internal zone temperature and an external temperature low limit as controlling parameters in ventilation strategies. There is no major correlation between the set-point used and the climate. The overall range of set-point temperatures is observed to be between 20-24°C where the mean internal air temperature set-point is around 22°C. The range of low temperature limits for outside air is between 10-18°C, with a mean external low temperature limit set-point of around 14°C. Around 54% of the case study buildings have a manual override switch or allowed occupant controlled ventilation during occupied hours as part of their typical occupied control strategies. All natural ventilation case studies allowed a form of occupant interaction with the ventilation system while 60% of hybrid systems allowed occupant interaction with the ventilation system. For systems that controlled depending on relative humidity, an average set-point of 60% is observed. There are differing ranges of acceptability depending on whether the ventilative cooling system is mechanical or natural. 69% of the case studies investigated incorporated a night ventilation strategy as well as an occupied ventilation control strategy. Typically, night ventilation strategies have different control parameters than ventilation strategies during occupied hours. The night ventilation strategies incorporated typically have a set-point for the zone as well as a limit on the properties of the air brought into the building. The mechanical night ventilation strategies observed only used a combination of internal and external air temperature. The range of internal temperatures used for night ventilation strategies is between 15-23°C while the low limits on the external air temperature are between 10-18°C. Night ventilation is also dependent on the presence or absence of rain and wind speeds above a certain value. Typically, the wind speed has to be below 10-14 m/s and with no rain for night ventilation systems to operate. In cases where relative humidity is the control parameter night ventilation will not be activated unless the relative humidity was below 70% for a given zone. Parameters specifically related to indoor air quality are not considered in any of the night ventilation strategies.

8.3. Sizing and simulation of VC Systems

8.3.1. Sizing of VC systems

Information on the recommended aperture area when sizing ventilative cooling systems is critical for the building designer. For almost all case studies, natural ventilation was adopted as either the sole source of ventilative cooling or as part of a wider strategy, with, for example, natural supply and mechanical exhaust. It is generally beneficial to identify possible dimensionless parameters that provide a characterisation of the system, thus allowing for similarity investigations across multiple different systems. Owing to this and the inherent importance of the ventilation opening geometry to the delivered airflow rate, a parameter calculated as the percentage opening area to floor area ratio (POF) is calculated for each case study. The opening area used is the maximum available geometric opening area and does not incorporate the flow effects of the opening. Figure 39 presents POF values for all cases where this is relevant.

A large spread of values for the case studies is noted. 65% of the buildings have a POF values less than 4%. There seems to be no correlation with the building category. The two highest values are from Csa climates (i.e. temperate with dry, hot summers). Two of the lowest three values are from fully naturally ventilated offices. Natural ventilated buildings have a POF of 3.6% while hybrid buildings had a POF of 4.6%, or 6.0% when the Italian case study is included. Although several building regulations impose a minimum floor to opening area ratio of 5%, there is a generally accepted rule of thumb for designers when sizing openings at the concept stage of 1-3%. The low end of this range appears inadequate when compared with these case studies. A range of 2-4% seems more reasonable. Discharge coefficients range from 0.25 to 0.7 across the case studies although these are only measured in a few cases with many estimated.

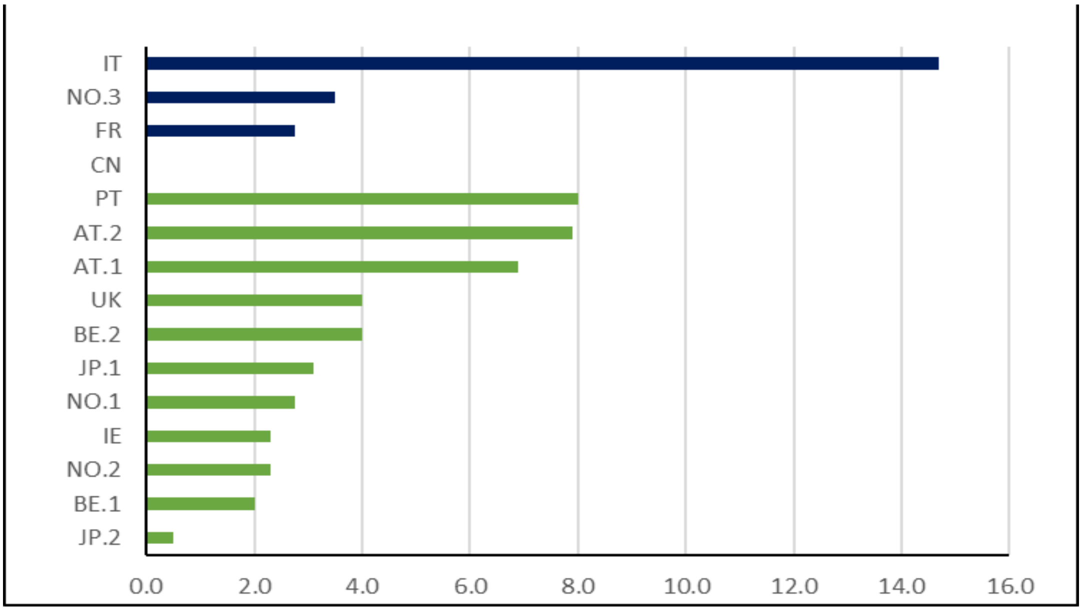


Figure 39: Percentage openable area to floor area for selected case studies. (Residential shown in blue)

8.3.2. Simulation of VC systems

Both the airflow performance and capacity sizing of the ventilative cooling strategies and components, along with the building thermal performance, are investigated at various design stages using appropriate simulation tools. National standards and engineering guidance documents, such as those published by CIBSE in the UK, are used by some countries. Some countries develop models in different design packages such as PHPP and TAS while the Portugal case study uses EnergyPlus from the initial stage right through to the operational performance evaluation stage. There is no single dominant tool for modelling ventilative cooling across all case studies. For example, at the detailed design BSim is used for the naturally ventilated house in France, WindmasterSIMIEN for all three cases in Norway, EnergyPlus is used in Portugal and in Italy. IES Apache is used in Ireland and the UK for the detailed design but TRNSYS is adopted for the Irish case study for operational performance evaluations. Only in Japan is CFD used. IDA Ice is adopted in Norway for all operational performance evaluations.

8.4. Performance evaluation

All case studies completed performance evaluations involving various measurement campaigns. Each case study adopts different approaches and investigates different phenomena, including ventilation rate measurements, thermal comfort studies, analysis of internal thermal environments, investigation of the performance of specific solutions such as displacement ventilation, chimney-stacks, hybrid systems, cross flow ventilation etc. It is not possible to present in this summary chapter the individual findings from these campaigns.

IEA EBC Annex 62 identifies that, in order to assess the minimum performance of the ventilative cooling strategy, one cooling season of internal air temperatures data should be obtained. This data should then be compared with a previously defined overheating risk criteria based on two static thresholds. Table 23 presents a selection of results from the case studies. There are some measuring campaigns still under way and as such results are unavailable for these. Overall there is very good performance from the ventilative cooling solutions adopted in all case studies.

Table 23: Preliminary results of VC performance evaluation

Country		**Building**	**Summer Design Values**		**Overheating criteria / note**	**% Occ hrs above threshold**		**Occ hrs**
			T_e	$T_{i,o}$		28°C	25°C	
01	IE	Zero2020	26.0	25.0	T_i<28°Cfor 99% occ hrs	0.7	5.5	2600
02	NO.1	Brunla school	25.0	26.0	T_i> 26°C	0.0	0.0	2600
03	NO.2	Solstad Kidergarten	25.0	24.0	T_i> 26	0.0	0.0	2860
05	AT.1	UNI Innsbruck	34.0	27.0	T_i< 26 for 95% occ hrs	1.1	16.2	2600
06	AT.2	wkSimonsfeld	34.5	24.0	T_i> 26 zone / T > 29 gallery	0.0	5.0	3250
08	BE.2	KU Leuven Ghent	-	25	T_i < 26°C for 95 % hr occ	0.3	5.1	1560
11	JP.1	Nexus Hayama	26.0	26.0	T_i< 28 for 99% occ hrs	1.0	40.0	8736
13	PT	CML Kindergarten	30.0	26.0	80% acceptability 99% hr occ	2.6	16.0	3640
14	UK	Bristol University	26.0	25.0	Adaptive TC Model	-	-	

8.5. Lessons Learned

The case studies analysed in this project yielded over sixty four key lessons learned, the majority of which are considered important. Thirty one lessons are contributed based on the design and construction and 33 lessons contributed from case studies buildings during operation and post occupancy. These are summarised separately.

8.5.1. Lessons from design and construction

Designing a building to incorporate VC can be challenging and may require a lot of detailed building information. While each challenge is different, the main key lessons are as follows:

- Detailed building simulation is important when simulating VC strategies. Most case studies analysed highlighted the need for reliable building simulations in the design phase of a VC system. This is considered most important when designing for hybrid ventilation strategies where multiple mechanical systems need harmonization. Some studies also say that simulating the window opening in detail was important.
- Customisation may be an important factor in designing a VC system. In order to ventilate certain buildings, it may be necessary to design custom components. Some case studies highlight the need to have custom design systems that were specific to country regulations and the use of a building or space. Some consideration should also be given to the clients' expectations around specific issues like rain ingress and insect prevention.
- VC systems are considered a cost-effective and energy efficient in design by most case studies, but particularly with naturally ventilated systems. It is indicated that designing with the integration of manual operation and control is important, particularly in a domestic setting.

8.5.2. Lessons from operation and post occupancy

While systems may be designed to have high levels of comfort, IAQ and energy performance, achieving this is difficult. All case studies emphasised that monitoring a buildings performance post occupancy is important if not essential in building performance optimisation. While some key lessons are more specific than others the following general observations are made;

- Engaging with the building owners or operators as soon as possible is integral to guaranteeing building performance for IAQ, comfort or energy savings. For some case studies this specifically mean educating or working with the facilities operator or manager for the building, for others it meant educating the building occupiers themselves.
- It is suggested by some that this engagement should occur already in the design stage.
- VC in operation is generally a good option. Case studies comment on the reduction of overheating and improvement of comfort conditions in the buildings that used outside air. However, correct maintenance and calibration of the systems is integral to maintaining performance.

- Some case studies highlight the need to exploit the outside air more with lower external air control limits during typical and night-time operation. Others suggested that exploiting the thermal mass of a building is key. However, it is noted that care must be taken with considering these low temperatures as some case studies, particularly in cold climates observe more incidences of overcooling than overheating.

Some additional specific lessons learned from various case studies are summarised in Table 24 below. These are a sample from certain case studies. Each brochure includes lessons learned in a dedicated section at the end of the brochure.

Table 24: Examples of Specific Lessons Learned From Selected Case Studies

Country		Case Study	Specific Lessons Learned
01	IE	Zero2020	o Design simulations easily overestimate the ventilation rates for cooling. This must be considered in the design phase. Design should be conservative when estimating the cooling potential.
05	AT.1	UNI Innsbruck	o Detailed evaluation of the building location, building structure and its operation profile during the concept phase is essential to adapt the ventilative cooling system to the building. o A data monitoring system is essential to optimize the building performance and interaction of different technical building systems. More than one cooling/heating period is needed to optimize systems.
11	JP.1	Nexus Hayama	o Regarding ventilation windows, it is important to install a screen door in the opening to prevent sounds and the invasion of insects. Securing a ventilation path (cooling & heating pit) that can be opened regardless of the outside conditions is also effective. However, consideration must be given to air quality and pressure loss.
12	JP.2	GFO	o Manual control is unsuitable for high-rise buildings to prevent a fall accident. The natural ventilation opening should be controlled for each individual tenant to meet their own needs. o Automated control can reduce cooling load, keeping low velocity in the occupied zone. o Natural ventilation opening can be controlled even in the time of disaster by emergency power supply.
13	PT	CML Kindergarten	o User training is essential and may need to be periodic (every 3-4years). In this school the current users were convinced that the chimneys were poorly designed skylights o Stack driven natural ventilation is very effective and selfregulating and can meet the airflow rate goals in spring and winter
14	UK		o Reliable sizing tools are needed which consider both the use of the space (internal heat gains and variability) and external weather patterns

9. References

[1] O'Sullivan, P. and Zhang, G.Q. Ventilative Cooling Case Studies. IEA-EBC Annex 62 Ventilative Cooling. Available at: www.iea-ebc.org

[2] Flourentzou, F., Pantet, S., Ritz, K. Automatic natural ventilation in large spaces: a passive ventilation technology for passive buildings. 36th AIVC Conference " Effective ventilation in high performance buildings", Madrid, Spain, 23-24 September 2015.

[3] Holzer, P. and Psomas, T. Ventilative cooling Source Book, IEA-EBC Annex 62 Ventilative Cooling. Available at: www.iea-ebc.org

[5] Kolokotroni M, Heiselberg P. Ventilative cooling. State of the art review. 2015; ISBN 87--91606--25--X. Available at: www.iea-ebc.org

[6] Carlucci, S. (2013). *Thermal comfort assessment of buildings*. London: Springer.

[7] Carlucci, S., Pagliano, L., & Sangalli, A. (2014). Statistical analysis of the ranking capability of long-term thermal discomfort indices and their adoption in optimization processes to support building design. *Building and Environment, 75*, 114-131. doi:https://doi.org/10.1016/j.buildenv.2013.12.017

[8] U.S. Department of Energy. (2016). *EnergyPlus™ version 8.6 documentation - engineering reference*

[9] Coblentz, C.W., and P.R. Achenbach. 1963. Field measurement of air infiltration in ten electrically-heated houses. ASHRAE Transactions 69(1).

[10] Emmerich, S. J., Polidoro, B., & Axley, J. W. (2011). Impact of adaptive thermal comfort on climatic suitability of natural ventilation in office buildings. *Energy and Buildings, 43*(9), 2101-2107. doi:https://doi.org/10.1016/j.enbuild.2011.04.016

[11] Belleri, A., Avantaggiato, M., Psomas, T., & Heiselberg, P. (2017). Evaluation tool of climate potential for ventilative cooling. *International Journal of Ventilation,* , 1-13. doi:10.1080/14733315.2017.1388627

[12] Chiesa, G., & Grosso, M. (2015). Geo-climatic applicability of natural ventilative cooling in the mediterranean area. *Energy and Buildings, 107*, 376-391. doi:http://dx.doi.org/10.1016/j.enbuild.2015.08.043

[13] Givoni, B. (1994). *Passive low energy cooling of buildings* John Wiley & Sons.

[14] Chiesa, G., Huberman, N., Pearlmutter, D., & Grosso, M. (2017). Summer discomfort reduction by direct evaporative cooling in southern mediterranean areas. *Energy Procedia, 111*, 588-598. doi:https://doi.org/10.1016/j.egypro.2017.03.221

[15] Artmann, N., Manz, H., Heiselberg, P. 2007. Climatic potential for passive cooling of buildings by night-time ventilation in Europe, Applied Energy, 84, pp.187–201

[16] Zhai, Z., Johnson, M.-H., Krart, M. Assessment of natural and hybrid ventilation models in whole-building energy simulations, Energy and Buildings, 43(9), pp 2251-2261, 2011.

[17] Belleri, A., Lollini, R., Dutton S. M. Natural ventilation design: An analysis of predicted and measured performance, Building and Environment, 81, pp 123-138., 2014.

[18] Belleri A., Dutton S., Oberegger, U. F., Lollini, F. A sensitivity analysis of natural ventilation design parameters for non residential buildings, Proceedings of BS 2013:

13th Conference of the International Building Performance Simulation Association, pp. 3300-3307, 2013.

[19] Heiselberg, P., Perino, M. Short Term Airing by Natural Ventilation – Implications on IAQ and Thermal Comfort, *Indoor Air, Vol. 20, No. 2, pp126-140, April 2010.*

[20] Perino, M., Heiselberg, P. Short-Term Airing by Natural Ventilation – Modelling and Control Strategies. *Indoor Air, Vol. 19; pp 357-380, 2009.*

[21] O'Donovan, Adam, P. D. O'Sullivan, and Michael D. Murphy. 2017. "A Field Study of Thermal Comfort Performance for a Slotted Louvre Ventilation System in a Low Energy Retrofit."*Energy and Buildings* 135:312–23. Retrieved (http://dx.doi.org/10.1016/j.enbuild.2016.11.049).

[22] O'Sullivan, Paul D. and Maria Kolokotroni. 2014. "Time-Averaged Single Sided Ventilation Rates and Thermal Environment in Cooling Mode for a Low Energy Retrofit Envelope."*International Journal of Ventilation* 13(2):153–68. Retrieved (http://ijovent.org/doi/abs/10.5555/2044-4044-13.2.153).

[23] O'Sullivan, Paul D. and Maria Kolokotroni. 2016. "A Field Study of Wind Dominant Single Sided Ventilation through a Narrow Slotted Architectural Louvre System." *Energy and Buildings* 138:733–47. Retrieved (http://linkinghub.elsevier.com/retrieve/pii/S0378778816315614).

[24] Mateus, Nuno M., Goncalo Nunes Simoes, Cristiano Lucio, and Guilherme Carrilho da Graca. 2016. "Comparison of Measured and Simulated Performance of Natural Displacement Ventilation Systems for Classrooms." *Energy and Buildings* 133:185–96.

[25] Causone, Francesco, Salvatore Carlucci, Lorenzo Pagliano, and Marco Pietrobon. 2014. "A Zero Energy Concept Building for the Mediterranean Climate." *Energy Procedia* 62:280–88. Retrieved (http://dx.doi.org/10.1016/j.egypro.2014.12.389).

[26] Santos, Thiago, Nick Hopper, and Maria Kolokotroni. 2016. "Performance in Practice of a Ventilation System with Thermal Storage in a Computer Seminar Room." *12th CLIMA REHVA World Congress* (May):11. Retrieved (http://vbn.aau.dk/files/233719310/paper_142.pdf).

.

Participants

Australia
University of Wollongong
Paul Cooper
E-mail: pcooper@uow.edu.au

Austria
Institute of Building Research and Innovation
Peter Holzer
E-mail: peter.holzer@building-research.at

e7 Energie Markt Analyse GmbH
Gerhard Hofer
E-mail: gerhard.hofer@e-sieben.at

Belgium
KU Leuven
Hilde Breesch
E-mail:
hilde.breesch@kuleuven.be

BBRI
Peter Wouters
E-mail: peter.wouters@bbri.be

China
Hunan University
Guo Qiang Zhang
E-mail: gqzhang@188.com

Denmark
Aalborg University
Per Heiselberg
E-mail: ph@civil.aau.dk

Danish Technical University
Bjarne W. Olesen
E-mail: bwo@byg.dtu.dk

VELUX A/S
Karsten Duer
E-mail:
karsten.duer@velux.com

WindowMaster A/S
Jannick Roth
E-mail:
jkr.dk@windowmaster.com

Finland
Turku University of Applied Sciences
Hannu Koskela
E-mail:
Hannu.Koskela@turkuamk.fi

SAMK
Jarkko Heinonen
E-mail:
jarkko.heinonen@samk.fi

Ireland
Cork Institute of Technology
Paul O'Sullivan
E-mail: Paul.OSullivan@cit.ie

Italy
Eurac Research
Annamaria Belleri
E-mail:
annamaria.belleri@eurac.edu

Politecnico di Torino
Giacomo Chiesa
E-mail:
Giacomo.chiesa@polito.it

Politecnico di Milano
Lorenzo Pagliano
E-mail:
paglianolorenzo5@gmail.com

UNIPA
Maurizio Cellura
E-mail:
mcellura@dream.unipa.it

Japan
Osaka University
Hisashi Kotani
E-mail:
kotani@arch.eng.osaka-u.ac.jp

Ritsumeikan University
Tomoyuki Chikamoto
E-mail:
tomoyuki@se.ritsumei.ac.jp

Multidisciplinary Research Institute, LIXIL Corporation
Toshihiro Nonaka
E:mail: nonakat3@lixil.co.jp

The Netherlands
Eindhoven University of Technology
Jan Hensen
E-mail: j.hensen@tue.nl

TUDelft
Regina Bokel
E-mail: R.M.J.Bokel@tudelft.nl

Norway
Norwegian University of Science and Technology
Hans Martin Mathisen
E-mail:
hans.m.mathisen@ntnu.no

SINTEF Energy Research
Maria Justo Alonso
E-mail:
maria.justo.alonso@sintef.no

Portugal
University of Lisbon
Guilherme Carrilho da Graça
E-mail: gcg@fc.ul.pt

Switzerland
Estia
Flourentzos Flourentzou
E-mail: flou@estia.ch

United Kingdom
Brunel University
Maria Kolokotroni
E-mail:
maria.kolokotroni@brunel.ac.uk

USA
Massachusetts Institute of Technology
Leon Glicksman
E-mail: glicks@MIT.EDU

www.iea-ebc.org

EBC

Energy in Buildings and
Communities Programme

EBC is a programme of the International Energy Agency (IEA)