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INDOOR AIR QUALITY AND ENERGY CONSUMPTION IN VENTILATED BUILDINGS

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INDOOR AIR QUALITY AND ENERGY CONSUMPTION IN VENTILATED BUILDINGS

By

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Dedication

To my parents:

Khadij & Mansour

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Abstract

Energy demand has been increasing worldwide and the building sector represents a large percentage of global energy consumption. Therefore, promoting energy efficiency in buildings is essential. Among all building services, Heating, Ventilation and Air Conditioning (HVAC) systems are significantly responsible for building energy use. In HVAC, ventilation is the key issue for providing suitable Indoor Air Quality (IAQ), while it is also responsible for energy consumption in buildings. Thus, improving ventilation systems plays a vital role not only in fostering energy efficiency in buildings, but also in providing better indoor air quality for the occupants and decreasing the possibility of health and well-being issues in consequence.

Among several methods for improving energy efficiency in buildings, this thesis focuses on development of several ventilation control strategies in order to maintain the indoor air quality in a good level while lower energy use. To do so, firstly, ventilation control strategies have been developed and implemented in office room. The reasons for choosing an office room, which all experiments and simulation has been carried out with, are not only being available in the Department of Mechanical Engineering (DEM) at University of Coimbra and being equipped with the required facilities to perform the experiments, but also the role of offices in general where many people are spending about one third of their daily times. Unlike to 19th and 20th century, nowadays more people are doing office works and investigating indoor condition is not only important because of the occupants well-being but also because of their functionality and productivity. Moreover, the variation of occupancy level in offices is also a promoting challenge.

The experimental arrangements have been designed and setup in order to test the functionality of the developed ventilation control strategies. The ventilation control strategies have been implemented using an application developed in *LabVIEW* and the required results have been collected using the sensors, data loggers and other facilities available in the laboratory at DEM. Then, all ventilation strategies have been simulated using the building energy simulation software, *EnergyPlus*. Moreover, sensitivity analyses have been performed in simulation cases, to assess the influence of changes in several relevant factors on the final results. Finally, the Smart Readiness Indicator (SRI), introduced by the revised Energy Performance of Buildings Directive (EPBD), has been presented and the SRI concept has been used to evaluate the smart readiness of developed ventilation control strategies.

Keywords: Indoor Air Quality, Smart Window, Ventilation Control Strategies, Energy Efficiency, Demand-Controlled Ventilation, Smart Readiness Indicator

Resumo

A procura de energia a nível mundial tem aumentado significativamente, sendo o sector dos edifícios responsável por uma grande percentagem do consumo global de energia. Consequentemente, a promoção da eficiência energética nos edifícios é essencial. Entre todos os serviços de edifícios, os sistemas de Aquecimento, Ventilação e Ar Condicionado (AVAC) são responsáveis por uma parte significativa do consumo total de energia. No AVAC, a ventilação é o elemento-chave para proporcionar a Qualidade do Ar Interior (QAI) adequada, sendo também responsável por uma parte do consumo de energia nos edifícios. Assim, é crucial melhorar o desempenho dos sistemas de ventilação não só na promoção da eficiência energética nos edifícios, mas também no fornecimento de melhor qualidade do ar interior aos ocupantes, que se traduz numa diminuição da possibilidade de ocorrência de problemas de saúde e bem-estar.

Entre os vários métodos existentes para melhorar a eficiência energética nos edifícios, esta tese foca-se no desenvolvimento de várias estratégias de controlo da ventilação, a fim de manter um bom nível de qualidade do ar interior e baixos consumos energéticos. Para este efeito, numa primeira fase, foram desenvolvidas e implementadas estratégias de controlo da ventilação em salas de edifícios de escritório.

As razões para escolher uma sala de escritório, na qual todas as experiências e simulações foram realizadas, deve-se não só ao facto de existirem instalações experimentais devidamente monitorizadas no Departamento de Engenharia Mecânica (DEM) da Universidade de Coimbra, mas também porque, de forma geral, as pessoas passam cerca de um terço do seu tempo diário no interior destes espaços.

Ao contrário do que acontecia nos séculos XIX e XX, hoje em dia há mais pessoas a desenvolver atividade em escritórios e é importante investigar as condições interiores destes espaços, não só devido ao bem-estar dos ocupantes, mas também devido à influência da condições ambientais na funcionalidade e produtividade dos ocupantes. Além disso, a variabilidade do nível de ocupação nos escritórios é também um desafio.

As instalações experimentais foram concebidas e montadas de modo a testar a funcionalidade das estratégias de controlo da ventilação que foram desenvolvidas. As estratégias de controlo da ventilação, foram implementadas utilizando uma aplicação computacional desenvolvida em *LabVIEW* e os resultados necessários foram recolhidos utilizando sensores, sistemas de aquisição de dados e outras instalações disponíveis no laboratório do DEM. De seguida, todas as estratégias de ventilação foram simuladas utilizando o software, *EnergyPlus*, para simulação energética de edifícios. Além disso, foram realizadas análises de sensibilidade nas simulações, para avaliar a influência de alterações em vários fatores relevantes nos resultados finais. Finalmente, foi apresentado o Smart Readiness Indicator (SRI), introduzido pela Diretiva revista de Desempenho Energético de Edifícios (EPBD), e o conceito de SRI foi utilizado para avaliar o estado de prontidão para o uso das estratégias de controlo de ventilação desenvolvidas.

Palavras-chave: Qualidade do Ar Interior, Janelas Inteligentes, Estratégias de Controlo da Ventilação, Eficiência Energética, Ventilação Controlada pela Procura, Smart Readiness Indicator

Table of Contents

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List of Figures

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List of Tables

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Acronyms

ADAI Associação para o Desenvolvimento da Aerodinâmica Industrial

AER Air Exchange Rate

AIVC Air Infiltration and Ventilation Centre

ASCII American Standard Code for Information Interchange

ASHRAE American Society of Heating, Refrigeration and Air-Conditioning Engineers

ASTM American Society for Testing and Materials

CAV Constant Air Volume

COMF Comfort

CONV Convenience

CS Control Strategy

DC Direct Current

DCV Demand-Controlled Ventilation

DEM Departamento de Engenharia Mecânica

DHW Domestic Hot Water

DSM Demand-Side Management

DSPF Double-Skin Perforated Facade

EC European Commission

EE Energy Efficiency

EfS Energy for Sustainability Initiative

EN European Norm (or Standard)

EPBD Energy Performance of Buildings Directive

ESOS Energy Saving On-Site

EU European Union

HVAC Heating, Ventilation and Air Conditioning

I2L Indoor Live Lab

IAQ Indoor Air Quality

IC Indoor Climate

ICT Information and Communication Technology

IDF Input Data File

IEQ Indoor Environmental Quality

IoT Internet of Things

IR Infra-Red

ISO International Standardization Organization

LAETA Laboratório Associado de Energia, Transportes e Aeronáutica

MCDA Multi Criteria Decision Analysis

MCDM Multi Criteria Decision Making

MMV Mixed-Mode Ventilation

MPC Model Predictive Control

nZEB nearly-Zero Energy Buildings

OL Occupancy Level

OP Occupancy Period

PD Percentage of Dissatisfied

PMV Predicted Mean Vote

PPD Predicted Percentage Dissatisfied

ppm parts per million (by volume)

RBC Rule-Based Control

REHVA (Originally: Representatives of European Heating and Ventilating Associations) Federation of European Heating, Ventilating and Air-conditioning Associations

RH Relative Humidity

SA Sensitivity Analysis

SBDCV Sensor-Based Demand-Controlled Ventilation

SBS Sick Building Syndrome

SDG Sustainable Development Goals

SRI Smart Readiness Indicator

SRT Smart Ready Technology

UC University of Coimbra

UK United Kingdom

US United States (of America)

VAV Variable Air Volume

VOC Volatile Organic Compound

WBAH Well-Being And Health

WHO World Health Organization

WP Workplace

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Symbols

C gas concentration

ext exterior

t time

0 initial

e Euler’s number

v velocity

A area

Q fan airflow rate

Δp fan pressure rise

η fan efficiency

P fan power

λ air exchange rate

V volume

CO_2 carbon dioxide

CO carbon monoxide

NO_2 nitrogen dioxide

SO_2 Sulfur dioxide

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Chapter 1

INTRODUCTION

1.1. Context and Motivation

Energy demand has been increasing worldwide, therefore, the environmental impact resulting from energy production and consumption has become a major public concern. Buildings are one of the biggest contributors to energy consumption in the modern world, as shown in figure 1.1, building sector is responsible for 40% of EU final energy consumption. Energy consumption in buildings refers to many factors such as lighting, domestic and commercial appliances as well as HVAC systems [1].

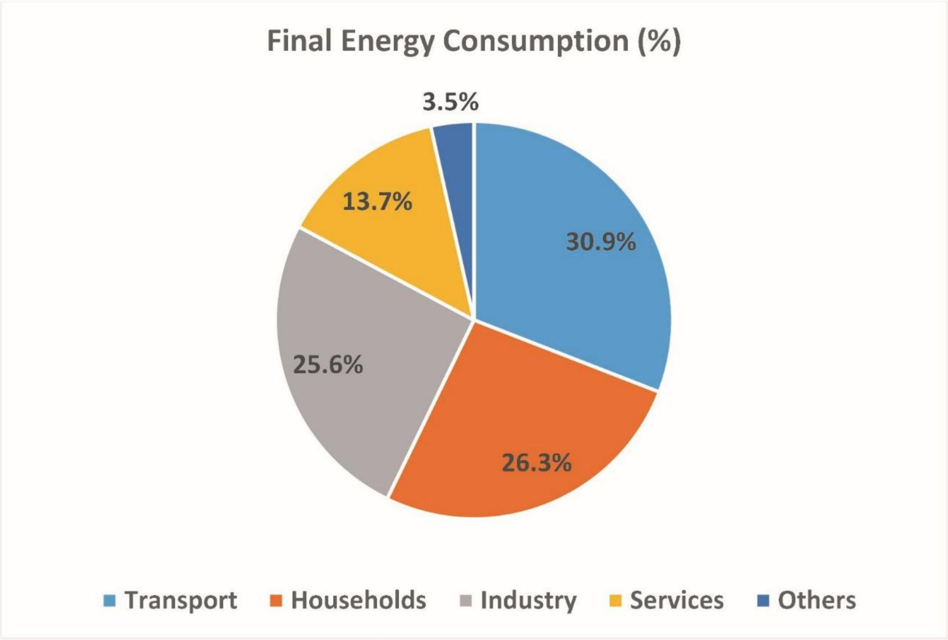

Figure 1.1 – Final Energy Consumption in EU by Sector. (Reproduced from [2]).

After the energy crisis in 1970s, buildings were constructed thermally insulated which decreased the amount of energy required for heating and cooling. This is still an ongoing effort to promote more thermally insulated facades and ceilings. Different insulation materials are tested and entered the market in order to provide better thermal insulation conditions for buildings, lowering energy consumption in consequence. There was also much effort on promoting energy-efficient domestic appliances such as refrigerators. Going forward, conventional lighting bulbs have been replaced by energy-efficient lighting systems and then with LEDs. Moreover, by development of renewable energy technologies, in some areas, electrical or gas water heaters have been replaced by solar ones. Then rooftop photovoltaic panels have been integrated into buildings in order to produce at least some portions of electricity demand in buildings.

Many innovative solutions have been proposed for more energy-efficient buildings, and there is an ongoing effort in promoting and demonstrating their energy saving potential. The majority of these solutions, however, is directed towards new buildings and future building designs, and is difficult to implement them in existing buildings. Across Europe, only about 1% of the building stock is currently being renovated each year, and there have been recent renewed calls for higher renovation rates, as high as 3% [3]. These higher rates need to be sustained for the next 40 years if the long term carbon and economic goals set out in the context of the European Economic Recovery Plan [4] are to be met. Retrofitting existing buildings with energy-efficient solutions has been identified by the European Commission (EC) as one of the research priorities in the coming decades [5], and the EU policy for sustainability includes ambitious targets, not only for increased energy efficiency (thus reducing wastage) but also, and more importantly, for reducing the overall energy consumption [6].

As mentioned above, many efforts were carried on to foster energy efficiency in buildings during previous decades, but in this period, less attention has been paid to environmental air quality in buildings as well as using novel ventilation strategies for buildings [7]. Owing to the framework of Energy Performance of Buildings Directive (EPBD) [8], there are many studies focusing on developing energy-efficient products and designs for buildings in which integrating efficient ventilation strategies to building is one of the hot topics that can provide the same ventilation rate consuming less energy.

Among all building services, HVAC systems play a significant role in energy consumption [9]. As much as 40% of the energy consumed in office buildings in the EU is used by HVAC systems [10]. These systems are aerodynamic circuits consisting of fans and ductwork to supply outdoor fresh air and to remove polluted air from the building. Depending on the complexity, they can include heat exchangers and humidifiers for conditioning the air, mixing chambers for adding fresh air to the circuit, filters for cleaning the air, dampers for regulating the flow velocity, and silencers to attenuate fan noise. These components, in turn, introduce pressure losses, which must be overcome with higher fan power. Centralized HVAC systems are standard in modern buildings while split-system air conditioning units are commonly installed in older buildings that do not have ventilation ductwork. Despite HVAC systems having reached a high level of technological maturity, coupled with the benefits of a constant and easily controllable flow, ventilation and air conditioning energy consumption in buildings has been increasing in the EU. It happened particularly in the southern countries, not only because there are more systems in operation, but also because there has been a generalized preference for installing higher power, with over-dimensioned systems. According to the Directive 2010/31/EU [11], EPBD, all new buildings in EU member states should be nearly-Zero Energy Buildings (nZEBs) by 2020 (for buildings occupied or owned by public authorities by 2018). Also, all EU member states shall draw up national plans such as retrofitting existing buildings to increase the number of nZEBs. Energy-efficient design for HVAC systems in new buildings and efficient renovation of HVAC systems during retrofitting process of existing buildings act positively to achieve the EPBD targets.

As aforementioned, building sector is a large contributor in energy consumption in EU and almost half of this amount accounts for HVAC systems. Giving the EU Directive, EPBD, on promoting energy efficiency in buildings and EU energy target 2020 (reduction of energy consumption by 20%), developing an energy-efficient product seems motivating, because they can be used not only in new buildings but also in existing building throughout their retrofit process. Reviewing the literature in energy and buildings field and more specifically in ventilating system areas made the author more motivated to carry on this research, as less attention was paid to develop energy efficient ventilation strategies in offices. Also, smart ventilation technologies to be integrated to buildings, which not only decrease energy use but also provide acceptable IAQ, is addressed. Furthermore, as emphasized in the 2018 revision of the EPBD [12] to improve the potential of smart technologies in buildings, smart readiness indicator has been integrated to this research to assess smart readiness of the buildings with ventilation strategies presented in this research work.

1.2. Problem Statement

Recently, due to the national and European polices, most of the new buildings are built more and more energy-efficient which lowers the increase in energy demand of building sector. The reason is the energy consumption in existing buildings that most of them are not really efficient in terms of energy use. This implies the importance of energy efficient solutions that can be used not only in new buildings but also in the existing buildings in order to improve their energy performance. Ventilation is an important element of energy consumption in buildings, it contributes to energy use and the well-being, comfort and productivity of the building occupants.

Many research work focused on development methods to improve energy efficiency in buildings. However, less attention has been paid dealing with energy-efficient ventilation methods in buildings. Therefore, this research focuses on developing, implementing and testing various ventilation strategies to improve energy efficiency in buildings while maintaining the IAQ in an acceptable level.

Accordingly, the following problems will be addressed by this research:

- The social general awareness about ventilation and IAQ;
- The low ventilation and/or over (excess) ventilation in both new and existing buildings;
- Development of energy-efficient ventilation strategies in buildings;
- Introducing smart ventilation as a smart ready technology for buildings.

1.3. Research Goals and Objectives

The general objective of this research work is to develop novel ventilation control strategies and then implement them on a case study (e.g. an office room) analyzing the obtained results in order to find the most energy-efficient control strategies, which provide acceptable indoor air quality.

The specific goals of this research work can be listed as follows:

- Identifying the critical factors to be considered in ventilation strategies;

- Developing various ventilation strategies based on these factors;
- Implementing and testing the ventilation strategies on a case study;
- Numerical simulation of the developed ventilation control strategies;
- Assessing the performances of all strategies and explain their advantages and drawbacks;
- Evaluating the smart readiness of this strategies using smart readiness indicator.

The final objective of the present research is to address the following research questions:

- How to implement ventilation control strategies in order to improve indoor air quality and energy efficiency?
- Can a smart window be a suitable product for improving building’s energy efficiency while maintaining suitable indoor air quality?
- What are the best control strategies to mitigate energy consumption while providing good indoor air quality?
- Can SRI be a suitable framework to assess human beings’ adaptation with modern digitalization?

1.4. Research Focus and Strategy

In order to limit the scope of this study, the focus is directed to an office room. The reasons for choosing an office room, where all experiments and simulations have been carried out with, are not only being available in DEM and being equipped with the required facilities to perform the experiments but also the role of offices in general, since many people are spending about one third of their times in this type of buildings. Unlike to 19th and 20th century, nowadays more people are doing office works and investigating indoor conditions. This is not only important on account of the occupants well-being but also because of their functionality and productivity. Hence it is also relevant for lucrativeness of the businesses. Moreover, the variability of occupancy level in office rooms is quite high, which implies that a better fitting of the provided conditions may represent a significant gain in terms of the reduction of energy consumption and environmental impacts.

The strategy begins with the development of a research framework. The research framework of this study includes the state-of-the-art (Chapter 3), smart window experimental prototypes development, implementation and test (Chapter 4), demand-controlled ventilation strategies simulated in chapter 5 and an assessment of smart readiness of these strategies in chapter 6. The overall structure of this research is graphically illustrated below (Figure 1.2).

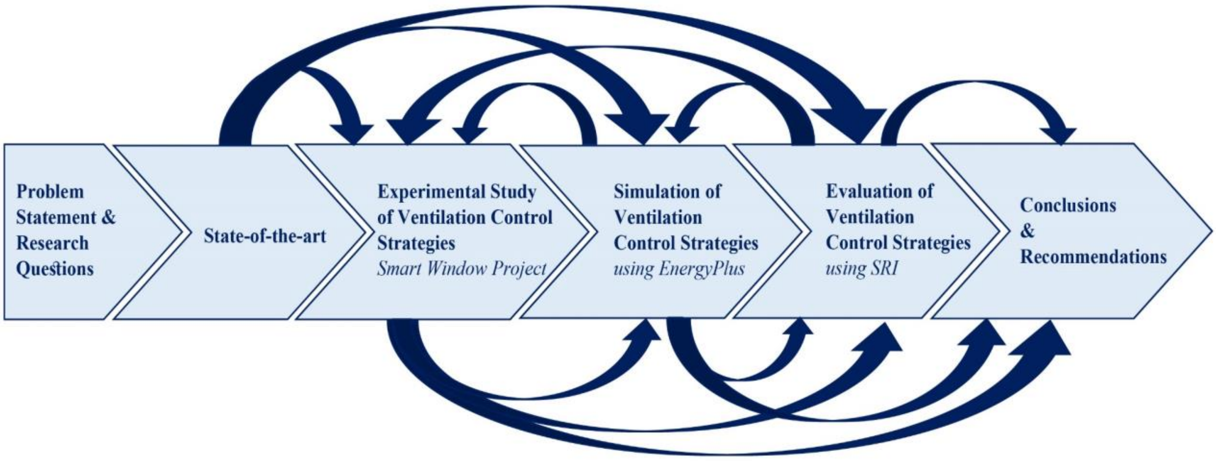

Figure 1.2 – Overall structure of the thesis.

1.5. Methodology

This thesis focuses on developing, analyzing and evaluating various ventilation strategies in an office room as a case study. Firstly, ventilation strategies are implemented using application developed in *LabVIEW* (a graphical programming environment to develop automated research, validation, and production test systems) and the required results are collected using the sensors, data loggers available in our laboratory in the Department of Mechanical Engineering at University of Coimbra.

Then, all ventilation control strategies are simulated using *EnergyPlus* (a whole building energy simulation program) and the results are presented. Moreover, sensitivity analyses are performed in simulation cases, to assess the influence of changes in one factor on the final results.

Furthermore, the energy consumption, as well as IAQ associated to ventilation strategies are compared to find out the best suited strategies.

Finally, smart readiness indicator concept is used to evaluate the smart readiness of developed ventilation strategies.

1.6. Thesis Structure

This thesis is divided into 7 chapters, from which 4 chapters (besides Introduction, Background and conclusion) are the core chapters, that corresponds to 7 publications resulting from the present research work: 3 published in peer reviewed journals and 4 in conference proceedings.

Chapter 1 addresses the context and motivation, problem statement, objective of the research and research question as well as the research methodology.

Chapter 2 provides an overview of ventilation and indoor environmental quality.

Chapter 3 provides an extensive literature review of the field under research about ventilation methods, ventilation effectiveness, IAQ, correlation of ventilation with building occupants etc. In particular, this chapter provides an overview on state-of-the-art on existing energy-efficient ventilation models and how useful and applicable they are.

Chapter 4 starts with introducing the smart window project. Then it explains the experiment model, condition and implementation. Finally, the results from this section are presented and a summary is provided.

Chapter 5 starts with definition the simulated of ventilation control strategies. Following, the simulation steps are presented. Finally, the results from this section are presented and a summary is provided.

Chapter 6 introduces the smart readiness indictor as a EU project aimed in raising awareness about advantages of integrating smart technologies in buildings. Later, the smart readiness of ventilation strategies developed in previous chapter is calculated and compared. This chapter concludes with a description of recent improvement of SRI.

Finally, in the last chapter, the work will be summarized and conclusions will be presented. Moreover, this chapter outlines the possible future developments of this research.

A graphical outline of the thesis structure is depicted in figure 1.3.

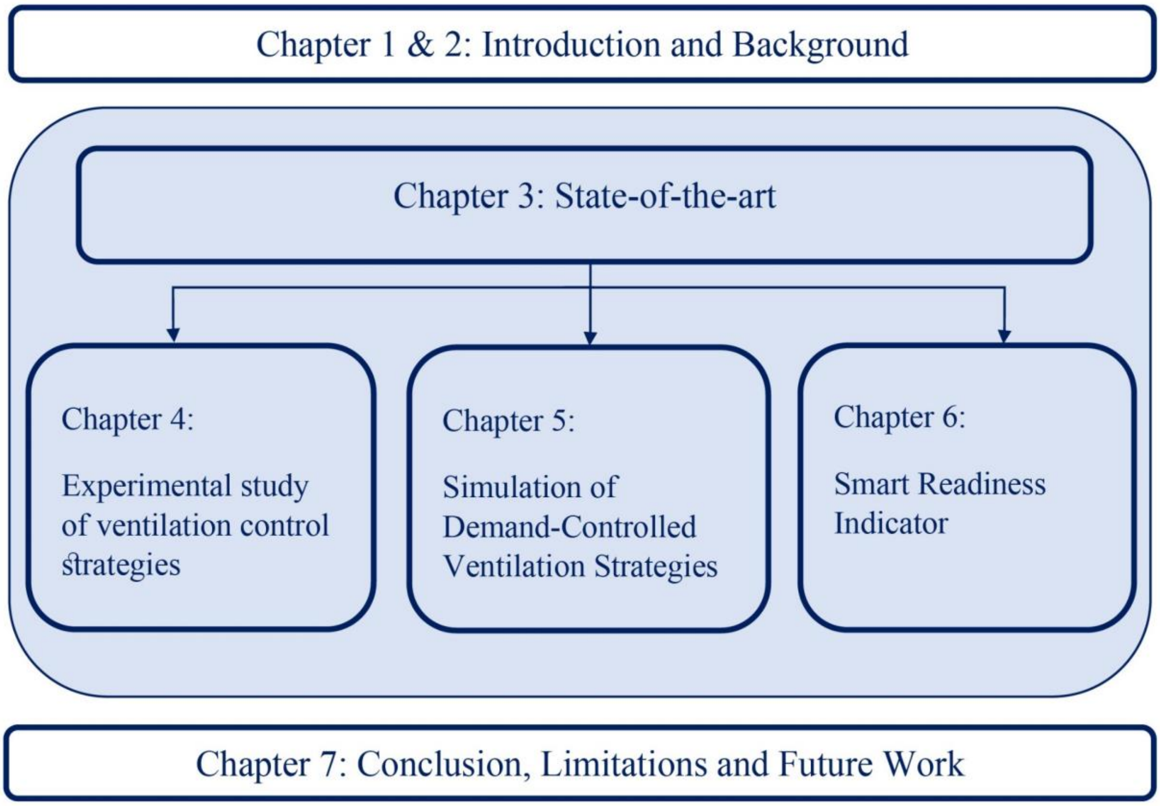

Figure 1.3 – Thesis outline

Chapter 2

BACKGROUND

2.1. Introduction

This chapter provides a preliminary information for the present research work. It addresses a simple overview on ventilation, its principles and elements, as well as indoor environmental quality, with a focus on indoor air quality.

New buildings and existing buildings that are undergoing renovation, are subject to minimum requirements for energy efficiency. Satisfying these requirements, however, must not be favored at the expense of the Indoor Environmental Quality (IEQ) and comfort of the occupants and visitors. The IEQ represents a domain that contains various sub-domains that affect the human health and comfort inside a building. The European standard EN 16798-1 [13] published in 2019 by the European Committee for Standardization, addresses specific requirements for indoor environmental parameters, such as thermal comfort, indoor air quality, noise, and lighting in regards to building design. This standard identifies the thermal environment as one of the IEQ criteria to be considered in rating the energy performance of buildings. The thermal environment inside a building can be controlled with more or less success, essentially depending on the constructive solutions and on the installed systems. Like the standards ASHRAE 55 [14] and ISO 7730 [15], the standard EN 15251 [16] (recently replaced by EN 16798-1) establishes criteria for the classification of the thermal environment of a building based on either the Predicted Mean Vote (PMV) or the Predicted Percentage of Dissatisfied (PPD) indices, originally proposed by Fanger [17].

In addition to influencing directly the thermal comfort of the occupants, the indoor thermal environment also influences the perception of air quality and can directly or indirectly produce unwanted effects on the health and productivity of building occupants [18]. The IAQ can have an influence both in the sensation of comfort and in the health of the occupants and visitors. In the past, up to the beginning of 20th century, it was considered that the building occupants were the main source of indoor pollution, due to human bio-effluents and/or tobacco smoke. In today's contemporary world, however, the indoor environment is made up of elements such as furniture and office equipment, internal partitions, surface paint and decorative pieces which contain and release chemicals to the indoor air and can present increased health risks to the occupants. The World Health Organization (WHO) published, in 2010, guidelines on protecting the public from health risks associated with exposure to chemicals commonly present inside buildings [19]. Other pollutants and contaminants commonly found in buildings are of a biological nature. Condensation spots provide good growing media for fungi, while micro-organisms such as the Legionella bacteria thrive in wet and warm environments such as those found in HVAC cooling towers or evaporative condensers, swimming pools, and hot water distribution systems.

Ventilation is the key issue for providing suitable indoor air quality as it is the process of replacing stale indoor air by fresh outdoor air. This process can be done either using mechanical equipment such as fans or blowers, being called mechanical ventilation, or without interaction of any mechanical means, known as natural ventilation. Mechanical ventilation generally uses electricity in order to provide proper ventilation rate. Nowadays, buildings are mostly mechanically ventilated [20], which increases energy consumption and the risk of climate change and global warming, in consequence. In natural ventilation, the air motion results from temperature and pressure difference between indoor and outdoor environment. Using wind driven or buoyancy driven forces, natural ventilation can have a noticeable sharing of required ventilation in buildings and causes notable energy saving. Moreover, naturally-ventilated buildings play a significant role in mitigating the risk of climate change because of their lower energy consumption and consequent CO_2 emission comparing to mechanically-ventilated buildings [21]. Besides natural and mechanical ventilation, there is another type of ventilation, known as hybrid ventilation or mixed-mode ventilation. This type is a combination of mechanical and natural ventilation. In hybrid ventilation, mechanical fans compensate the lack of natural ventilation when conditions are not favorable. Cao et al. [22] reviewed the performance of various ventilation methods such as mixing ventilation, displacement ventilation, personalized ventilation, hybrid air distribution, stratum ventilation, protected occupied zone ventilation, local exhaust ventilation and piston ventilation in buildings.

They pointed out that the ventilation effectiveness should be in accordance with the ventilation system purposes such as air distribution, air exchange rate, pollutant removal, heat removal and reduction of occupants' exposure to contaminants. For instances, when it is not possible to remove or control the source of indoor air pollution, and air filtration is ineffective, the pollutant concentration can be lowered by ventilation with fresh air, i.e. by diluting the indoor pollutants with outdoor fresh air or in case of bio-contaminants with air purification. The ventilation of a space with outdoor fresh air serves a number of purposes [23]:

- provision of oxygen for human respiration;
- dilution of gaseous contaminants to achieve short-term exposure limits to odors and vapors, and harmful chemical compounds;
- control of aerosols inside buildings using (filtered) outdoor air with lower aerosol concentration;
- control of internal humidity as outside air normally has lower moisture content;
- promotion of comfort and a healthy environment to the occupants by proper air distribution.

Throughout history, considering different climatic zones, as well as the daily and seasonal cycles of change, human beings have improved their capability to adjust to different outdoor conditions. Using fireplaces in the center of rooms for heating purposes and using wind catchers for cooling can be mentioned as examples. Discovery of fire, and using it for space heating might be earliest indoor air quality issue that humans faced. The solution that they found was to incorporate chimneys into their living space or even putting vent holes in the roofs to vent the smoke out. Besides, the airborne contaminants generated by human activities, the lack or poor existence of neither bath nor waste systems made early houses almost odorous and poor in terms of hygiene. Later, some let's say rules have been established. For instance, to build houses in specific orientations, with high ceilings and especial conditions for windows to allow natural ventilation. This was the earliest solution that human beings created to provide a better indoor condition for the occupants.

Dealing with indoor air quality was continuously an issue for human beings. In 20th century, mechanical ventilation and air conditioning technologies have been incorporated to provide the desired thermal comfort and indoor air quality. Various solutions have been developed and appeared in the building market but still the focus is on simpler, stronger and more energy-efficient solutions. Chapter 3 will further discuss the recent improvements that have happened in ventilation technologies and methods.

2.2. Ventilation

Ventilation is the process by which clean outdoor air is deliberately inserted to a space and stale air is removed. This might be accomplished by either natural or mechanical means. In addition to intentional ventilation, air unavoidably enters a building by the process of air infiltration. This is the uncontrolled flow of air into a space through gaps and cracks in the building envelope (wall, roof, window, door etc.). Ventilation is the key factor to maintain the indoor air quality in an acceptable level by providing fresh air including oxygen for occupants' metabolism and diluting pollutants. It can be also used for cooling purposes especially in dwellings. Therefore, ventilation is a main contributor to the health, well-being and comfort of buildings occupants.

Regarding the ventilation methods, as previously mentioned, buildings can be ventilated using one of the following three methods, namely, natural ventilation, mechanical ventilation and hybrid, also known as mixed-mode, ventilation [22].

Natural ventilation is the process of exchanging air between indoor and outdoor environment without using any mechanical means, mainly based on natural driving forces like wind, thermal buoyancy or both. In addition to driving forces, natural ventilation concept includes principles and elements. Single-sided, double-sided (cross) and stack ventilation are natural ventilation principles. Furthermore, natural ventilation elements such as wind towers, chimneys, double-skin façades, windows, and vent openings are needed to achieve the required ventilation in a space. The main drawback of natural ventilation is the matter of control. Actually, the driving forces cannot be predicted and this may cause insufficient or over ventilation which anyhow will result in discomfort.

Mechanical ventilation is the process of exchanging air between indoor and outdoor environment using mechanical fans or ventilators. Fans are installed in windows or walls, or in air ducts for supplying air into (supply ventilation), or exhausting air from a space (extract ventilation), or both (balance supply/extract ventilation). Unlike natural ventilation, the main advantage is the control over the system, in which the air flow rate can be controlled.

Hybrid ventilation counts on natural driving forces to provide the desired air flow rate and uses mechanical ventilation when the natural ventilation flow rate is too low or insufficient. In case hybrid ventilation is well organized and implemented in a building, the occupants can rarely experience discomfort.

Ventilation is responsible for an important portion of energy delivered to buildings. As reported by [24], approximately 30% of the energy delivered to buildings is used by the ventilation and exfiltration air streams. It is even more critical in high thermally insulated buildings, where the amount of airborne energy loss can represent a significant part of the overall energy demand. This implies the importance of considering energy use in ventilation models. Energy consumption associated to ventilation can be reduced by developing various energy-efficient ventilation methods. Minimizing preventable indoor pollutants such as tobacco smoke which lowers the need for ventilation, using heat recovery systems, using air pre-conditioning and more importantly applying demand controlled ventilation will reduce the energy use associated to ventilation.

During the development of energy-efficient ventilation methods, an important issue to be taken into account is that satisfying energy efficiency in these methods must not be at the expense of the indoor environmental quality.

2.3. Indoor environmental quality

The IEQ encompasses the thermal environment, the IAQ, as well as other health, safety and comfort aspects such as ergonomics, acoustics and lighting. Indoor environmental quality contains the factors that affect human life inside a building. It is related to the coexistence of thermal comfort, indoor air quality, visual comfort and acoustic comfort. The indoor environmental quality can be affected by several factors which are categorized as outdoor conditions, building elements, building services and occupant activities. Figure 2.1 shows an overview of the indoor environmental quality indices, the factors that affect it and their risk for human health and well-being.

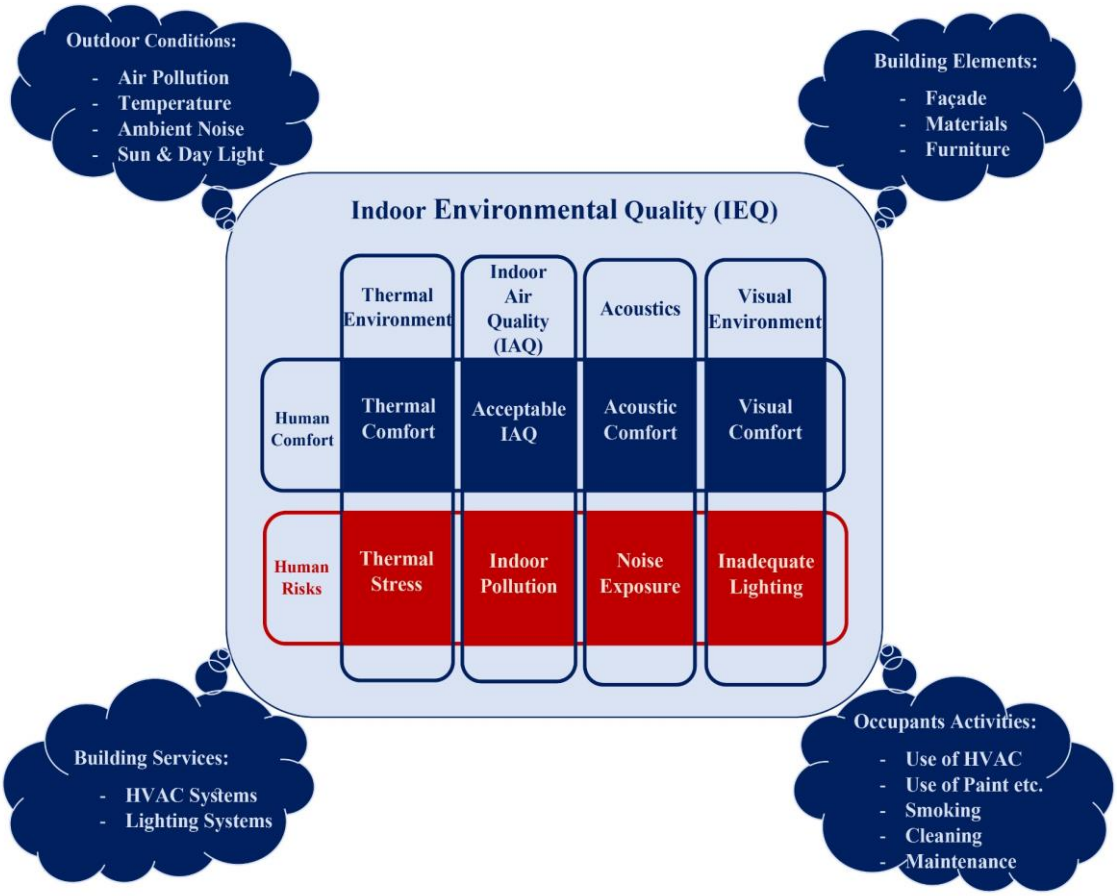

Figure 2.1 – Factors that affect IEQ and their risk for human health and comfort.

The thermal environment and the IAQ, together, make up Indoor Climate (IC). During the ventilation process, these are the IEQ factors that are more affected.

Thermal comfort is the state of mind at which occupant expresses satisfaction with its surrounding thermal environment without requiring a noticeable effort to maintain its body temperature. In other word, thermal comfort is the perceived sensation of satisfaction with the thermal environment. Fanger [17], introduced predicted mean vote (PMV), as an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale, presented in table 2.1. Six main parameters act in the function to calculate the PMV, namely, metabolic rate, clothing insulation, air temperature, mean radiant temperature, relative air velocity and relative humidity (see figure 2.2).

Table 2.1 – The PMV seven-point sensation scale.

Cold	Cool	Slightly cool	Neutral	Slightly warm	warm	hot
-3	-2	-1	0	+1	+2	+3

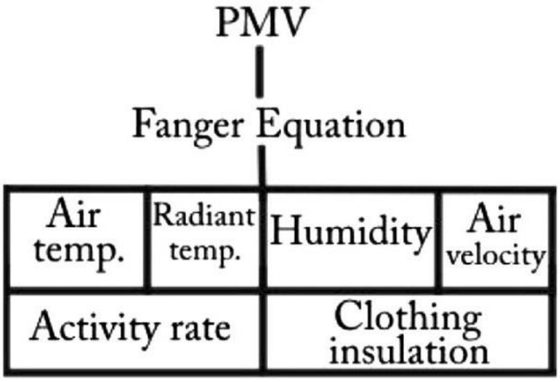

Figure 2.2 – Parameters acting in the function to calculate the PMV.

Fanger [17] also defined another index, predicted percentage of dissatisfied (PPD) that represents the percentage of people that vote too cold or too warm. The PPD index quantifies the expected percentage of dissatisfied people with a given thermal environment. This varies between 5% and 100%, in a symmetrical way as a function of the PMV index. The lowest value of 5% corresponds to an ideal environment, neutral in relation to thermal sensation, and reflects the fact that, in a large group of people, there will always be someone who expresses dissatisfaction, even if the majority of people feel most comfortable in that environment. In practice, it is not possible to provide a thermal environment in a room that would satisfy every single person, as different persons have different metabolism, clothing and preferences about their thermal environment. Therefore, a level of thermal comfort that can satisfy the majority of occupants should be provided. Figure 2.3 shows the PPD curve as a function of the PMV index.

Good *indoor air quality* may be defined as air which is free of pollutants that cause irritation, discomfort or ill health to occupants. There are several definitions for IAQ but, generally, it is a descriptor of the amount and the type of contaminants in the air [25]. Moreover, according to the ASHRAE 62.1 definition [26], acceptable indoor air is the air in which the concentration of pollutants is not in an identified harmful level and the occupants (80% or more) do not express dissatisfaction. There are, however, large differences between occupants’ preferences. Some people are more sensitive to the IAQ than others, therefore, more likely to feel dissatisfied. Like PMV and PPD in thermal comfort, Percentage Dissatisfied (PD) can be used as a subjective method to measure the level of IAQ [27]. The European standards EN 16798-1 [13] and EN CR 1752 [28], published by European Committee for Standardization, classified IAQ into different categories according to a graph showing the relation between outdoor fresh air flow rate per person and the PD in which higher outdoor flow rates results in better IAQ and a lower number of dissatisfied occupants (see figure 2.4).

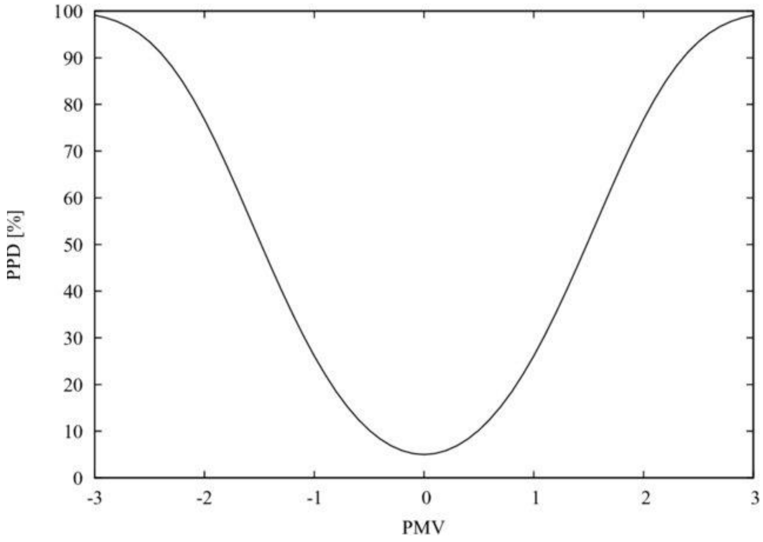

Figure 2.3 – Predicted percentage dissatisfied versus predicted mean vote as two methods of determining thermal comfort in a population.

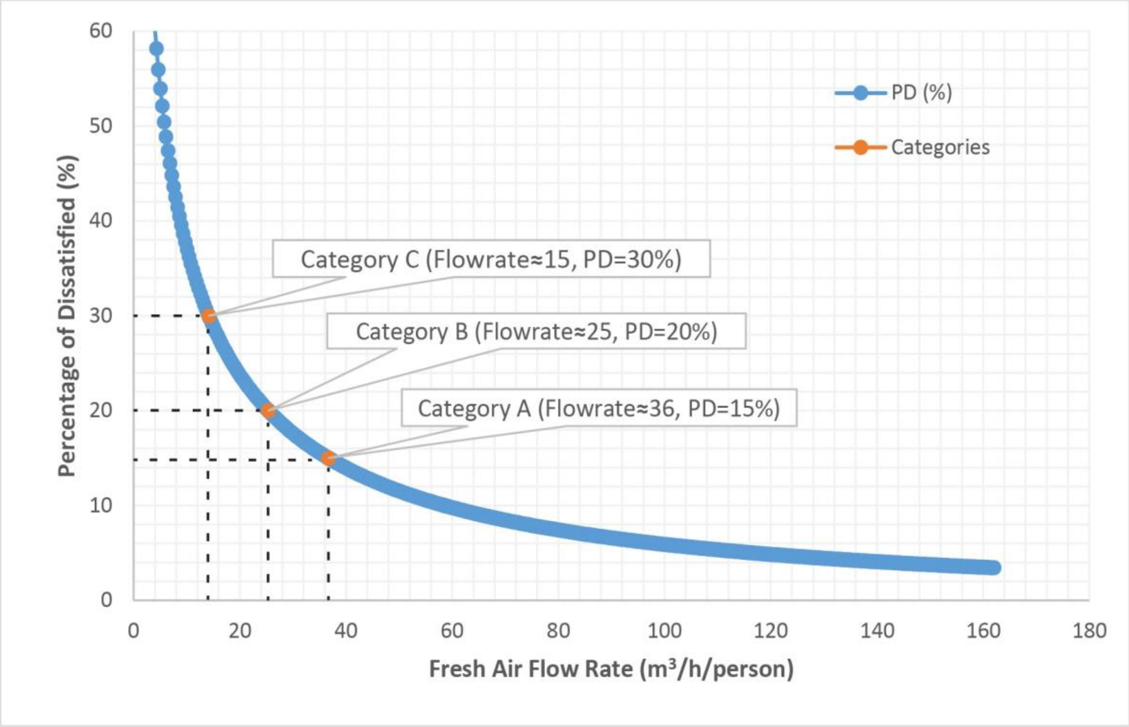

Figure 2.4 – Percentage dissatisfied versus fresh air flow rate and the three indoor air quality categories (reproduced from [29]*).*

As mentioned earlier, IAQ is very fundamental because an environment with poor IAQ can cause health, productivity and comfort issues for its occupants. Since nowadays, most of people’s time is being spent in indoor environments, a poor indoor air quality can cause syndromes such as sick building syndrome (SBS) which involves several symptoms such as dry throat, nausea, lack of concentration, headache, eye irritation etc. fundamental reasons for SBS could be poor ventilation, poor infiltration and therefore, excess of contaminants which will cause discomfort for building occupants.

Contaminants can be categorized as indoor and outdoor contaminants. Those entering the space from outdoor environment are normally generated by industrial sources (SO, NO VOCs etc.), street traffic (CO, lead, carbon dusts etc.), soil borne (radon, methane and moisture), fungal and pollens. The indoor contaminants are carbon dioxide, generated by human metabolism, tobacco smoke, cooking process etc., carbon monoxide as a result of incomplete combustion, mainly in the kitchen, bio-effluents, generated by human respiration, transpiration and sweating, VOCs, from paint, glue, furniture fabrics etc. A list of selected pollutants is presented in Table 2.2, along with the source, the known health risks and the recommended exposure limits.

As the contaminant sources are both from outdoor and indoor environment, so it is important to first control the outdoor air pollutant by techniques such as filtration of intake air, avoid ventilation in polluted peaks and improving air-tightness of buildings. However, urban pollution, especially from high traffic densities, remains a problem. Additionally, as ventilation plays an essential role in securing good indoor air quality, more attention has to be paid to efficiently ventilate the space in an optimal manner.

The ventilation rates necessary for dilution are determined by the pollutants’ generation rates. In the US, the ventilation rates are established by adding the flow rates necessary to dilute each pollutant whereas in the EU it is common practice to choose the maximum of those ventilation rates. The majority of the existing regulations on building ventilation and IAQ, however, fix the required ventilation rates according to comfort criteria of 20% PD for people that enter the indoor space, i.e. for occupants whose sensory perception has not yet adapted to that environment. This will produce ventilation rates that reduce to acceptable levels the effects of odors and sensory irritants from human bio-effluents, and pollutants emitted from the building fabric, the building systems and its furnishings. In the state-of-the-art chapter, different ventilation methods studied by several research work has been extensively reviewed.

Table 2.2 – List of selected pollutant sources, risks and limits [19].

Contaminant	Source	Potential risk	Exposer limits
Carbon Monoxide	Combustion (indoor/outdoor)	Acute reduction of exercise tolerance; Increase in symptoms of heart disease	8 hours - 10 mg/m^3
Formaldehyde	Pressed wood, fiberboard (indoor)	Sensory irritation	0.1 mg/m^3 (30 minute average)
Nitrogen Dioxide (NO_2)	Combustion (indoor/outdoor)	Respiratory symptoms, bronchoconstriction, increased bronchial reactivity, airway inflammation and decrease in immune defense, respiratory infection	40 µg/m^3 (annual average)
Radon	Soil (indoor/outdoor)	Lung cancer; other cancers	4 pCi/litre
Sulphur Dioxide (SO_2)	Industry- unvented space heaters (indoor/outdoor)	Lung cancer, Respiratory symptoms	80mg/m^3
Total Volatile Organic Compounds (TVOC’s)	Building materials Furnishings (indoor/outdoor)	eye, nose and throat irritation Higher exposer cause irritation of the lungs, damage liver, kidney, or central nervous system	<300mg/m^3 (good) 300 - 3000mg/m^3 (OK) > 3000mg/m^3 (complaints)
Ozone	Electrostatic appliances (indoor/outdoor)	coughing and sore or scratchy throat	60 µg/m^3
PM 2.5	Combustion (indoor/outdoor)	Cancer	15 µg/m^3
PM 10	Carpeting Gypsum board and concrete, stove, fireplace, cigarettes	Allergic symptoms	50 µg/m^3

Chapter 3

STATE-OF-THE-ART

3.1. Introduction

An enormous amount of research has been carried out on a global scale on all aspects of ventilation and its energy use. Aspects such as natural ventilation, demand controlled ventilation, energy-efficient ventilation strategies etc. that are absolutely interconnected and can rarely be dealt with separately. In this chapter, a great quantity of research studies on ventilation methods and indoor environmental quality in buildings was reviewed, with special focus on those related to energy saving and improving indoor climate as well as the correlation between ventilation and health and productivity.

3.2. Literature Review Up to 2016, Paper I: Towards Sustainable, Energy-Efficient and Healthy Ventilation Strategies in Building: A Review

A comprehensive literature review has been carried out about energy-efficient ventilation strategies, natural ventilation, hybrid ventilation, influence of occupants' behavior on ventilation and energy consumption as well as the correlation between ventilation and health and productivity of the occupants in 2016. The outcome of this literature review has been published as an article in the Renewable and Sustainable Energy Reviews Elsevier Journal, titled "Towards sustainable, energy-efficient and healthy ventilation strategies in building: A review".

Author Contributions: B. Chenari as the main author, conducted the research, reviewing dozens of articles published in international scientific journals, conference proceedings, reports, book chapters, standards, etc., gathering and collecting data; The paper *manuscript was written together with J. Dias Carrilho; and M. Gameiro da Silva supervised the work, reviewed the contents and contributed to enhancing its quality.*

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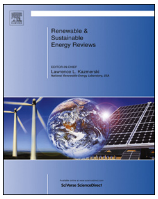

Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review

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ABSTRACT

Energy demand has been increasing worldwide and the building sector represents a large percentage of global energy consumption. Therefore, promoting energy efficiency in buildings is essential. Among all building services, Heating, Ventilation and Air Conditioning (HVAC) systems are significantly responsible for building energy use. In HVAC, ventilation is the key issue for providing suitable Indoor Air Quality (IAQ), while it is also responsible for energy consumption in buildings. Thus, improving ventilation systems plays an important role not only in fostering energy efficiency in buildings, but also in providing better indoor climate for the occupants and decreasing the possibility of health issues in consequence. In the last decades, many energy-efficient ventilation methods are developed by researchers to mitigate energy consumption in buildings. This paper reviews scientific research and reports, as well as building regulations and standards, which evaluated, investigated and reported the development of energy-efficient methods for ventilation in buildings. Besides energy-efficient methods such as natural and hybrid ventilation strategies, occupants' behaviours regarding ventilation, can also affect the energy demand in buildings. Therefore, the influence of occupants' behaviour on the energy use and the correlation between ventilation and the occupants' health and productivity were also considered. The review showed that ventilation is interrelated with many factors such as indoor and outdoor conditions, building characteristics, building application as well as users' behaviour. Thus, it is concluded that many factors must be taken into account for designing energy-efficient and healthy ventilation systems. Moreover, it should be mentioned that utilizing hybrid ventilation in buildings integrated with suitable control strategies, to adjust between mechanical and natural ventilation, leads to considerable energy savings while an appropriate IAQ is maintained.

Contents

Abbreviations: HVAC, Heating, Ventilation, and Air Conditioning; IAQ, indoor air quality; IEQ, Indoor Environmental Quality; PMV, Predicted Mean Vote; PPD, Predicted Percentage of Dissatisfied; WHO, World Health Organization; PD, percentage dissatisfied; CFD, computational fluid dynamics; TAS, thermal analysis simulation; LES, large eddy simulation; TRV, Thermal Resistance Ventilation; RBC, rule-based control; MPC, Model Predictive Control; DCV, demand-controlled ventilation; SBDCV, sensor based demand-controlled ventilation; MATLAB, MATrix LABoratory; SIMBAD, simulator of building and devices; RLF, residential load factor; RH, relative humidity; CAV, constant air volume; VAV, variable air volume; IR, infra-red; ASHRAE, American Society of Heating, Refrigerating, and Air-Conditioning Engineers; SBS, sick building syndrome; ppm, parts-per-million; nZEBs, nearly zero energy buildings; ISO, International Organization for Standardization; BBR, Swedish Building Standards

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1. Introduction

Energy demand has been increasing worldwide, therefore, the environmental impact resulting from energy production and consumption has become a major public concern. Buildings are one of the biggest contributors to energy consumption in the modern world. Energy consumption in buildings refers to many factors such as lighting, domestic and commercial appliances as well as HVAC systems. Many innovative solutions have been proposed for energy-efficient buildings, and there is an ongoing effort in promoting and demonstrating their energy saving potential. The majority of these solutions, however, is directed towards new buildings and future building designs, and is difficult to implement in existing buildings. Across Europe, only about 1% of the building stock is currently being renovated each year, and there have been recent renewed calls for higher renovation rates, as high as 3% [1]. These higher rates need to be sustained for the next 40 years if the long term carbon and economic goals set out in the context of the European Economic Recovery Plan are to be met. Retrofitting existing buildings with energy-efficient solutions has been identified by the European Commission as one of the research priorities in the coming decades [2], and the EU policy for sustainability includes ambitious targets, not only for increased energy efficiency (thus reducing wastage) but also, and more importantly, for reducing the overall energy consumption [3].

Among all building services, HVAC systems play a significant role in building energy consumption [4,5]. As much as 40% of the energy consumed in office buildings in the EU is used by HVAC systems [6]. These systems are aerodynamic circuits consisting of fans and ductwork to supply fresh air from the exterior and to remove polluted air from the building. Depending on their complexity, they can include heat exchangers and humidifiers for conditioning the air, mixing chambers for adding fresh air to the circuit, filters for cleaning the air, dampers for regulating the flow velocity, and silencers to attenuate fan noise. These components, in turn, introduce pressure losses, which must be overcome with higher fan power. Centralized HVAC systems are standard in modern buildings while split-system air conditioning units are commonly installed in older buildings that do not have ventilation ductwork. Despite HVAC systems having reached a high level of technological maturity, coupled with the benefits of a constant and easily controllable flow, ventilation and air conditioning energy consumption in buildings has been increasing in the EU, particularly in the southern countries, not only because there are more systems in operation but also because there has been a generalized preference for installing higher power, over-dimensioned systems. According to the Directive 2010/31/EU [7], Energy Performance of Buildings Directive (EPBD), all new buildings in EU member states must be nearly-Zero Energy Buildings (nZEBs) by 2020 (for buildings occupied or owned by public authorities by 2018). Also, all EU member states shall draw up national plans such as retrofitting existing buildings to increase the number of nZEBs. Energy-efficient design for HVAC systems in new buildings and efficient renovation of HVAC systems during retrofitting process of existing buildings act positively to achieve the EPBD targets.

New buildings, and existing buildings that are undergoing renovation, are subject to minimum requirements for energy efficiency. Satisfying these requirements, however, must not be favoured at the expense of the Indoor Environmental Quality (IEQ) and comfort of the occupants and visitors. The IEQ encompasses the thermal environment, the IAQ, as well as other health, safety and comfort aspects such as ergonomics, acoustics and lighting. The thermal environment and the IAQ, together, make up the indoor climate. Thermal comfort is the perceived sensation of satisfaction with the thermal environment. In practice, it is not possible to provide a thermal environment in a room that would satisfy every single person, as different persons have different metabolism, clothing and preferences about their thermal environment. Therefore, a level of thermal comfort that can satisfy the majority of occupants should be provided.

The thermal environment inside a building can be controlled with more or less success, essentially depending on the constructive solutions and on the installed systems. The European standard EN 15251 [8], published in 2007 by the European Committee for Standardization, identifies the thermal environment as one of the five IEQ criteria to be considered in rating the energy performance of buildings. Like the standards ASHRAE 55 [9] and ISO 7730 [10], the EN 15251 standard establishes criteria for the classification of the thermal environment of a building based on either the Predicted Mean Vote (PMV) or the Predicted Percentage of Dissatisfied (PPD) indices, originally proposed by Fanger [11].

In addition to influencing directly the thermal comfort of the occupants, the indoor thermal environment also influences the perception of air quality and can directly or indirectly produce unwanted effects on the health and productivity of building occupants [12]. The IAQ can have an influence both in the sensation of comfort and in the health of the occupants and visitors. In the past, up to the beginning of 20th century, it was thought that the building occupants were the main source of indoor pollution, due to human bio-effluents and/or tobacco smoke. In today's contemporary world, however, the indoor environment is made up of elements such as furniture and office equipment, internal partitions, surface paint and decorative pieces which contain and release chemicals to the indoor air and can present increased health risks to the occupants. The World Health Organization (WHO) published, in 2010, guidelines on protecting the public from health risks associated with exposure to chemicals commonly present inside buildings. Other pollutants and contaminants commonly found in buildings are of a biological nature. Condensation spots provide good growing media for fungi, while micro-organisms such as the *Legionella* bacteria thrive in wet and warm environments such as those found in HVAC cooling towers or evaporative condensers, swimming pools, and hot water distribution systems.

According to Ref. [13], there are several definitions for IAQ but, generally, it is a descriptor of the amount and the type of contaminants in the air. Moreover, according to the ASHRAE definition [14], acceptable indoor air is the air in which the concentration of pollutants is not in an identified harmful level and the occupants (80% or more) do not express dissatisfaction. There are, however, large differences between occupants' preferences. Some people are more sensitive to the IAQ than others, therefore, more likely to feel dissatisfied. Like PMV and PPD in thermal comfort, Percentage Dissatisfied (PD) can be used as a subjective method to measure the level of IAQ [15]. The European standards EN 15251 [8] and EN CR 1752 [16], published by European Committee for Standardization, classified IAQ into different categories according to a graph showing the relation between outdoor fresh air flowrate per person and the PD in which higher outdoor flowrates results in better IAQ and a lower number of dissatisfied occupants.

Ventilation is the key issue for providing suitable indoor air quality as it is the process of replacing stale indoor air by fresh outdoor air. This process can be done either using mechanical equipment such as fans or blowers, being called mechanical ventilation, or without interaction of any mechanical means, known as natural ventilation. Mechanical ventilation generally uses electricity in order to provide proper ventilation rate. Nowadays, buildings are mostly mechanically ventilated [17], which increases energy consumption and the risk of climate change and global warming, in consequence. In natural ventilation, the air motion results from temperature and pressure difference between indoor and outdoor environment. Using wind driven or buoyancy driven forces, natural ventilation can have a noticeable sharing of required ventilation in buildings and causes notable energy saving. Moreover, naturally-ventilated buildings play a significant role in mitigating the risk of climate change because of their lower energy consumption and consequent CO_2 emission comparing to mechanically-ventilated buildings [18]. Besides natural and mechanical ventilation, there is another type of ventilation, known as hybrid ventilation or mixed-mode ventilation. This type is a combination of mechanical and natural ventilation. In hybrid ventilation, mechanical fans compensate the lack of natural ventilation when conditions are not favourable. Cao et al. [19] reviewed the performance of various ventilation methods such as mixing ventilation, displacement ventilation, personalized ventilation, hybrid air distribution, stratum ventilation, protected occupied zone ventilation, local exhaust ventilation and piston ventilation in buildings. They pointed out that the ventilation effectiveness should be in accordance with the ventilation system purposes such as air distribution, air exchange rate, pollutant removal, heat removal and exposure. For instances, when it is not possible to remove or control the source of indoor air pollution, and air filtration is ineffective, the pollutant concentration can only be lowered by ventilation with fresh air, i.e. by diluting the indoor pollutants with outdoor fresh air. The ventilation of a space with outdoor fresh air serves a number of purposes [20]:

- provision of oxygen for human respiration;
- dilution of gaseous contaminants to achieve short-term exposure limits to odours and vapours, and harmful chemical compounds;
- control of aerosols inside buildings using (filtered) outdoor air with lower aerosol concentration;
- control of internal humidity as outside air normally has lower moisture content;
- promotion of comfort and a healthy environment to the occupants by proper air distribution.

The ventilation rates necessary for dilution are determined by the pollutants' generation rates. In the US, the ventilation rates are established by adding the flow rates necessary to dilute each pollutant whereas in the EU, it is common practice to choose the maximum of those ventilation rates. The majority of the existing regulations on building ventilation and IAQ, however, fix the required ventilation rates according to comfort criteria of 20% PPD for people that enter the indoor space, i.e. for occupants whose sensory perception has not yet adapted to that environment. This will produce ventilation rates that reduce to acceptable levels the effects of odours and sensory irritants from human bio-effluents, and pollutants emitted from the building fabric, the building systems and its furnishings.

2. Energy-efficient ventilation methods

As aforementioned, there are many ongoing research focused on developing energy-efficient ventilation model for buildings. Some studies solely focused on natural ventilation and passive methods in order to make the process of ventilation more efficient, but as natural ventilation is not always available and/or suitable, more recent studies focused on hybrid ventilation. Hybrid ventilation excludes the drawbacks of both natural and mechanical ventilation systems while includes their advantages [21]. Another group of studies developed various ventilation control strategies that simultaneously provides acceptable indoor climate quality levels and lowers energy consumption. They believed that presence of control systems can increase the influence of hybrid and natural ventilation in improving energy saving in buildings.

In the last two decades, many studies focused on developing natural ventilation design for buildings and utilize it as long as possible, in order to decrease the amount of energy consumed by ventilation systems. Perhaps the single most pertinent question faced by building designers wishing to take advantage of natural ventilation is how to control the rate of air exchange with the exterior to provide the required amount of fresh air to the building while simultaneously removing excess heat in the cooling season or minimizing heat losses in the heating season. Whereas constant ventilation rates are easily guaranteed by mechanical systems, natural ventilation requires a different approach since the flow velocity and direction at the openings is not known beforehand. In addition, the way air moves in and around a building is an unsteady, complex phenomenon, being highly affected by design choices and very much dependent on the dynamics of both the internal and the external environment.

Natural ventilation is the process of exchanging air between indoor and outdoor environment without using mechanical systems, mainly based on wind, buoyancy or both. They are known as natural ventilation driving forces. Thermal buoyancy driven ventilation takes place as a result of density difference between indoor and outdoor air that is a consequence of temperature differences. This indicates the importance of opening position in buildings envelop. The wind driven ventilation results from pressure differences in the building façade, which can be inward or outward depending on position of openings, located in windward or leeward façade, respectively. In a study that developed a simple tool to assess the effects of wind and its direction for providing natural ventilation in a built environment, wind, air temperature and humidity have been introduced as the main parameters in human comfort [22].

Researchers from a variety of fields have been studying, analyzing and perfecting natural ventilation techniques for a few decades [23]. However, predicting and controlling the indoor environment in window-based ventilation systems remains essentially an open issue. Existing research outputs of relevance include theoretical and experimental work on the fluid mechanics of natural ventilation [24]; the physics of indoor thermally stratified flows [25]; the prediction of pressure coefficients on building façades [26]; flow and dispersion patterns in urban street canyons [27]; the positive and negative impacts of ventilation on occupants' health and productivity [28] the behavioural aspects of window opening by occupants [29]; the ingress of environmental noise through natural ventilation openings [30]; the impact of future climate change on the performance of passive cooling strategies [31] and the current barriers and difficulties faced by natural ventilation in gaining regulatory acceptance [32].

Linden [24] reviewed the work of several researchers on the mechanisms that drive and control natural ventilation. Early work was mainly concerned with wind-driven flows. A scale model of a building was placed in a wind tunnel, and the pressure distribution on the surface of the building was measured for different directions of the incoming flow. The pressure coefficients determined in this way were, and still are, used to calculate the flow rates through openings at different positions of the building façade. From this information, the flow rates through the building can be related to the wind speed and direction, but there is little information on what happens in the interior of the building.

Later, as a result of problems with interior heat gains, researchers became interested in flows driven by differences in the air temperature. These temperature differences produce buoyancy forces that drive the flow through openings in the façade. Depending on the location of these openings, the incoming flow can be in the form of a turbulent plume that will tent to mix the air within the space, or it can be a displacement type of flow, where the cooler outside air falls towards the floor, pushes warm air up and out through the upper openings. A well-defined stratified flow is established, and this flow regime has been shown experimentally to be a stable and predominant feature in flows driven by temperature differences [33]. While, for the same temperature difference and opening area, displacement ventilation leads to higher air exchange rates than mixing ventilation, the mixing type of flow produces a relatively uniform temperature distribution in the space, whereas the displacement type of flow, because of stratification, results in sensible temperature variations in the space. This, in turn, is associated with cold drafts, which is a major concern because of the potential for causing local discomfort to the occupants, particularly during the heating season.

Heiselberg and Perino [34] argued that an effective strategy for single-sided, buoyancy driven, ventilation is to explore the transient features of the initial flow, as opposed to traditionally leaving the windows open for a long time. They experimentally show that airing by open windows is most effective in the initial transient phase, the flow regime being of the displacement type, with high airflow rates and high ventilation efficiency. The air temperature decreases rapidly when the windows are open, until it reaches a quasi-steady state which is typically the average value between the indoor and the outdoor temperatures. Highest air velocities were found at the floor level, which means that the risk of discomfort by cold drafts is mainly at the floor level. They conclude that the optimum use of windows for buoyancy-driven ventilation should be a relatively short opening time and high opening frequency.

Other types of buoyancy flows, e.g. caused by differences in moisture content between the interior and the exterior air, have not been found in the literature and there remains a question as to what extent these can play a role in determining the ventilation rates. Andersen [35] does note, however, that when adding both heat and moisture to a parcel of air, the effect of heat will be dominant in changing the air density, and that only in very extreme conditions will an error over 10% be incurred in neglecting the effect of moisture differences on natural ventilation rates.

When there is a combined effect of wind and buoyancy, the incident wind may assist in increasing the ventilation rates due to the pressure drop between the windward and leeward openings [36], but this is not necessarily the case in opposing wind and buoyancy forces. In the latter situation the behaviour of the internal flow can be quite complex, with transitions between displacement and mixing regimes. Hunt and Linden [37] investigated the effect of an opposing wind on the flow in an enclosure with a heat source located on the floor. The enclosure had ventilation openings located at high level on the windward side and at low level on the leeward side. They found that two stable steady flow and a third unstable steady flow regimes could be established depending on the relative magnitudes of the wind-driven and buoyancy driven velocity fields. The transition between the two stable regimes shows hysteretic behaviour. Mostly, the combination of both wind and buoyancy driven ventilation occurs at the same time. However, they can oppose or complement each other depending on the position of the opening and the wind direction [38,39]. Through natural ventilation process, domination of wind speed or temperature difference (buoyancy effect) depends on the ratio between forces and wind direction [40].

Most of the analysis tools reported in the literature have been developed for steady-state conditions (e.g., see [41]). Building designers will have an idea of the required air exchange rates and use semi-empirical formulae and rules for determining the size and placement of the openings. These formulae are typically given in terms of the difference between the inside and outside air temperature. Larsen and Heiselberg [40] developed a semi-empirical expression for the combined wind and buoyancy effect which, they claim, can predict flow rates with an average error of 23%, a substantial improvement over the average error of 29% achieved by previous researchers.

Besides the classification taking into account different driving forces, natural ventilation can be done based on different principles such as, single-sided ventilation, cross ventilation or stack ventilation, as shown in Fig. 1. They are known as natural ventilation principles and show the way that indoor and outdoor environments are connected. Fordham [42] expressed his experience as an architect in designing buildings with controllable natural ventilation. He discussed various issues relevant to ventilation in building design, such as single-sided and cross ventilation, orientation of the building for absorbing heat from the sun and being oriented windward or leeward. Later, it was noted that the design phases of naturally-ventilated buildings are more complicated than those of mechanically ventilated, which is mainly due to different principles of natural ventilation [21]. High uncertainties associated with the natural ventilation driving forces and the random character of weather conditions are the main reasons for making the design phase more complex.

Single-sided ventilation happens when the openings are located on only one façade of a ventilated space. It mainly provides lower ventilation rate as well as less penetration of airflow comparing with other schemes. Providing openings in different heights with greater vertical size is the only way to strengthen the airflow rate and its penetration length [39]. It was also highlighted, as a result of an experimental study, that in a naturally ventilated space

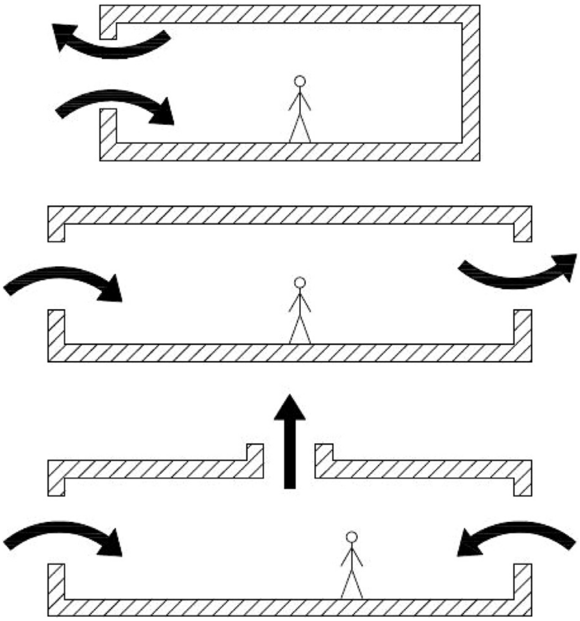

Fig. 1. Schematic view of different natural ventilation principles. Adapted from [18].

the higher the inlet supply air is located above the room floor, the better is the thermal comfort provided [43]. Recently, Chu et al. [44] experimentally assessed the wind-driven natural ventilation through two openings on the same external wall. They used the tracer gas decay method to measure the air exchange rate and highlighted that the exchange rate in naturally-ventilated buildings with two opening on the same wall is greater than those with one opening.

Cross ventilation occurs in spaces that normally have openings on opposite façades. In this case, the outdoor air enters the space from the windward façade and leaves from the leeward side. The position of opening is not only significant in single-sided ventilation but it is also important in cross ventilation [45]. A recent study [46] has assessed the influence of opening shape and position on efficiency of natural cross ventilation in buildings using a CFD model. In cross ventilation, there is a rule of thumb to have effective cross ventilation, which says that the building length (L) should be less than five times of ceiling height (H). Recently, Chu and Chiang [47] numerically assessed the reasons behind this rule of thumb. They revealed that ventilation rate of buildings with $L/H \geq 11$ is considerably less than those with $L/H \leq 2.5$, due to smaller pressure difference between windward and leeward facades in long buildings as well as the internal friction, which is higher in long buildings. They also pointed out that location of openings is significantly influential in cross ventilation in buildings.

Cross ventilation does not have always better performance comparing to single-sided ventilation. For instance, a study [39] assessed and compared different ventilation strategies in a narrow multi-storey office building. It has been concluded that, for cooling purposes, night ventilation (both single-sided and cross ventilation) can cause approximately 40% of energy saving while in day-time ventilation, single-sided ventilation performs much more efficiently than cross ventilation. Finally, it is recommended to use cross ventilation when favourable wind (both speed and direction) is available and single-sided ventilation when there is unfavourable wind.

Stack ventilation takes place when the airflows enter the ventilated space through openings located on different façades and go out through an opening located in a high level such as a chimney. For instance, solar chimneys, that have considerable effects on decreasing heat gains and enhancing natural cooling and ventilation, work with stack effects [48]. There are many studies about natural ventilation using solar chimneys. Recently, Jing et al. [49] developed an experimental study to predict the airflow rate through solar chimneys considering different gap-to-height ratios ranging from 0.2 to 0.6. They mentioned that the currently available method over predicts the airflow rate of the solar chimneys, especially in large gap-to-height ratios. Their experiments also showed that the maximum flowrate has been obtained in gap-to-height ratio around 0.5.

Besides solar chimneys, there are also many other characteristic elements or features for natural ventilation such as atria, wind towers, wind scoops, wind catchers, ventilation shafts, chimneys, double skin façades, ventilation openings and windows. Table 1 indicates advantages and disadvantages of these elements as well as surveyed studies focused on them.

Atrium is the most common feature to capture natural ventilation and daylighting in buildings. It is a space with glassy roof, typically in big commercial buildings, located in the core or the sides. Although atria have existed from ancient times, modern designs have been developed by many architecture researchers. A comprehensive review carried out on investigating natural ventilation in atria is available in [50].

Wind scoop is another roof top natural ventilation feature, which can capture the wind and let it enter the ventilated space. Similarly, wind towers are devices used for ventilation and cooling. It was used since ancient times in arid regions, especially in Persian Gulf countries. The one developed by Iranians, so called "Badgir", is able to both supply the air in and extract the air out of the buildings, simultaneously [21]. Wind catchers, has a sustainable passive technology for cooling and ventilation notably attracted attention of researchers in recent decades. An assessment of different types of traditional as well as modern wind tower designs such as wind vent and wind catchers is available in [51,52]. Moreover, a recent review on wind tower technology accompanied with a new design for wind tower has been conducted by [53]. They proposed a wind tower to be installed on roof in the direction of maximum prevalent wind speed. It is also capable to rotate based on the wind direction. They also listed some advantages of their proposed system such as easy installation, low maintenance cost, simple technology, capability of rotation according to the wind direction, energy saving, etc.

Double-skin façade is another natural ventilation feature that can be integrated into buildings. Basically, it is a second layer façade made by glass, which is useful for capturing daylighting, protecting against noise and preheating the supply air in sunny days.

A recent review on natural ventilation applications over the building façade elements in tropical regions [54] revealed that ventilation shaft, window-to-wall ratio and building orientation are main factors in capturing natural ventilation and should be carefully considered in design and construction phase. Natural ventilation may, not only provide sufficient IAQ using less energy, but sometimes it can also provide suitable thermal comfort level. For example, natural ventilation can be used for cooling the building interior whenever the outdoor temperature is lower than indoor temperature, cooling building envelopes based on thermal mass concept and cooling of occupants body by convection and evaporation [21]. The night ventilation, with purpose of cooling down indoor air as well as building structure, is a well-known passive cooling and ventilation strategy, and many researchers developed studies focusing on it [55–57]. Additionally, Wang et al. [58] recommended the use of night ventilation as an energy-efficient approach to improve indoor climate in moderate climates, especially for heavy construction buildings. They also presented ventilation rates, ventilation duration, building mass and climatic conditions as the most influential factors on night ventilation and reported that the closer night ventilation occurs to active hours the higher efficiency is achieved.

As thermal mass has an obvious influence on ventilation in buildings, Zhou et al. [59] developed a heat balance model coupling external and internal thermal mass and natural ventilation. They assessed the influence of external and internal thermal mass on indoor air temperature using an adiabatic wall and different realistic walls. This study shows the effect of thermal mass (both internal and external) on indoor air temperature, since this effect is significant to be considered for natural ventilation design and studies. A review about natural ventilation, building thermal mass and diffuse ceiling ventilation technologies has been conducted by Yu et al. [60]. They also proposed a novel system solution for energy-efficient ventilation and cooling systems in office buildings combining the three mentioned technologies. Their novel system showed notable energy saving potential comparing with the other HVAC systems, mostly in summer and intermediate seasons.

The results from a study [55] show that natural ventilation cooling potential is significantly influenced by the effect of each local climate, the thermal properties of the building, the ventilation types, the internal gains such as electrical devices and lighting as well as number of occupants and their activity level. Therefore, it recommends that the strategic design of natural ventilation should consider all aforementioned factors. It is also believed that in hot summer climate zones natural ventilation is not sufficient

Table 1
Characteristic elements/features of natural ventilation (summary of advantages and drawbacks).

Elements/features	Natural ventilation principle	Supply or exhaust	Main advantages	Main drawbacks	Studies focused on features
Atrium	Single-sided, Cross and Stack	Supply and Exhaust	1. It protects the space to be enclosed to noise and inappropriate wind. 2. In sunny days the supply air will be preheated (heating season). Also in cold days without sun, the atrium space is warmer than outside, so windows facing the atrium can be opened for ventilation purpose.	1. In sunny hot days the supply air will be preheated (cooling season). 2. The glassy layer causes noise transfer by reflection. 3. It will occupy a considerable area of the building, so this area can be used for limited purposes such as canteens, gardens and cafés.	[21,50,64–66]
Wind scoop	Cross and Stack	Supply	1. Suitable for buildings in which facades are not appropriate to use for ventilation purpose. 2. Can be installed either on the roof or, in case of no space, can be located in the landscape and being connected by ducts. 3. Can be either fixed to work with prevailing wind direction or omni-directional to capture winds unregard their direction.	1. The airflow is affected by wind speed and in fixed model, if the direction of wind is different it will be useless. 2. Rain and snow can go in the feature, which will negatively affect its performance.	[21,23,67]
Wind tower	Cross and Stack	Exhaust	1. They can be designed to function independent of the wind direction. 2. Rain and snow cannot enter the feature. 3. Roof cowl is one of effective models of wind towers.	1. Some models such as Venturi element are not effective enough, so it is not recommended.	[21,23,67]
Wind catcher	Cross and Stack	Supply and Exhaust	1. They can capture wind unregard their direction, as they normally have inlets in for sides. 2. They can supply the cooled air in and in the same time extract the hot air out through leeward side. 3. In absence or shortage of wind they can still ventilate the space by stack principle.	1. As the design of wind catcher is complicated, it should be designed and constructed carefully. 2. It is useful mostly for hot and dry regions.	[21,23,51,67,68]
Ventilation shaft	Single-sided, Cross and Stack	Supply and Exhaust	1. It is an effective ventilation element in order to achieve acceptable IAQ as well as thermal comfort (not in whole summer).	1. Mostly used for ventilating underground structures such as subways and mines. 2. This feature alone cannot provide good thermal comfort in summer.	[21,69–71]
Chimney	Cross and Stack	Exhaust	1. It is an effective and simple device for extracting air. 2. It takes advantages of both buoyancy and wind driven forces unregard wind direction.	1. It can be used solely for air extraction. 2. Rain and snow can enter the device if the top of chimney is not covered.	[21,72–74,75]
Ventilation openings on façade including windows	Single-sided, Cross and Stack	Supply and Exhaust	1. It can not only be used for ventilation but it also can be used for capturing day lighting. 2. The window model allows the inhabitants to control opening mode. 3. The window model can be integrated to control systems to work automatically in order to capture natural ventilation.	1. The fixed opening model cannot be adapted according occupants requirements. 2. In single-sided openings the ventilation effectiveness is quite low.	[21,29,38–40,61,76,77]
Double-skin façade	Single-sided, Cross and Stack	Supply and Exhaust	1. It protects the space to be enclosed to noise and inappropriate wind. 2. In sunny days the supply air will be preheated (heating season).it provides better comfort, as least in moderate climates. 3. Unlike atrium, it does not occupy any spaces in the building.	1. In sunny days the supply air will be preheated (cooling season), especially in higher floors, in case it is also using for extracting the air. 2. The glassy layer causes noise transfer by reflection in adjacent rooms. 3. If constructed only for ventilation purpose, the cost is too high.	[21,74,78–80]

Table 2
Summary of surveyed studies on natural ventilation.

Reference	Natural ventilation concept			Method	Main task(s)	Main finding(s)
	Driving force	Principle	Characteristic element			
Allocca et al. 2003 [38]	Buoyancy /wind	Single-sided	Windows	Numerical (CFD), analytical and empirical	Investigating natural ventilation driving forces	The results from Computational Fluid Dynamics (CFD) model of buoyancy-driven flow showed an acceptable discrepancy comparing with analytical results while the difference increased when they considered combination of wind and buoyancy-driven flows. This study also discovered that wind and buoyancy-driven flows may support or oppose
Gratia et al. 2004 [39]	Buoyancy /wind	Single-sided, Cross and Stack	Windows	Computational simulation (TAS software)	Analyzing airflow rates, temperature evolution, size, location and shape of openings as well as wind direction	In day time ventilation, cross ventilation performed less effective comparing with single-sided ventilation. Use cross ventilation when favourable wind (speed and direction) is available and single-sided ventilation when there is unfavourable wind. This study also discovered that wind and buoyancy-driven flows may support or oppose. Use two openings in de=different heights in order to increase the efficiency of single-sided ventilation.
Larsen and Heiselberg 2008 [40]	Buoyancy /wind	Single-sided	Windows	Wind tunnel experiment	Develop a new expression for airflow calculation in naturally-ventilated buildings, influence of wind direction on prediction of airflow rate trough openings in different cases such as leeward, wind ward and parallel flow.	Domination of wind speed or temperature difference in natural ventilation depends on the ratio between forces and wind direction, progress in predicting airflow rate with an uncertainty of 23%.
Stavridou and Prinos 2013 [45]	Buoyancy /wind	Cross	Ventilation openings	Laboratory (experiment) and computational simulation (FLUENT)	Investigation of cross ventilation due to buoyancy assisted by wind	The position of openings considerably affects the ventilation flowrate
Jiang et al. 2003 [81]	Wind	Single-sided and Cross	Ventilation openings	Experimental (wind tunnel) and numerical (CFD, LES)	Investigation of wind-driven natural ventilation	As there is a good agreement between experimental and simulation results, LES can be used for assessing wind-driven natural ventilation
Chu and Chiang 2014 [47]	Wind	Cross	Ventilation openings	Experimental (wind tunnel) and numerical (CFD, LES)	Investigation of the rule of thumb to have effective cross ventilation, which says, the building length (L) should be less than five times of ceiling height (H)	The study proved the rule of thumb, reduction in ventilation rate when the building length increases. They also pointed out that location of openings is significantly influential in cross ventilation in buildings.
Gratia and Herde 2004a [78]	Buoyancy /wind	Single-sided, Cross and Stack	Double-skin façade	Computational simulation (TAS software)	Assessment of double-skin façade behaviour considering different parameters such as double-skin façade orientation, wind direction and how it project to building	In a sunny summer day, excessive increase in temperature in the space between the facade skins creates some difficulties, such as disturbing the comfort of the occupants due to the hot radiation coming from the interior skin.
Gratia and Herde 2004b [79]	Buoyancy /wind	Single-sided, Cross and Stack	Double-skin façade	Computational simulation (TAS software)	Efficiency investigation of various strategies in an office building with and without a double-skin façade with a focus on possibility of natural night ventilation	Night ventilation performed better that day ventilation. They found out that the dynamic use of double-skin is important, which means, it really depends on the climate condition.
Gratia and Herde 2004 c [80]	Buoyancy /wind	Single-sided, Cross and Stack	Double-skin façade	Computational simulation (TAS software)	Investigating possibility of applying daytime natural ventilation to an office building with double/skin façade.	In a hot sunny day, a building with a southern double-skin façade has some difficulties to be ventilated naturally.
Prajongsan and Sharples 2012 [71]	Wind	Single-sided	Ventilation shaft	Computational simulation (DesignBuilder)	Evaluating potential of energy saving by natural ventilation in high-rise buildings integrated with ventilation shafts	Their results showed that the comfort hours in the room facing ventilation shaft raised almost 50% comparing with the room without ventilation shaft. They also proposed integration of fan and damper to the ventilation shaft in order to control, optimize and assist natural ventilation.
Jamaludin et al. 2014 [57]	Buoyancy /wind	cross	Windows	Experimental measurements		Position or the floor level of the room has more influence on effectiveness of ventilation rather than

					Assessing various ventilation approaches in selected rooms considering temperature and relative humidity	the orientation of it, as rooms located in higher floors shows greater mean temperature and relative humidity. Night ventilation as the most effective ventilation strategy among all, as it provides lower mean temperature and higher relative humidity.
Yao et al. 2009 [55]	Buoyancy /wind	Single-sided, Cross and Stack	Windows	Thermal Resistance Ventilation (TRV) model	Investigating the cooling potential of natural ventilation considering three scenarios: Day-time ventilation to cool down the building interior, night-time ventilation for pre cooling of interior thermal mass and combined day-time and night-time ventilation	In strategic Natural ventilation design, the climatic condition, building's thermal characteristics as well as internal gains such as electrical devices, lightings, number of occupants and their activity level must be taken into account. In the climate zone with the hot summer natural ventilation is not sufficient for space cooling and hybrid ventilation is recommended as an alternative.
Oropeza-Perez and Østergaard 2014 [82]	Buoyancy /wind	Single-sided and Cross	Windows	Computational simulation (EnergyPlus)	Assessing feasibility of using natural ventilation for cooling purpose in hot summer time in Denmark	Natural ventilation can provide acceptable thermal comfort in 90% of the investigated period. Internal heat sources, outdoor temperature, temperature set-point, wind speed and solar heat gains are introduced as the parameters with highest effect on ventilation control model.

for space cooling and hybrid ventilation is recommended as an alternative. This is also recommended by other studies [61, 62]. However, using adaptive thermal comfort model, the results from [63] showed high satisfaction of occupants in a well-designed naturally ventilated building in summer time. It is reported by ASHRAE standard 55 [9] that dwellers can adapt to higher or lower indoor temperature if they can control the indoor environment. Table 2 summarizes some surveyed research regarding natural ventilation in buildings.

Although natural ventilation has some advantages comparing to mechanical ventilation such as savings of energy in cooling and fan power as well as savings in cost and space for HVAC systems, there is also some shortcomings such as lower control and reliability, less possibility of air treatment, acoustics issues and security concerns [83]. Computer based control systems may help natural ventilation to overcome some of the drawbacks by providing the possibility to predict its availability. Many studies such as [61,84–89] pointed out that presence of control systems and proper use of them in naturally ventilated buildings can cause considerable energy saving amount because control system can predict when natural ventilation is sufficient to be used. The main factors affecting ventilation control are internal heat sources, outdoor temperature, indoor temperature set-point, wind speed and solar heat gains [82].

It has been seen in many of aforementioned studies that natural ventilation cannot always maintain IAQ and thermal comfort in the acceptable levels. Therefore, newly developed research mostly focused on hybrid ventilation. They integrated control system to predict when mechanical ventilation is required [88].

One way to achieve a significant reduction in the energy consumption of buildings required to have mechanical ventilation systems installed, is to harness the natural energy of the wind and temperature gradients for additional “free” ventilation and cooling, rather than relying solely on the mechanical systems. At times when wind pressure or temperature gradients are not sufficient to drive the flow by natural means, the desired ventilation rates can still be maintained by the mechanical systems. This is the working principle of hybrid ventilation [90], also known as mixed-mode ventilation. This approach is characterised by the use of building elements, such as windows and doors, for space ventilation and cooling by natural means, and HVAC systems for ventilation and air conditioning when needed. The purpose is to provide a healthy and comfortable indoor climate by passive means at the times of the day when conditions are favourable. At times when outdoor temperatures are above comfortable ranges, night-time natural ventilation combined with adequate thermal inertia can be an effective strategy for providing a comfortable environment in the cooling season. Several studies have reported on the preference of building occupants for natural or hybrid ventilation over fully mechanical ventilation systems [91–93]. The combination of natural and mechanical ventilation-known as hybrid ventilation-is recommended by many studies in order to compensate drawbacks of natural ventilation and provide comfortable indoor climate. In other words, in hybrid ventilation, the active mode (mechanical ventilation) reflects the outdoor environment and benefits from ambient condition by a passive system (natural ventilation). For instance, in intermediate season natural ventilation can provide acceptable IAQ and thermal comfort when outdoor temperature is lower than room temperature and in the rest of the year combination of natural and mechanical ventilation provides comfort condition [94].

The concept of hybrid ventilation was largely popularized by the International Energy Agency program on buildings in annex 35 “Hybrid Ventilation in New and Retrofitted Office Buildings”, in a project known as HybVent [95]. This project ran between 1998 and 2002, and had the participation of eleven European countries, the

United States, Japan, Canada and Australia. Outcomes of this project were, among others, an analysis of the state of the art of hybrid ventilation solutions implemented in contemporary buildings, and a number of recommendations for strategies to control hybrid ventilation systems. Twenty-two buildings were analyzed as case studies, seven of whom had been recently renovated and the remaining fifteen were new construction. Most of the solutions encountered exploit the stack effect for natural ventilation, either through dedicated ducting or through the use of building elements such as corridors and hallways. The interaction of the occupants with the ventilation system is permitted in about half of the buildings and control strategies are varied, some based on the temperature difference inside and outside of the building, others using both temperature difference and CO_2 concentration, and still others making use of occupation information via infra-red (IR) sensors.

Utilizing natural ventilation, as long as possible, is the main benefit of applying energy-efficient hybrid ventilation strategies to buildings. Homod and Sahari [96] developed a physical and empirical hybrid model to calculate building thermal (heating and cooling) load focusing on effective control of indoor temperature by ventilation airflow rate. They calculated the energy saving of their hybrid model, which was 27.92% comparing to solely mechanical air conditioning system. They also reported the need of variable supply of airflow by mechanical ventilation (e.g. variable-speed fan) for providing acceptable indoor air quality. Moreover, Ezzeldin and Rees [97] studied the potential of hybrid ventilation as well as passive cooling methods by simulation of an office building using EnergyPlus. They found that implementing hybrid strategies for ventilation can cause 40% of energy saving comparing with active conventional system only by changing between natural and mechanical ventilation. They also reported more energy savings by applying night-time ventilation especially for cooling purposes. As solely naturally-ventilated building design can be applicable in limited range of climates, a study [98] developed ventilation strategies based on combination of natural and mechanical ventilation with air treatment (cooling or heating). They prepared an innovative and energy-efficient design for a library building based on four HVAC system operating models (mechanical ventilation with heating, mechanical ventilation with cooling, passive ventilation and passive ventilation with heating) for different times of year together with night time ventilation for cooling building's thermal mass. Likewise, a newer research [99] evaluated indoor climate quality and energy performance of a high-rise building in Tokyo, Japan after applying hybrid ventilation. They recorded notable amount of energy reduction while maintaining indoor climate with little problems in thermal comfort.

In addition, wind characteristics, as one of the main parameters of natural ventilation, has been introduced in [100,101] as an influential factor in hybrid ventilation strategies. This is due to the significant role of natural ventilation in development of a hybrid ventilation model. Therefore, not only wind characteristics but also all parameters affecting natural ventilation such as climatic condition, building location and orientation, openings' location, size and height must be considered in very basic design steps. Effectiveness of hybrid ventilation depends on having really careful building design from its beginning steps. To do so, a technical report by [102] developed a simplified method to assess the achievability of hybrid ventilation in early building design phase.

In buildings with hybrid ventilation, natural and mechanical ventilation can work separately or both at the same time. Comparative studies on assessing different types of ventilation reported that natural ventilation is more efficient compared to hybrid ventilation when cross ventilation and sufficient wind speed is available while hybrid ventilation performs more efficient in single-sided ventilation and unavailability of sufficient wind characteristics [103,104].

Similar to natural ventilation, hybrid ventilation may be categorized in three main principles [90], as follows:

- Natural and mechanical ventilation;
- Fan-assisted natural ventilation;
- Stack and wind-assisted mechanical ventilation.

Buildings with hybrid ventilation can follow either one the principles or a combination of them. Fig. 2 illustrates the pattern of each abovementioned principles.

The Liberty Tower of Meiji University in Tokyo, Japan, shown in Fig. 3, uses a natural ventilation system (a combination of stack and cross ventilation) to provide acceptable indoor climate in intermediate season and mechanical ventilation and air conditioning is used for the same purpose in the rest of the year, which caused an annual energy saving of 17% [105]. The Bang and Olufsen Headquarters building in Struer, Denmark, shown in Fig. 4, is an example of fan-assisted natural ventilation, which is normally ventilated through controllable windows by natural ventilation, while a low-consumption fan with variable speed located in cowl on the roof works in case the required ventilation flowrate is not provided by natural ventilation [106]. In the concept of RESHYVENT project, Antvorskov [107] listed and described possible renewable energy technologies that can be integrated with hybrid ventilation in buildings in which some natural ventilation elements are mentioned such as solar chimney, wind turbine, wind cowl and wind catcher. The Mediå School in Grong, Norway, shown in Fig. 5, uses balanced (supply and exhaust) mechanical ventilation to provide acceptable indoor climate in which the air intake is coming from a wind tower connected to the building's basement via underground duct [108]. These commercial buildings were some of the case studies for the HYBVENT project in which different hybrid ventilation principles were assessed.

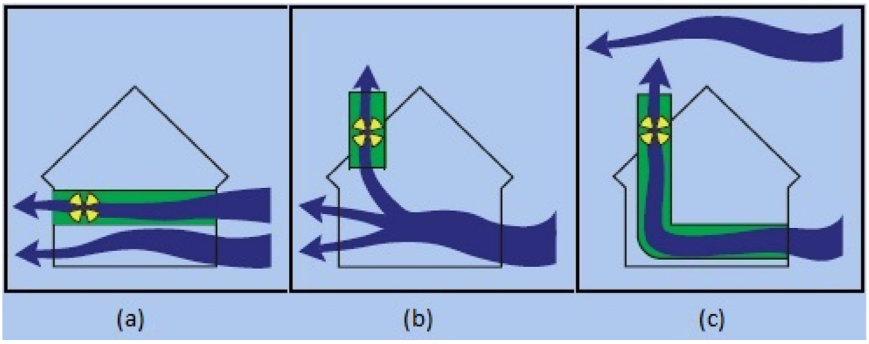

Fig. 2. Schematic view of different hybrid ventilation principles. Reproduced with permission from [90]. (a) Natural and mechanical ventilation; (b) Fan-assisted natural ventilation; (c) Stack and wind-assisted mechanical ventilation.

Fig. 3. Liberty Tower of Meiji University. Reproduced with permission from [90].

Fig. 4. Bang and Olufsen Headquarters building. Reproduced with permission from [90].

Proper design for hybrid ventilation usually results in providing better indoor climate condition for building occupants. However, hybrid ventilation can perform more energy-efficient by integrating proper control systems and ventilation control strategies.

The main difference between a conventional system and a hybrid system is that, with hybrid systems, there are two or more ways to perform the same task, each with their particular advantages and disadvantages, whereas with conventional systems there is only one way to perform the task. In order to explore the benefits of having more than one system to perform the same task, the hybrid system controller must have the capability to make an informed decision as to which of the available individual systems is most suited for the task at hand, at any given time, given a set of criteria to fulfil and a set of objectives to achieve. This capability is generally implemented in the form of a supervisory controller, which decides and commands the operating modes of each of the individual systems that make the hybrid system.

Although the conventional approach-and today's industry standard-to controlling the indoor climate is through Rule-Based Control (RBC), where *IF (condition) THEN (action)* rules are used to introduce expert knowledge in the control loop [110], there have been two active lines of research in advanced control strategies, during the last two decades, one with a background in optimal and predictive control theory, which relies on a mathematical model of the underlying thermal and airflow dynamics of the building and its surroundings, and another with a background in computational intelligence, based on neural networks. Dounis and Caraiscos [111] reviewed works on advanced control systems for energy and comfort management, with an emphasis on applications from the computational intelligence branch.

In the last few years, however, there seems to have been a renewed interest in incorporating predictive capabilities into the control strategy, so as to further improve the quality of the indoor climate while optimizing the usage of energy in buildings [112–121]. This predictive capability, however, can only be effectively achieved through a mathematical model that represents the behaviour of the system or phenomenon under control. The quality of the predictions is highly dependent on the fidelity of the model and, in the process of developing such control strategies, there must be an effort in quantifying the added potential of energy saving and of occupants' satisfaction in relation to the complexity invested in the control system.

Oldewurtel et al. [122] reported on a large-scale simulation study, performed under the SwissElectric funded project OptiControl, on the potential of Model Predictive Control (MPC) coupled with weather forecasts for climate control in office buildings. They show that, in more than half of the cases simulated, the additional energy (non-renewable primary energy) use of a system based on RBC can be more than 40% of a theoretical performance bound and, as such, there is scope for exploiting this savings potential in introducing MPC with weather forecasting. Replacing the weather predictions by 24 h persistence predictions, however, resulted in more than double the energy used (well over the energy used by the RBC system), revealing an important dependence of their controller's performance on the accuracy of the weather prediction. Moreover, Djuric and Novakovic [123] used multivariate analysis to identify which variables drive the consumption of energy in buildings. They found that the important variables in the case of total and fan electricity use are the same throughout the year, whereas for heating energy the important variables are different at different times of the year. Total electricity is well explained by occupancy level and fan input signals.

A considerable amount of research has been previously done on supervisory control of mechanical HVAC systems [124], but only recently has research on supervisory control of hybrid natural-mechanical ventilation systems started appearing in the literature [100,101,117,125–127]. Nowadays, studies investigating natural and/or hybrid ventilation are mostly focused on developing energy-efficient ventilation control strategies. They found control strategies as the key factor of improving energy performance of ventilation system. Different types of control system can be applied to hybrid ventilation, such as natural ventilation control, mechanical ventilation control, fan-assisted natural ventilation control, night ventilation control and a control system to switch between natural and mechanical ventilation [110]. The control systems can vary from simple and basic to advanced control

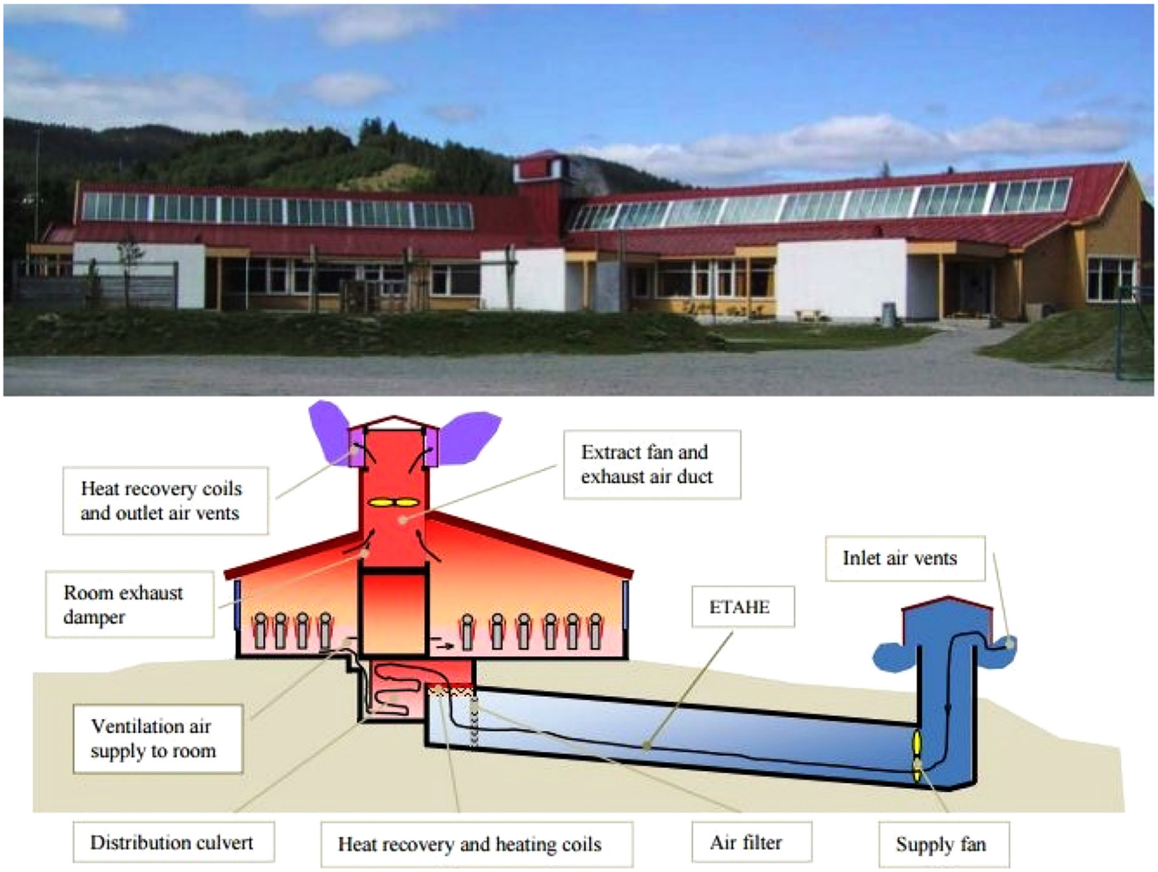

Fig. 5. Mediå School. Reproduced with permission from [108, 109].

methods. Recent research utilizes intelligent control systems, which are applied to hybrid ventilation in order to automatically adjust between natural and mechanical ventilation mode whenever it is required. The main purpose of ventilation control systems in buildings is providing occupant satisfaction with least energy consumption. Therefore, IAQ, thermal comfort and energy use are the main actors in control systems. For instance, Mankibi et al. [128] conducted a research aiming to identify optimal control strategies based on hybrid ventilation to simultaneously provide comfortable indoor air quality and reach energy savings. They concluded that hybrid ventilation system has a higher consumption during winter and spring accompanied with better indoor air quality and thermal comfort while it has better performance in energy consumption in summer with mildly higher CO_2 concentration. In terms of energy saving, combination of hybrid ventilation with ventilation control strategies showed 90% reduction in energy consumed by the exhaust fan comparing with only mechanical exhaust while providing the same thermal comfort level [129].

In ventilation control strategies, normally, set points are considered for different parameters affecting indoor climates. For IAQ, CO_2 concentration set points are the most popular ones because this gas is considered as an indicator for occupant-related pollutant concentration. As regards thermal comfort, indoor air temperature set point is the mostly used one. It is also possible to use other set points throughout ventilation control process. For example, Mossolly et al. [130] introduced various control strategies and using optimization model selected the best control strategy that has highest reduction in energy consumption comparing to conventional strategy, while still satisfies indoor climate. They reported 11% of energy saving by varying the supply air temperature and fresh air flow rate, and 30.4% of saving when they use PMV set points instead of temperature set points while still varying the supply air flow rate, its temperature and fresh air flow rate. Similarly, Walker and Sherman [131] assessed the effect of different ventilation strategies on concentration of contaminant, particularly ozone, in indoor environment. They reported that building envelop has high influence on concentration of ozone by filtration of it. They also reported that extracting ventilation provides lower concentration of ozone comparing with balance (supply-exhaust) ventilation system. Finally, they recommended turning off the ventilation system when the outdoor concentration is in high level.

In RBC, which is mostly used in studies investigating ventilation in buildings, different parameters such as indoor and outdoor temperatures, relative humidity, concentration of CO_2, wind speed and its direction can be considered to prepare a rule-based ventilation control strategy. In order to do the measurements some sensors are required to be installed in the building as well as weather data required from weather station. For instance, Ji et al. [132] simulated low energy building in South China using hybrid ventilation. They developed a CFD model to assess passive ventilation accompanied with simple rule-based control strategies. Performing the simulations, they revealed the capability of the new ventilation mode to mitigate energy consumption by 30–35% comparing to purely mechanical mode.

Advanced control of openings size and of the outdoor flow rate is another important issue that should be considered in both naturally and hybrid ventilated buildings. In this subject, Schulze and Eicker [133] assessed the airflow rate through openings considering different opening types and control strategies. The results indicated that the indoor air quality maintained in acceptable level in different climate zones but the thermal comfort, especially in summer, varies with the selected natural ventilation control strategy. It is also mentioned by this study that control strategies for openings are necessary in order to avoid over-cooling and providing required fresh air. Likewise, another study [134] implemented a CFD analysis to assess the capability of a hybrid ventilation system in providing thermal comfort and suitable indoor air quality in a 100 m^2 apartment, considering three different ventilation rates. They summarized that 60 m^3/h is the flow rate that satisfies all criteria, 30 m^3/h satisfies thermal comfort with lower energy consumption but not indoor air quality and 120 m^3/h obviously satisfies the IAQ in a shorter time but not thermal comfort while uses higher amount of energy. Moreover, a recent study [135] experimentally and analytically investigated the effects of four different ventilation rates (0.1, 0.2, 0.35 and 0.7 L/s m^2) on IAQ and energy saving in a single-family house in order to prove the overestimation of ventilation rate in Swedish Building Standards (BBR). The results showed that the ventilation rate of 0.2 L/s m^2 not only provides an acceptable IAQ with indoor CO_2 concentration of 950 ppm but it also has an energy saving of more than 40% comparing to the ventilation rate of 0.35 L/s m^2. They concluded that a ventilation rate of 0.3 ACH can save energy and maintain the acceptable IAQ level, while the recommended ventilation rate by BBR is 0.5 ACH.

Moreover, demand-controlled ventilation (DCV) strategies have very significant effects on improving the energy efficiency of a ventilation system. Using DCV method, the space is ventilated based on its occupancy level, as presented in Fig. 6, or concentration of contaminants. DCV is a suitable strategy for ventilation of spaces where the occupancy level varies frequently such as restaurants, canteens, lecture halls, shopping malls and sport halls. For instance, office buildings are mostly ventilated based on constant air volume systems, which causes wasting of energy for ventilating empty offices or those with fewer occupants. It is strongly believed that the actual level of occupancy is much lower than the design level in U.S., which causes over ventilation of the buildings [136]. In other words, in DCV systems, the demand of a space for air exchange is always being measured by IAQ sensors and the outside flowrate is being attuned to match the real demand. For example, Mysen et al. [137] has calculated the profits of implementing DCV systems on each cellular office on a reference office building in Norway. In DCV, supply is continuously matched with demand, so it results in always having acceptable IAQ accompanied by notable energy and cost savings.

In beginning steps, occupancy schedules were the primary way to implement DCV strategies. Nowadays, CO_2 and motion sensors, infra-red and video or camera [138] occupant counters as well as 3D depth sensors [139] are devices used in DCV approaches. Furthermore, by applying sensor based demand-controlled ventilation (SBDCV) ventilation flowrate can be modulated over time based on occupancy or pollutant level, which causes better control of indoor pollutant concentrations, and lower energy use [140]. In the late 1990s, Fisk and Almeida [140] reviewed existing work relating to SBDCV. They announced that SBDCV offers efficient strategies for the following reasons: it is capable of control by most pollutants, it is capable of control by the occupancy level, it is useful for hot and cold climates as well as where the energy is expensive. CO_2 sensors are the most used IAQ sensors in DCV studies in which the outdoor air intake is based on the concentration of CO_2 in a space. Another study [141] reviewed studies on CO_2-based DCV and concluded that, although the energy saving potential of this method is proved, there are still significant issues on implementing CO_2-based DCV. They revealed that CO_2-based DCV alone cannot provide acceptable IAQ because it cannot control non-occupant related pollutants as it was later mentioned in [142]. Furthermore, in [141] the location of CO_2 sensors has been discussed as a critical issue because non-uniformity of air distribution and buildings' occupancy. Later on the proposed location for CO_2 sensors in single and multiple zones discussed in [143]. Recently, some studies such as [142,144] report the placement of the CO_2 sensors inside the ventilation supply and return ducts. Additionally, Lu et al. [145] developed a dynamic flexible and energy-efficient DCV control strategy to control indoor concentration of CO_2 and to reduce energy consumption. They tested their novel control strategy in a sport training centre as well as a common office building, which resulted in substantial energy saving in both cases. Table 3 summarizes more studies that reported energy savings throughout investigating and developing various energy-efficient ventilation methods.

3. Occupants' behaviour, ventilation and energy consumption

So far, different ventilation methods and control strategies, and the influence of building characteristics and the indoor and outdoor environment conditions on efficiency of ventilation in buildings have been discussed. However, the behaviour of the building occupants also affects ventilation rate [157] and subsequently energy consumption in buildings. For instance, studies such as [158,159] indicated that behavioural factors have more effect on energy performance and comfort than those related to building, using experimental measurements and sensitivity analysis to compare the role of building characteristics and occupants' behaviour on ventilation, comfort and energy consumption. Therefore, not considering occupants' behaviour in building energy simulation leads to increased uncertainty in its energy performance [160,29]. For illustration, Daniel et al. [161] examined the influence of occupants' behaviour on cooling and heating energy consumption using simulation in the context of the Australian regulatory house energy rating scheme and showed that

Fig. 6. Occupancy-based control for ventilation. Reproduced with permission from [110].

Table 3
Summary of surveyed studies recorded energy saving throughout investigating efficient ventilation control strategies.

Reference	Buildings application	Climatic region	Control strategy	Method	Main task(s)	Main finding(s)	Energy saving
Jreijiry et al. 2007 [129]	Residential building (single family house)	Athens (Greece), Nice and Trappes (France), Stockholm (Sweden)	DCV (Occupancy detection and CO_2 concentration)	Numerical Simulation (MATLAB/SIMULINK and SIMBAD Toolbox)	Develop and analyze control strategies for hybrid ventilation to compare solely mechanical extract ventilation with low pressure hybrid ventilation	The colder the climate, the better the potential of stack effect, therefore exposure to high CO_2 concentration and fan energy consumption is lower. Hybrid system decrease exposure of occupants to high CO_2 concentration and reduces at the same time energy consumption of fan.	About 90% (Fan)
Karava et al. 2012 [146]	Institutional building	Montreal (Canada)	Model-predictive control strategies	Full-scale experimental setup	Providing reliable experimental data for buildings with hybrid cooling strategies and investigating night cooling strategies	Hybrid ventilation system showed good performance accompanied by considerable energy saving during cooling season (April-October). Performing night cooling strategies causes more energy saving (as it cool down the building's internal thermal mass and walls)	More than 30% (free cooling)
Homod et al. 2013 [96]	Residential building	Kuala Lumpur (Malaysia)	Rule-based control strategies for Temperature and PMV	Numerical calculation, Empirical model (RLF method)	Calculating energy saving of controlling building indoor condition by natural and mechanical ventilation	Mechanical ventilation is necessary to control IAQ (Use of variable speed fan is recommended). The proposed method is capable to mitigate energy consumption.	27.92% (comparing to conventional system)
Menassa et al. 2013 [147]	Commercial building	Madison (USA)	Basic control strategies	Experimental measurements, Computational simulation, Optimization	Developing and testing different basic hybrid ventilation control strategies	Substantial energy saving can be achieved by automatically controlled hybrid ventilation.	20%(comparing with conventional system)
Ezzeldin and Rees 2013 [97]	Office buildings	Alice Springs (Australia), Manama (Bahrain), El Arish (Egypt), Madinah (Saudi-Arabia)	Rule-based control strategies + passive cooling strategies	Computational simulation (EnergyPlus)	Assessing feasibility of providing acceptable indoor climate using mixed mode ventilation in arid areas	Considerable amount of energy saving is achieved by implementing the mixed mode strategies and facilitating adaptive behaviour. More saving can be achieved by applying night time ventilation.	More than 40% (by switching between natural and mechanical ventilation)
Pavlovas 2004 [148]	Residential building	Sweden	DCV (Occupancy, CO_2 and humidity control)	Computational simulation (IDA Indoor Climate and Energy) and Experimental measurements	Assessing capability of DCV in energy saving. Evaluating capability of IDA software for analyzing DCV performance.	Possibility of energy saving by reducing average ventilation while the indoor air quality is acceptable. Occupants' behaviour can affect DCV performance. The simulation results showed a good agreement against measured data.	More than 50% (RH and CO_2) about 20% (occupancy control)
Chao and Hu 2004 [142]	Academic building (auditorium)	Hong Kong	DCV (Occupant related and non-occupant related contaminants)	Experimental measurements	Developing a dual-mode demand controlled ventilation based on CO_2 and Radon	Using only CO_2-based DCV, non-occupant related pollutant level is not acceptable. Dual-mode DCV is able to provide suitable IAQ with notable amount of energy saving comparing with constant rate ventilation.	8.3–28.3% (daily electrical energy)
mysen et al. 2005 [149]	Academic building (classroom)	Oslo (Norway)	Constant air volume (CAV) and DCV (CO_2 and IR occupancy detector)	Experimental measurements	Comparing ventilation energy consumption based on three different control strategies	CAV is defined based on full design occupancy and full time function while the occupancy level is less than 75% and occupied time is typically 40%. CO_2 and IR DCV resulted in considerable amount of energy saving.	38% (CO_2) and 51% (IR)
Xu et al. 2009 [150]	Commercial building	Various weather conditions	model-based control	Computational simulation and Optimization	Developing an optimal model-based control strategy to provide acceptable indoor climate and reduce energy consumption	Comparing with multi-zone and conventional demand-controlled ventilation, the results showed considerable amount of energy saving comparing	7.55% (cooling) and 4.65% (total power consumption)

						with the former and notable improve in thermal comfort and indoor air quality comparing with the latter.	
Congradac and Kulic 2009 [151]	Office building	Belgrade (Serbia)	Genetic algorithms based on CO_2 control	Computational simulation (EnergyPlus), Mathematical model (MATLAB/ SIMULINK)	Evaluating amount of energy saving by CO_2 concentration model in a HVAC system	The energy saving of the HVAC system is calculated based on for different CO_2 limits in control cases.	20–82%
Mossolly et al. 2009 [152]	Academic building	Beirut (Lebanon)	base strategy (VAV) and Advanced control strategies	Visual DOE software	Investigating the influence of different optimized control strategies on energy consumption while maintaining IAQ and thermal comfort	The multi-variable control strategies are capable to improve energy performance of HVAC systems and in the same time, maintain IAQ and thermal comfort.	11% (Temperature set point)- 30.4% (PMV set point)
Nielsen and Drivsholm 2010 [153]	Residential building (single family house)	Denmark	DCV (CO_2 and humidity)	Experimental measurements	Investigating indoor climate and energy consumption using DCV strategy with high and low flow rates	The low ventilation rate (recommended by IAQ standards) can guarantee acceptable IAQ in 37% of occupied time, which has notable saving comparing with high ventilation rate (Danish building regulation requirements)	35% (Fan)
Laverge et al. 2011 [154]	Residential building	Belgium	DCV	Computational simulation (Contam)	Investigating the energy saving potential of four different DCV strategies	Considerable amount of energy saving is recorded by simulating different strategies. Humidity based strategy was the least suited to maintain IAQ level.	25–60%
Sun et al. 2011 [155]	Super high-rise office building	Hong Kong	CO_2-based DCV	Experimental measurements	Testing and evaluating the energy and environmental performance of CO_2-based DCV comparing with Constant outdoor flow rate strategy	In summer and warm mid-season days the DCV strategy is able to reduce both fan and cooling energy consumption while in winter and cold mid-season days use of enthalpy Control strategies are recommended instead.	55.80%
Ng et al. 2011 [156]	Gymnasium	Indiana (USA)	CO_2-based DCV	Experimental measurements	Assessing IAQ and energy saving by implementing CO_2-based DCV strategies in a gymnasium under the new and old ASHRAE ventilation standards	The energy saving from CO_2-based DCV under the new ASHRAE 62.1 is lower than the same under the old ASHRAE 62 comparing with constant ventilation rate. The result can also be used for other humid continental climates.	0.03% (ASHRAE 62.1) 1.86% (ASHRAE 62)

the present regulation cannot assume occupants influences correctly and needs to be improved. This section reviews some existing literature that investigated the influence of occupants' behaviour on ventilation rate and energy consumption in buildings.

People's behaviour in naturally ventilated spaces closely follows the outdoor climate in the way they use windows to adjust their indoor environment [29,162]. Although the debate about the advantages and disadvantages of the exclusive use of natural ventilation is far from finished, natural ventilation can provide a healthy and comfortable indoor environment, allowing energy savings compared to purely mechanical ventilation [163]. The simplicity of opening a window makes natural ventilation extremely attractive in principle but, though seemingly simple, the conditions and the parameters that affect the behaviour of this type of ventilation are very complex. Given the uncertainties associated with the performance of natural ventilation, architects and engineers avoid its use as it is difficult to implement and control. In naturally ventilated spaces there is a risk that, over time, it is not possible to satisfy the ventilation needs and the desired level of comfort, requiring a high degree of flexibility on the part of the occupants in relation to their indoor environment.

Many modern residential buildings have a low air infiltration rate (around 0.2 h^{-1}), which, by itself, is not appropriate to dilute the contaminants and provide acceptable IAQ [164,165] and can lead to increased health issues [166]. A review on existing literature shows that almost 10% of dwellers do not use their ventilation system [167] and this ventilation behaviour is independent of infiltration rate or space size [168]. As a case in point, Park and Kim [166] investigated influence of occupants' behaviour on ventilation of their apartments throughout a heating season. The evaluation has been made by a field study, questionnaire survey as well as airflow rate measurements. Their results showed that almost 70% of occupants did not use mechanical ventilation at all due to different reasons. As shown in Fig. 7, among all matters, raising heating energy cost was the main reason not to use mechanical ventilation by about 60%. Based on the survey results and ventilation period per day, the study divided the dwellers into four categories in which the first category has the highest level of dissatisfaction while the fourth category has the lowest. The study also calculated the energy consumed by operation of a fan for four hours per day (category four) to be about 1 US$/$m^2$ on average for the whole heating season.

The main factors associated with energy consumption in building are categorized in [169] in which building occupants' behaviour and activities are mentioned as crucially influential factors. This shows the need for investigating influence of occupants' behavioural aspects on energy consumption in building and find out new methods to develop energy efficiency in buildings with the cooperation of occupants. Some of the studies that developed and proposed new methods to investigate influence of occupants' behaviour on energy consumption are presented below:

- Modelling of user behaviours, such as their presence and activities, using numerical simulation is proposed in [170] to be integrated with building energy simulation in order to improve its energy performance.
- Authors of [169,171] developed methodologies to evaluate the effects of occupants' behaviour on energy consumption in residential buildings in Japan. The methods are not only capable to identify the occupant's behaviour that required to be improved but they also provide practical recommendation for making decisions, which lead to energy efficiency improvements. In other words, the developed methods enable researchers and building actors to identify the energy saving potential throughout occupants' behaviour modification.
- A methodology developed in [172] considers a combination of climatic data and occupants' behaviour as input data for building energy simulation. This model decreases the uncertainty of building energy simulation by reducing the discrepancy between calculated and actual energy performance.
- Gunay et al. [160] reviewed and categorized existing studies on adaptive occupants' behaviour and explained developed methodologies as well as the limitation of their application. They presented logistic regression models as proper methods for occupants' behaviour modelling and concluded that it is possible to mitigate the influence of occupants' behaviour on energy performance of buildings by using occupant-predicting control strategies.

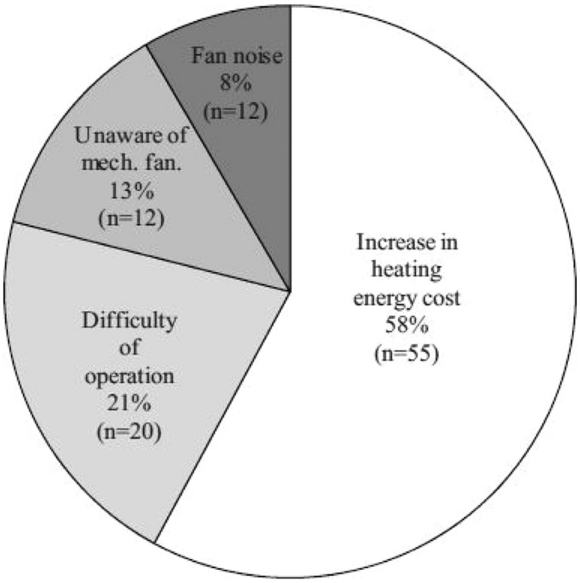

Fig. 7. Major reasons for not using mechanical ventilation during heating season. Reproduced with permission from [166].

Where possible, occupants can have control on their clothing and activity level but they might also have control on the indoor environment through adjusting fans, windows, blinds, lights, as well as cooling and heating systems. On the other extreme, a strict dress code in a professional setting can be very limiting on the capability of a person to adapt to its environment. Andersen et al. [173] assessed the influence of occupants' behaviour on energy consumption by simulating one person located in a single room with all aforementioned controls based on two different (energy expensive and energy efficient) behavioural modes. Fig. 8 illustrates influence of different behavioural modes on controlling PMV and energy consumption in consequence.

One of the most influential occupants' behaviour is their tendency to open or close windows. This is well-accepted that window opening behaviour has very crucial effects on indoor climate and energy consumption because operable windows offer the opportunity to control the indoor environment and link the occupants to the outdoor environment. Some of the studies that assessed the window opening behaviours are summarized below:

- The results from questionnaire surveys in [174] showed that outdoor temperature has the most significant effect on window opening behaviour among other factors such as IAQ, noise, floor area, gender and so on.

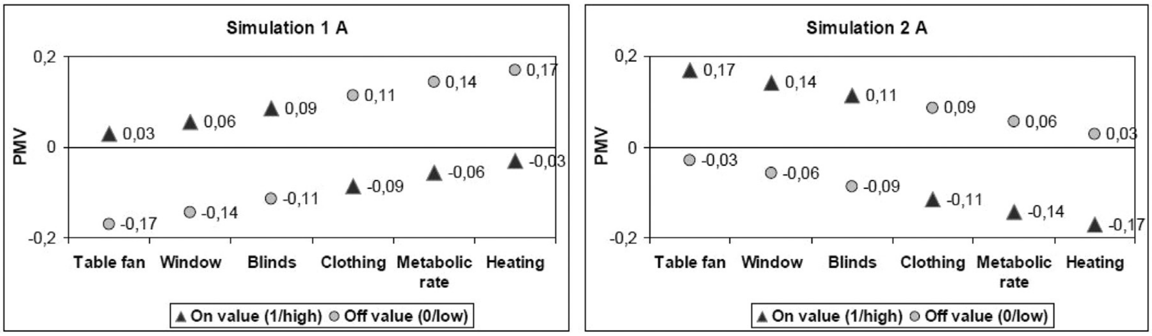

Fig. 8. PMV control in energy expensive and energy efficient modes. Reproduced with permission from [173].

- occupants' window state adjusting behaviour assessed in [175] based on various influential factors such as indoor temperature and climatic data (i.e. temperature, wind characteristics, relative humidity and rainfall) throughout seven years continuous measurements. They developed three different window adjusting models. A Bernoulli process based on a logit probability distribution, a discrete-time Markov process with sub-models for different occupancy statuses and extended this latter to a continuous-time random process. They also tested combination of these models, so called hybrid model to benefit from including advantages of all while excluding drawbacks.
- Roetzel et al. [29] carried out a comprehensive review on investigating effects of occupants' behaviour on controlling natural ventilation in buildings. They assessed various parameters that affect occupants' behaviour for window opening such as outdoor environment condition (i.e. occurrence of temperature, wind, rain and noise), season, time of day, window opening type, size and location as well as previous window state. The main reason to modify window state is to let fresh air come in during heating and cooling season and cool down the space during cooling season.
- Fabi et al. [176] investigated and presented dominant factors and driving forces of window adjusting behaviour of occupants in residential buildings by reviewing existing studies as well as the result from a field study survey conducted in Denmark.
- Fabi et al. [177] provided an extensive literature review on window adjusting behaviour and they indicated lack of more realistic and precise occupants' behaviour model.
  And more recently:
- Schakib-Ekbatan et al. [178] evaluated the interaction of occupants with natural ventilation by a long-time monitoring of an office as a case study. They found out that users' interaction with window opening causes some increase in energy consumption during winter as the heating demand increases but not in summer (when outdoor temperature is higher than indoor) as there is no cooling system.
- Wang and Greenberg [179] assessed various control strategies on window opening behaviours using EnergyPlus simulation software. They highlighted the significant role of window opening behaviour on occupants comfort and HVAC system energy saving potential that is calculated up to 47% in hybrid ventilated buildings.

In addition to window opening behaviour, Wymelenberg [180] and Zhang and Barrett [181] focused on occupants' control on blinds. The latter reference [181] revealed that solar radiation has the highest influence on blind adjusting and occupants mostly tend to put the blinds position completely up or completely down.

Most of studies in this field focused on energy saving potential during occupied hours but dissimilarly, a study [182] focused on wasting of energy during non-occupied hours, so called the dark side of occupants' behaviour and reported that in commercial buildings more than half of energy use accounts for non-occupied hours, which is mainly due to lightings and equipment needlessly left on by the users.

Recently, more studies investigated influence of occupant behaviour on ventilation and energy consumption in buildings. The existing research indicates that the influence of occupants on ventilation and energy consumption is rather high. Therefore, more studies to investigate this relation can aware dwellers on their energy and ventilation behaviour, which results in improving energy efficiency [183] and IAQ in the same time.

4. Correlation of ventilation with health and productivity of occupants

While the main purpose of ventilation is to provide fresh air to the building occupants and to dilute pollutants down to acceptable concentrations, it can present a substantial energy load to the heating and cooling subsystems. For that reason, ventilation systems are designed and operated in such a way as to provide acceptable air quality through minimum ventilation rates requirements, such that known harmful contaminants are only present in small enough concentrations and, for which, only a statistical minority of the building occupants, say, 20% or less, would express dissatisfaction in relation to odours and smells. This is frequently achieved with recirculation of the indoor air by introducing some of the exhaust air back into the supply stream to conserve energy.

Consequently, and mostly due to poor cleaning and maintenance of the various HVAC system components, many people find their indoor environment hardly acceptable, and several adverse health effects are reportedly caused by the low quality of air that people are exposed to inside buildings. The debate about the effects of mechanical ventilation and air conditioning on people's health is still open today but there are already strong suggestions of an association between inadequate ventilation and the prevalence of respiratory and other building related symptoms, even more so for those systems which include air conditioning capabilities [28,184]. Still, despite the standards and best practice guidelines being frequently revised, there continue to be many problems during the operation lifetime of mechanical ventilation systems including insufficient fresh air supply, inadequate settings for the air temperature, humidity and velocity, and improper or neglected cleaning and maintenance.

As people spend most of their time inside buildings, it is crucially important to provide adequate IAQ in addition to thermal comfort, especially for office buildings and schools, where people are working and learning. Insufficient ventilation may lead to Sick

Building Syndrome (SBS), which causes health issues for occupant and lowers their productivity [184]. It is well-accepted that improving indoor climate condition can significantly increase the productivity and health of occupants [185,186]. Moreover, not well-designed ventilation systems may lead to destructive effects on building occupants' health and performance [187]. Therefore, health, productivity and comfort of occupants are significant issues that should be considered throughout building design and operation [188].

Ventilation standards specify minimum ventilation rates required for buildings in order to meet acceptable indoor air quality. According to the findings of [186], however, ventilation rates requirements of standards might not be sufficient for always providing suitable IAQ, in particular for formaldehyde level [189]. Table 4 summarizes the ventilation standards of different countries for general non-smoking spaces. Some of the standards have defined different flowrates required for different types of spaces such as office, classroom, auditorium, shop and restaurant. For spaces in which smoking is permitted the demand of outside flowrate significantly increases. Moreover, a recent review of ventilation in dwellings of 12 European countries [190] concluded that an air exchange rate of $0.5\ h^{-1}$ as a minimum requirement in many European standards might not satisfy health criteria. A recent review about development of ventilation and IAQ standards, mostly based on ASHRAE 62, is also available in [191].

Many studies investigated the use of ventilation rate above standards requirements in order to increase performance and decrease health issues. Findings of some studies are listed below:

- Increasing the standard ventilation rate 25% to 90% can cause 0.33% to 0.91% increase in productivity of workers accompanied with improvements in preventing SBS symptoms and short-term absence of them accompanied with more energy consumption while using economizer, improvement in all criteria is recorded [197].
- Increasing the ventilation up to 25 L/s per person decreases occurrence of SBS symptoms while short-term absence, respiratory infections and asthma symptoms increases by low ventilation rate [184].
- Ventilation rate higher than 10 L/s per person and up to 20 L/s per person reduces prevalence of SBS symptoms and respiratory diseases [187].
- A recent review about the relationship between ventilation and health in public and residential buildings [198] has mentioned that higher ventilation rates lead to lower health risks while has indicated some limitations in available literature such as inadequate statistical power, lack of data about pollution sources, diversity of ventilation rates at which the health problems have been seen, etc. They also pointed out that the available information cannot be universally applicable.

Besides different ventilation rates, the following studies have investigated and compared influence of different ventilation systems on health and productivity.

- Dutton et al. [199] investigated workers health conditions in retrofitted office buildings in which traditional mechanical ventilation and air-conditioning is replaced by natural ventilation and they found increasing several health problems in occupants due to exposure to outdoor contaminant such as ozone. However, they revealed that the number of workers experiencing SBS symptoms is decreasing. As the care cost of increased health problems dominates the saving from decreased SBS symptoms, they recommended use of mechanical ventilation and air-conditioning instead of natural ventilation when the outdoor ozone and particulate matter concentration is high.
- Muhič and Butala [91] evaluated and compared the health condition of occupants in naturally and mechanically ventilated buildings through 6 month measurements and a questionnaire survey. They pointed out that in terms of occupants' health condition naturally ventilated building performs better, except in eye inflammation and swollen eyelids. They also reported significantly high occurrence of SBS symptoms in mechanically ventilated building.
- From a field study survey in [200] that assessed three buildings with different ventilation systems (HVAC system, fan coil unit and natural ventilation), it is reported that comparing with workers in naturally ventilated building, those worked in office with HVAC system experienced more short-term throat irritation and those who worked in office with fan coil experienced greater number of short-term sinusitis while both of them experienced more usual coughing in cold air.

Table 5 shows that significant profit can be gained from improving indoor climate like increasing productivity and decreasing health-related effects such as SBS symptoms, respiratory illnesses and allergies. Based on data available in Table 5, many employers prefer to neglect energy efficiency to improve productivity because the employees' remunerations and profits considerably exceeds energy costs [201]. Therefore, developing methods to design ventilation systems that can improve indoor climate and energy efficiency in the same time is promising.

Among all factors affecting workers' productivity, Seppänen et al. [202] investigated the influence of indoor temperature on performance of workers. The highest productivity has been recorded in temperature around 22 °C and by increasing temperature to 30 °C it showed about 10% reduction. Furthermore, another study [203] investigated various factors affecting workers' productivity in different indoor climates in two factories in China using a field study. They announced that, although IAQ has the highest influence on productivity, thermal feeling of workers can significantly affect their productivity. They found that workers perform more productive in either a little cooler or a little warmer comparing with neutral condition, however, the highest productivity has been recorded for slightly cooler temperature in both case studies.

Additionally, as children spend most of their time at indoor spaces, concentration of pollution can have more adverse effects on their performance and health. In this subject, Franklin [204] and Etzel [205] studied the effects of indoor air pollution on respiratory health of children. The latter reference, [205], particularly assessed exposure of children to tobacco smokes, and recommended legislation of new policies to decrease this exposure immediately. Putting the fresh air intake in the cleanest

Table 4
Recommended outdoor flowrate and indoor CO_2 level in different ventilation standards.

Country		Standard	Rate of outside air (m^3/h person)	CO_2 level (ppm)
Switzerland		SIA382/1 [192]	12–30	1000–1500
Austria		ÖN6000-3 [193]	20–70	1000
Europe	IDA1 (High IAQ)	EN13779 [194]	≥ 54	≥ 400*
	IDA2 (Medium IAQ)		36–54	400–600*
	IDA3 (Moderate IAQ)		22–36	600–1000*
	IDA4 (Low IAQ)		< 22	< 1000*
Germany	DIN 1946-2 [195]		20–60	1000–1500
USA	ASHRAE 62 [196]		29–36	700*

* Means above outdoor concentration

Table 5
Estimated potential productivity gains in 1996 $US [185]

Source of Productivity Gain	Potential Annual Health Benefits	Potential Annual Savings or Gains.
Reduced respiratory illness	16 to 37 million avoided cases of common cold or influenza	$6–$14 billion
Reduced allergies and asthma	10% to 30% decrease in symptoms within 53 million allergy sufferers and 16 million asthmatics	$2–$4 billion
Reduced SBS symptoms	20% to 50% reduction in SBS health symptoms experienced frequently at work by ~15 million workers	$10–$30 billion
Improved performance from thermal and lighting changes	Not applicable	$20–$160 billion

outdoor location, protecting the HVAC components from dusts and pollutant sources, using local exhausts and using high-quality filters with low pressure drop results in better IAQ and in consequence more productivity and energy efficiency [206]. Temperature fluctuation should be controlled not to exceed 4 °C in a working shift [207].

5. Conclusion

Energy demand is continuously increasing worldwide and the building sector is responsible for a large portion of global energy consumption. Thus, promoting energy efficiency in buildings is essential. Among all building services, HVAC systems are significantly responsible for building energy use. Therefore, improving ventilation systems plays an important role not only in fostering energy efficiency in buildings but also in providing better indoor climate for the occupants and in decreasing the occurrence of health issues. In consequence, energy-efficient ventilation system causes reduction in building-related GHG emission and reduces the climate change risks. The present paper reviewed existing literature in energy-efficient ventilation methods, the influence of occupants' behaviour on ventilation and energy consumption and the relation of ventilation with health and productivity. A summary of findings in this review is listed below:

- Natural ventilation driving forces can either oppose or complement each other.
- As noted by many authors, the position and size of openings plays a significate role in natural ventilation effectiveness.
- In hybrid ventilation, mechanical ventilators compensate the shortcomings from natural ventilation, when required.
- Utilizing hybrid ventilation not only provides acceptable IAQ level but also causes notable amount of energy saving due to lower use of mechanical ventilation.
- Integrating ventilation control strategies to hybrid ventilation leads to considerable amount of energy saving.
- A large amount of energy is annually wasted in the world due to ventilating spaces during low or even zero occupancy. In this case, DCV improves ventilation energy performance through considering occupancy level.
- Besides building characteristics, environmental condition and ventilation methods, and occupants' behaviour on controlling their environment significantly affects IAQ and energy performance in buildings.
- Not well-designed ventilation systems might lead to increasing health issues and symptoms among building occupants. This shows the tight relation between ventilation rate, occupants' health and their performance.
- Regarding healthy and productive environment, many studies propose ventilation rates higher than minimum requirements of the standards and regulations.
- More research is required to broadly assess the relation of ventilation and occupant health, not only for offices but also for homes, schools and day care centres in various climates especially regions with high outdoor pollution and more attention is required to be paid for air cleaning and efficient filtration systems.

Nowadays, ventilation requirements are addressed by most of the standards dealing with Indoor Environmental Quality in buildings. The process of definition of a ventilation requirement, e.g. the fresh air flow rate, usually starts with the fixation of a reference value for a health or comfort criterion based on the indoor air quality or on the removal of the heating or cooling load. The fresh air flow rate may be the result of a prescriptive method, usually corresponding to a table where, depending on the type of space, it is defined, or, in a different way, it may be calculated applying an analytical method. There are still important differences between the requirements defined by different national standards, and also international standards are far from being consensual. There is a need of a better harmonization of the existing standards and also the difference between infiltration and ventilation rates needs to be more discussed and clarified. As regards the integration of standards and codes with international building certification methods, this is an important issue. Most of the certification schemes consider some ventilation requirement, which usually is coincident with the prescription of national or international used standards. What is expected and desirable is that building certification schemes and standards will keep an evolutionary character changing together with the evolution of the state-of-the-art of ventilation science.

Based on this review, it was found that, despite considerable advances in the field in the last two decades, there remain open questions which are pertinent to the wider acceptance and implementation of novel hybrid ventilation strategies. One fundamental question that remains open relates to what extent today's state-of-the-art rule based control strategies can be improved upon for hybrid ventilation systems, and whether a different approach to control could introduce substantial improvements in a real use situation. In particular, there is no study in the existing literature, addressing intelligent window-based hybrid ventilation strategies for maintaining the IAQ and reducing the energy consumption at the same time. On the other hand, many researchers have reported on various approaches to controlling ventilation with various degrees of performance in terms of energy savings and occupants' satisfaction. It is pertinent, nevertheless, to think in terms of a lower bound for the energy requirements in order to provide a comfortable and healthy indoor environment for people, and it does not make sense to reduce energy consumption further if it affects negatively people's comfort and health. With the introduction of more and more nZEBs in the coming decades, the energy consumption in buildings paradigm will shift from a long time scale (yearly) assessment metric to a short time scale (daily) quest for a balance between local production, demand and storage capacity. In this new paradigm, it is envisaged that dynamic, predictive control of the building systems, including hybrid ventilation, can become a much more effective strategy to condition the indoor climate, not necessarily because energy consumption is reduced, but because the available renewable energy resources are used most efficiently.

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References

[1] Tofield B, Ingham M. Refurbishing Europe—an EU strategy for energy efficiency and climate action led by building refurbishment Build with CaRe, Norwich 2012.
[2] Melton K. Research priorities for renewable energy technology by 2020 and beyond; 2010.
[3] Energy Efficient buildings PPP. Multi-annual roadmap and long term strategy. Prepared by the Ad Hoc Industrial Advisory Group. European Commission, Directorate-General Research, Industrial Technologies. 2010. Retreived from ⟨⟨http://www.ectp.org/cws/params/ectp/download_files/36d1191v1_eeb_roadmap.pdf⟩⟩.
[4] Liddament MW. A review of ventilation and the quality of ventilation air. Indoor Air 2000;10:193–9.
[5] Pérez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy Build 2008;40:394–8. http://dx.doi.org/10.1016/j.enbuild.2007.03.007.
[6] Gruber E, Plesser S, Dusée R, Sofronis I, Lima P, Rivière P, et al. Deliverable D26: Report on the project results. Technical report, EL-TERTIARY project, Intelligent Energy - Europe; August 2008.
[7] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Published in Official Journal of the European Union.
[8] European standard EN 15251:2007. Indoor environmental input parameters for de- sign and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. European Committee for Standardization, Bruss; 2007.
[9] ANSI/ASHRAE Standard 55-2010. Thermal Comfort Conditions for Human Occupancy. American Society of Heating, Air-Conditioning, and Refrigeration Engineers, Inc., Atlanta, GA; 2010.
[10] International Standard ISO 7730:2005. Ergonomics of the thermal environment-Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Organization for St.2005.
[11] Fanger PO. Thermal comfort: analysis and applications in environmental engineering. Copenhagen: Danish Technical Press; 1970.
[12] Fang L, Clausen G, Fanger PO. Impact of temperature and humidity on the perception of indoor air quality. Indoor Air 1998;8:80–90.
[13] Corgnati SP, Gameiro da Silva M, Ansaldi R, Asadi E, Costa JJ, Filippi M, Kaczmarczyk J, Melikov AK, Olesen BW, Popiolek Z, Wargocki P. Indoor climate quality assessment/REHVA guidebook No. 14. Brussles: REHVA; 2011.
[14] ASHRAE 62.1. Ventilation for Acceptable Indoor Air Quality 2010.
[15] Fanger PO. Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors. Energy Build 1988;12:1–6. http://dx.doi.org/10.1016/0378-7788(88)90051-5.
[16] CEN REPORT. EN CR 1752 Ventilation for buildings-Design criteria for the indoor environment 1998.
[17] Op't Veld P. Introduction to EC RESHYVENT–EU cluster project on demand controlled hybrid ventilation for residential buildings. Build Environ 2008;43:1342–9. http://dx.doi.org/10.1016/j.buildenv.2007.01.043.
[18] Lomas KJ, Ji Y. Resilience of naturally ventilated buildings to climate change: advanced natural ventilation and hospital wards. Energy Build 2009;41:629–53. http://dx.doi.org/10.1016/j.enbuild.2009.01.001.
[19] Cao G, Awbi H, Yao R, Fan Y, Sirén K, Kosonen R, et al. A review of the performance of different ventilation and airflow distribution systems in buildings. Build Environ 2014;73:171–86. http://dx.doi.org/10.1016/j.buildenv.2013.12.009.
[20] Awbi Hazim B. Ventilation of buildings. 2nd ed. London: Spon Press; 2003.
[21] Kleiven T. Natural ventilation in buildings. Norwegian University of Science and Technology; 2003.
[22] Capeluto IG. A methodology for the qualitative analysis of winds: natural ventilation as a strategy for improving the thermal comfort in open spaces. Build Environ 2005;40:175–81. http://dx.doi.org/10.1016/j.buildenv.2004.07.003.
[23] Khan N, Su Y, Riffat SB. A review on wind driven ventilation techniques. Energy Build 2008;40:1586–604. http://dx.doi.org/10.1016/j.enbuild.2008.02.015.
[24] Linden PF. The fluid mechanics of natural ventilation. Annu Rev Fluid Mech 1999;31:201–38.
[25] Gao Jun, Zhao Jia Ning, Gao Fu Sheng, Zhang Xu. Modeling of indoor thermally stratified flows on the basis of Eddy viscosity/diffusivity model: state of the art review. J Build Phys 2009;32:221–41. http://dx.doi.org/10.1177/1744259108098337.
[26] Cóstola D, Blocken B, Hensen JLM. Overview of pressure coefficient data in building energy simulation and airflow network programs. Build Environ 2009;44:2027–36. http://dx.doi.org/10.1016/j.buildenv.2009.02.006.
[27] Ahmad K, Khare M, Chaudhry KK. Wind tunnel simulation studies on dispersion at urban street canyons and intersections—a review. J Wind Eng Ind Aerodyn 2005;93:697–717. http://dx.doi.org/10.1016/j.jweia.2005.04.002.
[28] Seppänen O a, Fisk WJ. Summary of human responses to ventilation. Indoor Air 2004;14:102–18. http://dx.doi.org/10.1111/j.1600-0668.2004.00279.x.
[29] Roetzel A, Tsangrassoulis A, Dietrich U, Busching S. A review of occupant control on natural ventilation. Renew Sustain Energy Rev 2010;14:1001–13. http://dx.doi.org/10.1016/j.rser.2009.11.005.
[30] Oldham DJ, de Salis MH, Sharples S. Reducing the ingress of urban noise through natural ventilation openings. Indoor Air 2004;14:118–26. http://dx.doi.org/10.1111/j.1600-0668.2004.00294.x.
[31] Holmes MJ, Hacker JN. Climate change, thermal comfort and energy: meeting the design challenges of the 21st century. Energy Build 2007;39:802–14. http://dx.doi.org/10.1016/j.enbuild.2007.02.009.
[32] LIDDAMENT MW. The applicability of natural ventilation-technical editorial. Int J Vent 2009;8:189–99.
[33] Heiselberg P, Svidt K, Nielsen PV. Characteristics of air ow from open windows; 2001. 36. p.859–69.
[34] Heiselberg P, Perino M. Short-term airing by natural ventilation-implication on IAQ and thermal comfort. Indoor Air 2010;20:126–40. http://dx.doi.org/10.1111/j.1600-0668.2009.00630.x.
[35] Andersen KT. Theory for natural ventilation by thermal buoyancy in one zone with uniform temperature. Build Environ 2003;38:1281–9. http://dx.doi.org/10.1016/S0360-1323(03)00132-X.
[36] HUNT GR, LINDEN PF. Steady-state flows in an enclosure ventilated by buoyancy forces assisted by wind. J Fluid Mech 2001;426:355–86. http://dx.doi.org/10.1017/S0022112000002470.
[37] HUNT GR, LINDEN PF. Displacement and mixing ventilation driven by opposing wind and buoyancy. J Fluid Mech 2005;527:27–55. http://dx.doi.org/10.1017/S0022112004002575.
[38] Allocca C, Chen Q, Glicksman LR. Design analysis of single-sided natural ventilation. Energy Build 2003;35:785–95. http://dx.doi.org/10.1016/S0378-7788(02)00239-6.
[39] Gratia E, Bruyère I, De Herde a. How to use natural ventilation to cool narrow office buildings. Build Environ 2004;39:1157–70. http://dx.doi.org/10.1016/j.buildenv.2004.02.005.
[40] Larsen TS, Heiselberg P. Single-sided natural ventilation driven by wind pressure and temperature difference. Energy Build 2008;40:1031–40. http://dx.doi.org/10.1016/j.enbuild.2006.07.012.
[41] Emmerich SJ, Polidoro B, Axley JW. Impact of adaptive thermal comfort on climatic suitability of natural ventilation in office buildings. Energy Build 2011;43:2101–7. http://dx.doi.org/10.1016/j.enbuild.2011.04.016.
[42] Fordham M. Natural ventilation. Renew Energy 2000;19:17–37.
[43] Wildeboer J, Fitzner K. Influence of the height of the supply air opening for natural ventilation on thermal comfort. In: Proceedings of the ROOMVENT2002, 8th International Conference on Air Distrib. Rooms: Copenhagen; 2002.
[44] Chu C-R, Chiu Y-H, Tsai Y-T, Wu S-L. Wind-driven natural ventilation for buildings with two openings on the same external wall. Energy Build 2015;108:365–72. http://dx.doi.org/10.1016/j.enbuild.2015.09.041.
[45] Stavridou AD, Prinos PE. Natural ventilation of buildings due to buoyancy assisted by wind: investigating cross ventilation with computational and laboratory simulation. Build Environ 2013;66:104–19. http://dx.doi.org/10.1016/j.buildenv.2013.04.011.
[46] Shetabivash H. Investigation of opening position and shape on the natural cross ventilation. Energy Build 2015;93:1–15. http://dx.doi.org/10.1016/j.enbuild.2014.12.053.
[47] Chu CR, Chiang BF. Wind-driven cross ventilation in long buildings. Build Environ 2014;80:150–8. http://dx.doi.org/10.1016/j.buildenv.2014.05.017.
[48] Zhai XQ, Song ZP, Wang RZ. A review for the applications of solar chimneys in buildings. Renew Sustain Energy Rev 2011;15:3757–67. http://dx.doi.org/10.1016/j.rser.2011.07.013.
[49] Jing H, Chen Z, Li A. Experimental study of the prediction of the ventilation flow rate through solar chimney with large gap-to-height ratios. Build Environ 2015;89:150–9. http://dx.doi.org/10.1016/j.buildenv.2015.02.018.
[50] Moosavi L, Mahyuddin N, Ab Ghafar N, Azzam Ismail M. Thermal performance of atria: an overview of natural ventilation effective designs. Renew Sustain Energy Rev 2014;34:654–70. http://dx.doi.org/10.1016/j.rser.2014.02.035.
[51] Saadatian O, Haw LC, Sopian K, Sulaiman MY. Review of windcatcher technologies. Renew Sustain Energy Rev 2012;16:1477–95. http://dx.doi.org/10.1016/j.rser.2011.11.037.
[52] Hughes BR, Calautit JK, Ghani SA. The development of commercial wind towers for natural ventilation: a review. Appl Energy 2012;92:606–27. http://dx.doi.org/10.1016/j.apenergy.2011.11.066.

[53] Dehghani-sanij a R, Soltani M, Raahemifar K. A new design of wind tower for passive ventilation in buildings to reduce energy consumption in windy regions. Renew Sustain Energy Rev 2015;42:182–95. http://dx.doi.org/10.1016/j.rser.2014.10.018.

[54] Aflaki A, Mahyuddin N, Al-Cheikh Mahmoud Z, Baharum MR. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. Energy Build 2015;101:153–62. http://dx.doi.org/10.1016/j.enbuild.2015.04.033.

[55] Yao R, Li B, Steemers K, Short A. Assessing the natural ventilation cooling potential of office buildings in different climate zones in China. Renew Energy 2009;34:2697–705. http://dx.doi.org/10.1016/j.renene.2009.05.015.

[56] Ramponi R, Gaetani I, Angelotti A. Influence of the urban environment on the effectiveness of natural night-ventilation of an office building. Energy Build 2014;78:25–34. http://dx.doi.org/10.1016/j.enbuild.2014.04.001.

[57] Jamaludin AA, Hussein H, Mohd Ariffin AR, Keumala N. A study on different natural ventilation approaches at a residential college building with the internal courtyard arrangement. Energy Build 2014;72:340–52. http://dx.doi.org/10.1016/j.enbuild.2013.12.050.

[58] Wang Z, Yi L, Gao F. Night ventilation control strategies in office buildings. Sol Energy 2009;83:1902–13. http://dx.doi.org/10.1016/j.solener.2009.07.003.

[59] Zhou J, Zhang G, Lin Y, Li Y. Coupling of thermal mass and natural ventilation in buildings. Energy Build 2008;40:979–86. http://dx.doi.org/10.1016/j.enbuild.2007.08.001.

[60] Yu T, Heiselberg P, Lei B, Pomianowski M, Zhang C. A novel system solution for cooling and ventilation in office buildings: a review of applied technologies and a case study. Energy Build 2015;90:142–55. http://dx.doi.org/10.1016/j.enbuild.2014.12.057.

[61] Fracastoro GV, Mutani G, Perino M. Experimental and theoretical analysis of natural ventilation by windows opening. Energy Build 2002;34:817–27.

[62] Lin JT, Chuah YK. A study on the potential of natural ventilation and cooling for large spaces in subtropical climatic regions. Build Environ 2011;46:89–97. http://dx.doi.org/10.1016/j.buildenv.2010.07.007.

[63] Wagner A, Moosmann C, Gropp T, Gossauer E. Thermal comfort in a naturally ventilated office building in Karlsruhe , Germany – results of a survey. Clima; 2007, 2007.

[64] Hussain S, Oosthuizen PH. Numerical investigations of buoyancy-driven natural ventilation in a simple three-storey atrium building and thermal comfort evaluation. Appl Therm Eng 2013;57:133–46. http://dx.doi.org/10.1016/j.applthermaleng.2013.03.033.

[65] Holford JM, Hunt GR. Fundamental atrium design for natural ventilation. Build Environ 2003;38:409–26. http://dx.doi.org/10.1016/S0360-1323(02)00019-7.

[66] Ray SD, Gong N-W, Glicksman LR, Paradiso JA. Experimental characterization of full-scale naturally ventilated atrium and validation of CFD simulations. Energy Build 2014;69:285–91. http://dx.doi.org/10.1016/j.enbuild.2013.11.018.

[67] Tantasavasdi C, Srebric J, Chen Q. Natural ventilation design for houses in Thailand. Energy Build 2001;33:815–24. http://dx.doi.org/10.1016/S0378-7788(01)00073-1.

[68] Moghaddam EH, Amindeldar S, Besharatizadeh A. New approach to natural ventilation in public buildings inspired by Iranian's traditional windcatcher. Procedia Eng 2011;21:42–52. http://dx.doi.org/10.1016/j.proeng.2011.11.1985.

[69] Yang A-S, Wen C-Y, Juan Y-H, Su Y-M, Wu J-H. Using the central ventilation shaft design within public buildings for natural aeration enhancement. Appl Therm Eng 2014;70:219–30. http://dx.doi.org/10.1016/j.applthermaleng.2014.05.017.

[70] Jóźwiak R, Kacprzyk J, Żurański JA. Influence of wind direction on natural ventilation of apartment buildings. J Wind Eng Ind Aerodyn 1996;60:167–76. http://dx.doi.org/10.1016/0167-6105(96)00031-1.

[71] Prajongsan P, Sharples S. Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts. Build Environ 2012;50:104–13. http://dx.doi.org/10.1016/j.buildenv.2011.10.020.

[72] Chan H-Y, Riffat SB, Zhu J. Review of passive solar heating and cooling technologies. Renew Sustain Energy Rev 2010;14:781–9. http://dx.doi.org/10.1016/j.rser.2009.10.030.

[73] Zhai XQ, Song ZP, Wang RZ. A review for the applications of solar chimneys in buildings. Renew Sustain Energy Rev 2011;15:3757–67. http://dx.doi.org/10.1016/j.rser.2011.07.013.

[74] Ding W, Hasemi Y, Yamada T. Natural ventilation performance of a double-skin façade with a solar chimney. Energy Build 2005;37:411–8. http://dx.doi.org/10.1016/j.enbuild.2004.08.002.

[75] Krzaczek M, Florczuk J, Tejchman J. Field investigations of stack ventilation in a residential building with multiple chimneys and tilted window in cold climate. Energy Build 2015;103:48–61. http://dx.doi.org/10.1016/j.enbuild.2015.06.034.

[76] Cruz-Salas MV, Castillo JA, Huelsz G. Experimental study on natural ventilation of a room with a windward window and different windexchangers. Energy Build 2014;84:458–65. http://dx.doi.org/10.1016/j.enbuild.2014.08.033.

[77] Bangalee MZI, Lin SY, Miau JJ. Wind driven natural ventilation through multiple windows of a building: a computational approach. Energy Build 2012;45:317–25. http://dx.doi.org/10.1016/j.enbuild.2011.11.025.

[78] Gratia E, De Herde A. Natural ventilation in a double-skin facade. Energy Build 2004;36:137–46. http://dx.doi.org/10.1016/j.enbuild.2003.10.008.

[79] Gratia E, De Herde A. Natural cooling strategies efficiency in an office building with a double-skin façade. Energy Build 2004;36:1139–52. http://dx.doi.org/10.1016/j.enbuild.2004.05.004.

[80] Gratia E, De Herde A. Is day natural ventilation still possible in office buildings with a double-skin façade? Build Environ 2004;39:399–409. http://dx.doi.org/10.1016/j.buildenv.2003.10.006.

[81] Jiang Y, Alexander D, Jenkins H, Arthur R, Chen Q. Natural ventilation in buildings : measurement in a wind tunnel and numerical simulation with large-eddy simulation. J Wind Eng Ind Aerodyn 2003;91:331–53.

[82] Oropeza-Perez I, Østergaard PA. Potential of natural ventilation in temperate countries – a case study of Denmark. Appl Energy 2014;114:520–30. http://dx.doi.org/10.1016/j.apenergy.2013.10.008.

[83] Emmerich S, Dols W, Axley J. Natural ventilation review and plan for design and analysis tools. Springfield, VA: US Department of Commerce, Technology Administration, National Institute of Standards and Technology; 2001.

[84] Raja IA, Nicol JF, McCartney KJ. Natural ventilated buildings: use of controls for changing indoor climate. Renew Energy 1998;15:391–4.

[85] Raja IA, Nicol JF, Mccartney KJ, Humphreys MA. Thermal comfort : use of controls in naturally ventilated buildings. Energy Build 2001;33:235–44.

[86] Dear RJ, De, Brager GS. Thermal comfort in naturally ventilated buildings : revisions to ASHRAE Standard 55. Energy Build 2002;34:549–61.

[87] Rijal HB, Tuohy P, Humphreys M a, Nicol JF, Samuel a, Clarke J. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. Energy Build 2007;39:823–36. http://dx.doi.org/10.1016/j.enbuild.2007.02.003.

[88] Homod RZ, Sahari KSM, Almurib H a F. Energy saving by integrated control of natural ventilation and HVAC systems using model guide for comparison. Renew Energy 2014;71:639–50. http://dx.doi.org/10.1016/j.renene.2014.06.015.

[89] Belleri A, Lollini R, Dutton SM. Natural ventilation design: an analysis of predicted and measured performance. Build Environ 2014;81:123–38. http://dx.doi.org/10.1016/j.buildenv.2014.06.009.

[90] Heiselberg P. Principles of hybrid ventilation. Aalborg: Aalborg University; 2002.

[91] Muhič S, Butala V. The influence of indoor environment in office buildings on their occupants: expected–unexpected. Build Environ 2004;39:289–96. http://dx.doi.org/10.1016/j.buildenv.2003.09.011.

[92] Hummelgaard J, Juhl P, Sæbjörnsson KO, Clausen G, Toftum J, Langkilde G. Indoor air quality and occupant satisfaction in five mechanically and four naturally ventilated open-plan office buildings. Build Environ 2007;42:4051–8. http://dx.doi.org/10.1016/j.buildenv.2006.07.042.

[93] Brager G, Baker L. Occupant satisfaction in mixed-mode buildings. Build Res Inf 2009;37:369–80. http://dx.doi.org/10.1080/09613210902899785.

[94] Chang H, Kato S, Chikamoto T. Effects of outdoor air conditions on hybrid air conditioning based on task/ambient strategy with natural and mechanical ventilation in office buildings. Build Environ 2004;39:153–64. http://dx.doi.org/10.1016/j.buildenv.2003.07.008.

[95] HYBVENT, 〈〈http://www.hybvent.civil.aau.dk/〉〉.

[96] Homod RZ, Sahari KSM. Energy savings by smart utilization of mechanical and natural ventilation for hybrid residential building model in passive climate. Energy Build 2013;60:310–29. http://dx.doi.org/10.1016/j.enbuild.2012.10.034.

[97] Ezzeldin S, Rees SJ. The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates. Energy Build 2013;65:368–81. http://dx.doi.org/10.1016/j.enbuild.2013.06.004.

[98] Lomas KJ, Cook MJ, Fiala D. Low energy architecture for a severe US climate: design and evaluation of a hybrid ventilation strategy. Energy Build 2007;39:32–44. http://dx.doi.org/10.1016/j.enbuild.2006.03.032.

[99] Miura K, Takemasa Y, Katoh M, Hiraoka M. Effect of hybrid ventilation system on indoor environment and annual cooling load in a high-rise building. ASHRAE Trans 2012;118:831–46.

[100] Spindler HC, Norford LK. Naturally ventilated and mixed-mode buildings-Part I: thermal modeling. Build Environ 2009;44:736–49. http://dx.doi.org/10.1016/j.buildenv.2008.05.019.

[101] Spindler HC, Norford LK. Naturally ventilated and mixed-mode buildings-Part II: optimal control. Build Environ 2009;44:750–61. http://dx.doi.org/10.1016/j.buildenv.2008.05.018.

[102] Fracastoro GV, Perino M, Mutani G. A Simple Tool to Assess the Feasibility of Hybrid Ventilation Systems; 2002.

[103] Niachou K, Hassid S, Santamouris M, Livada I. Comparative monitoring of natural, hybrid and mechanical ventilation systems in urban canyons. Energy Build 2005;37:503–13. http://dx.doi.org/10.1016/j.enbuild.2004.09.016.

[104] Niachou K, Hassid S, Santamouris M, Livada I. Experimental performance investigation of natural, mechanical and hybrid ventilation in urban environment. Build Environ 2008;43:1373–82. http://dx.doi.org/10.1016/j.buildenv.2007.01.046.

[105] Kato S, Chikamoto T. The Liberty Tower of Meiji University; 2002.

[106] Hendriksen OJ, Brohus H, Frier C, Heiselberg P. Bang Olufsen Head Quarter; 2002.

[107] Antvorskov S. Introduction to integration of renewable energy in demand controlled hybrid ventilation systems for residential buildings. Build Environ 2008;43:1350–3. http://dx.doi.org/10.1016/j.buildenv.2007.01.045.

[108] Tjelflaat PO, Haugen JA, Buvik K, Vik TA. Mediå School; 2000.

[109] Tjelflaat PO, Zhang J, Haghighat F. Measurements of cooling performance for an earth-to-air heat exchanger with an axial entrance fan. Trondheim: Roomvent; 2011.

[110] Michel P, Mankibi M El. Advanced control strategy; 2000.

[111] Dounis AI, Caraiscos C. Advanced control systems engineering for energy and comfort management in a building environment—a review. Renew Sustain Energy Rev 2009;13:1246–61. http://dx.doi.org/10.1016/j.rser.2008.09.015.

[112] Huang G, Wang S, Xu X. A robust model predictive control strategy for improving the control performance of air-conditioning systems. Energy Convers Manag 2009;50:2650–8. http://dx.doi.org/10.1016/j.enconman.2009.06.014.

[113] Kolokotsa D, Pouliezos A, Stavrakakis G, Lazos C. Predictive control techniques for energy and indoor environmental quality management in buildings. Build Environ 2009;44:1850–63. http://dx.doi.org/10.1016/j.buildenv.2008.12.007.

[114] Coffey B, Haghighat F, Morofsky E, Kutrowski E. A software framework for model predictive control with GenOpt. Energy Build 2010;42:1084–92. http://dx.doi.org/10.1016/j.enbuild.2010.01.022.

[115] Schuss M, Pröglhöf C, Orehounig K, Mahdavi A. A simulation-powered approach to ventilation, lighting and shading systems control. Bauphysik 2010;32:391–8. http://dx.doi.org/10.1002/bapi.201010045.

[116] Sivakumar P, Palanthandalam-Madapusi HJ, Dang TQ. Control of natural ventilation for aerodynamic high-rise buildings. Build Simul 2010;3:311–25. http://dx.doi.org/10.1007/s12273-010-0014-3.

[117] May-Ostendorp P, Henze GP, Corbin CD, Rajagopalan B, Felsmann C. Model-predictive control of mixed-mode buildings with rule extraction. Build Environ 2011;46:428–37. http://dx.doi.org/10.1016/j.buildenv.2010.08.004.

[118] Castilla M, Álvarez JD, Berenguel M, Rodríguez F, Guzmán JL, Pérez M. A comparison of thermal comfort predictive control strategies. Energy Build 2011;43:2737–46. http://dx.doi.org/10.1016/j.enbuild.2011.06.030.

[119] Keblawi A, Ghaddar N, Ghali K. Model-based optimal supervisory control of chilled ceiling displacement ventilation system. Energy Build 2011;43:1359–70. http://dx.doi.org/10.1016/j.enbuild.2011.01.021.

[120] Ma J, Qin J, Salsbury T, Xu P. Demand reduction in building energy systems based on economic model predictive control. Chem Eng Sci 2012;67:92–100. http://dx.doi.org/10.1016/j.ces.2011.07.052.

[121] Figueiredo J, Sá da Costa J. A SCADA system for energy management in intelligent buildings. Energy Build 2012;49:85–98. http://dx.doi.org/10.1016/j.enbuild.2012.01.041.

[122] Oldewurtel F, Parisio A, Jones CN, Gyalistras D, Gwerder M, Stauch V, et al. Use of model predictive control and weather forecasts for energy efficient building climate control. Energy Build 2012;45:15–27. http://dx.doi.org/10.1016/j.enbuild.2011.09.022.

[123] Djuric N, Novakovic V. Identifying important variables of energy use in low energy office building by using multivariate analysis. Energy Build 2012;45:91–8. http://dx.doi.org/10.1016/j.enbuild.2011.10.031.

[124] Wang S, Ma Z. Supervisory and optimal control of building HVAC systems: a review. HVACR Res 2008;14:3–32. http://dx.doi.org/10.1080/10789669.2008.10390991.

[125] Henze G, Ostendorp PM. HVAC control algorithms for mixed-mode buildings. 2012.

[126] Yu Yuebin. Model-based multivariate control of conditioning systems for office buildings. Pittsburgh, Pennsylvania: Carnegie Mellon University; 2012.

[127] Hu J, Karava P. Model predictive control strategies for buildings with mixed-mode cooling. Build Environ 2014;71:233–44. http://dx.doi.org/10.1016/j.buildenv.2013.09.005.

[128] El Mankibi M, Cron F, Michel P, Inard C. Prediction of hybrid ventilation performance using two simulation tools. Sol Energy 2006;80:908–26. http://dx.doi.org/10.1016/j.solener.2005.08.003.

[129] Jreijiry D, Husaunndee A, Inard C. Numerical study of a hybrid ventilation system for single family houses. Sol Energy 2007;81:227–39. http://dx.doi.org/10.1016/j.solener.2006.03.013.

[130] Mossolly M, Ghali K, Ghaddar N. Optimal control strategy for a multi-zone air conditioning system using a genetic algorithm. Energy 2009;34:58–66. http://dx.doi.org/10.1016/j.energy.2008.10.001.

[131] Walker IS, Sherman MH. Effect of ventilation strategies on residential ozone levels. Build Environ 2013;59:456–65. http://dx.doi.org/10.1016/j.buildenv.2012.09.013.

[132] Ji Y, Lomas KJ, Cook MJ. Hybrid ventilation for low energy building design in south China. Build Environ 2009;44:2245–55. http://dx.doi.org/10.1016/j.buildenv.2009.02.015.

[133] Schulze T, Eicker U. Controlled natural ventilation for energy efficient buildings. Energy Build 2013;56:221–32. http://dx.doi.org/10.1016/j.enbuild.2012.07.044.

[134] Kim MH, Hwang JH. Performance prediction of a hybrid ventilation system in an apartment house. Energy Build 2009;41:579–86. http://dx.doi.org/10.1016/j.enbuild.2008.12.003.

[135] Hesaraki A, Myhren JA, Holmberg S. Influence of different ventilation levels on indoor air quality and energy savings: a case study of a single-family house. Sustain Cities Soc 2015;19:165–72. http://dx.doi.org/10.1016/j.scs.2015.08.004.

[136] Roth KW, Dieckmann J, Brodrick J. Demand control ventilation. ASHRAE J 2003;45(7):91–2.

[137] Mysen M, Rydock JP, Tjelflaat PO. Demand controlled ventilation for office cubicles — can it be profitable? Energy Build 2003;35:657–62.

[138] Erickson VL, Lin Y, Kamthe A, Brahme R, Surana A, Cerpa AE, et al., Energy efficient building environment control strategies using real-time occupancy measurements, BuildSys '09 Proceedings of the First *ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, 2009, 19–24, http://dx.doi.org/10.1145/1810279.1810284.

[139] Diraco G, Leone A, Siciliano P. People occupancy detection and profiling with 3D depth sensors for building energy management. Energy Build 2015;92:246–66. http://dx.doi.org/10.1016/j.enbuild.2015.01.043.

[140] Fisk WJ, Almeida AT De. Sensor-based demand-controlled ventilation: a review. Energy Build 1998;29:35–45.

[141] Emmerich S, Persily A. State-of-the-art review of CO_2 demand controlled ventilation technology and application. Darby, PA: Diane Publishing; 2001.

[142] Chao CYH, Hu JS. Development of a dual-mode demand control ventilation strategy for indoor air quality control and energy saving. Build Environ 2004;39:385–97. http://dx.doi.org/10.1016/j.buildenv.2003.11.001.

[143] Jeannette E, Phillips T. Designing and Testing Demand Controlled Ventilation Strategies. Natl. Conf. Build. Comm.; 2006, p. 1–13.

[144] Nassif N. Supply air CO_2 -based demand-controlled ventilation for multi-zone HVAC systems. ASHRAE Trans 2012;118:1–8.

[145] Lu T, Lü X, Viljanen M. A novel and dynamic demand-controlled ventilation strategy for CO_2 control and energy saving in buildings. Energy Build 2011;43:2499–508. http://dx.doi.org/10.1016/j.enbuild.2011.06.005.

[146] Karava P, Athienitis a K, Stathopoulos T, Mouriki E. Experimental study of the thermal performance of a large institutional building with mixed-mode cooling and hybrid ventilation. Build Environ 2012;57(313):26. http://dx.doi.org/10.1016/j.buildenv.2012.06.003.

[147] Menassa CC, Taylor N, Nelson J. A framework for automated control and commissioning of hybrid ventilation systems in complex buildings. Autom Constr 2013;30:94–103. http://dx.doi.org/10.1016/j.autcon.2012.11.022.

[148] Pavlovas V. Demand controlled ventilation A case study for existing Swedish multifamily buildings. Energy Build 2004;36:1029–34. http://dx.doi.org/10.1016/j.enbuild.2004.06.009.

[149] Mysen M, Berntsen S, Nafstad P, Schild PG. Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools. Energy Build 2005;37:1234–40. http://dx.doi.org/10.1016/j.enbuild.2005.01.003.

[150] Xu X, Wang S, Sun Z, Xiao F. A model-based optimal ventilation control strategy of multi-zone VAV air-conditioning systems. Appl Therm Eng 2009;29:91–104. http://dx.doi.org/10.1016/j.applthermaleng.2008.02.017.

[151] Congradac V, Kulic F. HVAC system optimization with CO_2 concentration control using genetic algorithms. Energy Build 2009;41:571–7. http://dx.doi.org/10.1016/j.enbuild.2008.12.004.

[152] Mossolly M, Ghali K, Ghaddar N. Optimal control strategy for a multi-zone air conditioning system using a genetic algorithm. Energy 2009;34:58–66. http://dx.doi.org/10.1016/j.energy.2008.10.001.

[153] Nielsen TR, Drivsholm C. Energy efficient demand controlled ventilation in single family houses. Energy Build 2010;42:1995–8. http://dx.doi.org/10.1016/j.enbuild.2010.06.006.

[154] Laverge J, Van Den Bossche N, Heijmans N, Janssens a. Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. Build Environ 2011;46:1497–503. http://dx.doi.org/10.1016/j.buildenv.2011.01.023.

[155] Sun Z, Wang S, Ma Z. In-situ implementation and validation of a CO_2-based adaptive demand-controlled ventilation strategy in a multi-zone office building. Build Environ 2011;46:124–33. http://dx.doi.org/10.1016/j.buildenv.2010.07.008.

[156] Ng MO, Qu M, Zheng P, Li Z, Hang Y. CO_2-based demand controlled ventilation under new ASHRAE Standard 62.1-2010: a case study for a gymnasium of an elementary school at West Lafayette, Indiana. Energy Build 2011;43:3216–25. http://dx.doi.org/10.1016/j.enbuild.2011.08.021.

[157] Iwashita G, Akasaka H. The effects of human behavior on natural ventilation rate and indoor air environment in summer — a field study in southern Japan. Energy Build 1997;25:195–205. http://dx.doi.org/10.1016/S0378-7788(96)00994-2.

[158] Bekö G, Toftum J, Clausen G. Modeling ventilation rates in bedrooms based on building characteristics and occupant behavior. Build Environ 2011;46:2230–7. http://dx.doi.org/10.1016/j.buildenv.2011.05.002.

[159] Ioannou a, Itard LCM. Energy performance and comfort in residential buildings: sensitivity for building parameters and occupancy. Energy Build 2015;92:216–33. http://dx.doi.org/10.1016/j.enbuild.2015.01.055.

[160] Gunay HB, O'Brien W, Beausoleil-Morrison I. A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices. Build Environ 2013;70:31–47. http://dx.doi.org/10.1016/j.buildenv.2013.07.020.

[161] Daniel L, Soebarto V, Williamson T. House energy rating schemes and low energy dwellings : the impact of occupant behaviours in Australia. Energy Build 2015;88:34–44. http://dx.doi.org/10.1016/j.enbuild.2014.11.060.

[162] Zhang Y, Barrett P. Factors influencing the occupants' window opening behaviour in a naturally ventilated office building. Build Environ 2012;50:125–34. http://dx.doi.org/10.1016/j.buildenv.2011.10.018.

[163] Santamouris M, Allard F. Natural ventilation in buildings: a design handbook. London: James & James; 1998.

[164] ASHRAE Standard 62.2. Ventilation for Acceptable Indoor Air Quality in Low-Rise Residential Buildings; 2013.

[165] Park JS, Ikeda K. Variations of formaldehyde and VOC levels during 3 years in new and older homes. Indoor Air 2006;16:129–35. http://dx.doi.org/10.1111/j.1600-0668.2005.00408.x.

[166] Park JS, Kim HJ. A field study of occupant behavior and energy consumption in apartments with mechanical ventilation. Energy Build 2012;50:19–25. http://dx.doi.org/10.1016/j.enbuild.2012.03.015.

[167] Leech J a, Raizenne M, Gusdorf J. Health in occupants of energy efficient new homes. Indoor Air 2004;14:169–73. http://dx.doi.org/10.1111/j.1600-0668.2004.00212.x.

[168] Brundrett GW. Ventilation: a behavioural approach. Int J Energy Res 1977;1:289–98. http://dx.doi.org/10.1002/er.4440010403.

[169] Yu Z, Fung BCM, Haghighat F, Yoshino H, Morofsky E. A systematic procedure to study the influence of occupant behavior on building energy consumption. Energy Build 2011;43:1409–17. http://dx.doi.org/10.1016/j.enbuild.2011.02.002.

[170] Hoes P, Hensen JLM, MGLC Loomans, de Vries B, Bourgeois D. User behavior in whole building simulation. Energy Build 2009;41:295–302. http://dx.doi.org/10.1016/j.enbuild.2008.09.008.

[171] Haghighat F, BCM Fung, Morofsky E, Yoshino H. A methodology for identifying and improving occupant behavior in residential buildings. Energy 2011;36:6596–608. http://dx.doi.org/10.1016/j.energy.2011.09.002.

[172] Encinas Pino F, De Herde A. Definition of occupant behaviour patterns with respect to ventilation for apartments from the real estate market in Santiago de Chile. Sustain Cities Soc 2011;1:38–44. http://dx.doi.org/10.1016/j.scs.2010.08.005.

[173] Andersen R, Olesen B, Toftum J. Simulation of the effects of occupant behaviour on indoor climate and energy consumption. Clima 2007 WellBeing Indoor Congr.; 2007.

[174] Andersen RV, Toftum J, Andersen KK, Olesen BW. Survey of occupant behaviour and control of indoor environment in Danish dwellings. Energy Build 2009;41:11–6. http://dx.doi.org/10.1016/j.enbuild.2008.07.004.

[175] Haldi F, Robinson D. Interactions with window openings by office occupants. Build Environ 2009;44:2378–95. http://dx.doi.org/10.1016/j.buildenv.2009.03.025.

[176] Fabi V, Andersen RV, Corgnati SP. Main physical environmental variables driving occupant behaviour with regard to natural ventilation. In: Proceedings of the 5th International Build. Phys. Conf.; 2012.

[177] Fabi V, Andersen RV, Corgnati S, Olesen BW. Occupants' window opening behaviour: a literature review of factors influencing occupant behaviour and models. Build Environ 2012;58:188–98. http://dx.doi.org/10.1016/j.buildenv.2012.07.009.

[178] Schakib-Ekbatan K, Çakıcı FZ, Schweiker M, Wagner A. Does the occupant behavior match the energy concept of the building? – Analysis of a German naturally ventilated office building Build Environ 2015;84:142–50. http://dx.doi.org/10.1016/j.buildenv.2014.10.018.

[179] Wang L, Greenberg S. Window operation and impacts on building energy consumption. Energy Build 2015;92:313–21. http://dx.doi.org/10.1016/j.enbuild.2015.01.060.

[180] Van Den Wymelenberg K. Patterns of occupant interaction with window blinds: a literature review. Energy Build 2012;51:165–76. http://dx.doi.org/10.1016/j.enbuild.2012.05.008.

[181] Zhang Y, Barrett P. Factors influencing occupants' blind-control behaviour in a naturally ventilated office building. Build Environ 2012;54:137–47. http://dx.doi.org/10.1016/j.buildenv.2012.02.016.

[182] Masoso OT, Grobler LJ. The dark side of occupants' behaviour on building energy use. Energy Build 2010;42:173–7. http://dx.doi.org/10.1016/j.enbuild.2009.08.009.

[183] Ouyang J, Hokao K. Energy-saving potential by improving occupants' behavior in urban residential sector in Hangzhou City, China. Energy Build 2009;41:711–20. http://dx.doi.org/10.1016/j.enbuild.2009.02.003.

[184] Sundell J, Levin H, Nazaroff WW, Cain WS, Fisk WJ, Grimsrud DT, et al. Ventilation rates and health: multidisciplinary review of the scientific literature. Indoor Air 2011;21:191–204. http://dx.doi.org/10.1111/j.1600-0668.2010.00703.x.

[185] Fisk WJ. Review of health and productivity gains from better IEQ. Heal. Build., Lawrence Berkeley National Laboratory; 2000, p. 23–34.

[186] Fanger PO. Provide good air quality for people and improve their productivity. In: Proceedings of the seventh Int. Conf. air Distrib. rooms, Roomvent; 2000, p. 1–5.

[187] Seppänen O a, Fisk WJ. Effect of ventilation on health and other human responses in office environment. In: Proceedings of the 9th Int. RoomVent Conf., Coimbra, Portugal; 2004.

[188] Zhao J, Lasternas B, Lam KP, Yun R, Loftness V. Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining. Energy Build 2014;82:341–55. http://dx.doi.org/10.1016/j.enbuild.2014.07.033.

[189] Han K, Zhang JS, Guo B. A novel approach of integrating ventilation and air cleaning for sustainable and healthy office environments. Energy Build 2014;76:32–42. http://dx.doi.org/10.1016/j.enbuild.2014.02.055.

[190] Dimitroulopoulou C. Ventilation in European dwellings: a review. Build Environ 2012;47:109–25. http://dx.doi.org/10.1016/j.buildenv.2011.07.016.

[191] Persily A. Challenges in developing ventilation and indoor air quality standards: the story of ASHRAE Standard 62. Build Environ 2015;91:61–9. http://dx.doi.org/10.1016/j.buildenv.2015.02.026.

[192] SIA382/1. Swiss standard: Technical requirements for ventilation systems, 1992, Schweizerische Normen Vereinigung, Zürich; 1992.

[193] ÖN6000-003. Austrian standard: Ventilation systems: Basic regulations, hygiene and physiological requirements for occupied spaces.

[194] EN 13779. European Standard, Ventilation for non-residential buildings – Performance requirements for ventilation and room conditioning systems, CEN, Brussels; September 2004.

[195] DIN1946-2. DIN 1946 – Part 2, Heating, ventilation and air conditioning – Requirements relating to health (VDI code of practice), Deutsches Institut für Normung e.V; 1994, Berlin.

[196] ASHRAE62. ANSI/ASHRAE Standard 62-2001, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc.; 2001.

[197] Fisk WJ, Black D, Brunner G. Changing ventilation rates in U.S. offices: implications for health, work performance, energy, and associated economics. Build Environ 2012;47:368–72. http://dx.doi.org/10.1016/j.buildenv.2011.07.001.

[198] Carrer P, Wargocki P, Fanetti A, Bischof W, De Oliveira Fernandes E, Hartmann T, et al. What does the scientific literature tell us about the ventilation–health relationship in public and residential buildings? Build Environ 2015;94:273–86. http://dx.doi.org/10.1016/j.buildenv.2015.08.011.

[199] Dutton SM, Banks D, Brunswick SL, Fisk WJ. Health and economic implications of natural ventilation in California offices. Build Environ 2013;67:34–45. http://dx.doi.org/10.1016/j.buildenv.2013.05.002.

[200] Vincent D, Annesi I, Festy B, Lambrozo J. Ventilation system, indoor air quality, and health outcomes in Parisian modern office workers. Environ Res 1997;75:100–12. http://dx.doi.org/10.1006/enrs.1997.3764.

[201] Fisk WJ. How IEQ affects health, productivity. ASHRAE J 2002;44:56–8.

[202] Seppanen O, Fisk WJ, Lei QH. Room temperature and productivity in office work. 2006.

[203] Ye X, Chen H, Lian Z. Thermal environment and productivity. ASHRAE Trans 2010;116:590–9.

[204] Franklin PJ. Indoor air quality and respiratory health of children. Paediatr Respir Rev 2007;8:281–6. http://dx.doi.org/10.1016/j.prrv.2007.08.007.

[205] Etzel R. a. Indoor and outdoor air pollution: tobacco smoke, moulds and diseases in infants and children. Int J Hyg Environ Health 2007;210:611–6. http://dx.doi.org/10.1016/j.ijheh.2007.07.016.

[206] Seppänen O. Scientific basis for design of ventilation for health, productivity and good energy efficiency. Indoor Air Congr.: Copenhagen; 2008, p. 17–22.

[207] Ajimotokan H, Oloyede L, Ismail M. Influence of indoor environment on health and productivity. NY Sci J 2009;2:46–9.

3.3. Updated Literature Review - 2016 Up to Now

As the article presented in the previous section was published in 2016, this section presents an updated literature review from 2016 up to now. The review will follow the same structure as the previously presented article. It starts with reviewing the recent research studies about natural ventilation and then moves to studies on mixed-mode ventilation and energy efficient ventilation control strategies in buildings. Afterwards, it addresses the influence of occupant behavior on ventilation and energy use, as well as the correlation of ventilation with health and productivity of the occupants. Since the COVID-19 pandemic draws attention to the importance of ventilation requirements in buildings, the final topic appeared even more in the literature in the past 2 years. Moreover, and in addition to the previous article, some recent research work that investigated the newly presented indicator for evaluation of smart readiness of buildings has also been reviewed.

Since the recent global awareness toward environmental sustainability and indoor environment quality, naturally-ventilated buildings have been comprehensively welcomed [30]. As an important player that contributes to building energy performance and occupants comfort, natural ventilation has been considered as a desirable feature of sustainable buildings [31]. Although the demand for natural ventilation has increased with development of more sustainable buildings, there are still challenges with regards to the uncertainties associated to it which need to be overcome [32].

It was reported by many studies such as [33] that air movement into and around buildings is highly influenced by building design. Similarly, the natural ventilation performance highly depends on building design and its interaction with the local environment, which proves the importance of taking natural ventilation into account since the early stage building design. Ref. [34], proposed an evaluation approach to estimate the feasibility of wind-driven natural ventilation during early stage building design. It used CFD to simulate various single-sided and cross-ventilation models with different opening sizes and windows. Table 3.1, summarizes some recent studies on natural ventilation considering its principles, namely, single-sided, cross-ventilation and stack ventilation with natural ventilation, its characteristics elements and driving forces. As it can be seen in table 3.1, most of the studies on natural ventilation considered either thermal buoyancy or wind as the driving force and less considered both as of the complexity associated. This was also reported by [35], which carried out a critical review of combined natural ventilation techniques in sustainable buildings.

Additionally, natural ventilation highly interacts with outdoor environment condition such as weather and climate condition as well as outdoor pollution. Many research works studied the influence of weather data on availability, feasibility and effectiveness of natural ventilation in different climate zones [36]–[39]. Considering hot and humid or Tropical Climates as critical climates for use of natural ventilation, ref. [30] revealed that most of recent research on the topic is focused on these critical climates that shows the added value of natural ventilation in other climates is quite proven. Also, delivery of required ventilation rate with passive energy efficient method like natural ventilation in buildings has caused an increase in indoor pollutant concentration coming from outdoor fonts, which has been proven to put building occupants' health in significant risk. Taking it into account, ref. [31] investigated the influence of PM2.5, PM10, and ozone as the three main outdoor air pollutants on natural ventilation effectiveness in several major US cities and climate zones, using the outdoor air pollutant histories from the US Environmental Protection Agency. This study concluded that PM2.5 is the most influential factor to be considered in natural ventilation design while the effect of PM10 is quite insignificant. They also mentioned that, although the influence of ozone is not noticeable in most cases, it cannot be neglected. Similarly, [40] experimentally studied the influence of natural ventilation rate on PM2.5 deposition in indoor space and come up with the same conclusion as [31]. It is also concluded that ignoring the influence of natural ventilation on indoor PM2.5 deposition may cause an underestimation for air cleaner systems. It is reported by several studies such as [30], [35] that continuous outdoor conditions monitoring must be an integrated part of natural ventilation system design to avoid being affected by the disadvantages of external conditions. Accordingly, integrating automated openings and other control strategies to natural ventilation is proposed to lower these effects and provide acceptable indoor climate.

Recently, [41] has reviewed the studies on natural ventilation in warm climates and made the following main conclusions:

- Indoor air quality is adversely affected by outdoor air pollution;
- Current natural ventilation methods mostly meet thermal comfort standards;

- solar chimney and windcatchers (stack ventilation) are the natural ventilation characteristic elements that provide the best thermal comfort and indoor air quality due to their ability to induce air movement;
- cross ventilation proves to be satisfactory as well but single-sided ventilation although provides acceptable indoor air quality but associates to poorest thermal comfort.

Owing to the initiative launched by Building and Environment journal on “Ten Questions” in built environment research, [42] prepared a ten question and answers papers with regard to natural ventilation in non-domestic buildings. This study presented several issues about natural ventilation. As such, the issue in hot climates, increasing the number of overheating hours caused by climate change negative impacts and of course increasing the hours to take advantage of natural ventilation in transition and cold months have been mentioned.

It has been seen, in many of aforementioned studies, that natural ventilation is not always capable to sustain the indoor climate in an acceptable level for building occupants and suggested the use of control system to predict or check the natural ventilation adequacy to meet the required condition. It is pointed out that in cases where natural ventilation cannot satisfy these needs, the presence of mechanical ventilation is required. This is called hybrid (mixed-mode) ventilation, which is neither solely dependent on natural ventilation nor mechanical ventilation. Actually, it uses the advantages of both methods while excludes their drawbacks.

Table 3.1 – Summary of surveyed studies on natural ventilation.

Reference	**Natural ventilation concept**			**Method**	**Main task(s)**	**Main finding(s)**
	Driving force	**Principle**	**Characteristic element**			
[43]	buoyancy	single-sided	windows	Computational simulation	evaluating if whether natural ventilation is a sustainable solution to protect occupants from heat-related health risks during heatwaves	the preliminary results are promising because the indoor environment in the tested example is safe if the windows are widely opened at the relevant times.
[37]	wind	Cross	windows	Computational simulation (DesignBuilder)	evaluating the effects of regional climate variations on the potential of natural ventilation in building design.	during July and August, due to the unfavorable weather conditions, solely natural ventilation cannot satisfy the requirements while it is advantageous during transition seasons (spring and autumn)
[44]	buoyancy	single-sided	windows	numerical (CFD, ANSYS Fluent) and analytical	evaluating the performances of several typical windows in the case of buoyancy-driven, single-sided natural ventilation and quantifying the ventilation rates through variable window configurations	It was shown that the window pane can have an adverse effect on the ventilation rates, and the tilt and awning window styles performed the worst because the openings were either at the top or the bottom window edge. Unlike other cases, there was no obvious difference in ventilation rates between the horizontal pivot window and vertical pivot window case and both are acceptable styles.
[45]	buoyancy / wind	single-sided	windows	experimental and questionnaire	analyzing the effect of natural ventilation in student dormitories on indoor air quality and thermal comfort in Beijing's winter	results showed that windows opening area less than 0.077 m^2 will cause general CO_2 level higher than the acceptable indoor CO_2 concentration (<1000 ppm) while when the opening area exceeds this value the temperature lowers to less than 20 C just after 4 hours.

[46]	wind	Cross	windows	numerical (CFD, scSTREAM CFD tool)	investigating the thermal comfort of a naturally ventilated hostel operational building by developing different natural ventilation strategies	Cross Ventilation is an effective technique for improving airflow through the building. An increase in air velocity up to 0.50 m/s was achieved by cross ventilation.
[32]	buoyancy / wind	single-sided	windows	experimental (chamber) and mathematical model	investigating the predictability of natural ventilation rate by developing predictive models with eight machine learning algorithms	deep neural network (DNN) have shown the best prediction performance among all algorithms. It has been mentioned that this prediction model can be used in design phase.
[47]	buoyancy	single-sided, Cross and Stack	double-skin façade / solar chimney	numerical (CFD, ANSYS Fluent)	comparing the clear glazing and the low-e glazing in the use of a naturally ventilated double-skin façade	Applying the low-e glass as the inner facade of the naturally ventilated double-skin façade provided more natural ventilation rate at all incident angles
[48]	buoyancy / wind	single-sided, Cross and Stack	double-skin façade / solar screen	Computational simulation (DIVA Rhinoceros and Design Builder)	evaluating the performance of a double-skin façade integrated with perforated screens to both daylight and natural ventilation	the optimum rate of the perforated percentage for balancing natural ventilation and daylight varies with the season and outdoor condition. When it is a good time of bringing natural ventilation interior, the optimum percentage is 60% in spring, 10% in autumn and 30% through a year.
[49]	buoyancy / wind	single-sided	window with trickle ventilator	experimental measurements	quantifying the natural ventilation rate in real time through a single-sided, small-opening trickle ventilator	The ventilation rate of the trickle ventilator was quantified by four methods: the tracer gas method, inlet air velocity-based, pressure difference-based, and reference wind velocity-based. The tracer gas method was considered the reference to which the other three methods were compared.
[50]	buoyancy	single-sided, Cross and Stack	double-skin façade / solar chimney	numerical (CFD, ANSYS Fluent)	evaluating the influences of an operable outlet louver on the natural ventilation performance of an NVDSF, with louver angles of 30°–150° under various solar conditions	the significance of outlet louvers' impacts on NVDSFs' performance is highlighted, so it cannot be neglected in practice. Louvers can be used to adjust or control natural ventilation under various louver angles.

[51]	buoyancy	single-sided, Cross and Stack	ventilation openings	experimental measurements	assessing the ventilation characteristics of thermal buoyancy-induced natural ventilation in experimental study	as mentioned previously by other studies, it also confirmed that the opening area is the key factor for ventilation rate and it increases with opening area for a given temperature difference.
[52]	wind	single-sided / Double-sided	windows	Computational simulation (EnergyPlus) and numerical (CFD)	evaluating the impact of permeability ratio on natural ventilation potential and cooling load of a terraced office building	among the permeable models, the best natural ventilation performance and the lowest cooling energy consumption are attributed to 50 % and 20 % permeable groups respectively.
[34]	wind	single-sided and Cross	windows	numerical (CFD, ANSYS Fluent)	exploring a fast and accurate evaluation approach in the form of empirical equations to estimate the ventilation rate and potential of wind-driven natural ventilation	a series of natural ventilation potential maps were produced. These maps could improve the understanding of natural ventilation potential in different climates and benefit the climate-conscious design of buildings

Hybrid ventilation is an efficient method to reduce ventilation energy and improve indoor climate [53]. During the recent years, hybrid ventilation methods are becoming increasingly welcomed as a more energy-efficient alternative solution [54]. The key factor for the success of hybrid ventilation is a suitable ventilation control strategy [55]. It attracts the attention of both building designers and researchers, which recent progresses of the ventilation control strategies have proven the potential hybrid ventilation control strategies both in saving energy and providing acceptable indoor climate [56]–[58].

Different aspects of hybrid ventilation and its influence on provision of comfortable, energy-efficient solution has been reviewed by [59]–[61]. The last one focused on ceiling fan-assisted hybrid ventilation and highlighted the applied methods to evaluate ceiling fan impacts on indoor areas and described their advantages and limitations. Like natural ventilation, the thermal environment and indoor air quality, as well as energy saving, are the main topics to be assessed in hybrid ventilation studies. Ref. [54] investigated occupant thermal comfort in hybrid ventilated buildings and concluded that the mixed-mode building under study effectively provided a high level of thermal comfort. In a similar study, [62] examined occupant thermal comfort in university campus using different ventilation strategies, namely, hybrid ventilation, air-conditioning and natural ventilation buildings and pointed out that hybrid ventilated spaces have shown a more satisfactory thermal environment. Moreover, thermal comfort and energy saving of hybrid ventilation have been addressed by several recent studies, integrating CFD with *EnergyPlus* simulation software, by [63], using adaptive comfort approach by [64], and using adaptive control algorithms by [65]. Table 3.2, summarizes the methods and key findings of some recent studies on hybrid ventilation.

When going further to the topic of natural and hybrid ventilation, control strategies started to appear more and more in the literature. Among various energy-efficient ventilation control strategies, here, those recent studies focusing on demand controlled are being reviewed. Demand controlled ventilation (DCV) strategies have an outstanding influence on reduction of ventilation energy consumption. In demand controlled ventilation, the space is ventilated when needed, which means when it is occupied and the concentration of indoor contaminants is higher than the defined set-point. As regards thermal comfort, indoor air temperature is the most widely used set-point parameter. It has been used by

[66], [67], while there are studies that used PMV and/or PPD as set-point variables [68], [69].

For indoor air quality, indoor CO_2 concentration is the most widely used set-point [66], [70], [71], while there are few studies that used other indoor contaminants such as formaldehyde [72], volatile organic compounds (VOCs) [73]–[75] or ozone [57], [76]. Besides indoor contaminants, the real time occupancy level is another factor that has been used in several studies for demand controlled ventilation. The real time occupancy level is normally sensed by motion sensors, camera counters, infra-red sensors, etc. [77], [78]. Table 3.3 summarizes the methods and key findings of some recent studies on demand controlled ventilation.

In addition to occupancy level, clothing type and activity level, occupants’ behavior also interacts with ventilation and its associated energy use in buildings. Occupants interaction with their indoor environment is through adjusting windows, blinds, lights and HVAC systems, which has direct effects on indoor environment quality and energy consumption. During the last decade, more attention has been paid to study this field. Recently, [79] has reviewed the influence of occupant behavior on energy consumption of buildings. The study revealed that window opening behavior of occupants has been rarely considered in relevant studies for calculating its energy impact. Also, it is found that window opening behavior is influenced by factors such as outdoor temperature, indoor thermal comfort, CO_2 concentration, occupancy schedule, personal habits, and PM2.5 concentration [80].

Ref. [81], in an original research on evaluating indoor air quality and energy consumption in hybrid ventilated buildings, also investigated occupants' window-opening behavior during the heating season by means of window sensors. The authors also pointed out the indoor air temperature and CO_2 concentration as the main influencers on occupants’ window opening behavior and recommended to consider them in design and development of ventilation control strategies to improve the building performance.

Table 3.2 – Summary of surveyed recent studies on hybrid ventilation

Reference	Building application	Climate/ region	Method	Key finding(s)
[82]	residential building	hot and humid climates (Hong-Kong)	Computational simulation (EnergyPlus) and optimization (Pareto)	The findings from this paper can provide a potential design optimization procedure for passive designs in hot and humid area
[55]	office building	3A-Atlanta, 3B-Los Angeles, 3C-San Francisco, 4C-Seattle	experiment and Computational simulation	neural network indicated the best performance considering both prediction and computation time. Also the comparison between the model predictive control and the rule-based control (RBC), clearly showed that the MPC is better at providing the thermal comfort of hybrid ventilated buildings as well as energy savings.
[83]	institutional building	Montreal, Canada	Full-scale Experimental	the benefits of adding fan assist at the top of the atrium by considering a floor below the neutral plane with inflow trough the motorized inlets. Also considering thermal comfort for this corridor as a transitional space demonstrated that the mixed air conditions from the warm indoor and cool outdoor air should not cause excessive discomfort to the occupants
[84]	institutional building	Montreal, Canada	Full-scale Experimental and numerical (CFD, ANSYS Fluent)	predictive control strategy satisfies thermal comfort, but also increases energy savings potential (4 times better that heuristic control). Lowering thermal comfort criteria during the night in order to precool the building further increases energy savings potential.
[53]	industrial building	Xi'an, China	experimental	the mechanical exhaust velocity lower than the critical mechanical exhaust velocity, caused hybrid ventilation to improve the indoor thermal environment by increasing the mechanical exhaust velocity. By contrast, the mechanical exhaust velocity higher than the critical mechanical exhaust velocity, caused the indoor thermal environment become worse.
[85]	institutional building (LUCIA nZEB)	Valladolid, Spain	Full-scale Experimental	hybrid ventilation system uses heat exchangers for 70% of the operational time, in order to achieve the set parameters successfully. Also, control and optimal operation of the hybrid ventilation system allows high energy recovery values with minimum additional electricity consumption and significant reduction of carbon emissions and operational costs have been achieved

On the other side, [86] investigated thermal comfort and indoor air quality in low-income houses while monitoring the window opening behavior. In winter time, and in some cases, the CO_2 concentration reached 4000 to 5000 ppm, which is completely unhealthy. Besides the energy issues, occupants must be aware of the need for ventilation to provide healthy indoor environment for their living space.

Nowadays, people spend most of their daily time in indoor environment (mostly offices), therefore it is highly important to maintain the indoor air quality as well as thermal comfort in a standard level. Otherwise it can cause Sick Building Syndrome and seriously affect occupants' health and productivity. Recently, COVID-19 outbreak proved that low ventilation rate increases the risk of infection to contagious viruses [87]. Ref. [88] assessed the indoor air quality and daily health symptoms of both adults and children residing in energy-efficient homes compared to conventional buildings and the results showed that both indoor air quality factors and as well as those from thermal comfort was more favorable in energy-efficient homes. More importantly, during a year of analysis, much lower health issue was reported by energy-efficient homes residence while from the others there were complains such as eye fatigue, allergic rhinitis, and atopic dermatitis. Finally, [89] verified that well-designed ventilation causes lower health issues such as respiratory illness, eye dryness etc. and improves the performance and productivity of occupants.

The literature reviewed in this chapter clearly proves the need for development of new ventilation strategies, not only to reduce energy consumption and maintain acceptable indoor climate but also to provide healthy and productive indoor environment.

In the next two chapters, several ventilation strategies that have been developed, implemented and tested both experimentally and by simulation software will be presented. Meanwhile, in the era of global digitalization and developments in the information and communication technology (ICT) sector, a new concept, Smart Readiness Indicator, emphasized introduced in the 2018 revision of the European Energy Performance of Buildings Directive (EPBD) [90] will be shortly reviewed in the existing literature.

Table 3.3 – Summary of surveyed recent studies on demand controlled ventilation

Reference	**Building application**	**Control strategy**	**Method**	**Key finding(s)**
[91]	office building	DCV (occupancy-based)	simulation (EnergyPlus)	the optimal combinations of setpoint/setback schedules and distances for each zone were identified. A minimum of 10.4% and a maximum of 28.3% load reduction were achieved compared to the baseline control.
[92]	office building	DCV (CO_2-based)	simulation	It is concluded that a large number of sensors is crucial to guarantee optimal comfort and to reduce energy consumption. If in addition a large number of actuators is employed, the maximum energy savings can be obtained. However, a system featuring more actuators than sensors leads to poor results.
[93]	Residential building	DCV (occupancy-based)	simulation (EnergyPlus)	occupancy information can add additional energy saving impact by 20%
[94]	Residential building	DCV (occupancy-based)	simulation (DOE2)	occupancy-based thermostat settings can save up to 38.7% of total annual electricity consumption
[95]	Office building	DCV (occupancy-based)	simulation (EnergyPlus)	occupancy-based strategies for HVAC control are highly effective, yielding 22-50%and 47-87% reduction in electricity and natural gas use, respectively, compared to no thermostat control
[96]	school and office building	DCV (CO_2-based)	experimental measurements	The variable air volume (VAV) boxes react well to predefined set points for CO_2 concentration. During the measurement period, the reduction for fan energy ranges from 25 to 55% compared to a constant air volume system (CAV)
[97]	educational building	DCV (CO_2-based)	experimental measurements	measurements indicate as CO_2-based DCV has provided a reduction in the energy requirement equal to 31% for thermal energy demand during winter period and 40% for fan electricity consumption compared with a traditional system with constant ventilation air flow
[98]	educational building	DCV (CO_2-based)	experimental measurements	proposed DCV optimization improves energy efficiency by up to 88% while meeting demanded indoor air quality and durability
[69]	real-scale climatic chamber	DCV PMV-based)	experimental measurements and simulation	PMV control strategies using MRT estimation models improved thermal comfort and reduced energy consumption by more than 10%
[99]	secondary school	DCV (based on CO_2, indoor air temperature, RH and VOC level)	experimental measurements	results highlight the impact of both indoor temperature and CO_2 concentration on students' feeling of fatigue. Students showed adaptability to indoor temperature change.

This indicator allows for rating the smart readiness of buildings, i.e. the capability of buildings (or building units) to adapt their operation to the needs of the occupant, also optimizing energy efficiency and overall performance, and to adapt their operation in reaction to signals from the grid (energy flexibility) [100]. The smart readiness indicator will raise awareness, amongst building owners and occupants, of the value behind building automation and electronic monitoring of technical building systems and should give confidence to occupants about the actual advantages and savings of those new enhanced functionalities [101].

Ref. [102] outlined the challenges of the Smart Readiness Indicator developed by the EPBD and pointed out that it should be more quantitative to be able to test the performance and development of smart technologies used in buildings, suggesting improvements to be considered in further developments of SRI. Newly, [103] investigated the SRI of two case study buildings. It concluded that the SRI framework needs more research and development to consider all possible aspects and resolve the current issues. This topic will be further discussed in chapter 6.

3.4. Conclusion

An immense amount of research carried out on various ventilation aspects such as natural ventilation, demand controlled ventilation, energy-efficient ventilation strategies etc. has been reviewed in this chapter. The focus was on those related to energy saving and improving indoor climate as well as the correlation between ventilation and health and productivity. Finally, the studies on Smart Readiness Indicator introduced by the revised EPBD were briefly reviewed.

Chapter 4

EXPERIMENTAL STUDY OF VENTILATION CONTROL STRATEGIES

4.1. Introduction

There are several strategies to improve IAQ, namely, source removal or attenuation, localized extraction, air purification and ventilation. Depending on the situation one or a combination of these strategies might be used to improve the IAQ. In this research, ventilation, as one of the effective approaches to provide a good indoor air quality and to increase occupants' productivity in office buildings, has been considered. Different ventilation systems, as already introduced in previous chapters, namely, natural ventilation, mechanical ventilation or a mix of them so called hybrid ventilation can be applied in buildings. Moreover, during the last two decades, smart devices and control systems for ventilation have been developed and rolled out, which can predict, control and provide the adequate ventilation rate when it is required.

This chapter presented the contribution of the author with regard to development, implementation, test and analyzing various ventilation control strategies in an office room at the Department of Mechanical Engineering (DEM), at University of Coimbra (UC). It also presented the contribution of this research in the Smart Window project as well as a showcase project called Indoor Live Lab (I2L) at DEM, UC.

4.2. Contributions to the Smart Window Project and Indoor Live Lab

The Smart Window project has been presented by a consortium of two small and medium sized enterprises and one research center at UC, namely, WSBP Electronics Ltd, a technology-based engineering electronics and software enterprise, AMM Alumínios, an industrial enterprise producing aluminum profiles and window frames, and Associação para o Desenvolvimento da Aerodinâmica Industrial (ADAI), a research unit of the DEM, at UC. The consortium aimed at developing, testing and bringing to market a novel and energy-efficient window-based hybrid ventilation system. This system will enable the use of natural ventilation and mechanical ventilation, either individually or in combination. It may be used as a low cost solution for new construction and retrofit buildings, and is particularly suitable for cases where the installation of a network of ventilation ducts is not convenient.

The Indoor Live Lab has been developed as a new platform for research and technology demonstration in IEQ and energy consumption at DEM, UC, which enables the researchers and decision makers to access continuously monitored data of IEQ and energy use on all aspects of building functioning.

The author of the present thesis was in charge of development, test and analyze several ventilation control strategies in smart window project. To do so, the preliminary mechanical ventilation boxes have been developed, the ventilation control strategies have been implemented and tested in the I2L.

In the next section, more details about developments, implementations, and the results of the DCV strategies tests have been presented. Meanwhile, the contribution of this research in the smart window project and the I2L has been communicated by the following articles.

4.2.1. Paper II: Towards Energy-Efficient Ventilation in Buildings: Development of the Smart Window Ventilation System

Although recent studies have shown research activities in development of control strategies to employ natural and mechanical ventilation, there is still an obvious gap in the literature about employing intelligent window-based ventilation control strategies, not only for increasing the share of natural ventilation but also for integrating mechanical ventilation to compensate drawbacks of natural ventilation. The Smart Window project aimed to fulfil this gap in literature. The final prototype of the smart window has been illustrated in Appendix A. An introduction to this project including the objectives, the developments by the time of publication and general explanation of the ventilation control strategies to be developed have been presented and published as an article in Journal of Clean Energy Technologies, titled “Towards Energy-Efficient Ventilation in Buildings: Development of the Smart Window Ventilation System”.

Author Contributions: Behrang Chenari as the main author, designed and built the prototypes, performed experiments, gathered and collected data, and wrote the paper together with João Dias Carrilho; Gustavo Botte has led the research project, and Manuel Gameiro da Silva reviewed the contents and contributed to enhancing its quality.

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Towards Energy-Efficient Ventilation in Buildings: Development of the Smart Window Ventilation System

Behrang Chenari, João Dias Carrilho, Gustavo Botte, and Manuel Gameiro da Silva

***Abstract*—As the building sector is responsible for a large portion of total primary energy consumption in developed countries, it is crucial to improve energy efficiency of buildings' systems. Heating, ventilation, and air conditioning systems play a noticeable role in energy consumption of buildings, therefore, developing efficient strategies for ventilation not only can provide comfortable indoor climate but can also mitigate energy consumption in buildings, which, consequently, will lessen the associated environmental impacts. This paper presents development steps of an intelligent window-based hybrid ventilation system in an ongoing research and development project at the University of Coimbra, known as the Smart Window project. Firstly, the motivation and objectives of the project are provided. Secondly, the current state of development of the project as well as the test condition and location in an Indoor Live Lab is presented. Finally, the future steps of development of the project accompanied by the expecting results are presented and discussed.**

***Index Terms*—Control strategies, demand-controlled ventilation, energy efficiency, hybrid ventilation, indoor environmental quality, Smart Window.**

I. INTRODUCTION

Nowadays, energy demand is continuously increasing worldwide, therefore, the negative environmental impact resulting from energy production and consumption has become a major public concern. The building sector is one of the biggest contributors to energy consumption in the world, which is responsible for a large portion of total primary energy consumption in developed countries. Heating, ventilation, and air conditioning systems play a noticeable role in energy consumption of buildings, thus, the design and development of new energy-efficient strategies and products for ventilation systems in buildings is crucially essential. Currently, there is ongoing research promoting energy saving potential in buildings in the framework of the EU Energy Performance of Building Directive (EPBD) [1], which has focused on energy efficiency in buildings. Some authors investigated new energy-efficient solutions for improving ventilation systems in buildings. On the other hand, in the last decade, many studies have concentrated on improving indoor air quality (IAQ) in buildings. There is a tight correlation between ventilation and IAQ, and the reduction of energy consumption associated to ventilation cannot be an excuse to neglect the provision of a suitable indoor climate. Therefore, in developing energy-efficient solutions for ventilation systems, maintaining the indoor climate at an acceptable level must be considered.

As aforementioned, ongoing research is focused on developing energy-efficient ventilation models for buildings. Some studies have only focused on natural ventilation as a passive method in order to make the process of ventilation more efficient [2]-[5]. Some authors used natural ventilation elements such as atria [6], wind towers [7], double-skin facades [8] as well as ventilation openings and windows [9] to provide required ventilation by natural driving forces, namely wind and buoyancy forces. Additionally, some studies investigated energy savings from utilizing different principles of natural ventilation, such as single-sided [3], cross ventilation [10] and stack effects [11]. But, as natural ventilation is not always available, say, sufficient to provide required ventilation rate, more recent studies [12], [13] focused on hybrid ventilation [14]. Hybrid ventilation will exclude the drawbacks of both systems, whereas including their advantages [15].

Moreover, several authors have developed ventilation control strategies that provide acceptable indoor climate quality levels and lowers energy consumption. They believe that the presence of control systems can increase the influence of hybrid and natural ventilation in improving energy saving in buildings, while maintaining a suitable indoor climate. These authors conducted research activities in developing new control strategies to employ natural cooling and ventilation. For instance, Homod *et al.* [16] developed control strategies, which can predict when mechanical ventilation is required in order to maintain acceptable IAQ. In addition to predictive control strategies, rule-based and demand-controlled ventilation (DCV) strategies, as used in [17]-[21], have significant effects on improving energy efficiency of ventilation systems.

Motivation and Objectives

As people spend most of their time inside buildings, it is very important to maintain an adequate IAQ, in addition to thermal comfort, especially for office buildings and schools in which people are working, learning and studying, and where the level of personal control over their indoor environment can be very limited. IAQ and building ventilation are intimately related because ventilating indoor spaces with outdoor air is perhaps the most often used mechanism to dilute pollutants generated inside the building. Ventilation is

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the key issue for providing suitable IAQ, as it is the process of replacing stale indoor air by fresh outdoor air. It can be performed either by mechanical means (mechanical ventilation) or natural driving forces (natural ventilation) or even a combination of them (hybrid ventilation). Employing natural ventilation in buildings results in the reduction of energy consumption, while maintaining an acceptable level of IAQ. Therefore, developing ventilation control strategies that can predict when natural ventilation is available and sufficient, and select between natural and mechanical ventilation as needed, are desirable.

Although recent studies have shown research activities in development of new control strategies to employ natural cooling and ventilation, there is still an obvious gap in the literature about employing intelligent window-based ventilation control strategies, not only for increasing the share of natural ventilation but also for integrating mechanical ventilation to compensate drawbacks of natural ventilation. This ongoing research and development project aims to fulfill this gap in literature.

This paper presents development steps of an ongoing research and development project, aiming at developing a novel product, the Smart Window, and test a number of ventilation control strategies in order to find the most energy-efficient control strategies that provide acceptable indoor climate.

II. SMART WINDOW: CURRENT STATE OF DEVELOPMENT

A. Project Description

In this project, a Smart Window system that allows the use of hybrid ventilation, is being developed to employ the advantages and exclude the drawbacks from both natural and mechanical ventilation. Moreover, several ventilation control strategies are being developed and tested using Smart Window in order to find out the best strategies that can provide an appropriate indoor climate with lower energy consumption. The control strategies, which are based on indoor and outdoor environmental parameters, such as concentration of CO_2, indoor and outdoor temperature difference, wind speed and its orientation, are defined in a way to use natural ventilation as long as possible, otherwise, putting the mechanical system on circuit to provide the required space ventilation. The Smart Window is accompanied by a mechanical ventilator as well as a control system.

B. Prototypes of the Mechanical Boxes

By now, two prototypes of mechanical boxes are built. Fig. 1 shows the first prototype, which is driven by a tangential blower and is currently being installer in the Indoor Live Lab (I2L) [22] facility, located in Department of Mechanical Engineering at University of Coimbra.

Fig. 2 shows the second prototype, which is based upon a centrifugal blower and automatically operable window. The automatically operable windows will have a positive impact in IAQ and energy consumption, while permitting the manual override by the office occupants.

Fig. 1. Prototype of the mechanical ventilation subsystem of the Smart Window hybrid ventilation system (tangential blower).

Fig. 2. Prototype of the mechanical ventilation subsystem of the Smart Window hybrid ventilation system: centrifugal blower (top); automatically operable window actuator (lower left) and control board (lower right).

C. Control Strategies

A number of control strategies were identified as potentially suitable, based on indoor environment parameters and outdoor weather as input data. In particular, the indoor concentration of CO_2 is used to see whether ventilation is required or not. Temperature difference between indoor and outdoor (ΔT), wind speed (WS) and its direction (D) are used to detect the availability of natural ventilation.

In the control strategies, the availability of buoyancy-driven natural ventilation is evaluated according to (1), whereas (2) evaluates the availability of wind-driven natural ventilation.

$$Q = CA\sqrt{2gH\frac{Ti - To}{Ti}} \tag{1}$$

where Q represents the ventilation airflow rate (m^3/s), C is the discharge coefficient for opening (typically 0.62), A indicates the cross section area of opening (m^2), g is the gravitational acceleration (m/s^2), H represents the height from midpoint of lower opening to midpoint of upper opening (m), Ti is the average indoor temperature (K) and To is the outdoor temperature in (K).

$$Q = KAV \tag{2}$$

where Q represents the ventilation airflow rate (m^3/h), A indicates the cross section area of opening (m^2) and K is coefficient of effectiveness. This coefficient varies with the angle between wind direction and the facade opening. For instance, if the angle at which wind hits the building is 45 °, then the coefficient is estimated to be around 0.4, whereas, if wind hits the building perpendicularly, the coefficient is becomes about 0.8.

According to all the aforementioned parameters, various rule-based (*if CONDITION, then ACTION*) control strategies were reported in the literature (e.g., see Ref. [23]), in which indoor and outdoor environmental parameters are the conditions and different operations of window and fan are the actions.

The control strategies start with simple CO_2-based demand-controlled ventilation (DCV) strategies in the beginning and, going forward, reach more advanced control strategies, considering all the parameters and more advanced operations of window and fan. Table I presents characteristics of some of the developed controls from simple to advanced strategies. As shown, different input parameters and different operations of window and fan, define the control strategy either simple or advanced. Moreover, Fig. 3 demonstrates a simple control strategy in a flowchart.

TABLE I: THE CHARACTERISTICS OF CONTROL STRATEGIES

Rule-based control	Mechanical ventilation operation	Natural ventilation operation	Input parameters
Simple	On/Off	Open/Close (O/C)	CO_2
.	Leveling speed	Leveling O/C	CO_2
.	Modulating speed	Modulating O/C	CO_2
.	On/Off	O/C	CO2+ ΔT+D
.	Leveling speed	Leveling O/C	CO2+ ΔT+D
Advanced	Modulating speed	Modulating O/C	CO2+ ΔT+D

D. Installation and Test

As aforementioned, the first prototype is being installed and tested in the I2L. The I2L is equipped with various types of instruments and sensors to measure and monitor energy consumption and IEQ elements, such as thermal comfort, IAQ, lighting, sound level and so on. Fig. 4 shows a set of instruments and sensors installed in the I2L. They are all connected to a computer, which continuously monitors all these elements. Moreover, Fig. 5 depicts a daily monitored IEQ elements in the I2L. The graphs show the changes in each element during a full day, whereas the numbers shows the current value of each element.

For thermal comfort, the Predicted Mean Vote (PMV) thermal comfort index is used. This index was originally introduced by Fanger [24] and has been adopted in current international standards such as, for instance, ISO 7730 [25]. It predicts how a large number of people would vote, on average, about their perception of thermal comfort in a given indoor environment. The scale goes from -3, corresponding to the sensation of cold, with 0 corresponding to a neutral sensation, and up to +3, corresponding to the sensation of hot. Similarly, for IAQ, the concentration of CO_2 is being measured as an indicator of the balance between the ventilation rate and the generation rate of occupant-related pollutants. This shows when outdoor flow rate is required to ventilate the space and provide acceptable IAQ level. For instance, as recommended by many IAQ standards and building regulations, 1000 ppm is normally being considered as a threshold for indoor CO_2 concentration, from which ventilation is required in order to decrease the concentration of pollutants.

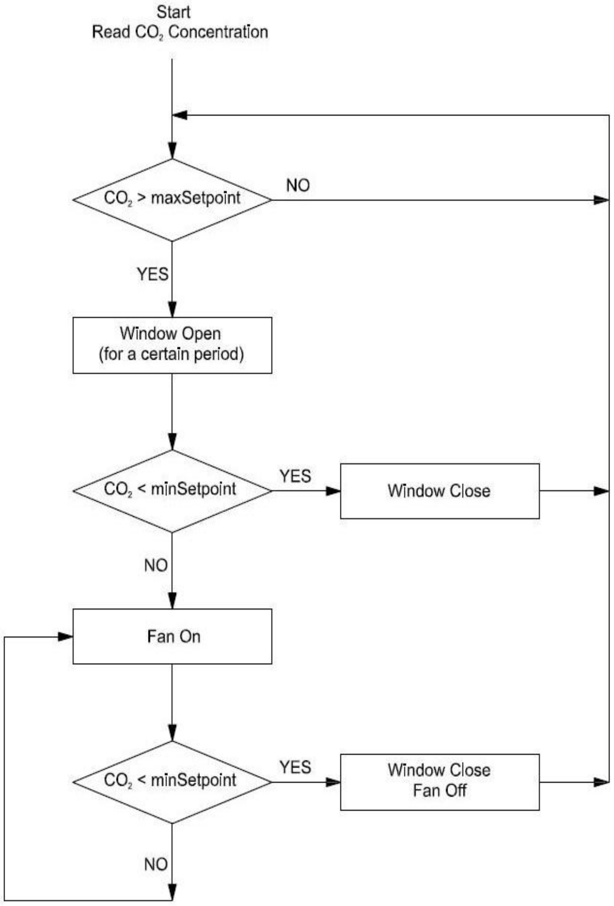

Fig. 3. Simple CO_2-based control strategy.

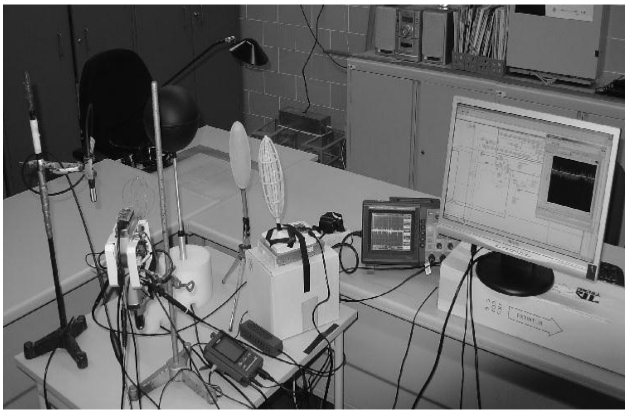

Fig. 4. Set of instruments and sensors at the I2L.

Installing the prototype in the I2L allows us to test all the control strategies, using the available instruments and sensors.

Besides the IAQ and thermal comfort assessment, it is possible to assess the energy consumption associated to each control strategy.

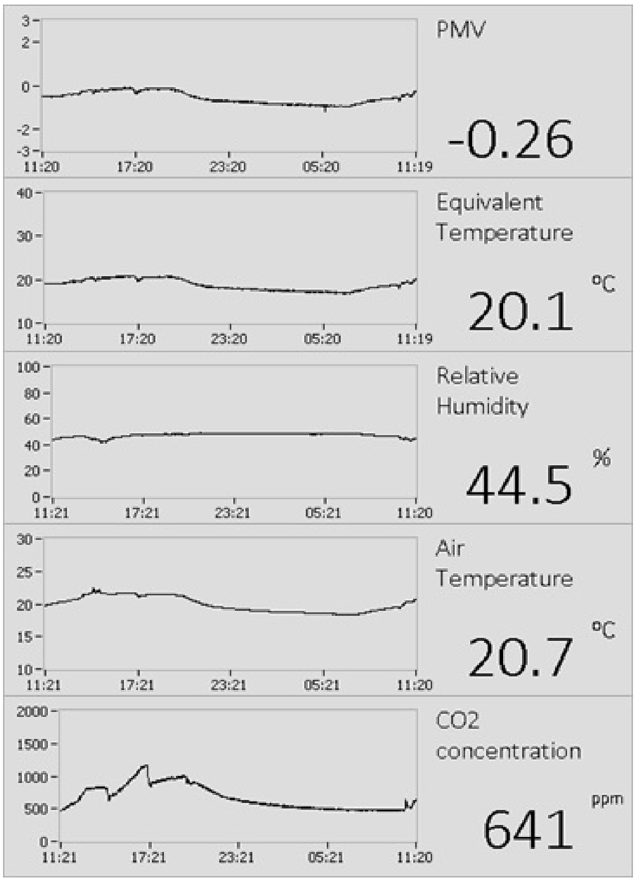

Fig. 5. Monitored IEQ indicators in the I2L.

III. SMART WINDOW: FUTURE DEVELOPMENTS

Besides the completed tasks, there are some more tasks in the project work plan. This section presents the future developments of the Smart Window project.

A. *Prototypes of Mechanical Boxes*

The new prototypes of mechanical boxes are under development, using other types of fan (axial, tangential and centrifugal) with different airflows. This is to assess airflow rate and fresh air penetration inside the space as well as the associated noise and energy consumption by each model. With regard to these data, it is possible to optimize all these parameters.

B. *Occupancy Counter*

An occupant counter is being developed to be installed at the entrance door of the I2L. This is capable of detecting people entering and leaving the room with two infrared beams, therefore, it can calculate how many people are in the room at any moment in time. Fig. 6 shows the infrared occupancy counter set being developed. This enables the adjustment of the ventilation rate based on real occupancy level, which will help preventing energy wastage. Moreover, a comparative energy performance analysis of different ventilation model (constant volume of airflow, CO_2-based DCV and occupancy-based DCV) is being carried out.

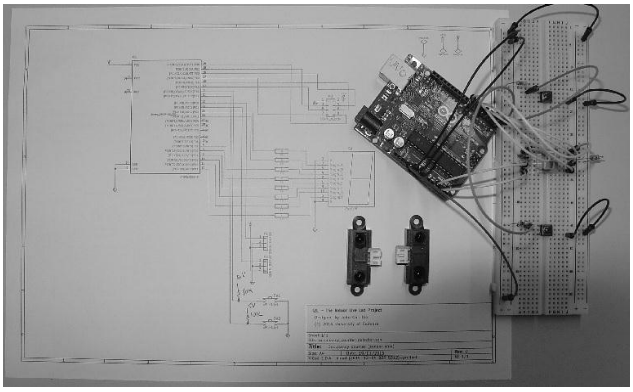

Fig. 6. Development of infrared occupancy counter.

IV. CONCLUSIONS

Ventilation is the key issue for providing suitable IAQ, as it is the process of replacing stale indoor air by fresh outdoor air. It is also responsible for a notable percentage of energy consumption in both residential and commercial buildings. Therefore, improving ventilation systems is vital both for improving energy efficiency in buildings and for providing acceptable IAQ. The Smart Window project described in this paper integrates hybrid ventilation to the building facade in order to employ the advantages and exclude the drawbacks from both natural and mechanical ventilation. The paper presented the current development steps of the intelligent window-based hybrid ventilation system in an ongoing research and development project, at University of Coimbra. The motivation and objectives behind this project as well as the current development, ongoing tasks and future work plans were presented and discussed.

REFERENCES

[1] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, *Official Journal of the European Union*, vol. 153, issue 13, June18, 2010.

[2] C. Allocca, Q. Chen, and L. R. Glicksman, "Design analysis of single-sided natural ventilation," *Energy Build*, vol. 35, no. 8, pp. 785–795, Sep. 2003.

[3] T. S. Larsen and P. Heiselberg, "Single-sided natural ventilation driven by wind pressure and temperature difference," *Energy Build*, vol. 40, no. 6, pp. 1031–1040, Jan. 2008.

[4] R. Yao, B. Li, K. Steemers, and A. Short, "Assessing the natural ventilation cooling potential of office buildings in different climate zones in China," *Renew. Energy*, vol. 34, no. 12, pp. 2697–2705, Dec. 2009.

[5] I. Oropeza-Perez and P. A. Østergaard, "Potential of natural ventilation in temperate countries — A case study of Denmark," *Appl. Energy*, vol. 114, pp. 520–530, 2014.

[6] S. D. Ray, N.-W. Gong, L. R. Glicksman, and J. A. Paradiso, "Experimental characterization of full-scale naturally ventilated atrium and validation of CFD simulations," *Energy Build*, vol. 69, pp. 285–291, Feb. 2014.

[7] C. Tantasavasdi, J. Srebric, and Q. Chen, "Natural ventilation design for houses in Thailand," *Energy Build.*, vol. 33, no. 8, pp. 815–824, Oct. 2001.

[8] E. Gratia and A. de Herde, "Natural ventilation in a double-skin facade," *Energy Build*, vol. 36, no. 2, pp. 137–146, Feb. 2004.

[9] M. Z. I. Bangalee, S. Y. Lin, and J. J. Miau, "Wind driven natural ventilation through multiple windows of a building: A computational approach," *Energy Build*, vol. 45, pp. 317–325, Feb. 2012.

[10] A. D. Stavridou and P. E. Prinos, "Natural ventilation of buildings due to buoyancy assisted by wind: Investigating cross ventilation with computational and laboratory simulation," *Build. Environ.*, vol. 66, pp. 104–119, 2013.

[11] X. Q. Zhai, Z. P. Song, and R. Z. Wang, "A review for the applications of solar chimneys in buildings," *Renew. Sustain. Energy Rev.*, vol. 15, no. 8, pp. 3757–3767, 2011.

[12] S. Ezzeldin and S. J. Rees, "The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates," *Energy Build.*, vol. 65, pp. 368–381, Oct. 2013.

[13] K. Miura, Y. Takemasa, M. Katoh, and M. Hiraoka, "Effect of hybrid ventilation system on indoor environment and annual cooling load in a high-rise building," *ASHRAE Transactions*, vol. 118, pp. 831–846, 2012.

[14] P. Heiselberg, *Principles of Hybrid Ventilation*, Aalborg: Aalborg University, 2002.

[15] T. Kleiven, "Natural ventilation in buildings," Ph.D. dissertation, Department of Architectural Design, History and Technology, Norwegian University of Science and Technology, 2003.

[16] R. Z. Homod, K. S. M. Sahari, and H. A. F. Almurib, "Energy saving by integrated control of natural ventilation and HVAC systems using model guide for comparison," *Renewable Energy*, vol. 71, pp. 639-650, 2014.

[17] M. Mysen, J. P. Rydock, and P. O. Tjelflaat, "Demand controlled ventilation for office cubicles — can it be profitable?" *Energy and Buildings*, vol. 35, pp. 657-662, 2003.

[18] M. Mysen *et al.*, "Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools," *Energy and Buildings*, vol. 37, pp. 1234-1240, 2005.

[19] D. Jreijiry, A. Husaunndee, and C. Inard, "Numerical study of a hybrid ventilation 20-system for single family houses," *Solar Energy*, vol. 81, pp. 227-239, 2007.

[20] T. Lu, X. Lv, and M. Viljanen, "A novel and dynamic demand-controlled ventilation strategy for CO_2 control and energy saving in buildings," *Energy and Buildings*, vol. 43, pp. 2499-2508, 2011.

[21] Z. Sun, S. Wang, and Z. Ma, "In-situ implementation and validation of a CO_2-based adaptive demand-controlled ventilation strategy in a multi-zone office building," *Building and Environment*, vol. 46, pp. 124-133, 2011.

[22] J. D. Carrilho, B. Chenari, M. R. Gomes, G. Botte, M. Mateus, and M. G. da Silva, "Development of a live laboratory for research and technology demonstration in indoor environment assessment and control," in *Proc. the 2nd Energy for Sustainability Multidisciplinary Conference - EfS 2015*, Coimbra, Portugal.

[23] P. Michel and M. E. Mankibi, "Advanced control strategy," 2000.

[24] P. O. Fanger, *Thermal Comfort*, Danish Technical Press, Copenhagen, 1970.

[25] ISO, "Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria," International Standards Organization, Geneve, Switzerland, 2005.

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4.2.2. Paper III: Teaching and Researching the Indoor Environment: From Traditional Experimental Techniques Towards Web-Enabled Practices

Considering the indoor environment quality as the main factor in improving the occupants' health, well-being, productivity and their quality of life, it must be taken carefully into account by the building designers when developing strategies to promote energy efficiency either in new buildings or in those being retrofitted. Researchers at the Energy, Environment and Comfort research group of ADAI working in several research activities that have the duality of Energy Efficiency in Buildings and Indoor Environmental Quality in common, prepared an article presenting a collection of reports on work that was being performed at the time as well as their contribution to development of the I2L. The article entitled "Teaching and researching the indoor environment: From traditional experimental techniques towards web-enabled practices" has been published in the Journal of Sustainable Cities and Society.

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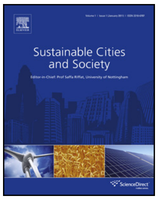

Teaching and researching the indoor environment: From traditional experimental techniques towards web-enabled practices

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ABSTRACT

In this paper some of the recent developments and ongoing work at the Energy, Environment and Comfort research group of ADAI (Association for the Development of Industrial Aerodynamics), in the areas of Indoor Environmental Quality and Energy Efficiency in Buildings are presented. Summarily, it is showcased a state of the art of the Indoor Live Lab, developed at the Mechanical Engineering Department of the University of Coimbra.

The Indoor Live Lab (I2L) is a new platform for research and technology demonstration in Indoor Environmental Quality (IEQ). The main motivation for initiating this effort arose from the increasing necessity that researchers, educators and decision makers have for continuously available monitored data on all aspects of building functioning. This paper aims at presenting early developments at the I2L, as well as associated research projects which were at the centre of its creation. Firstly, the objectives of the I2L are presented. Secondly, ongoing research on both residential buildings and services buildings is exposed. After, the several IEQ parameters studies are discussed in particular. This is followed by the I2L description, location and specific features. Finally, a conclusion and future work section are presented.

1. Introduction

In Europe there is a growing awareness and concern towards how energy is used in buildings, especially with respect to people's quality of life and also to its repercussions on the environment and the economy. This interest and concern can be understood due to the increased population density in urban areas, since around 75% of the European population lives in cities (EEA, 2013; UN, 2006), and the pressures related to urbanization, pollution and depletion of natural resources are at the origin of significant differences in the quality of life across the European Union Member States.

To meet the targets for a Low Carbon Economy by 2050, all new and existing buildings must significantly reduce their energy footprint, and progressively make a transition towards low carbon energy supplies. In Europe, residential buildings represent 75% of the built area and in 2009 the residential sector was responsible "for 68% of the total final energy use in buildings" (BPIE, 2011). New buildings, and existing buildings that are undergoing renovation, are subject to minimum requirements for energy efficiency (EE), related to the European Union policy to achieve nearly zero energy buildings in the near future (Kylili & Fokaides, 2015; Corgnati et al., 2011; Nimlyat & Kandar, 2015; d'Ambrosio Alfano et al., 2010; Agdas, Srinivasan, Frost, & Masters, 2015). Satisfying these requirements, however, must not be favoured at the expense of the Indoor Environmental Quality (IEQ) and comfort of the building occupants and visitors (Corgnati et al., 2011), since "occupants spend over 85% of their time indoors" (Nimlyat & Kandar, 2015). IEQ is a major factor conditioning the health and productivity of people (d'Ambrosio Alfano et al., 2010) encompassing the thermal environment, the indoor air quality, as well as other health, safety and comfort aspects such as ergonomics, acoustics and lighting. Undeniably, these factors play an important role in energy performance of buildings (Agdas et al., 2015).

One of the aspects of IEQ that greatly affects EE in buildings is the thermal environment, since HVAC systems in mechanical ventilated buildings consume significant amounts of energy when running. From a database presented in (Department of Energy US, 2013), the authors of (Dias Pereira, Raimondo, Corgnati, & Gameiro da Silva, 2014a) showed that space heating accounts for more than 45% of the energy use profile of secondary schools in the USA. Recently, in 2014, the authors of (Katafygiotou & Serghides,

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Nomenclature

ADAI	Association for the development of industrial aerodynamics (in portuguese: *Associação para o desenvolvimento da Aerodinâmica industrial*)
ACH	Air changes per hour
AER	Air exchange rates
DEHEMS	Digital environment home energy management system
DEM	Department of mechanical engineering at the UC
DHW	Domestic hot waters
ECTS	European credit transfer and accumulation system
EE	Energy efficiency
EPBD	Energy performance of buildings directive
GWP	Global warming potential
HVAC	Heating, ventilation, and air conditioning
I2L	Indoor live lab
IAQ	Indoor air quality
IECB	E-learning course on indoor environmental comfort in buildings at the university of coimbra
IEQ	Indoor environmental quality
IIC	Initial investment cost
LCC	Life cycle cost
LCIA	Life cycle impact assessment
Moodle	Modular object-Oriented dynamic learning
MV	Mechanical ventilation
NSA	Neighborhood sustainability assessment
NV	Natural ventilation
Q	Ventilation airflow rate (m^3/s)
REH	Regulation for the characteristics of thermal behaviour of residential buildings (in portuguese: *Regulamento de desempenho energético dos edifícios de habitação*)
RH	Relative humidity
TC	Thermal comfort
TPE	Total primary energy
UC	University of coimbra
UNESCO	United nations educational, scientific and cultural organization
WS	Wind speed (m^3/h)
3Es	Energy efficient schools project (in portuguese: *Escolas energeticamente eficientes*)

2014) showed the result of a thermal comfort study conducted in a secondary school in Cyprus unveiling that the representative secondary "typical school building *did* not provide the required indoor thermal comfort conditions for its occupants". In Ref. (Dias Pereira, 2016), it was reported that IEQ negative results in Portuguese secondary school buildings were mostly due to excessive CO_2 concentration indoors, i.e. poor Indoor Air Quality (IAQ).

Improving EE in buildings without considering occupants' comfort might have harmful effects on occupants' health and their productivity. Therefore, EE and IEQ have to be considered simultaneously throughout building design, construction and operation. To make their buildings places where people feel good and perform well, building designers and building managers must balance the selection of strategies that promote EE and energy conservation with those that address the needs of the occupants and promote well-being. Ideally, design and operational strategies would do both: the solutions that conserve energy, would also contribute to the best indoor environment. In reality, however, it is not possible to achieve a best indoor environment for all the occupants of a building, because people do not share the same preferences or the same expectations about their indoor environment. Therefore, it is not possible to satisfy every building occupant all of the time. It is possible, nevertheless, to satisfy the majority of the occupants most of the time, and it is this fine balance between the best achievable IEQ and the associated energy necessary to maintain it, that makes Indoor Sciences such a challenging and exciting field of research.

In this context, the authors present a summary of recent developments and ongoing work at ADAI's Energy, Environment and Comfort research group (ADAI, 2015), in the areas of Energy Efficiency in Buildings and Indoor Environmental Quality. Centre stage is given to the Indoor Live Lab—I2L (Dias Carrilho et al., 2015), a new platform for research, technology demonstration and IEQ teaching enhancement.

2. I2L: the indoor live lab

There has been a tendency in building management research towards developing supervisory control systems for improving IEQ and energy efficiency in buildings (Shaikh, Nor, Nallagownden, Elamvazuthi, & Ibrahim, 2014). In studies focusing on building energy and comfort management, conventional control systems are being replaced by intelligent controls (Dounis & Caraiscos, 2009). It should be mentioned that many Live Labs have formerly been developed for many purposes in a variety of research areas. For instance, a project, known as the Digital Environment Home Energy Management System (DEHEMS, 2015) has developed Live Labs in five European cities to assess the behaviour of the occupants on energy use as well as the advantages of energy monitoring.

The concept of the I2L has been proposed as an online platform for high availability of IEQ and energy data in an office setting, as well as the physical instrumented space where the data is acquired. It is a peculiar proposal in the sense that it is not intended to be a carefully controlled experimental setup. Rather, it is meant to be a permanent instrumented installation in an existing 6 person office, where the indoor and outdoor environmental conditions as well as energy use can be continuously monitored in the long term and in a non-intrusive way, as the office occupants go about their daily routine.

2.1. Research methodologies on IEQ, EE and infiltration rates

Air infiltration through the building envelope is one of main mechanisms that directly affect both the energy performance of buildings and the quality of the indoor environment (Hesaraki, Myhren, & Holmberg, 2015; Hassouneh, Alshboul, & Al-Salaymeh, 2012). Air infiltration is a term commonly used to designate uncontrolled and unintentional air flows through the building envelope, through holes, cracks, voids and unsealed joints. Some authors, particularly in the HVAC literature, distinguish between infiltration and exfiltration to mean the ingress of outdoor air into the building and the escape of indoor air out of the building, respectively (Li & Li, 2015; Brinks, Kornadt, & Oly, 2015). Herein, there is not a requirement to make such a distinction, and infiltration is used throughout to mean uncontrolled and unintentional air flow through the building envelope, regardless of direction.

In residential buildings, air infiltration provides the minimum air ventilation for the dilution and removal of indoor pollutants and the basic oxygen needs for human activities, when windows or vents are closed and mechanical ventilation (MV) systems are off. Air infiltration co-exists with installed natural or MV systems, and its unpredictable contribution to the total space ventilation often leads to an overestimation of the required ventilation rates, contributing to system overdesign and uncertainty in building simulation. Air infiltration represents heat loss in winter and excessive daytime heat load in summer (Hassouneh et al., 2012), and affects the performance of mechanical or hybrid ventilation sys-

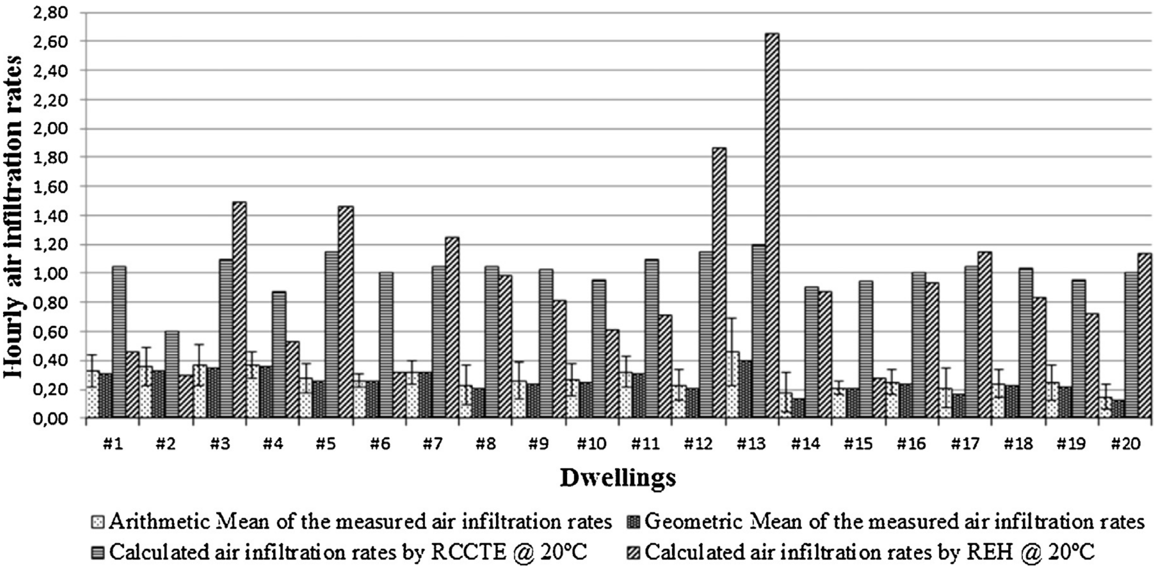

Fig. 1. Obtained mean infiltration rates and estimated infiltration rates in the assessment of 20 dwellings in Oporto, Portugal.

tems. Infiltration may represent a significant fraction of untreated air entering buildings with mechanical extraction, even with purposively designed inlet devices, or where unbalance is created by pressure differences in other types of mechanical systems.

To a large extent, the enhancement of the EE of buildings has been achieved by improving the thermal performance of the opaque envelope through the widespread use of thermal insulation systems (Nyers, Kajtar, Tomić, & Nyers, 2015; Mandilaras, Atsonios, Zannis, & Founti, 2014). Yet, in contemporary residential buildings, more than 50% of the energy consumption is used for space heating and air conditioning in EU members (Balaras et al., 2007; European Environment Agency, 2012), and the main mechanism through which energy is lost to the environment is associated with the renovation of indoor air. There is, therefore, a great potential for energy savings in buildings by controlling air infiltration through the building envelope. This potential is being explored in modern constructive solutions, through the use of window frames with high thermal performance and reduced air permeability. This has led, in some buildings, to an extreme reduction in effective ventilation rates, which is believed to be at the origin of health problems or symptoms of disease associated with permanency inside these buildings.

Lately, air infiltration through the building envelope became intrinsically a key issue in building regulations. When the EPBD recast (EPBD, 2010) became into force, however, uncertainty persisted about the magnitude of the national minimum or reference infiltration rate in each Member State, in Portugal in particular, regarding air infiltration rates in existing and newly built dwellings.

Thereat, an experimental field research in the assessment of fresh air infiltration rates in 20 naturally ventilated dwellings in the district of Oporto (Portugal), under regular occupation, was performed. Using the transient techniques of the tracer gas method with the metabolic CO_2 released by its occupants. The time evolution of the CO_2 concentration at each dwelling was measured and recorded for at least 3 days. The obtained infiltration rates were compared with the current Portuguese regulation on the thermal performance of residential buildings (REH, 2013). Subsequently, the short-term measurements were also adequate for evaluating the IAQ considering the metabolic CO_2 as an indicator.

The full results of this research, of which a summary is shown in Fig. 1, can be seen in (Rocheta Gomes et al., 2013a,b). In all tests, the obtained infiltration rates varied between 0.03 ACH and 0.6 ACH, except for the dwelling #13 with a maximum of 0.86 ACH. The arithmetic mean infiltration rate varied between 0.46 ± 0.23 ACH and 0.15 ± 0.08 ACH and the geometric mean infiltration rates between 0.4 ACH and 0.12 ACH, both respectively, in the dwelling #13 and in the dwelling #20. In the Portuguese regulations regarding thermal performance buildings it is assumed that residential buildings have construction characteristics or ventilation devices that ensure a minimum ventilation rate of 0.6 ACH and that this is needed to maintain a good IAQ. While the former regulations (RCCTE, 2006) were based on a simplified calculation with standard values, where the infiltration rates by natural ventilation varied from a minimum requirement of 0.6 ACH up to 1.25 ACH, the current ones are based on the EN 15242 with some adaptations and simplifications. The dwellings with estimated infiltration rates closer to those measured are the ones with a single facade, eventually without cross ventilation solutions, with a low height above ground and located in high terrain roughness sites, which implies a low wind exposure of the dwellings. Dwellings with higher deviations between estimated and measured infiltration rates were those located close to the coastline with low terrain roughness and high wind exposure.

This research played an important role in the revision of Portuguese regulations for the air infiltration requirements in residential buildings (REH, 2013; Portaria, 2013). It enabled a minimum infiltration rate requirement of 0.4 ACH for existing buildings and the calculation of an alternative value to the non-default value for the mean local velocity of wind in the calculation of air infiltration. These changes in the official infiltration rate calculation tool followed some critical aspects discussed in (Rocheta Gomes, Gameiro da Silva, & Simões, 2014). Recently, the authors of (Hesaraki et al., 2015) performed a study on a single family house in Sweden revealing that it was possible to achieve acceptable IAQ values with 0.30 ACH against the 0.50 ACH requirements from the Swedish legislation. By lowering the ventilation rate in accordance to the number of the occupants of a dwelling, 43% energy savings were estimated.

2.2. *New tracer gas techniques for measuring time-varying air ventilation rates*

The importance of being able to quantify infiltration rates in buildings is twofold: on one hand, air infiltration can represent an important component in a building's energy balance and there are now well established strategic policies that have resulted in regulatory pressure to reduce uncontrolled airflows through the building envelope; on the other hand, air infiltration has traditionally been relied upon to provide a minimum of building ventilation, particularly in the residential sector, the lack of which has been associated with health problems and lower productivity. As air infiltration is the primary way to ensure that there is a minimum of air renovation in most residential buildings, it is essential to understand the magnitude of these flow rates and to what extent there can be innovative solutions for controlling them, aiming at minimizing energy wastage while maintaining a healthy indoor environment.

Although the physical principles of natural ventilation (NV) are well understood, it has been generally recognized in the past that it is difficult, if not impossible, to obtain detailed information on the continuous time evolution of air exchange rates (AER) in buildings. Instead, established methods determine time-averaged ventilation rates by processing the concentration time series of a tracer gas over a period of time, usually several hours. This gives a useful indication of the magnitude of the AER over the assessment period but lacks the detail and precision required to quantify the dynamics of the phenomena involved.

To this end, novel tracer gas based approaches to measuring AER in buildings are being developed and tested against conventional tracer gas techniques. A technique for estimating the time evolution of AER, using metabolic CO_2 was presented in (Dias Carrilho, Batterman, & Gameiro da Silva, 2013). This technique relies, however, on the generation of CO_2 by the occupants, and it is not possible to apply it during extended periods of occupant absence, such as weekends and holidays. An alternative approach is to use a tracer that is already present in the outdoor atmosphere, which has a measurable cyclic variation. This method belongs to the class of tracer gas techniques but, unlike conventional methods that assume the background tracer concentration is constant, the proposed method recognizes that some tracers, such as CO_2, have daily quasi-periodic variations in the outdoor concentration (Fig. 2).

These daily variations, which can be small but are still within the detection range of existing monitoring equipment, can be successfully used for estimating building ventilation rates without the need of a source of tracer inside the building. The new method has the advantages that no tracer gas injection is needed, and time resolved results are easily obtained. A general application of the determination of time varying air infiltration rates is presented in (Dias Carrilho, Mateus, Batterman, & Gameiro da Silva, 2015), which does not rely on the tracer gas concentration having a well-defined period. This has a greater potential for application with tracers that occur in urban settings, for instance those generated by traffic pollution, which have variations with a broader frequency spectrum.

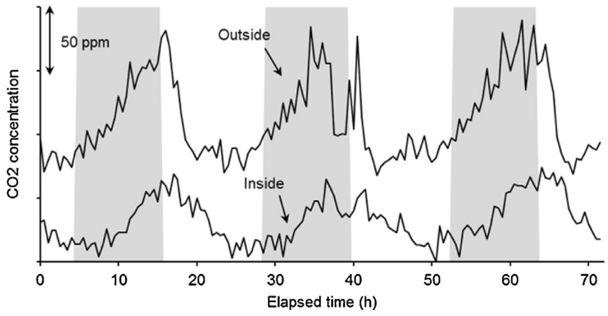

Fig. 2. Time series, recorded over 3 days, of exterior and interior CO_2 concentrations: raw data shown with an artificial vertical offset for better visualization. Ticks on the vertical axis are 50 ppm apart and the shaded areas identify night periods, between 20:00 and 07:00.

2.3. Environmental noise

One aspect of IEQ that is known to have direct repercussions in people's health is environmental noise. Like other pollutants, its source can be inside the building but, more often, environmental noise has its origin outdoors, for instance due to road traffic and other types of transportation, construction works, music events, to name a few. This factor leads necessarily to occupants' discomfort (Dascalaki, Gaglia, Balaras, & Lagoudi, 2009). The assessment of people's exposure to environmental noise is performed through the determination of long term acoustic descriptors. This determination is often done through sampling, using short term measurements. Having these measurements in mind, conclusions are drawn, and decisions are taken, that may have greater or lesser impact on the life of citizens, on economic activities and on the environment.

In (Mateus, 2014), a generic methodology was developed which, when applied to a temporal noise pattern, allows for the optimization of the sampling parameters in order to help in its definition when designing a sampling strategy and thus control the precision level of the sample. An urban site with road noise predominance was studied over four years. The data collected during that period allowed to statistically define the sound profile.

The permanent monitoring system (Fig. 3), based on a laptop computer with a data acquisition board, an external microphone and its respective pre-amplifier, and the data processing methodology is presented in Refs. (Mateus & Gameiro da Silva, 2012; Mateus, Dias Carrilho, & Gameiro da Silva, 2015a).

To evaluate the influence of the sampling parameters on the precision of the noise descriptors, the collected data was subjected to a re-sampling process through the Bootstrap method. The bootstrap method (Efron, 1987) is a type of resampling method which can be easily used to estimate statistical properties of a complete population, of which only a sample is known. It has been successfully applied in (Farrelly and Brambilla, 2003) and (Batko & Stepien, 2010) in estimating the uncertainty associated with environmental noise measurements. The advantage of the bootstrap method over the methods proposed in (JCGM 100, 2008) is the lack of the requirement to assign a probability distribution to the input quantities in the measurement model. It relies on the assumption, however, that the sample is statistically representative of the complete population.

The algorithm selects measurement starting times randomly from the available time series with a uniform probability distribution. This is repeated a large number of times, in order to generate

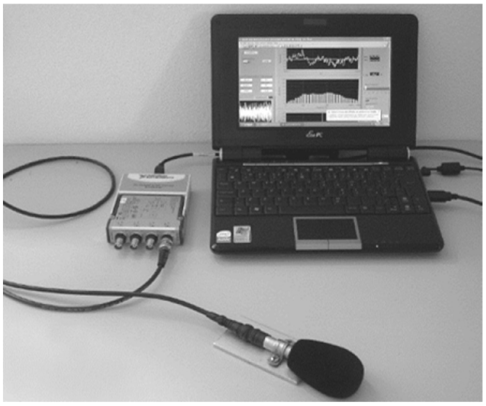

Fig. 3. Sound data-acquisition system—microphone, pre-amplifier, AD board and laptop.

Fig. 4. Panorama view of the Montarroio case study in Coimbra, Portugal. The building is signalled by the rectangle.

sequences of equivalent noise levels, $L_{Aeq,\Delta T(N),i}, i = 1, \ldots, M$, from which the average levels, defined by

$$\bar{L}_{Aeq,T} = \frac{1}{M}\sum_{i=1}^{M} L_{Aeq,\Delta T(N),i} \qquad (1)$$

and the sample standard deviations, defined by

$$S\left(L_{Aeq,T}\right) = \sqrt{\frac{\sum_{i=1}^{M}\left(L_{Aeq,\Delta T(N),i} - L_{Aeq,T}\right)}{M-1}} \qquad (2)$$

can be calculated.

In (3) the set of obtained results for the relationship between the uncertainty of the noise equivalent level and the sampling parameters (number (N) and duration (ΔT) of sampling episodes) allowed to obtain the following generalised expression that may be applied to the various reference periods (day, evening, night), where the coefficients c_1, α_1, α_2 and α_3 are characteristic of the site and must be determined experimentally (Mateus, 2014) and (Mateus, Dias Carrilho, & Gameiro da Silva, 2015b). Table 1 shows an example set of coefficients determined for the site studied in (Nyers et al., 2015).

$$s\left(L_{Aeq,T}\right) = c_1 \times \Delta T^{\alpha_1} \times N^{-[\alpha_2+\alpha_3\times\ln(\Delta T)]} \qquad (3)$$

3. I2L: case-studies

3.1. EE and IEQ in residential historic buildings

In Portugal, residential buildings represent 77% of the built area and an estimated 16% of the total primary energy consumption, from which 43% rely on electricity based energy distribution. Although it is largely assumed that retrofitting the existing building stock towards the nearly zero energy target only lacks funding to occur, a deep assessment carried out in (Brito, Gameiro da Silva, Mateus, & Brites, 2015) demonstrates that misconceptions about ancient buildings still endure, and that enhanced knowledge is needed to harness a wider renovation potential: energy efficiency as a driver, not a goal by itself. Findings from the ongoing PhD thesis on "Upgrade Opportunities for Ancient Buildings (in City Centres)" (Brito et al., 2015; Brites, Brito, Costa, Gaspar, & Gameiro da Silva, 2013; Brito, Gameiro da Silva, Brites, Castela, & Fonseca, 2014; Brito et al., 2015) confirm that detailed studies using imaging techniques such as 3D tools and thermography; IEQ assessment; and building information model depictions, are viable if applied to the building scale and neighbourhood scale. Complemented, for example, with the use of neighbourhood sustainability assessment (NSA) tools that aim at integrating "the four pillars of sustainability namely, environmental, social, economic, and institutional dimensions" (Komeily & Srinivasan, 2015).An ancient building dating back to the XVIth century located in Coimbra's UNESCO area was used as case study (Fig. 4). The building's stacked masonry walls provide peripheral support to wooden floor levels and ceilings, protected by ceramic roof tiles on a wood structure. Wood doors and simple glazing sash windows with interior shutters exist, with high air infiltration due to lack of maintenance. Thick walls reducing towards the upper levels define growing internal areas: 13.7 m^2 in a semi-buried level with separate entrance, 15.3 m^2 on the intermediate level, and 20.6 m^2 on the top level. Currently, only 35.9 m^2 are inhabitable, as the lower level has severe humidity problems.

Table 1
Numerical coefficients determined for the site studied in (Nyers et al., 2015).

Coef.	Day	Evening	Night
c_1	2.5224	2.2885	4.6034
$\alpha 1$	−0.086	−0.181	−0.068
$\alpha 2$	0.408	0.3695	0.4686
$\alpha 3$	0.010	0.034	0.002

The case study was documented using advanced tools for terrestrial laser scanning and digital photogrammetry, used to produce point clouds of the model and later tri-dimensional models (Brito et al., 2014). Thermographic imaging was used to visualize the original thermal behaviour of the building: a set of range-calibrated thermographic images from exterior (top) and interior (bottom) of the top South facing window, adjacent to attached building, at different times of a winter day are documented in Fig. 5.

Using an indoor air quality (IAQ) and energy monitoring online system (WSBP, 2015), environmental parameters such as CO_2, relative humidity and ambient temperature were measured in each level and outdoors. The CO_2 measurement effectively illustrated infiltration rates and human presence, while the temperature and humidity measurements depicted the influence of the vernacular materials inertia. These data were used to formulate a proposal that connects the known history of use and construction, with what is expected to guarantee the users comfort and safety. This proposal was carried out through the Energy Plus building simulation software.

Studies to evaluate the costs, both from an economic and an environmental perspective were also performed. The evaluation of five alternatives for the renovation of the Montarroio building, including demolition and reconstruction (Appendix A) was compiled in (Brito et al., 2015). Here, the economic indicators Initial Investment Cost (IIC) and the 30 years Life Cycle Cost (LCC) were reported (Table A1, Appendix A). The results demonstrated that higher IIC in efficient equipment reduces energy consumption (electricity and/or gas, as solar thermal and biomass are accounted as neutral in emissions in Portugal) and is, most of the time, favourable on the long term LCC. Nevertheless, the comparison between Option 0 ("Anyway Scenario") with Option 1 ("Business as Usual" regulation-inspired practices) casted doubts on building envelope options, and conclusions only emerge when tackling the Life Cycle Impact Assessment (LCIA) analysis.

Real data from a case study is important to become empathetic with building owners, and realize why apparently straightforward solutions fail to happen. Moreover, the LCIA evaluation of environmental impacts, expressed in parameters as Global Warming

Fig. 5. Terrestrial Laser Scan (left), Digital Photogrammetry (middle) and thermography (right). [Darker colours represent colder surfaces, with low width walls and low inertia]

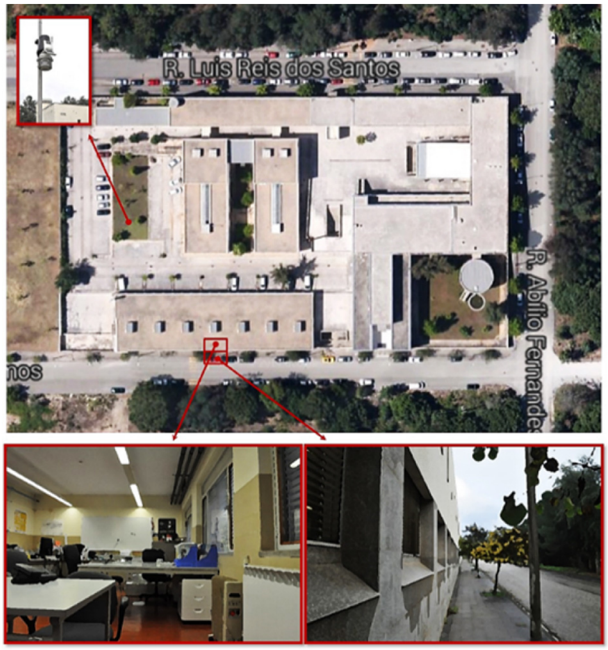

Fig. 6. Aerial view of the Mechanical Engineering Department of the University of Coimbra, retrieved from Google Maps, showing the 6 person office where the Indoor Live Lab is being developed (see text for detailed description).

Potential (GWP) and Total Primary Energy (TPE), demonstrated that in the Mediterranean climate, deep renovation interventions, recommended or imposed by regulations, such as interior insulation with windows replacement (Option 1) have worst long term impact on environment, and owners pocket, than a lower price option—as the case study in its current state (Option 0). It was shown that in this climate, for ancient buildings, installing heat pumps for acclimatization (air-air) and DHW (air-water) is cost-effective, even considering their replacement every 15 years. These findings confirm proposals for a generalised use of heat pumps in a session of the European Association for Heat Pumps, but what would be the consequences of placing exterior units in each façade of the UNESCO historic centre?

75% emission reductions and increased energy security might also be achievable considering insulation only in the building envelope horizontal faces (ceiling and floor over the basement) and solar based DHW and heating with electric resistance heater backup. By connecting future and past, it is demonstrated that a market exists in between the individual needs for comfort and safety, and the collective goals of Energy Efficiency, Security and Climate Change Mitigation, today.

3.2. EE and IEQ in public schools

As people spend most of their time inside buildings, it is crucially important to provide adequate indoor air quality (IAQ) in addition to thermal comfort (TC), especially for office buildings and schools in which people are working, learning and studying, and where the level of personal control over their indoor environment can be very limited. IAQ and building ventilation are intimately related because ventilating indoor spaces with outdoor air supply is the most often used mechanism to decrease the concentrations of pollutants generated inside the building.

Within the 3Es project (*Escolas Energeticamente Eficientes*—Energy Efficient Schools) (http://www.3es.pt/, 2013), it has been developed an integrated approach for energy performance and IEQ assessment in school buildings aiming at contributing to reduce the energy consumption in school buildings while providing good indoor environmental conditions to the occupants. This project was preceded of other studies on the field of TC and IAQ in schools (Dias Pereira, Gameiro da Silva, & Cardoso, 2015) and followed the context of a major rehabilitation and refurbishment program of secondary school buildings that has been carried out in the last few years in Portugal (Blyth et al., 2012). From a database provided by the state-owned company Parque Escolar E.P.E., energy consumption changes between the pre and post-intervention phases were characterized (Gameiro da Silva et al., 2013). Based on the characterization and a set of criteria, a group of eight representative schools was chosen as case studies within the project. Aiming at achieving a functional benchmarking indicator, significant to situate each of the schools in a proper ranking, an extensive literature review on the theme was performed (Dias Pereira et al., 2014a).

Energy and indoor climate quality post-occupancy audits, especially during the first occupancy phase of new and refurbished buildings, are important strategies to improve the energy use, since the indoor climate has a great impact on perceived human comfort and is related to the occupants' productivity (Corgnati et al., 2011). From this perspective, besides energy auditing, it was proposed a methodology to assess IAQ and TC in Portuguese secondary classrooms (subjective and objective evaluation) (Dias Pereira, 2016). Some of the typical data presentation achieved within this methodology was earlier presented in (Dias Pereira, Raimondo, Corgnati, & Gameiro da Silva, 2014b). In terms of ventilation requirements and its contributions towards energy consumption in school buildings, several studies were also developed (Dias Pereira, Correia, Gaspar, Costa da Silva, & Gameiro da Silva, 2014).

In terms of general conclusions, it was verified that students in secondary schools in Mediterranean climate under free running conditions accepted indoor air temperatures above 25 °C, and expressed thermal sensation votes for no change (Dias Pereira et al., 2014b; Dias Pereira, Neto, & Gameiro da Silva, 2015), i.e. "feel comfortable under a wider range of temperature than those recommended by the norms" and "confirmed that thermal neutrality is not the preferred state". These results contrary nevertheless, the

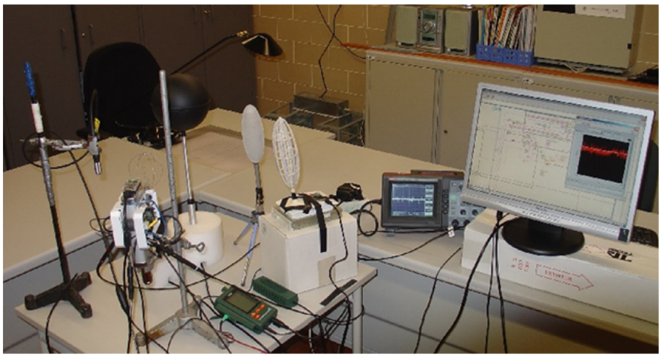

Fig. 7. Development of the instrumentation and data acquisition system used in the Indoor Live Lab.

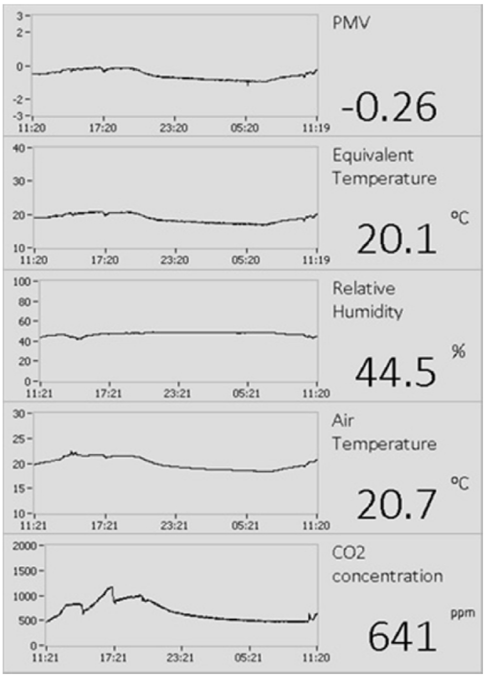

Fig. 8. IEQ indicators monitored in the Indoor Live Lab. From top to bottom: PMV and Equivalent Temperature (acquired from a Bruel & Kjaer 1212 Thermal Comfort Analyzer); Relative Humidity, Air Temperature and CO_2 concentration (acquired from an Extech SD800CO_2 monitor).

overheating concern recently exposed in the British classrooms (Montazami & Nicol, 2013; Teli, Jentsch, James, & Bahaj, 2011).

4. I2L: IEQ monitoring and web enabled practices

The main motivation behind the I2L platform (Dias Carrilho et al., 2015) arises from the increasing necessity that researchers, educators and decision makers have for continuously available monitoring data on all aspects of building functioning. The concept of the I2L is equally grounded on an online web service for high availability of IEQ data, as well as in the physical instrumented spaces where the data is acquired, where both the indoor and outdoor environmental conditions can be monitored continuously in the long term and in a non-intrusive way, as the occupants go about their daily routine. The main objective of the Indoor Live Lab was to enable researchers to access continuously monitored indoor environmental quality data and indicators of energy efficiency. Several educational and research areas can benefit from this new facility as follows:

- Training in the assessment and auditing of IEQ: TC, IAQ, Acoustic Comfort, and Lighting Comfort.
- Development of new techniques for continuous measurement of ventilation rates in buildings.
- Proof of concept and validation of energy efficiency plans.
- Development and testing of indoor climate control strategies.
- Training in the calibration and uncertainty assessment of building simulation models.
- Technology demonstration of building energy metering solutions.
- Development and demonstration of new technologies for energy efficient hybrid ventilation.

The first installation is being developed and tested at an existing 6 person office, in the Department of Mechanical Engineering (DEM), at the University of Coimbra (UC), located at the street level in the southwest building DEM-UC. Fig. 6 shows an aerial view of the complex, retrieved from Google Maps. The lower images show views of the office interior and exterior. The location of the new weather station, online since November 2013, is also shown at the top left inset (ADAI@DEM.UC, 2014).

The I2L installation relies on various types of instruments and sensors to measure and monitor energy consumption and IEQ descriptors, such as thermal comfort, indoor air quality, lighting and noise level. Fig. 7 shows a set of instruments and sensors already installed.

Initial development of the thermal environment monitoring system is undergoing. A Bruel & Kjaer Thermal Comfort Meter Type 1212 was installed with its analogue outputs connected to a National Instruments (NI) USB-6008 data acquisition board. Data is acquired and logged continuously at a rate of one sample per minute by means of a software application developed in NI's LabVIEW application development platform.

Moreover, Fig. 8 shows an example of daily monitoring of the indoor climate. The graphs show the history of the last 24 h for each quantity (other time periods are possible, e.g. weekly, monthly or yearly) and the numerical display shows the current value, which is updated every minute.

For TC, the Predicted Mean Vote thermal comfort index is used (Fanger, 1972; Moutela, Dias Carrilho, & Gameiro da Silva, 2015)—showed at the top. Fanger's PMV model combines four environmental variables (air temperature, mean radiant temperature, air velocity and humidity) and two personal parameters (activity level and clothing thermal insulation) into an index which has been universally adopted in TC studies.

In practice, other indexes are also used that can be measured directly, such as the Operative Temperature, the Effective Temperature and the Equivalent Temperature. The Equivalent Temperature, shown in the second plot of Fig. 8, is the air temperature that would be measured in an imaginary room with the mean radiant temperature equal to the air temperature and zero air velocity, where a person would experience the same heat losses as in the real room he/she is in. In addition, Fanger's Draught Model (Agdas et al., 2015) predicts the percentage of occupants dissatisfied with local draught, from the three physical variables air temperature, mean air velocity, and turbulence intensity. These quantities will be monitored using a Swema Air300 and a SWA03 low velocity probe to calculate the Draught Rate thermal comfort index, and this part of the monitoring system is currently undergoing implementation. Also undergoing implementation is the replacement of the existing hydronic heaters manual controls with computer controlled servo-valves, for local automatic control of the heating system.

Similarly, to monitor the IAQ, the concentration of CO_2 is being measured as an indicator of the balance between the ventilation rate and the generation rate of occupant-related pollutants. As previously stated, ventilation is the key issue for providing suitable IAQ

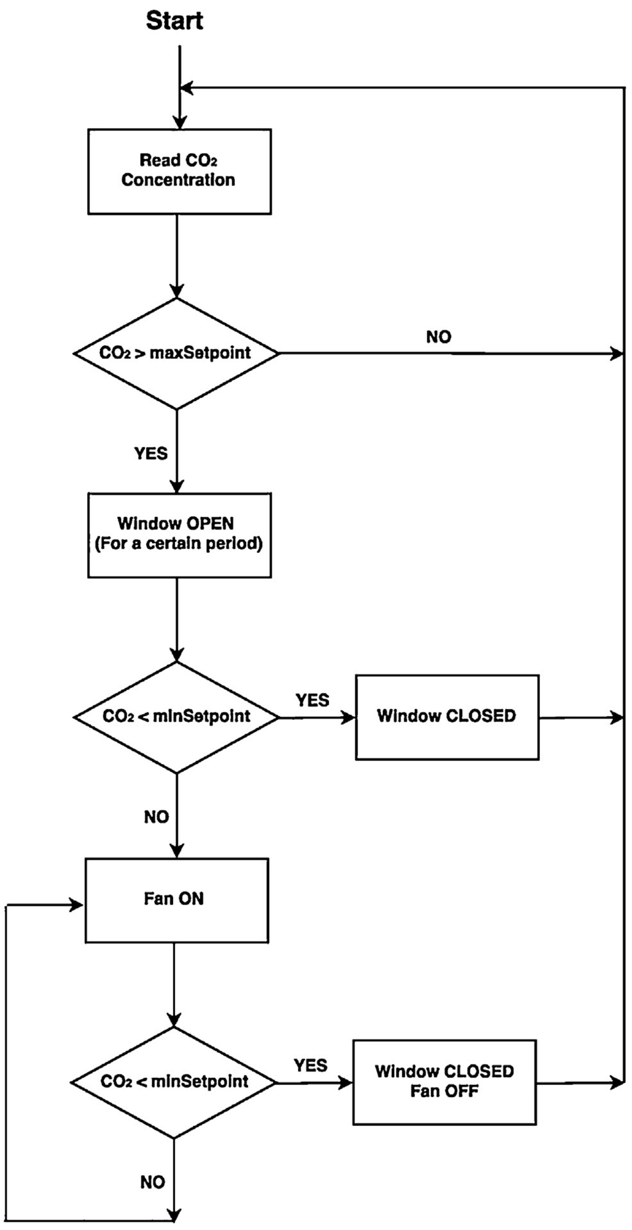

Fig. 9. Simple CO_2-based control strategy.

as it is the process of replacing stale indoor air by fresh outdoor air. Ventilation in buildings can be done either by mechanical means or by NV. Recent studies have shown research activities in developing new control strategies to employ natural cooling and ventilation. For instance, Homod, Khairul Salleh Mohamed Sahari, and Almurib, 2014 (Department of Energy US, 2013) developed control strategies, which can predict when mechanical ventilation is required in order to maintain acceptable IAQ. Besides predictive control strategies, demand-controlled ventilation (DCV) strategies, which is used in many research such as (Mysen, Rydock, & Tjelfaat, 2003; Mysen, Berntsen, Nafstad, & Schild, 2005; Jreijiry, Husaunndee, & Inard, 2007; Lu, Lü, & Viljanen, 2011; Sun, Wang, & Ma, 2011), has a very significant effect on improving EE of a ventilation system. Moreover, it was mentioned by reference (Chenari, Dias Carrilho, & Gameiro da Silva, 2016) that utilizing hybrid ventilation integrated with suitable control strategies, to adjust between active and passive ventilation, results in notable energy saving while delivers acceptable IAQ. However, there is still an obvious gap in the existing literature about employing intelligent window-based control strategies not only for increasing the share of NV but also integrating mechanical ventilation to compensate drawbacks of NV.

Within this context, a smart window system that allows the use of hybrid ventilation was installed in the I2L to employ the advantages and exclude the drawbacks from both natural and mechanical ventilation. In addition to TC and IAQ, lighting and sound quality in buildings can also influence occupants' satisfaction. In order to continuously measure these indices of IEQ, a lux meter as well as a sound level meter is installed in the I2L. The lux meter enables the users to adjust between natural and artificial lighting, which can causes mitigating the energy consumption from artificial lighting systems (Table 1).

4.1. The smart window project

In the Smart Window project, several ventilation control strategies are being developed and tested using Smart Window in order to find out the best strategies that can provide an appropriate indoor climate with lower energy consumption. The control strategies, which are based on indoor and outdoor environmental parameters, such as concentration of CO_2, indoor and outdoor temperature difference, wind speed and its orientation, are defined in a way to use natural ventilation (NV) as long as possible (if suitable), otherwise, putting the mechanical system on circuit to provide the required space ventilation.

A number of control strategies were identified as potentially suitable, based on indoor environment parameters and outdoor weather as input data (RCCTE, 2006). In particular, the indoor concentration of CO_2 is used to see whether ventilation is required or not. Temperature difference between indoor and outdoor (ΔT), wind speed (WS) and its direction (D) are used to detect the availability of NV. In the control strategies, the availability of buoyancy-driven NV is evaluated according to (4) (ASHRAE, 2009), whereas (5) (Walker, 2016) evaluates the availability of wind-driven natural ventilation.

$$Q = CA\sqrt{2gH\frac{Ti - To}{Ti}} \tag{4}$$

where Q represents the ventilation airflow rate (m^3/s), C is the discharge coefficient for opening (typically 0.62), A indicates the cross section area of opening (m^2), g is the gravitational acceleration (m/s^2), H represents the height from midpoint of lower opening to midpoint of upper opening (m), T_i is the average indoor temperature (K) and T_o is the outdoor temperature (K).

$$Q = \frac{KAV}{3600} \tag{5}$$

where Q represents the ventilation airflow rate (m^3/s), V indicates the outdoor WS (m/s), A indicates the cross section area of opening (m^2) and K is coefficient of effectiveness. This coefficient varies with the angle between D and the facade opening. For instance, if the angle at which wind hits the building is 45°, then the coefficient is estimated to be around 0.4, whereas, if wind hits the building perpendicularly, the coefficient is about 0.8.

According to all the aforementioned parameters, various rule-based (if *condition*, then *action*) control strategies were reported in the literature, in which indoor and outdoor environmental parameters are the conditions and different operations of window and fan are the actions.

The control strategies start with simple CO_2-based demand controlled ventilation strategies in the beginning and, going forward, reach more advanced control strategies, considering all the parameters and more advanced operations of window and fan. Table 2 presents characteristics of some of the developed controls from simple to advanced strategies. As shown, different input parameters and different operations of window and fan, define the control

Table 2
The characteristics of control strategies.

Rule-based control	Mechanical ventilation operation	**Natural ventilation operation**	**Input parameters**
Simple	On/Off	Open/Close (O/C)	CO_2
	Leveling speed	Leveling O/C	CO_2
	Modulating speed	Modulating O/C	CO_2
	On/Off	O/C	$CO_2 + \Delta T + D$
	Leveling speed	Leveling O/C	$CO_2 + \Delta T + D$
Advanced	Modulating speed	Modulating O/C	$CO_2 + \Delta T + D$

Fig. 10. Prototype of the mechanical ventilation subsystem of the Smart Window hybrid ventilation system.

strategy either simple or advanced. Moreover, Fig. 9 demonstrates a simple control strategy in a flowchart.

The Smart Window includes a mechanical ventilator as well as a control system. Fig. 10 shows the first prototype already installed at the I2L. Furthermore, other prototypes using different types of blowers (tangential, centrifugal and axial) will be developed in order to test the air flow rates, the energy consumption, the noise made by each type and so on. During this project, an extensive literature review about energy-efficient ventilation methods is carried out.

4.2. Further developments

In addition to controllable hybrid ventilation, a CO_2 monitoring equipment has been installed, which also measures the air Relative Humidity (RH) and Temperature (bottom 3 plots of Fig. 8). The use of CO_2 as a tracer gas has gained popularity within the building engineering community because its concentration can be easily detected by infrared absorption spectroscopy.

CO_2 is also considered relatively inert and safe; it is cheap and readily available. The fact that building occupants exhale CO_2 makes it especially attractive as a tracer gas since only a sensor and a datalogger are needed to obtain the data needed to estimate the ventilation Air Exchange Rate (AER) in any given zone of the building. This is possible because the dynamics of the tracer gas concentration within a zone are well modelled by a first order mass balance equation, where the associated time constant is the reciprocal of the AER. When the occupants enter a room, they act approximately like a constant emission source, and the CO_2 concentration will grow like an inverted exponential approaching a steady-state value, as time passes. This is typically the response of a first order system to a step-up input, where the asymptotic steady-state value is proportional to the CO_2 generation rate. Similarly, when the occupants leave the room, the concentration will decay exponentially, just like the response of a first order system to a step-down input. New methodologies for continuous monitoring of AERs based on automated analysis of time series of tracer gas concentrations have recently been proposed (Shaikh et al., 2014; Dounis & Caraiscos, 2009; DEHEMS, 2015) and are currently under development, testing and validation. The I2L is an important installation to test and validate these new methodologies in real operating conditions.

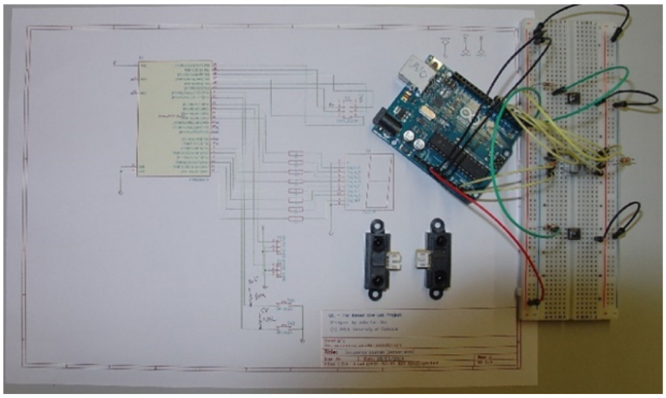

Fig. 11. Development of infrared occupancy counter.

Furthermore, an infrared occupancy counter is being developed to be installed at the entrance. This is capable to record all entering and leaving, therefore it accurately shows occupancy level of the I2L at each moment. Fig. 11 shows the infrared occupancy counter set. This will enable the adjustment of the ventilation rate based on real occupancy level, which will cause preventing energy wasting.

Besides continuously monitoring of IEQ elements, energy consumption is going to be continuously monitored in the I2L. An energy monitor prototype developed by WSBP (WSBP, 2015) will be used to separately record energy consumption from different consumers such as lighting, ventilation, computers and so on. Moreover, flow meters will be installed on radiators hot water supply pipes integrated with enthalpy meters in order to measure heating energy consumption.

Monitoring energy consumption also allows the I2L users to test and compare energy consumption throughout their research and development carrier improvements—as stated in (Murugesan, Hoda, & Salcic, 2015), "*Visualizing energy consumption is (...) an important way to motivate end-users to conserve energy*". For instance, in smart window, the energy consumption from each control strategy can be recorded in order to find out the best suited strategy, which not only maintains acceptable indoor climate but also has the least energy use. Furthermore, it enables the users to find out an optimal strategy for heating, ventilation and lighting that can satisfy occupants and lower the energy consumption at the same time.

5. Conclusions and future research

The indoor environment is an important element in the quality of life of people. To make their buildings places where people feel good and perform well, building designers and building managers must balance the selection of strategies that promote energy efficiency and energy conservation with those that address the needs of the occupants and promote well-being.

Among other areas of activity, ADAI's research group on Energy, Environment and Comfort is active in several lines of research that have in common the duality of Energy Efficiency in Buildings and Indoor Environmental Quality. In this paper, the authors presented a summary of recent advances and ongoing work over the last 3 years. Results from the continued research in this field are reported to stakeholders and policy makers, both at a national and at an international level, and novel developments are regularly presented at international conferences and published in scientific journals.

Moreover, the motivation and objectives behind developing the Indoor Live Lab is discussed. The current state of development of the I2L, located in Mechanical Engineering Department (DEM) at University of Coimbra, is presented and discussed. The I2L enables the researchers to access continuously monitored data of IEQ and energy use, which can be used for a variety of scientific purposes. Additionally, the proposed development of the I2L is briefly presented.

The authors believe that many educational and research areas can benefit from this online platform. One of the strategies to reach a wider group of professionals who will benefit from this web enabled platform is the e-learning course on Indoor Environmental Comfort in Buildings of the University of Coimbra.

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Appendix A.

A summary comparing the five alternatives [energy efficiency (EE.) related renovation options for Montarroio (EE.Ren.Options) describing their non-energy efficiency related costs (Non-EE.costs), necessary to render the building inhabitable, and Initial Investment Costs for the building envelope (IIC_EE.Envel.) and EE. equipment (IIC_EE.Equip)] is presented in Table A1 (Fig. A1).

Table A1
Renovation options: Initial investment (IIC) and lifecycle costs (LCC) per option and equipment.

EE.Ren.Options:	Opt.0		Opt.1		Opt.2		Opt.3		Opt.4	
Equipment type:	_erh:	_hp:	_erh:	_hp:	_erh:	_hp:	_st-bio:	_st-erh:	_st-bio:	_st-erh:
Useful area	*36* m^2	*36* m^2	*31* m^2	*31* m^2	*63* m^2	*63* m^2	*36* m^2	*36* m^2	*46* m^2	*46* m^2
Non-EE.costs (€/y)	7801	7801	7801	7801	45,039	45,039	7801	7801	12,545	12,545
IIC_EE.Envel. (€/y)			6906	6906	4957	4957	1188	1188	2733	2733
IIC_EE.Equip (€/y)		2120		2120	1874	3719	4840	2975	5490	3475
%EE.OverCost/m^2	**0%**	**27%**	**119%**	**150%**	**280%**	**293%**	**77%**	**53%**	**108%**	**88%**
Energy costs (€/y)	1546	423	811	218	160	44	36	92	32	82
Yearly LCC (€/y)	2321	1642	2192	2042	5724	5735	1924	1591	2686	2314
EE. Payback (y)	**no ROI**	**2y**	**9y**	**7y**	**5y**	**6y**	**4y**	**3y**	**5y**	**4y**
50% EE incentive?	no fund	1060	3453	4513	3415	4338	3014	2082	4112	3104

Note: Option 0 (Reference Case); Option 1 (common rehabilitation): Business as usual neighbourhood practices where interior insulation under plasterboard is placed to hide existing pathologies, with serious indoor air quality risks; Option 2 (Demolition and Reconstruction); Option 3 (Upgrade without extension): Detailed assessment to optimize the inherent building characteristics to achieve efficacy with users. Solar thermal heating and DHW require primary energy only for backup; Option 4 (Upgrade with extension): The previous strategy (Opt. 3) with added structural seismic reinforcement made financially viable with an area extension (IEA A50): safer users/investment, and space for a small family.

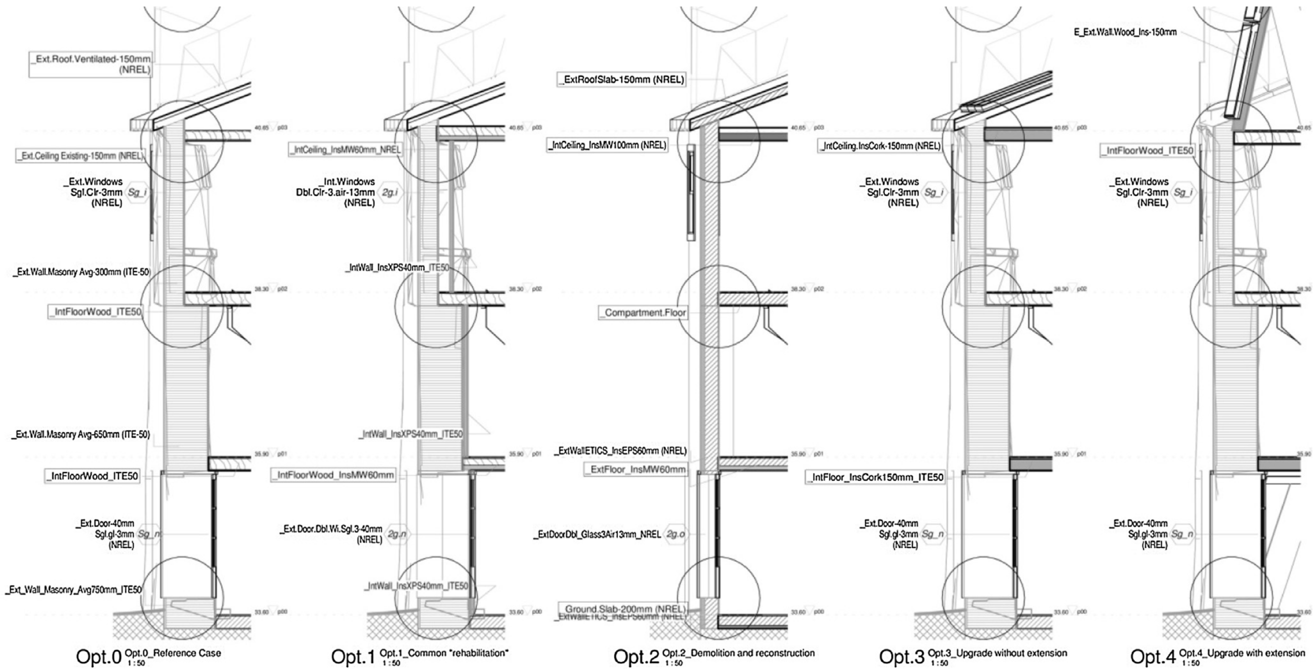

Fig. A1. Montarroio Case Study intervention options scheme of studied options (Brinks et al., 2015).

References

ASHRAE. (2009). *ASHRAE handbook 2009 fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Agdas, D., Srinivasan, R. S., Frost, K., & Masters, F. J. (2015). Energy use assessment of educational buildings: toward a campus-wide sustainable energy policy. *Sustainable Cities and Society*, *17*, 15–21.

Balaras, C. A., Gaglia, A. G., Georgopoulou, E., Mirasgedis, S., Sarafidis, Y., & Lalas, D. P. (2007). European residential buildings and empirical assessment of the Hellenic building Stock, energy consumption, emissions and potential energy savings. *Building and Environment*, *42*(3), 1298–1314.

Batko, W., & Stepien, B. (2010). Application of the bootstrap estimator for uncertainty analysis of the long-term noise indicators. *Acta Physica Polonica A*, *118*, 11–16.

Blyth, A., Almeida, R., Forrester, D., Gorey, A., Hostens, G., & OECD. (2012). *Modernising secondary school buildings in Portugal, OECD*. OECD Publishing.

Brinks, P., Kornadt, O., & Oly, R. (2015). Air infiltration assessment for industrial buildings. *Energy and Buildings*, *86*, 663–676.

Brites, G., Brito, N. S., Costa, J., Gaspar, A., & Gameiro da Silva, M. (2013). Solar cooling as an optimization of conventional solar thermal systems for existing buildings' upgrade interventions. *Clima 2013-11th Rehva world congress on energy efficient, Smart and healthy buildings & 8th International conference on IAQVEC*.

Brito, N. S., Fonseca, P., Gameiro da Silva, M., Traça de Almeida, A., Lamas, F., Brites, G., et al. (2015). Residential buildings as extended territory for ESCOs. *ECEEE 2015 summer study*.

Brito, N. S., Gameiro da Silva, M., Brites, G., Castela, R., & Fonseca, P. (2014). Learning from Traditional Knowledge towards engaged inhabiting. *ICOMOS – international council on monuments and sites – 18th general assembly and scientific symposium*.

Brito, N. S., Gameiro da Silva, M., Mateus, M., & Brites, G. (2015). Upgrade towards efficacy: 'Calculated' and/or 'measured' results? *Facade tectonics #14*.

Chenari, B., Dias Carrilho, J., & Gameiro da Silva, M. (2016). Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: a review. *Renewable & Sustainable Energy Reviews*, http://dx.doi.org/10.1016/j.rser.2016.01.074 [Accepted for publication]

DEHEMS. http://www.dehems.eu/ (accessed: 15.09.15)

Dascalaki, E. G., Gaglia, A. G., Balaras, C. a., & Lagoudi, A. (2009). Indoor environmental quality in Hellenic hospital operating rooms. *Energy Building*, *41*(5), 551–560.

Dias Carrilho, J., Batterman, S., & Gameiro da Silva, M. (2013). Estimating time varying air exchange rates. *Clima 2013—11th Rehva world congress on energy efficient, Smart and healthy buildings & 8th International conference on IAQVEC*.

Dias Carrilho, J., Chenari, B., Rocheta Gomes, M., Botte, G., Mateus, M., & Gameiro da Silva, M. (2015). Development of a live laboratory for research and technology demonstration in indoor environment and control assessment. *Energy for sustainability 2015 sustainable cities: designing for people and the planet*.

Dias Carrilho, J., Mateus, M., Batterman, S., & Gameiro da Silva, M. (2015). Air exchange rates from atmospheric CO2 daily cycle. *Energy Building*, *92*, 188–194.

Dias Pereira, L. (2016). *Modernised portuguese Schools—From IAQ and thermal comfort towards energy efficiency plans, PhD thesis*. University of Coimbra.

Dias Pereira, L., Correia, N., Gaspar, A. R., Costa da Silva, C. D., & Gameiro da Silva, M. (2014). The impact of ventilation requirements on energy consumption in school buildings. *Roomvent 2014—13rd SCANVAC international conference on air distribution in rooms*, 736–743.

Dias Pereira, L., Gameiro da Silva, M., & Cardoso, E. (2015). Indoor air quality audit and evaluation on thermal comfort in a school in Portugal. *Indoor and Built Environment*, *24*(2), 256–268.

Dias Pereira, L., Neto, L., & Gameiro da Silva, M. (2015). Indoor air quality and thermal comfort assessment of two Portuguese secondary schools: main results. *REHVA annual conference 2015*, 49–56.

Dias Pereira, L., Raimondo, D., Corgnati, S. P., & Gameiro da Silva, M. (2014a). Energy consumption in schools—a review paper. *Renewable & Sustainable Energy Reviews*, *40*, 911–922 [December].

Dias Pereira, L., Raimondo, D., Corgnati, S. P., & Gameiro da Silva, M. (2014b). Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: methodology and results. *Building and Environment*, *81*, 69–80.

Dounis, A. I., & Caraiscos, C. (2009). Advanced control systems engineering for energy and comfort management in a building environment—a review. *Renewable & Sustainable Energy Reviews*, *13*(6–7), 1246–1261.

Efron, B. (1987). Better bootstrap confidence intervals. *Journals American Statistical Association*, *82*(397), 171–185.

Fanger, P. O. (1972). *Thermal comfort: analysis and applications in environmental engineering*. New York: McGraw-Hil.

Farrelly, F. A., & Brambilla, G. (2003). Determination of uncertainty in environmental noise measurements by bootstrap method. *Journal of Sound and Vibration*, *268*(November 1), 167–175.

Gameiro da Silva, M., Antunes, C. H., Bernardo, H., Jorge, H., Cruz, L., Barata, E., et al. (2013). A preliminary assessment of energy performance in refurbished schools. *1st international congress on energy & environment (ICEE): bringing together economics and engineering* [May].

Hassouneh, K., Alshboul, A., & Al-Salaymeh, A. (2012). Influence of infiltration on the energy losses in residential buildings in Amman. *Sustainable Cities and Society*, *5*, 2–7 [December].

Hesaraki, A., Myhren, J. A., & Holmberg, S. (2015). Influence of different ventilation levels on indoor air quality and energy savings: a case study of a single-family house. *Sustainable Cities and Society*, *19*, 165–172.

Homod, Z. Raad, Khairul Salleh Mohamed Sahari, & Haider Almurib, A. F. (2014). Energy saving by integrated control of natural ventilation and HVAC systems using model guide for comparison. *Renew. Energy*, *71*(C), 639–650. http://dx.doi.org/10.1016/j.renene.2014.06.015

JCGM 100. (2008). Evaluation of measurement data—Guide to the expression of uncertainty in measurement. *International organization for standardization Geneva ISBN, vol. 50, no. september*, 134.

Jreijiry, D., Husaunndee, A., & Inard, C. (2007). Numerical study of a hybrid ventilation system for single family houses. *Solar Energy*, *81*(2), 227–239.

Katafygiotou, M. C., & Serghides, D. K. (2014). Thermal comfort of a typical secondary school building in Cyprus. *Sustainable Cities and Society*, *13*, 303–312.

Komeily, A., & Srinivasan, R. S. (2015). A need for balanced approach to neighborhood sustainability assessments: a critical review and analysis. *Sustainable Cities and Society*, *18*, 32–43.

Kylili, A., & Fokaides, P. a. (2015). European smart cities: the role of zero energy buildings. *Sustainable Cities and Society*, *15*, 86–95.

Li, H., & Li, X. (2015). A new method to assess the infiltration rate in large commercial complex in Beijing, China. *Procedia Engineering*, *121*, 628–634.

Lu, T., Lü, X., & Viljanen, M. (2011). A novel and dynamic demand-controlled ventilation strategy for CO2 control and energy saving in buildings. *Energy Building*, *43*(9), 2499–2508.

Mandilaras, I., Atsonios, I., Zannis, G., & Founti, M. (2014). Thermal performance of a building envelope incorporating ETICS with vacuum insulation panels and EPS. *Energy Building*, *85*, 654–665.

Mateus, M. (2014). *The influence of the sampling parameters on the uncertainty in environmental noise measurements*. University of Coimbra: PhD Thesis.

Mateus, M., Dias Carrilho, J., & Gameiro da Silva, M. (2015). An experimental analysis of the correction factors adopted on environmental noise measurements performed with window-mounted microphones. *Applied Acoustics*, *87*, 212–218.

Mateus, M., Dias Carrilho, J. A., & Gameiro da Silva, M. C. (2015). Assessing the influence of the sampling strategy on the uncertainty of environmental noise measurements through the bootstrap method. *Applied Acoustics*, *89*, 159–165.

Mateus, M., & Gameiro da Silva, M. (2012). *Estudo sobre o factor de correcção acústica nas medições de ruído ambiental com microfone aplicado directamente em elementos de fachada*. Acústica.

Montazami, A., & Nicol, F. (2013). Overheating in schools: comparing existing and new guidelines. *Building Research & Information*, *41*(3), 317–329.

Murugesan, L. K., Hoda, R., & Salcic, Z. (2015). Design criteria for visualization of energy consumption: a systematic literature review. *Sustainable Cities and Society*, *18*, 1–12.

Mysen, M., Berntsen, S., Nafstad, P., & Schild, P. G. (2005). Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools. *Energy Building*, *37*(December 12), 1234–1240.

Mysen, M., Rydock, J. P., & Tjelfaat, P. O. (2003). Demand controlled ventilation for office cubicles—can it be profitable? *Energy Building*, *7*, 657–662.

Nimlyat, P. S., & Kandar, M. Z. (2015). Appraisal of indoor environmental quality (IEQ) in healthcare facilities: a literature review. *Sustainable Cities and Society*, *17*, 61–68.

Nyers, J., Kajtar, L., Tomić, S., & Nyers, A. (2015). Investment-savings method for energy-economic optimization of external wall thermal insulation thickness. *Energy Building*, *86*, 268–274 [January].

RCCTE. (2006). *Decree-Law no. 80/2006 Regulation for the characteristics of thermal behavior of buildings*. pp. 2006. Portuguese: Regulamento das Características de Comportamento Térmico dos Edifícios—RCCTE, Official Gazette of the Portuguese Republic [Series A, No. 6. 2006].

REH. (2013). Decree-Law no. 118/2013 Regulation for the characteristics of thermal behavior of residential buildings. *Regulamento de desempenho energético dos edifícios de Habitação—REH, official gazette of the portuguese republic, 4th april, 2013*, 2013.

Rocheta Gomes, M., Gameiro da Silva, M., & Simões, N. (2013a). Assessment of air infiltration rates in residential buildings in Portugal. *Clima 2013—11th Rehva world congress on energy efficient, Smart and healthy buildings & 8th International conference on IAQVEC*.

Rocheta Gomes, M., Gameiro da Silva, M., & Simões, N. (2013b). Assessment of air infiltration rates in portuguese dwellings by the metabolic CO2 method. *Energy for sustainability 2013—Sustainable cities: designing for people and the planet*.

Rocheta Gomes, M., Gameiro da Silva, M., & Simões, N. (2014). Avaliaõço das taxas de infiltraõço de ar em edifãcios residenciais. *Energy e Edifãcios*, 58–62 [vol. Jan/Feb, no. (in Portuguese)].

Shaikh, P. H., Nor, N. B. M., Nallagownden, P., Elamvazuthi, I., & Ibrahim, T. (2014). A review on optimized control systems for building energy and comfort management of smart sustainable buildings. *Sustainable Energy Reviews*, *34*, 409–429.

Sun, Z., Wang, S., & Ma, Z. (2011). In-situ implementation and validation of a CO2-based adaptive demand-controlled ventilation strategy in a multi-zone office building. *Building and Environment*, *46*(1), 124–133.

Teli, D., Jentsch, M. F., James, P. A. B., & Bahaj, A. S. (2011). Overheating risk evaluation of school classrooms. *World renewable energy congress 2011-Sweden*, 1821–1828.

US Department of Energy US. (2013). *Advanced energy retrofit guide—practical ways to improve energy performance: K-12 schools*. Guide.

d'Ambrosio Alfano, F. R., Bellia, L., Boerstra, A., Van Dijken, F., Ianniello, E., Lopardo, G., et al. (2010). *REHVA – indoor environment and energy efficiency in schools – part 1*. pp. 2010. Brussels: REHVA.

Portaria no. 349-A/2013/Portaria no. 349-B/2013 (in Portuguese); Official Gazette of the Portuguese Republic, Series 1, No. 232, 29/11/2013, no. 232. 2013.

WSBP. (2015). *We Solve Building Problems [Online]*.. Available: http://www.wsbp.eu/. (accessed: 15.09.15)

Walker, A. (2016). *Natural Ventilation, Whole Building Design Guide, 2014. [Online]*.. Available: http://www.wbdg.org/resources/naturalventilation.php. (accessed: 04.01.16)

http://www.3es.pt/, 2013. [Online]. Available: http://www.3es.pt/.

R., Moutela, J., Dias Carrilho, M., Gameiro da Silva, Sensitivity of the PMV index to the thermal comfort parameters, in *Energy for Sustainability 2015 Sustainable Cities: Designing for People and the Planet*.

EPBD. (2010). recast), Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). *Off. J. Eur. Union*,. L153/13–153/35, 2010

B.P.I. Europe, Europe's buildings under the microscope Buildings Performance Institute Europe (BPIE) 2011 2016.

European Environment Agency. (2012). *Household energy consumption by end-use in the EU-27, Share of energy consumption by end uses in total households consumption in percent [Online]*.. Available: http://www.eea.europa.eu/data-and-maps/figures/households-energy-consumption-by-end-uses-4

EEA. (2013). *"European Environmental Agency," [Online]*.. Available: http://www.eea.europa.eu/themes/urban/intro. (accessed: 22.05.15)

UN, "World Urbanization Prospects—Percentage Urban by Major Area, Selected periods, 1950–2030," ESA/P/WP/200, 2006.

ADAI@DEM.UC. (2014). *Weather Underground—Coimbra, Portugal. [Online]*.. Available: http://www.wunderground.com/cgi-bin/findweather/getForecast?query=pws:ICOIMBRA14. (accessed: 29.12.14)

ADAI. (2015). *2015*. Available: http://www.adai.pt/v3/index2.php?lg=1. (accessed: 07.03.15)

Corgnati, S. P., Gameiro da Silva, M, Ansaldi, R., Asadi, E., Costa, J. J., Filippi, M., et al., REHVA—Indoor Climate Quality Assessment, Guidebook no. 14. REHVA, 2011, 2011.

4.3. Experimental Setups and Experiments in the I2L

The first step was to design and build the mechanical ventilator boxes using both linear (tangential) and centrifugal fans. The dimensions of ventilator boxes are 860*160*160 mm, which one is equipped by an Ebmpapst DC centrifugal blower with 14 watts input power and the nominal voltage ranging from 16 to 28 volts and the other one is equipped by an Ebmpapst DC linear blower with 8.7 watts input power and the nominal voltage ranging from 8 to 14 volts (the datasheets of the blowers can be found in Appendix B). Figure 4.1 and 4.2 depict the scheme of the test prototype while more detailed drawings of the ventilator boxes are presented in Appendix C. The air intake part is located in the bottom of the boxes and is equipped with a filter. The blowers drive the air to a rectangular box and then it is discharged to the room.

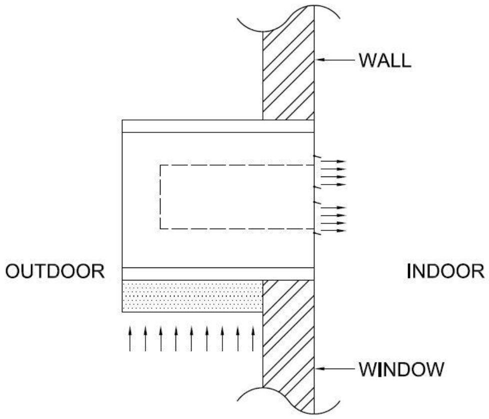

Figure 4.1 – Scheme of the centrifugal ventilator box.

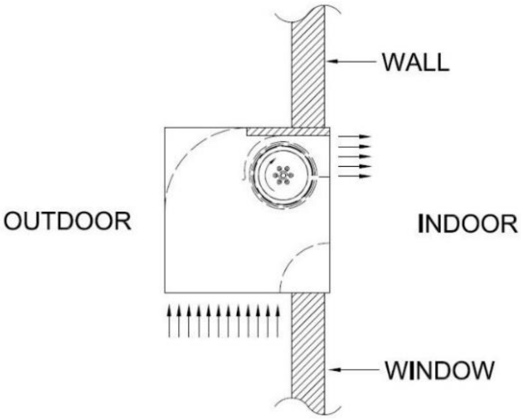

Figure 4.2 – Scheme of the linear ventilator box.

The mechanical ventilator boxes have been installed in the I2L in order to be tested. Figure 4.3 presents the prototypes installation process at the I2L office.

Figure 4.3 – Installation of the Smart Window ventilator boxes prototypes at the I2L office.

Moreover, an infrared occupancy counter sensor has been developed and installed at the entrance of the I2L. This was implemented with two units of SHARP infrared distance sensor, installed next to each other at the entrance and perpendicular to the occupants' movement direction. The occupancy counter detects the direction of movement of the occupants when passing through the office door (entering/leaving). Then the signals from the infrared sensors were treated using the application developed in *LabVIEW* and presented the real-time occupancy level on the screen. Figure 4.4 shows the development phase of the occupancy counter and the installed sensor at the entrance of the I2L. This counter is used to collect information about occupancy level in the room to pilot the ventilation strategies algorithms.

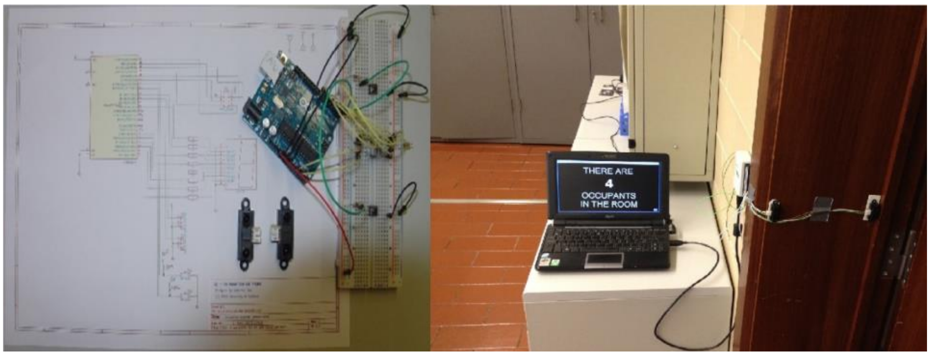

Figure 4.4 – The occupancy counter sensor development and installation at the I2L entrance and the screen showing real-time occupancy level.

Furthermore, as shown in figure 4.5, the I2l was equipped with an Extech SD800 device which was used to record CO_2 Concentration at a rate of one sample per minute. This sensor enabled to test the CO_2-based ventilation strategies using the accurate real-time concentration level recorded by the sensor.

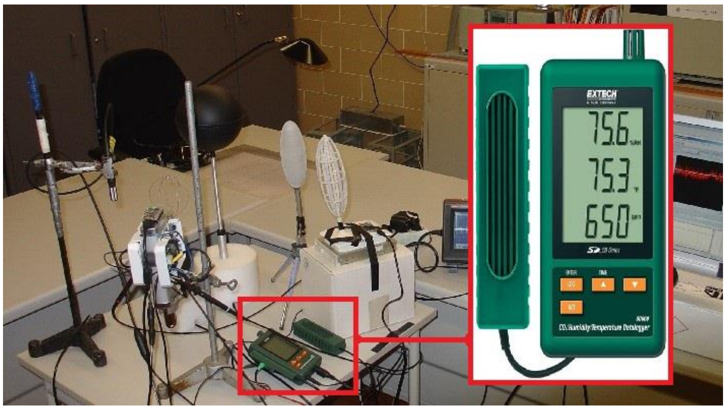

Figure 4.5 – The Extech SD800 among other IEQ instrumentation and data acquisition tools at the I2L.

There are several methods for measurement and evaluation air exchange rate (AER), caused by infiltration and/or ventilation (both for mechanical and natural ventilation systems). The most accurate, common and widely used method is the tracer gas method in which the tracer gas concentration will be measured along time with an appropriate gas analyzer. Once the tracer concentration evolution with time is measured, it is possible to evaluate and calculate the air flow rate with an appropriate mathematical analysis. The experiment can be implemented using different methods such as constant concentration, constant tracer emission and decay methods. In this work, the tracer gas decay method has been used as the most common method for single zones.

By means of the recorded concentration along the time, the AER can be calculated using the following equation:

(i) $$C(t) - C_{ext} = (C_0 - C_{ext})e^{-\lambda t}$$

where C(t) is the indoor CO_2 concentration at the time instant t, C_{ext} is the outdoor environment CO_2 concentration, C_0 is the indoor initial CO_2 concentration at the time t=0 and λ is the AER (symmetrical to the numerical constant in the exponent). The equation (i) can be simplified as follows:

(ii) $$Y = Ke^{-\lambda X}$$

Alternatively, logarithms can be applied on the equation (i) to obtain the equation (iii) that allows the linearization of the concentration evolution as simply described in equation (iv).

(iii) $$\ln\left(C(t) - C_{ext}\right) = \ln\left(C_0 - C_{ext}\right) - \lambda t$$

(iv) $$Y = mX + b$$

Here the fitting can be done through a linear regression and the AER is the symmetric of the slope of the obtained line. It should be noted that an outdoor ambient CO_2 concentration of 450 ppm has been assumed for all tests in this research.

The objective of this research is to develop, test and evaluate the performance of several mechanical DCV strategies. The mechanical DCV strategies have been defined considering the indoor concentration of CO_2 and the occupancy level as the input signals and the fan speed/power as the output signal. The ventilation control strategies have been settled and implemented using the applications developed in *LabVIEW* and tested on the experimental prototypes of smart window ventilator boxes at the I2L. The *LabVIEW* front panels and block diagrams related to the ventilation control strategies have been illustrated in Appendix F.

Before running the tests for ventilation strategies and in order to check the functionality of the developed testing platform, an example of the tests performed overnight. To do so, when all windows were closed, and as shown in figure 4.6, CO_2 has been injected using a fire extinguisher and mixed in the room environment.

Figure 4.6 – Releasing CO_2 into the I2L office for evaluation of the AER associated to the ventilation strategies for Smart Window system.

When the concentration reached to an amount around 1800 ppm, the ventilator has been switched on at maximum power and everyone left the room to assess the AER with the concentration decay during non-occupancy period.

This example test enabled us to find out the possible errors in the experiments setup and troubleshoot to achieve more precise results. Figure 4.7 shows the concentration decay obtained by running of this example test. The red line represents the selected profile, chosen for the calculation of the AER. Figures 4.8 and 4.9 depict exponential regression and liner regression of the concentration difference between indoor and outdoor environment respectively, from which the AER has been obtained, 0.593 h^{-1}. Moreover, the coefficient of determination (R-squared), which shows how close the data are to the fitted regression line, has been obtained (R^2=0.9978).

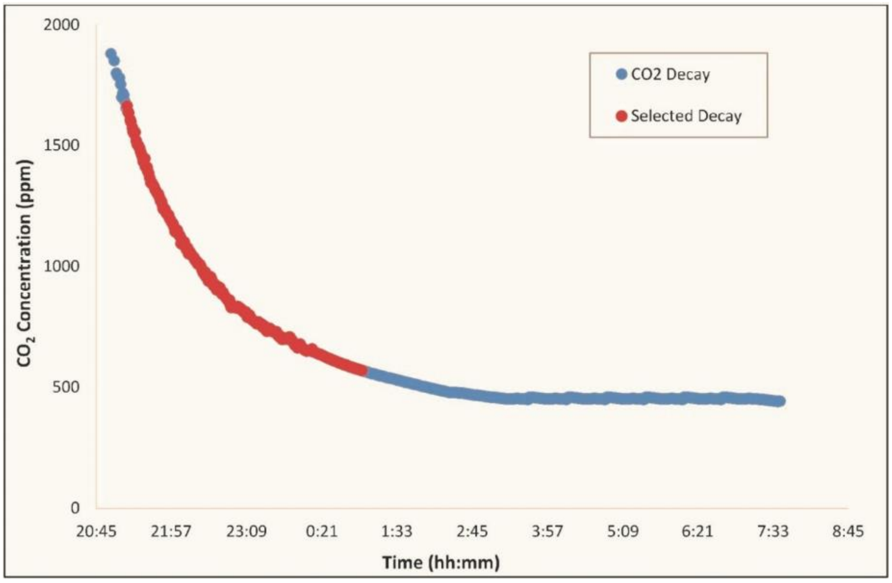

Figure 4.7 – Example test concentration decay. The blue dots are the whole recorded decay and the red dots illustrate the profile selected for analysis.

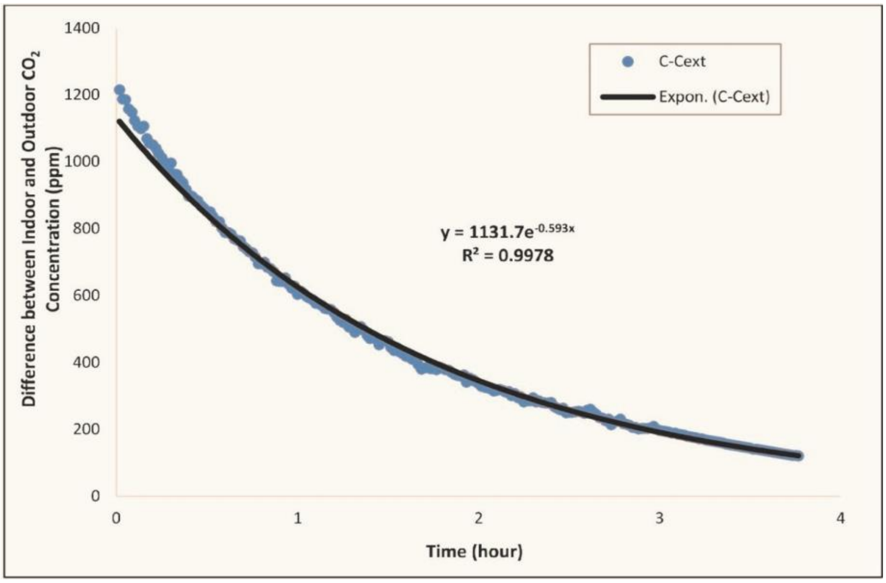

Figure 4.8 – Exponential regression of the concentration difference between indoor and outdoor environment.

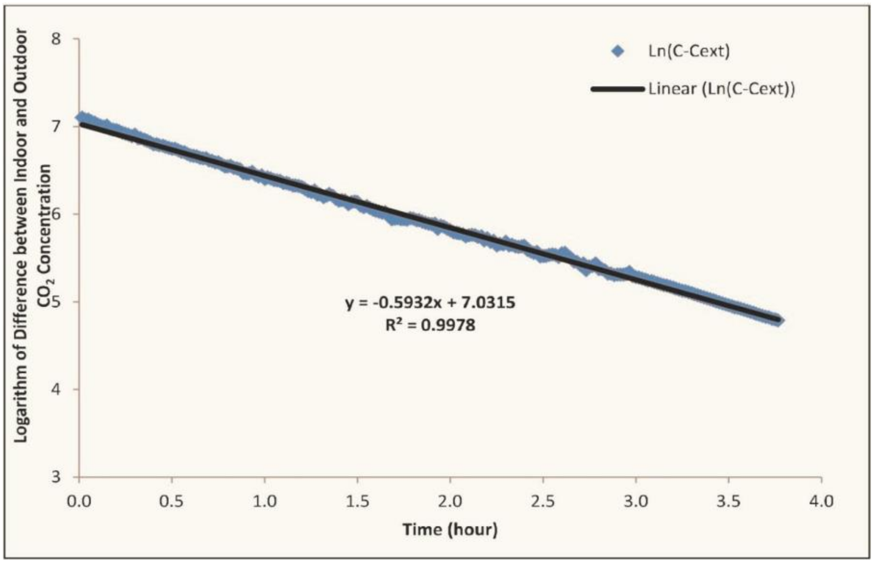

Figure 4.9 – Linear regression of the concentration difference between indoor and outdoor environment.

Although the example test has been carried out both using the centrifugal and the linear ventilator boxes, above only the results from the linear blower have been presented. This is due to better performance of the linear fan comparing with the centrifugal one and also lower energy consumption as well as lower noise level (in order to check if the mechanical ventilators disturb the occupants' acoustic comfort, the noise level tests have been performed and the results have been presented in appendix D). For the same reason, the results from the DCV strategies using the linear ventilator box have been presented in this section.

- *Control strategy 1 (Occupancy period based):*

In this strategy, regardless the number of occupants, the linear fan works at maximum power only when occupants exist in the room. Figure 4.10 presents the flowchart of the first control strategy.

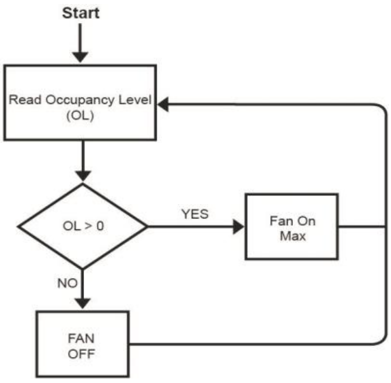

Figure 4.10 – Flowchart of ventilation control strategy 1

- *Control strategy 2 (Occupancy level based):*

Unlike the previous strategy, considering the number of occupants that exist in the room the linear fan works at percentage its maximum power (20% per occupant). Figure 4.11 shows the flowchart of the second control strategy.

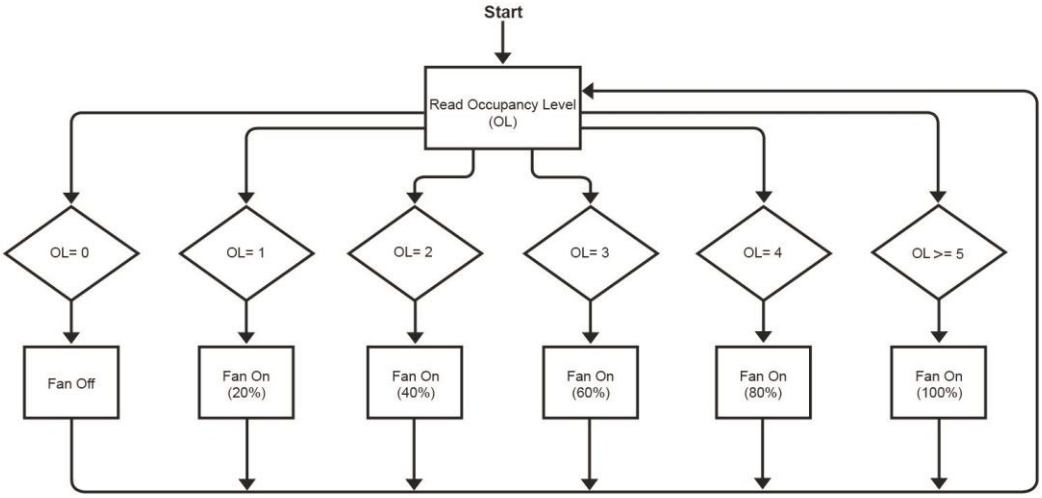

Figure 4.11 – Flowchart of ventilation control strategy 2

These two strategies have been evaluated during two entire days at the I2L. Figures 4.12 and 4.13 show the indoor CO_2 concentration and the occupancy level in the test room for strategies 1 and 2. These figures show that during the occupancy period the concentration slightly passed the popular value (1000 ppm), but still maintained a good IAQ, while the fan energy consumption in the first strategy is much higher the second strategy, more than two times. This emphasizes the importance of well designed and implemented DCV to avoid over ventilation. Table 4.1 represents the maximum and average CO_2 concentration in the I2L during the occupancy period as well as the energy consumption for each strategy. As the occupancy level is not the same in the two experiments, a definite comparison of the results cannot be made but it is obvious that the second strategy performed almost the same considering the IAQ while delivered a noticeable energy saving.

Table 4.1 – Results from occupancy based ventilation control strategies.

Control Strategy	**Room Maximum CO_2 Concentration (ppm)**	**Room Average CO_2 Concentration (ppm)**	**Fan Energy Consumption (kWh/day)**	**Occupancy Period (hours)**
CS_1	1077	902	0.088	≈ 10
CS_2	1094	947	0.034	≈ 9

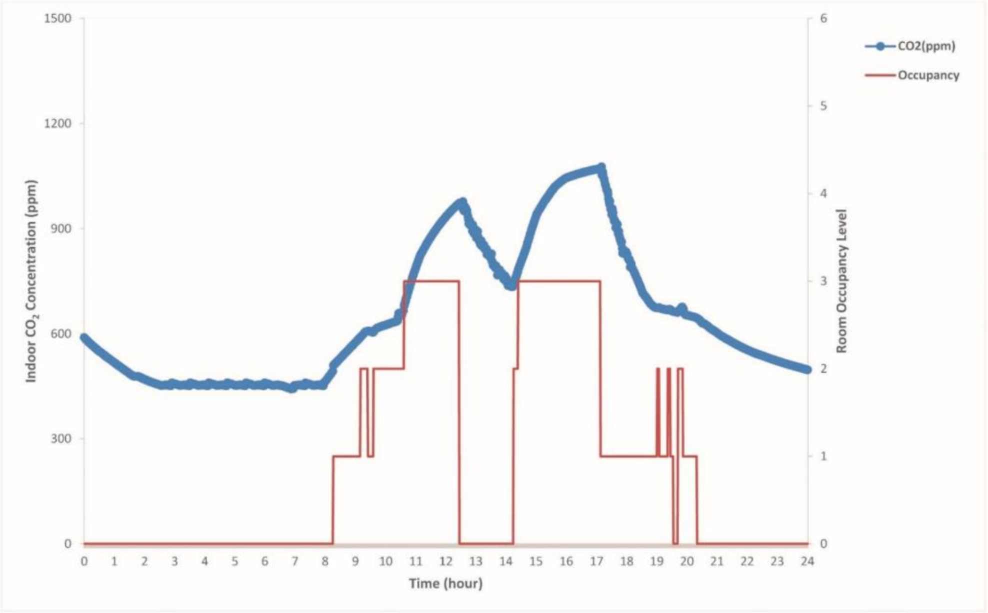

Figure 4.12 – CO$_2$ concentration and occupancy level over the day for control strategy 1.

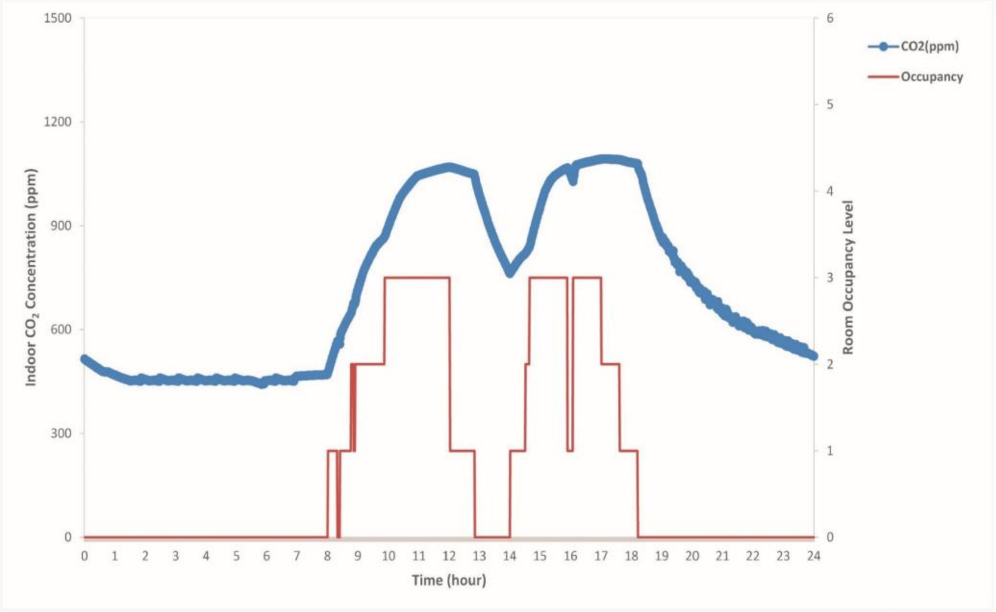

Figure 4.13 – CO$_2$ concentration and occupancy level over the day for control strategy 2.

- *Control strategy 3 (Double set-point ON-OFF CO$_2$-based):*

A maximum set-point (1000ppm) and a minimum set-point (500ppm) for indoor CO$_2$ concentration are defined. The ventilator switches on only when CO$_2$ concentration goes above the maximum set-point and it stops when the concentration reaches the minimum set-point or less. Figure 4.14 shows the strategy in a flowchart.

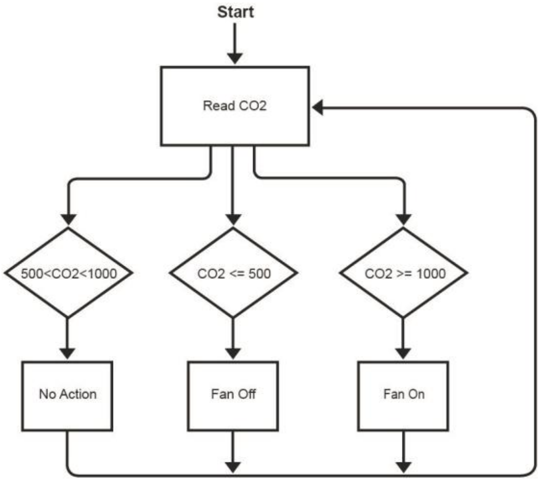

Figure 4.14 – Flowchart of ventilation control strategy 3.

- *Control strategy 4 (Leveling CO_2-based):*

Three set-points (1000ppm, 750ppm and 500ppm) for indoor CO_2 concentration are defined. For indoor concentration values over the minimum set-point, the ventilator operates on three different modes as shown in figure 4.15 and only stops when the concentration reaches the minimum set-point or less.

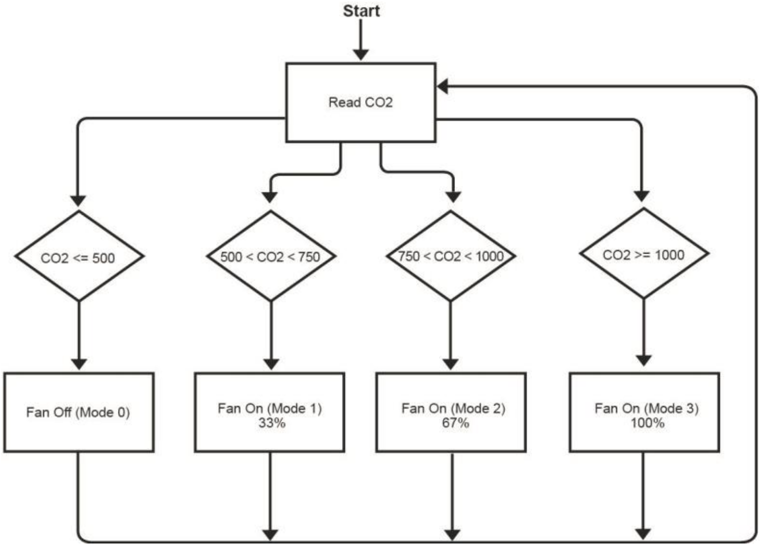

Figure 4.15 – Flowchart of ventilation control strategy 4.

- *Control strategy 5 (Modulating CO_2-based):*

A maximum set-point (1500ppm) and a minimum set-point (500ppm) for indoor CO_2 concentration are defined. For indoor concentration values greater than the maximum set-point, the ventilator works on maximum power and for those below the minimum set-point, it turns off. In this strategy, for indoor concentration values between the two setpoints the ventilator operates proportional to the difference of the maximum and minimum set-points. Figure 4.16 represents the flowchart of control strategy 5.

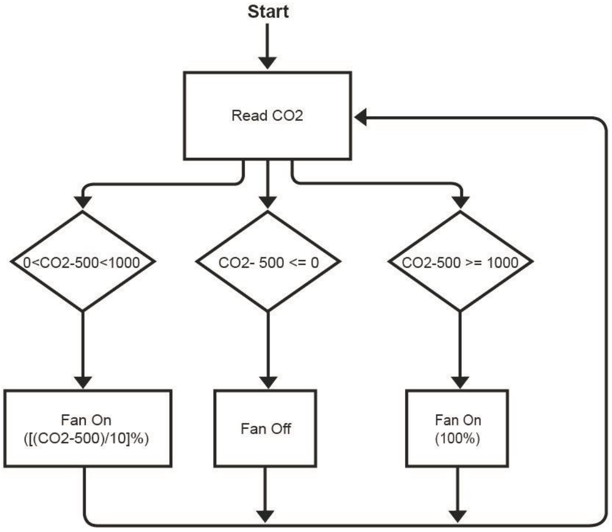

Figure 4.16 – Flowchart of ventilation control strategy 5.

These three strategies have been evaluated during the absence time in three nights, when all windows were closed. The difference with the first two strategies is that, instead of metabolic CO_2, a fire extinguisher has been used to inject CO_2 to a level around 2000 ppm before leaving the room. The concentration decay between 1500ppm and 500ppm has been selected for the evaluation of all the three strategies. Figures 4.17, 4.18 and 4.19 show the concentration decay, the linear regression and the fan operation of the control strategies 3, 4 and 5, respectively. Moreover, the results have been summarized in table 4.2.

Table 4.2 – Results from CO_2-based ventilation control strategies.

Control Strategy	**AER (h^{-1})**	**Room Average CO_2 Concentration (ppm)**	**Fan Energy Consumption (kWh/day)**	**Decay Period (hours)**
CS_3	0.61	791	0.04	≈ 4.6
CS_4	0.46	747	0.027	≈ 6.2
CS_5	0.31	716	0.016	≈ 8.2

Although these three ventilation strategies have been tested during the non-occupancy period, the results showed that the strategies are well implemented and completely functional. Moreover, the results indicated that linking the fan power to higher number of set-points or proportional to the real concentration level results in lower energy consumption.

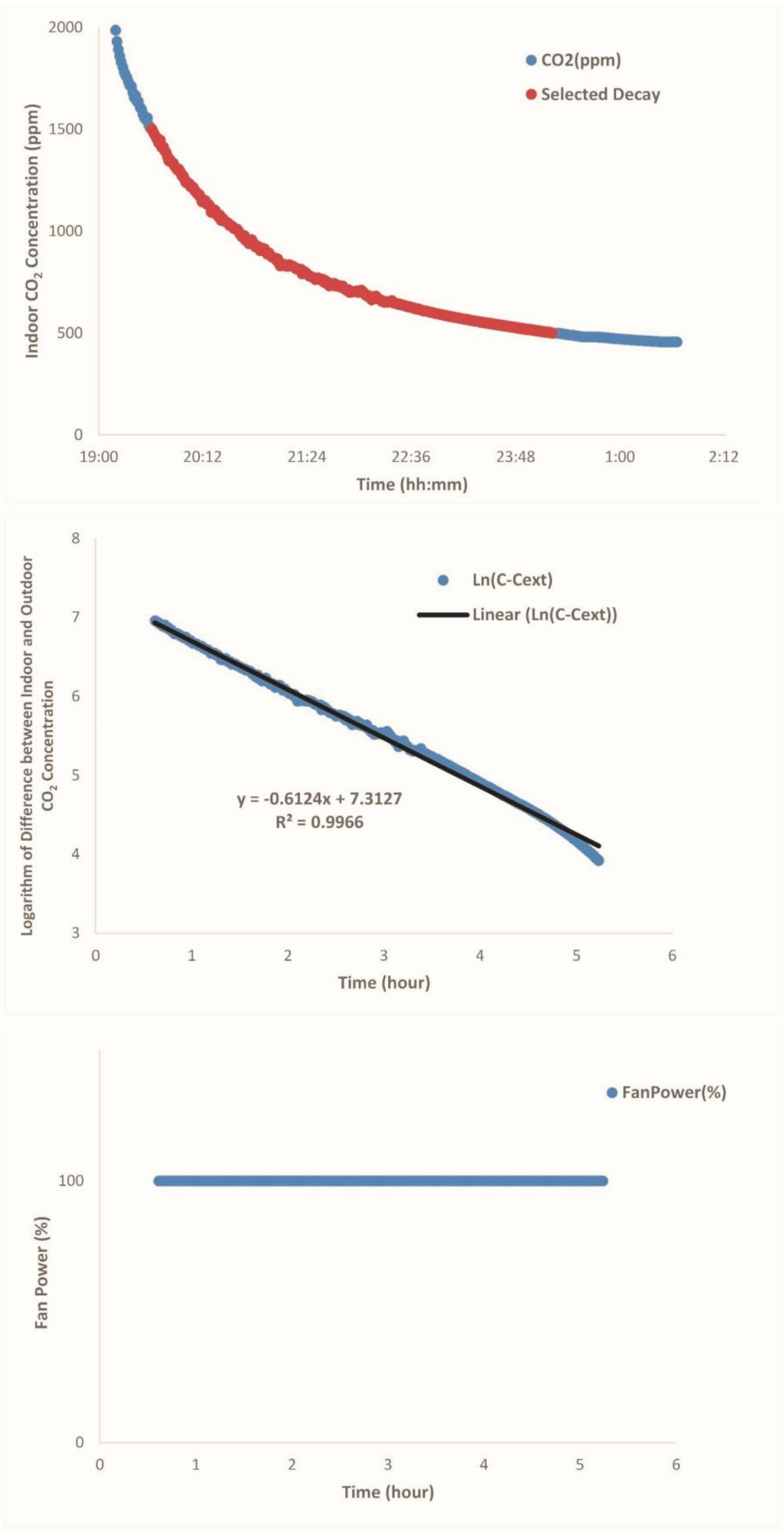

Figure 4.17 – CO_2 concentration decay, logarithm regression and fan power for control strategy 3.

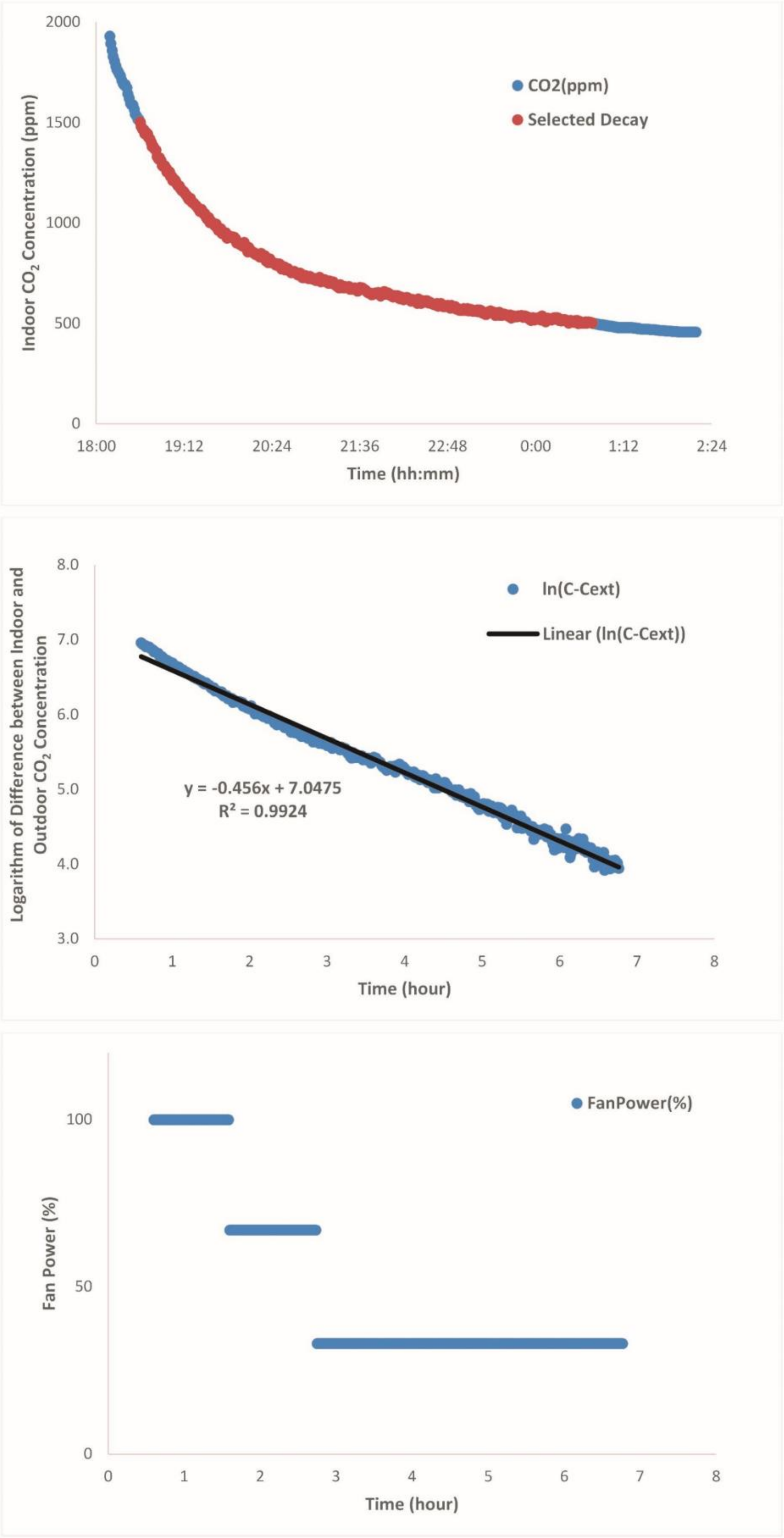

Figure 4.18 – CO_2 concentration decay, logarithm regression and fan power for control strategy 4.

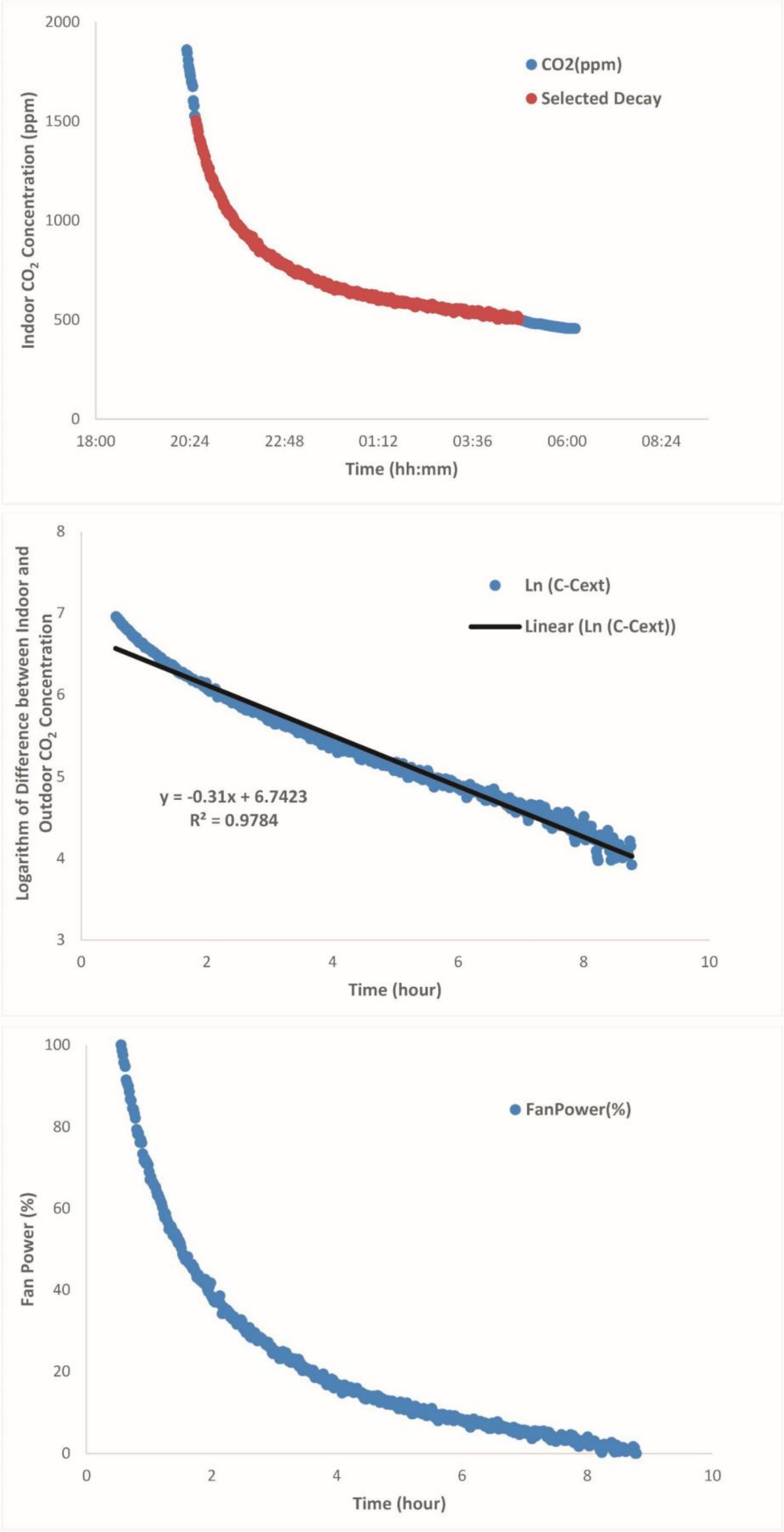

Figure 4.19 – CO_2 concentration decay, logarithm regression and fan power for control strategy 5.

4.4. Conclusion

The experimental studies of this research work on ventilation control strategies as well as its contribution to the Smart Window research project and the I2L showcase project have been presented in this chapter.

The results from the DCV strategies proved the influence of control and smartness in lowering energy consumption and providing good IAQ. The first two ventilation control strategy, occupancy period and occupancy level based strategies, showed the potential of simple sensor-based controls in reducing energy consumption comparing to for instance an always on method. The last three strategies, also showed the potential of CO_2-based ventilation control strategies in energy saving while providing good IAQ.

The experiments developed, implemented and analyzed in this chapter indicates the importance of using mechanical ventilation control strategies to avoid overventilation, energy saving, and avoid SBS by automatically ventilating the space when required.

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Chapter 5

SIMULATION OF DEMAND-CONTROLLED VENTILATION STRATEGIES

5.1. Introduction

As already mentioned in previous chapters, nowadays, people spend more time in indoor environment and the COVID-19 pandemic has even increased the amount of time spent indoors, therefore it is highly important to provide a good Indoor air quality (IAQ) for buildings occupants. Otherwise, it may cause serious health and productivity issues for the occupants. IAQ is closely linked with the ventilation rate. Although natural ventilation system does not consume energy for its operation, there is always uncertainty considering the forces that cause natural ventilation, namely, buoyancy and wind. Also natural ventilation system highly depends on unpredictable variables such as weather condition. Therefore, the need for an alternative and reliable ventilation system is essential to maintain a good IAQ. Unlike natural ventilation, the mechanical ventilation needs energy to run the mechanical means. Hence, it is important to develop control strategies to lower the ventilation energy use in buildings in order to meet the energy challenges established by the European Union.

In this chapter, a case study, the office room (already introduced in the previous chapter), has been simulated in order to test and evaluate the performance of several demand-controlled ventilation (DCV) strategies focusing on their energy consumption and ability to maintain a good IAQ. Rule-based DCV control strategies have been developed as one of the standard supervisory control models for ventilation system. In RBC, a threshold value or set-point is defined for certain parameters and the action is selected at the time when the condition falls into a specific criterion.

5.2. Case Study and Ventilation Control Strategies

The energy consumption and CO_2 generation due to mechanical ventilation have been assessed with a whole building energy simulation program, *EnergyPlus* [104]. This tool is one of the most-commonly used and versatile energy simulation programs and perfectly suitable for the analysis, having the ability to compute CO_2 generation, based on human occupancy, 3.82×10^{-8} m^3/s-W (obtained from ASHRAE Standard 62.1 at 0.0084 cfm/met/person (0.004 l/s/met/person) over the general adult population), predict its concentration evolution according to the generation rate or the decay caused either by external air infiltration or fresh air supply, while estimating the energy consumption involved in the complete process [105].

Building model has been drawn in OpenStudio, a plug-in for SketchUp (a design software tool to create 2D and 3D models), which converts the 3D building model into an Energy Plus file. After drawing the zone model in OpenStudio, envelope (materials and constructions) and internal parameters (schedules, occupation, infiltration and CO_2 generation rates, mechanical ventilation components and control strategies) has been specified in *EnergyPlus*. The model file for *EnergyPlus* is an American Standard Code for Information Interchange (ASCII) text file saved as Input Data File (IDF) that can be modified using any text editing tool. The methodology flowchart can be seen in the following figure (figure 5.1):

Figure 5.1 – Flowchart of the program utilization order.

The Indoor Live Lab (I2L), located in Mechanical Engineering Department (DEM) at University of Coimbra, with an area of 46.64 m^2 and 3 meters ceiling height, has been modeled to conduct simulations (see figure 5.2). Activity level of 1.2 met, average Du Bois body surface area of 1.8 m^2, infiltration rate of 0.2 h^{-1}, outdoor air flowrate of 24 m^3/h.person has been considered for the simulation of all ventilation strategies. Five main occupancy based (both period and level) as well as CO_2-based DCV strategies have been developed and analyzed in *EnergyPlus*. The ventilation strategies are as follows:

Figure 5.2 – Case study (I2L) - real aerial photo and modeled in SketchUp.

- *Control strategy 1 (Occupancy period based):*

In this strategy, regardless the number of occupants, a CAV fan that operates on maximum only during occupancy period has been considered. Figure 5.3 presents the flowchart of the first control strategy.

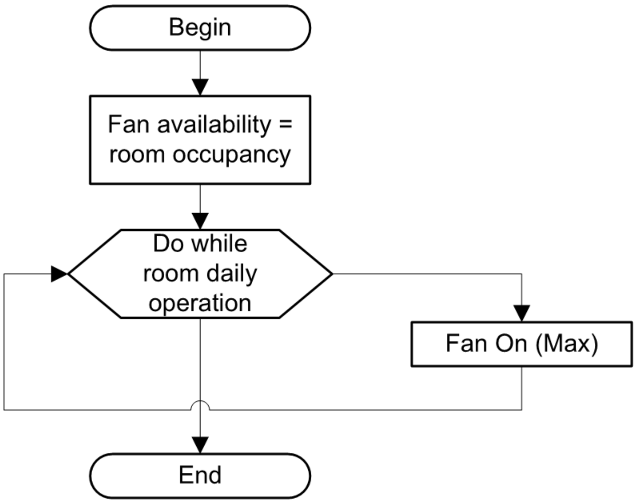

Figure 5.3 – Flowchart of ventilation control strategy 1.

- *Control strategy 2 (Occupancy level based):*

Unlike the previous strategy, this is an occupancy-based DCV in which a VAV fan is used to provide a specific amount of airflow rate per occupant. Figure 5.4 shows the flowchart of the second control strategy.

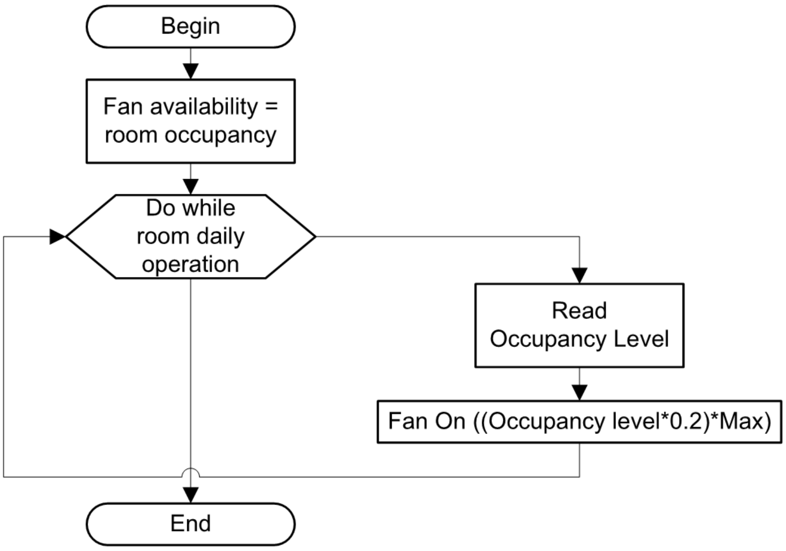

Figure 5.4 – Flowchart of ventilation control strategy 2.

- *Control strategy 3 (Single set-point CO_2-based):*

A maximum set-point for indoor CO_2 concentration (1000 ppm) is defined. In this case, a CAV fan operates only if the CO_2 concentration goes above the set-point and stops, when it is below the set-point during occupancy time. Figure 5.5 indicates the flowchart of the third control strategy.

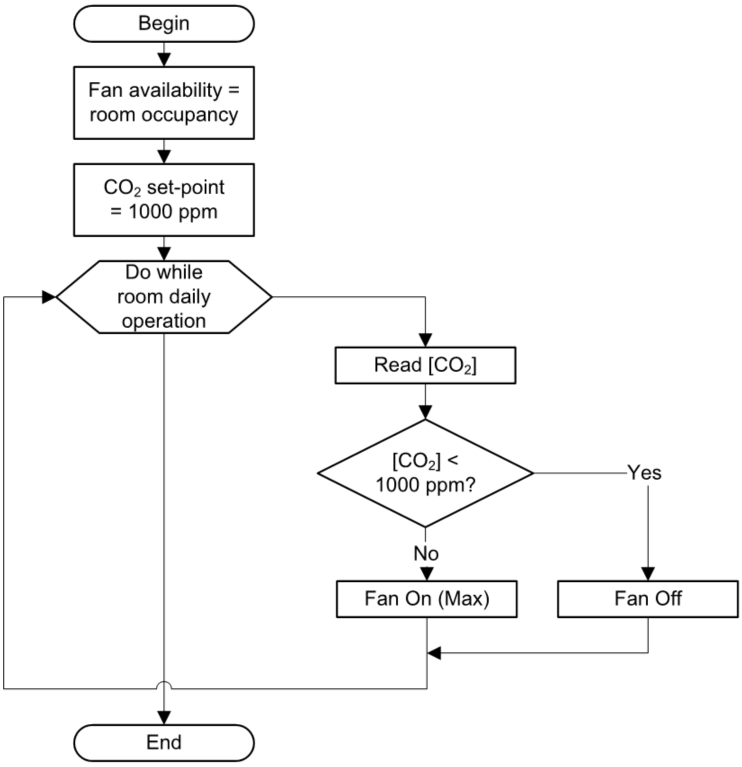

Figure 5.5 – Flowchart of ventilation control strategy 3.

- *Control strategy 4 (Double set-point CO_2-based):*

A maximum set-point for indoor CO_2 concentration (1000 ppm) is defined as well as a minimum set-point (500 ppm). Similar to the strategy 3, a CAV fan operates when the CO_2 concentration is above the maximum set-point and only stops when CO_2 concentration is below the minimum set-point during occupancy time. Figure 5.6 depicts the flowchart of the forth control strategy.

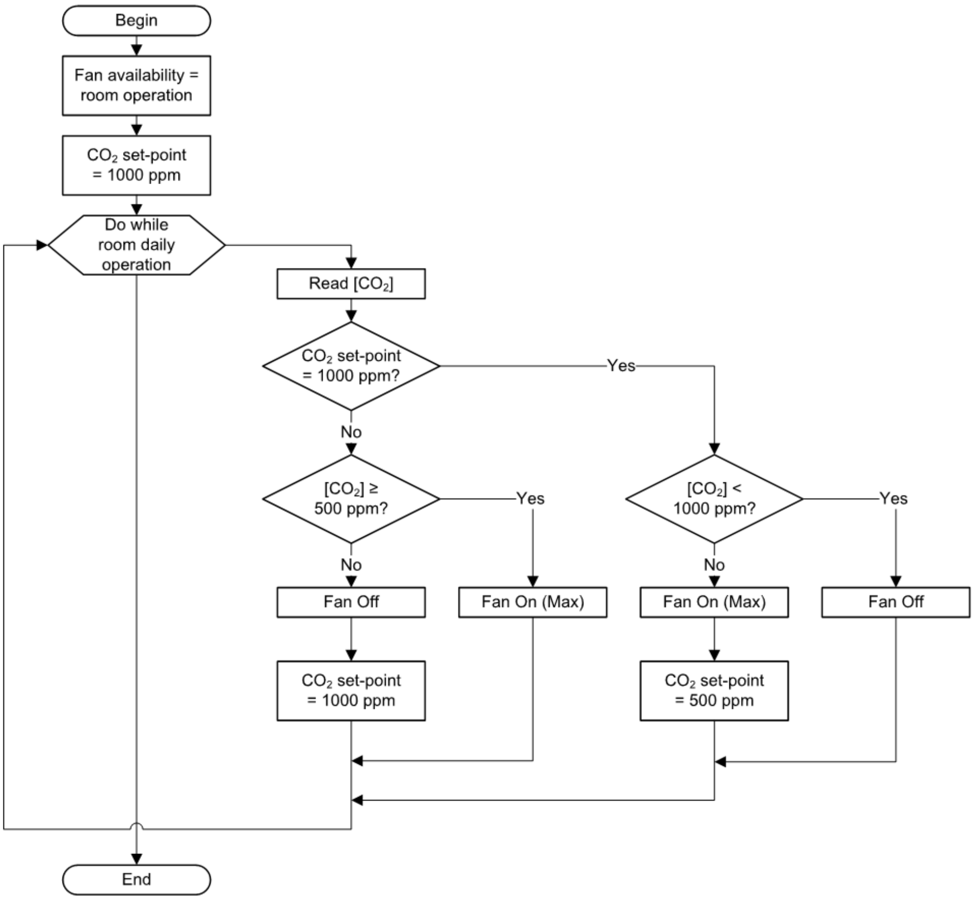

Figure 5.6 – Flowchart of ventilation control strategy 4.

- *Control strategy 5 (Double set-point CO_2-based proportional):*

A maximum set-point for indoor CO_2 concentration (1000 ppm) is defined as well as a minimum set-point (500 ppm). Unlike the previous strategy, a VAV fan operates when the CO_2 concentration is above the maximum set-point and the air flow rate decreases proportional to the decay of the CO_2 concentration. It only stops when CO_2 concentration is below the minimum set-point during occupancy time. Figure 5.7 illustrates the flowchart of the fifth control strategy.

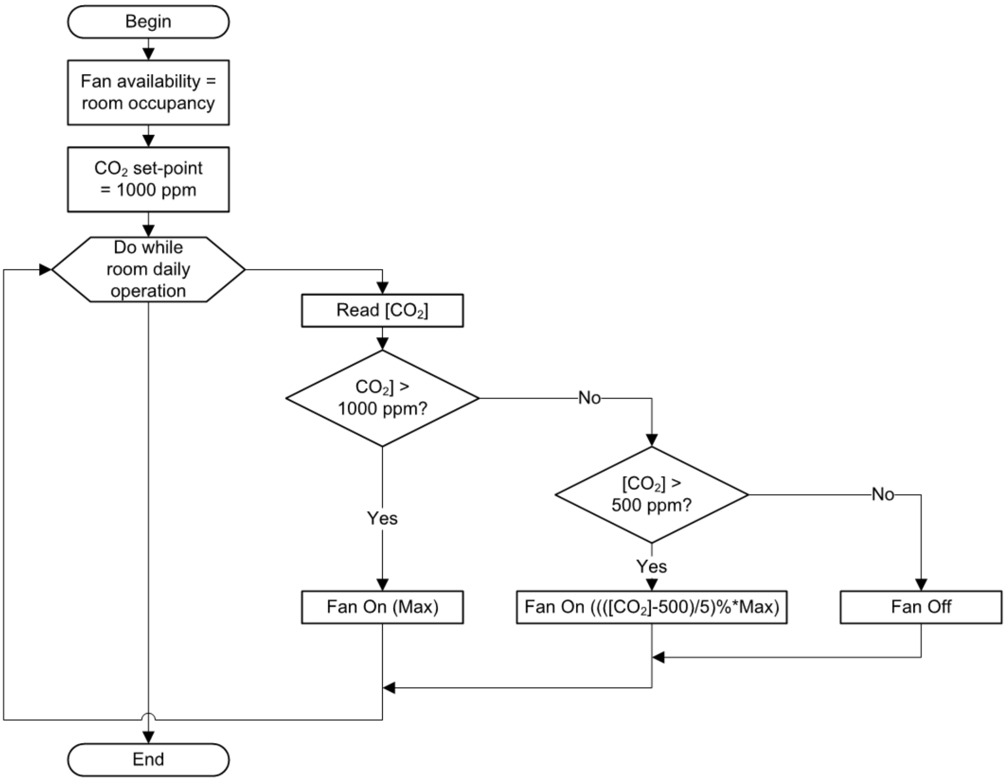

Figure 5.7 – Flowchart of ventilation control strategy 5.

These strategies can be used in spaces where occupants have difficulties in employing natural ventilation. Outdoor pollution and noise, as well as security and privacy purposes are the main reasons to employ solely mechanical ventilation.

In the simulation software, the CO_2 set-point is set through the *Contaminant Controller* in Zone Control. The *System Node CO_2 Concentration* variable measures and reports the average CO_2 concentration, in parts per million (ppm), in the Zone Air Node and the *People Occupant Count* variable counts and reports the number of occupants in People for the questioned time-step. Moreover, the *Fan Air Mass Flow Rate* variable actuates over the Fan component based on the report receives from the sensors. The abovementioned ventilation control strategies have been specified in *EnergyPlus* as follows:

- ***Control strategy 1 (Occupancy period based):***

```
IF (VERIFY_OCC > 0),
        SET FAN_OPR = FAN_MAX,
ELSE,
        SET FAN_OPR = 0.0,
ENDIF;
```

- ***Control strategy 2 (Occupancy level based):***

```
IF (VERIFY_OCC > 0),
        SET FAN_OPR = FAN_MAX*(VERIFY_OCC*0.2);
```

```
ELSE,
        SET FAN_OPR = 0.0,
ENDIF;
```

- ***Control strategy 3 (Single set-point CO*$_2$*-based):***

```
IF (CO2_CONC > 1000),
        SET FAN_OPR = FAN_MAX,
ELSE,
        SET FAN_OPR = 0.0,
ENDIF;
```

- ***Control strategy 4 (Double set-point CO*$_2$*-based):***

```
IF (CO2_CONC > 1000),
        SET FAN_OPR = FAN_MAX,
DO WHILE (CO2_CONC >= 500),
ELSE,
        SET FAN_OPR = 0.0,
END DO,
ENDIF;
```

- ***Control strategy 5 (Double set-point CO*$_2$*-based proportional):***

```
IF (CO2_CONC > 1000),
        SET FAN_OPR = FAN_MAX,
ELSEIF (CO2_CONC > 500),
        SET FAN_OPR = FAN_MAX*((CO2_CONC - 500)/5.0)/100.0,
ELSE,
        SET FAN_OPR = 0.0,
ENDIF;
```

Where “VERIFY_OCC” is the occupancy level, “FAN_OPR” is the fan operation power, “FAN_MAX” is the fan maximum power and “CO_2_CONC” is the indoor CO_2 concentration.

5.3. Simulation Results

In this section two articles communicated to international journals and conference have been presented. In the first article, the ventilation control strategies 1 to 4 have been simulated and analyzed and in the second one the ventilation control strategy 5 has been simulated and compared with those from the first article.

5.3.1. Paper IV: Simulation of Occupancy and CO_2-Based Demand-Controlled Mechanical Ventilation Strategies in an Office Room Using EnergyPlus

Four DCV strategies based on occupancy period, occupancy level and indoor concentration of CO_2 have been simulated and studied using the building simulation software, *EnergyPlus*. The collection of DCV strategies have been selected to prepare an article communicated in International Scientific Conference Environmental and Climate Technologies, which has been later published in Energy Procedia Elsevier Journal in 2017, titled "Simulation of Occupancy and CO_2-based Demand-controlled Mechanical Ventilation Strategies in an Office Room Using *EnergyPlus*".

Author Contributions: Behrang Chenari as the main author, has conducted the entire research, prepared and carried out the simulation, gathered and collected data, and wrote the papers; Francisco B. Lamas helped with preparing the simulation condition in EnergyPlus, Adelio R. Gaspar and M. Gameiro da Silva reviewed the contents and contributed to enhancing their quality.

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Simulation of occupancy and CO_2-based demand-controlled mechanical ventilation strategies in an office room using *EnergyPlus*

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Abstract

Buildings are responsible for a large sharing of energy consumption worldwide. Among all energy services in buildings, heating, ventilation and air conditioning systems not only account for a significant part of energy consumption but they are also highly influential on indoor climate and occupants' satisfaction in consequence. In this paper, four demand-controlled ventilation strategies based on occupancy schedule period, occupancy level and indoor concentration of CO_2 in an office room have been studied. The indoor air quality as well as the energy consumption levels associated to each demand-controlled ventilation strategy were assessed through simulations performed using *EnergyPlus*. The results showed the best suited ventilation strategies for the office room that can provide acceptable level of indoor air quality with the least energy use. Furthermore, three sensitivity analyses were performed in order to assess the influence of changing different criteria on the energy consumption and indoor air quality.

Peer-review under responsibility of the scientific committee of the International Scientific Conference "Environmental and Climate Technologies".

Keywords: demand-controlled ventilation; ventilation strategies; indoor air quality; energy consumption

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1. Introduction

The role of Heating, Ventilation and Air-Conditioning (HVAC) systems is to provide favorable indoor climate condition for occupants in buildings, regarding the thermal environment and the indoor air quality (IAQ). HVAC

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accounts for almost 40 % of energy use in buildings in which ventilation plays a significant role [1]. Ventilation also interacts with health, productivity and comfort of the occupants [2]. Many energy-efficient and sustainable ventilation methods such as natural ventilation, hybrid ventilation, ventilation control strategies and Demand-Controlled Ventilation (DCV) have been reviewed by [3]. In DCV, a technology for energy saving in HVAC systems [4], the fan velocity is regulated according to the demanded fresh air flow rate. So that, DCV improves the energy-efficiency by supplying fresh air to and/or extracting stale air from the space only in the right time and the right amount. It results to reduce the cost and prevent energy waste while provides acceptable IAQ. Various studies [5–10] have shown the potential of DCV in saving energy in buildings.

In this paper, four Sensor-based Mechanical Demand-Controlled Ventilation (SBMDCV) strategies have been defined and simulated to assess the energy consumption and IAQ associated to each strategy. Moreover, three sensitivity analyses were performed to assess the influence of changing different criteria on the final results. SBMDCV strategies are based on occupancy schedule period, occupancy level and CO2 concentration in the office. This research has been developed under framework of Smart Window project at university of Coimbra [11, 12]. One of the tasks of this project is to develop and test DCV strategies for mechanical ventilation. These SBMDCV strategies can be used in spaces where occupants have difficulties in employing natural ventilation. Outdoor pollution and noise as well as security and privacy purposes are the main reasons to employ mechanical ventilation.

2. Material and methods

2.1. Case study overview

The Indoor Live Lab (I2L) [13], located in Mechanical Engineering Department (DEM) at university of Coimbra, with an area of 46.64 m^2 and 3 meters ceiling height, has been chosen as the test room to conduct simulations. The I2L is equipped with several instruments and sensors which monitor Indoor Environmental Quality (IEQ) indices. The I2L has been modelled in *OpenStudio*, a plug-in for *SketchUp* (a design software tool to create 2D and 3D models), which converts the 3D building model into an *EnergyPlus* file. There are five permanent and one guest working places in this office. Five occupants were considered as the maximum occupancy level in the room. Moreover, the activity level of occupants was assumed 1.2 met with an average Du Bois body surface area of 1.8 m^2. The windows and door are assumed to be closed during all simulations period. An infiltration rate of 0.2 h^{-1}, obtained from a CO_2 decay test, was considered for the simulations.

2.2. Ventilation systems

Constant Air Volume (CAV) fans as well as Variable Air Volume (VAV) fans with different airflow rates have been considered during simulation of ventilation strategies. The fans power is obtained from the following equation:

$$P = \frac{Q_{fan} \cdot \Delta p}{\eta} \tag{1}$$

where

P	represents the fan power in watts;
Q_{fan}	represents the fan airflow rate in m^3/s;
Δp	represents the fan pressure rise in Pa (100 Pa is assumed);
η	represents the fan efficiency (0.7 is assumed).

2.3. Ventilation strategies

Four occupancy and CO_2-based ventilation strategies have been defined and simulated:

- Control strategy 1 (Occupancy period based): In this strategy, regardless the number of occupants, a CAV fan is used that operates only during occupancy period;

- Control strategy 2 (Occupancy level based): Unlike the previous strategy, this is an occupancy-based DCV in which a VAV fan is used to provide a specific amount of airflow rate per occupant;
- Control strategy 3 (Single setpoint CO_2-based): A maximum setpoint for indoor CO_2 concentration (1000 ppm) is defined. In this case, a CAV fan that operates only if the CO_2 concentration goes above the setpoint and stops, when it is below the setpoint, is used;
- Control strategy 4 (Double setpoint CO_2-based): A maximum setpoint for indoor CO_2 concentration (1000 ppm) is defined as well as a minimum setpoint (500 ppm). Similar to the strategy 3, a CAV fan that operates when the CO_2 concentration is above the maximum setpoint is used. The fan only stops when CO_2 is below the minimum setpoint during occupancy time.

Fig. 1 demonstrates the flowcharts of the simulated ventilation strategies. It should also be mentioned that, all strategies have been simulated based on the main occupancy schedule represented in Table 1.

Table 1. Main occupancy schedule.

Weekdays occupancy schedule									
Time	00–09	09–10	10–13	13–14	14–18	18–19	19–20	20–21	21–24
Occupancy	0	2	5	0	5	3	2	1	0

2.4. Simulation software

After drawing the zone model in *OpenStudio*, the envelope (materials and constructions) and internal parameters (schedules, occupation, infiltration and CO_2 generation rates, mechanical ventilation components and control) were specified in *EnergyPlus* simulation software. *EnergyPlus* is one of the most-commonly used and versatile energy simulation programs [14] and perfectly suitable for the analysis [15], having the ability to compute CO_2 generation (based on human occupancy, 3.82E-8 m^3/s-W), predict its concentration evolution according to the generation rate or the decay caused either by external air infiltration or fresh air supply, while estimating the energy consumption involved in the complete process.

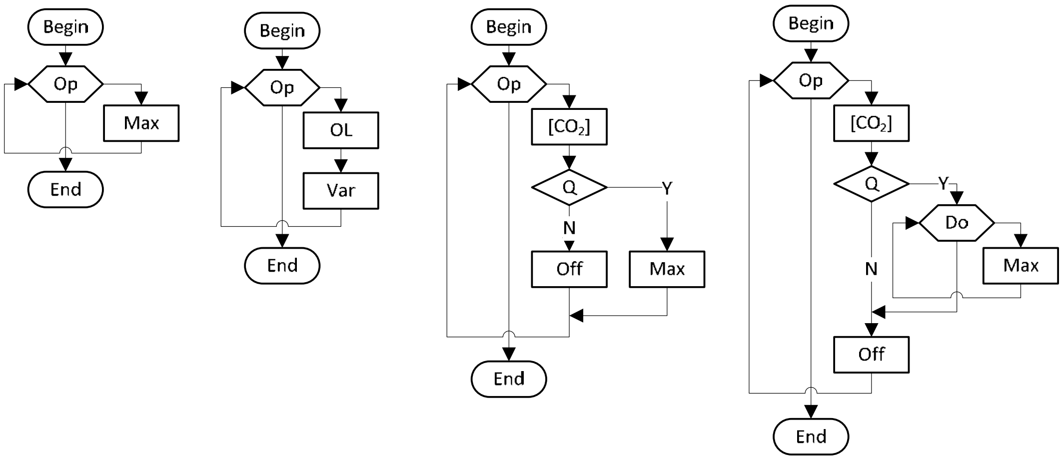

Fig. 1. Ventilation strategies flowcharts.

3. Simulation results and discussion

In this section the results from each strategy is being discussed. Moreover, comparisons between strategies considering the IAQ and energy consumption have been performed. Fig. 2 represents the zone CO_2 concentration during the day for all ventilation strategies.

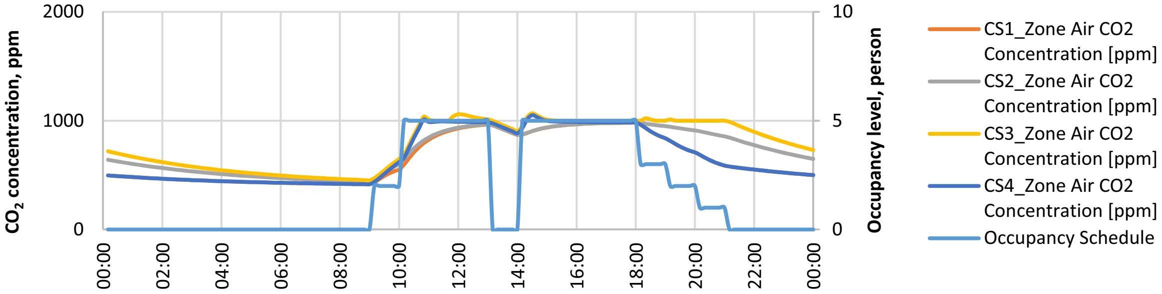

Fig. 2. Variation of CO_2 in the room associated to base ventilation strategies.

The chart above shows that using CS3, the occupants will be exposed to higher CO_2 concentration comparing with other strategies. Considering CS1 and CS2, the concentration in the room never reaches 1000 ppm in both of the strategies, while CS1 consumes 28 % more energy than CS2. CS4 shows a better performance in maintaining the room concentration below 1000 ppm comparing with CS3 but seems to have some unnecessary over ventilation during low density occupancy. Table 2 presents the results obtained from simulation such as maximum and average CO_2 concentration in the test office and the fan energy consumption associated to each strategy.

Table 2. The results from base ventilation strategies.

Control Strategy	Infiltration Rate, h^{-1}	Outdoor Airflow Rate, m^3/h.person	Zone Air Maximum CO_2 Concentration, ppm	Zone Air Average CO_2 Concentration, ppm	Fan Energy Consumption, kWh/day
CS1	0.2	24	981	833	0.0523
CS2	0.2	24	981	885	0.0408
CS3	0.2	24	1068	957	0.0387
CS4	0.2	24	1051	874	0.0419

The results from CS1 and CS2 presents the priority of real time occupancy-based strategy to the scheduled one with 22 % less energy consumption and providing almost the same IAQ level. Moreover, Fig. 3 presents a more practical view of these results in which CS3 can be indicated as the best suited strategy that provides acceptable IAQ for the occupants with lowest energy use.

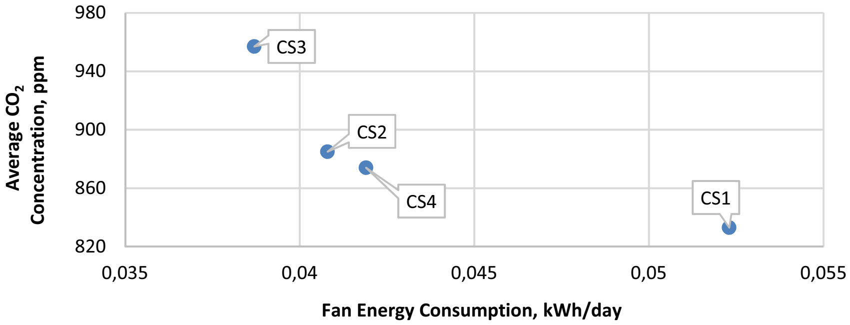

Fig. 3. Room average CO_2 Level and fan energy consumption for base ventilation strategies.

3.1. Sensitivity analyses

The first sensitivity analysis (SA1) considered in this research was changing the outdoor airflow rate from 24 to 20 m^3/h.person. All other parameters were maintained constant. This is to see how the energy consumption and IAQ are responding to these changes. Fig. 4 shows the variation of zone CO_2 concentration during the day. The concentrations in all strategies are slightly higher than those for the base situation. Although the time that occupants are exposed to concentrations higher than 1000 ppm is increased, still is not high enough to have negative influence on the occupants' comfort and productivity.

Table 3 shows the energy consumption, maximum and average CO_2 concentration level associated to each strategy as well as the energy savings and the IAQ drop. IAQ drop is the comparison between the average CO_2 concentration in sensitivity analysis strategies and the base strategies. The lowest IAQ drop and highest energy saving belong to CS3. In other strategies the IAQ drop is 7 % while the energy saving varies between 15–17 %.

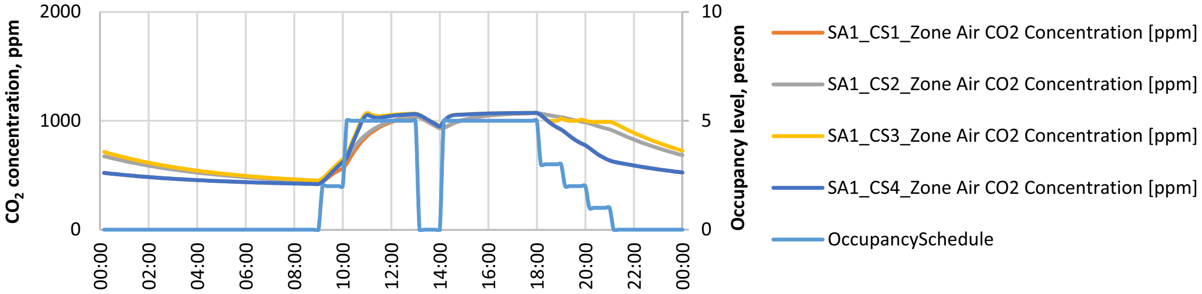

Fig. 4. Variation of CO_2 in the room associated to ventilation strategies after applying SA1.

Table 1. The results from ventilation strategies after applying SA1.

Control Strategy	Infiltration Rate, h^{-1}	Outdoor Airflow Rate, m^3/h.person	Zone Air Maximum CO_2 Concentration, ppm	Zone Air Average CO_2 Concentration, ppm	Fan Energy Consumption, kWh/day	Energy Saving Comparing with base strategies, %	IAQ Drop, %
SA1_CS1	0.2	20	1070	895	0.0435	17	7
SA1_CS2	0.2	20	1070	949	0.0340	17	7
SA1_CS3	0.2	20	1073	984	0.0310	20	3
SA1_CS4	0.2	20	1073	935	0.0356	15	7

In the second sensitivity analysis (SA2), besides changing the outdoor air flow from 24 to 20 m3/h.person, the infiltration rate was also modified, from 0.2 h^{-1} to 0.3 h^{-1}. All other parameters were maintained constant. Fig. 5 shows the variation of zone CO_2 concentration during the day which does not indicate a notable change in IAQ level comparing to the base strategies.

Table 4 shows the energy consumption, maximum and average CO_2 concentration level associated to each strategy as well as the energy savings and IAQ drop. SA2_CS2 and SA2_CS3 showed no changes in average CO_2 concentration while they had 17 % and 25 % lower energy consumption, respectively. The other two strategies also showed Energy savings up to 20 % and their IAQ drops are actually low and can be neglected. The results of SA2 revealed that increasing the infiltration rate will save fan energy while there would not be a noticeable change in IAQ.

Table 2. The results from ventilation strategies after applying SA2.

Control Strategy	Infiltration Rate, h^{-1}	Outdoor Airflow Rate, m^3/h.person	Zone Air Maximum CO_2 Concentration, ppm	Zone Air Average CO_2 Concentration, ppm	Fan Energy Consumption, kWh/day	Energy Saving Comparing with base strategies, %	IAQ Drop, %
SA2_CS1	0.3	20	1004	849	0.0435	17	2
SA2_CS2	0.3	20	1004	886	0.0340	17	0
SA2_CS3	0.3	20	1070	950	0.0290	25	0
SA2_CS4	0.3	20	1065	894	0.0336	20	2

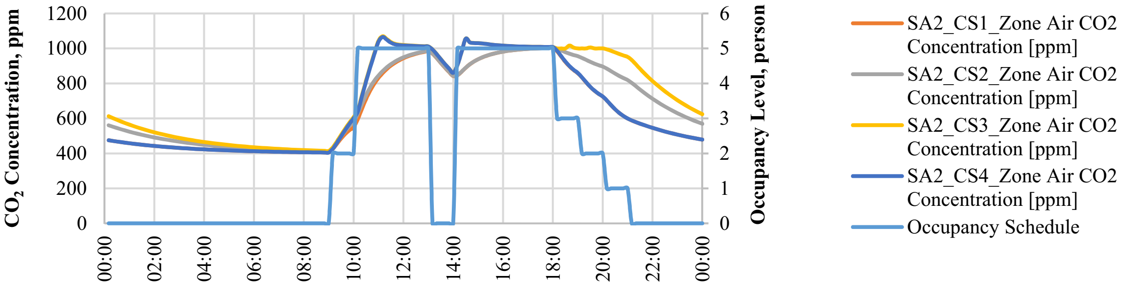

Fig. 5. Variation of CO_2 in the room associated to ventilation strategies after applying SA2.

Given to the CO_2 concentration graphs, there seemed to be some over ventilation during the low occupation density period in the evening. In the third Sensitivity analysis (SA3), the minimum setpoint in control strategy 4 has been modified to 800 pmm, to see how the results change with this modification.

Fig. 6 shows the CO_2 concentration and fan airflow rate in the zone during the day. As mentioned before, the over ventilation between 19:00 and 21:00 is observed. In the SA3_CS4, the fan stops almost two hours earlier than the CS4.

Moreover, table 5 exhibits the energy consumption and CO_2 concentration level associated to each strategy. The results show that increasing the minimum setpoint from 500 to 800 ppm leads to 15 % of energy saving and the daily average CO_2 concentration only increased 4 %. Also, by increasing the minimum setpoint to 900 ppm, the energy saving will increase up to 20 %.

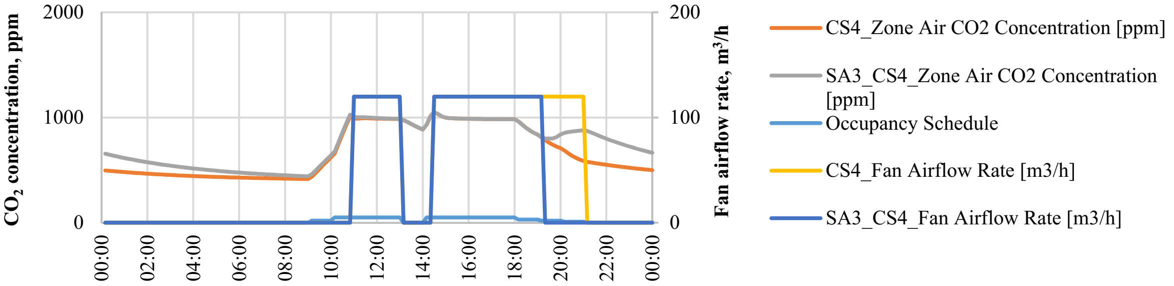

Fig. 6. Variation of CO_2 and fan airflow rate associated to CS4 before and after applying SA3.

Table 3. Comparison of the results from CS4 before and after applying SA3.

Control Strategy	Infiltration Rate, h^{-1}	Outdoor Airflow Rate, m^3/h.person	Zone Air Maximum CO_2 Concentration, ppm	Zone Air Average CO_2 Concentration, ppm	Fan Energy Consumption, kWh/day	Energy Saving, %	IAQ Drop, %
CS4	0.2	24	1051	874	0.0420	–	–
SA3_CS4	0.2	24	1052	906	0.0357	15	4

4. Conclusions

In this paper, four ventilation strategies have been defined based on occupancy schedule period, occupancy level and indoor concentration of CO_2 in an office room. The IAQ as well as the energy consumption levels associated to each strategy were evaluated through simulations performed using *EnergyPlus*. Three sensitivity analyses were also performed in order to assess the influence of different parameters on the energy consumption and IAQ. The main findings of the present study can be listed as following:

- A primary energy saving of 22 % was achieved from controlling the fan airflow rate based on the number of occupants instead of a fixed flow rate during occupancy period, while the IAQ level is kept acceptable;
- By decreasing the fan airflow rate per occupant, SA1_CS2 and SA1_CS4 showed the best integrated IAQ and energy performance, while SA1_CS3 presented the lowest consumption accompanying with an average CO_2 concentration, slightly over the setpoint, that could still be acceptable referring to some IAQ standards (e.g. Portuguese standard: Portaria n.º 353-A/2013 [16]);
- The third sensitivity analysis showed the importance of infiltration rate in providing acceptable IAQ with lower fan energy use (regardless the unforeseen influences on thermal comfort);
- Increasing the minimum setpoint for indoor CO_2 Concentration, made SA3_CS4 the best suited control strategy among all strategies in terms of both energy consumption and IAQ.

Acknowledgements

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References

[1] Laverge J, Van Den Bossche N, Heijmans N, Janssens A. Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. Build. Environ. 2011;46(7):1497–1503.

[2] Richieri F, Michel P, El Mankibi M. Occupancy Calculation for the Control of Mechanical Ventilation. Proceeding of the 4th European conference on energy performance & indoor climate in buildings, France, Lyon, 29 November – 1 December, 2005.

[3] Chenari B, Carrilho JD, Gameiro M. Towards sustainable , energy-efficient and healthy ventilation strategies in buildings : A review. Renew. Sustain. Energy Rev. 2016;59:1426–1447.

[4] Lawrence T. Demand-Controlled Ventilation and Sustainability. ASHRAE J. 2004;December:117–119.

[5] Lu T, Lu X, Viljanen M. A novel and dynamic demand-controlled ventilation strategy for CO2 control and energy saving in buildings. Energy Build. 2011;43(9):2499–2508.

[6] Pavlovas V. Demand controlled ventilation A case study for existing Swedish multifamily buildings. Energy Build. 2004;36(10):1029–1034.

[7] Mysen M, Berntsen S, Nafstad P, Schild PG. Occupancy density and benefits of demand-controlled ventilation in Norwegian primary schools. Energy Build. 2005;37:1234–1240.

[8] Ng MO, Qu M, Zheng P, Li Z, Hang Y. CO2-based demand controlled ventilation under new ASHRAE Standard 62.1-2010: A case study for a gymnasium of an elementary school at West Lafayette, Indiana. Energy Build. 2011;43(11):3216–3225.

[9] Chao CYH, Hu JS. Development of a dual-mode demand control ventilation strategy for indoor air quality control and energy saving. Build. Environ. 2004;39:385–397.

[10] El Mankibi M. Indoor air quality control in case of scheduled or intermittent occupancy based building: Development of a scale model. Build. Environ. 2009;44:7:1356–1361.

[11] Chenari B, Carrilho D, Botte G, Gameiro M. Towards Energy-Efficient Ventilation in Buildings : Development of the Smart Window Ventilation System. J. Clean Energy Technol. 2016;4(6):457–461.

[12] Pereira LD, Carrilho JD, Brito NS, Gomes MR, Mateus M, Chenari B, Gameiro M. Teaching and researching the indoor environment: From traditional experimental techniques towards web-enabled practices. Sustain. Cities Soc. 2016;26:543–554.

[13] Carrilho JD, Chenari B, Gomes MR, Botte G, Mateus M, Gameiro da Silva M. Development of a live laboratory for research and technology demonstration in indoor environment assessment and control. Proceedings of the 2nd EfS Conference, Portugal, Coimbra, 14–15 May, 2015.

[14] Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Huang YJ, Pedersen CO, Strand RK, Liesen RJ, Fisher DE, Witte MJ, Glazer J. EnergyPlus : creating a new-generation building energy simulation program. Energy Build. 2001;33:319–331.

[15] Crawley DB, Hand JW, Kummert M, Griffith BT. Contrasting the capabilities of building energy performance simulation programs. Build. Environ. 2008;43:661–673.

[16] Portaria n.o 353-A/2013, de 4 de dezembro. DR 1a série, no 235:6644-(2)-(9). Regulamento de desempenho energético dos edifícios de comércio e serviços (recs): requisitos de ventilação e qualidade do ar interior.

5.3.2. Paper V: Development of A New CO_2-Based Demand-Controlled Ventilation Strategy Using EnergyPlus

The fifth DCV strategy has been simulated and studied using the building simulation software, *EnergyPlus*. A supplementary research has been carried to compare the results from the new strategy with those already presented in the previous article. The outcome from this research has been communicated in Energy for Sustainability International Conference 2017, titled “Development of A New CO_2-based Demand-controlled Ventilation Strategy Using *EnergyPlus*”.

Author Contributions: Behrang Chenari as the main author, has conducted the research, prepared and carried out the simulation, gathered and collected data, and wrote the papers; Francisco B. Lamas helped with preparing the simulation condition in EnergyPlus, Adelio R. Gaspar and M. Gameiro da Silva reviewed the contents and contributed to enhancing their quality.

Energy for Sustainability International Conference 2017
Designing Cities & Communities for the Future
Funchal, 8-10 February, 2017

DEVELOPMENT OF A NEW CO_2-BASED DEMAND-CONTROLLED VENTILATION STRATEGY USING ENERGYPLUS

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Keywords: Demand-controlled ventilation, Ventilation strategies, Indoor air quality, Energy consumption

Abstract *A significant amount of energy is being used by ventilation and air conditioning systems to maintain the indoor environmental condition in a satisfactory and comfortable level. Many buildings, either new or existing (throughout their renovation process) are subjected to energy efficiency requirements but these must not be in the expenses of indoor environmental conditions. For instance, indoor air quality (IAQ) has to be considered while improving energy efficiency, otherwise occupants might be exposed to inappropriate indoor environment.*

Demand-controlled ventilation (DCV) is a method that provides comfortable IAQ level with lowest energy use. In this paper, the main objective is developing a new CO_2-based DCV strategy and simulating it using EnergyPlus. The IAQ and energy consumption associated to this strategy have been compared with the results of CO_2-based DCV strategies previously developed by the same authors in another article. The comparison shows that the new strategy performs better, both in energy use and IAQ. The recorded energy savings ranged between 6-14% comparing with the previously developed strategies while IAQ slightly improved.

1. INTRODUCTION

A significant amount of energy is being used by ventilation and air conditioning systems to maintain the indoor environmental condition in a satisfactory and comfortable level. As mentioned in [1], nearly 40% of energy use in buildings are consumed by HVAC systems. Nowadays, both new and existing buildings (throughout their renovation process) are subjected to energy efficiency requirements but these must not be in the expenses of indoor environmental conditions [2]. For instance, indoor air quality (IAQ) has to be wisely considered while improving energy efficiency, otherwise occupants might be exposed to inappropriate indoor environment which might cause health issues. Reviewing many energy-efficient and sustainable ventilation methods, reference [2], noted that integrating control strategies to ventilation systems leads to considerable amount of energy savings. Moreover, it is mentioned that DCV prevents energy waste during low or zero occupancy time because DCV supplies fresh air to and/or extracting stale air from the space only when it is required. For places such as classrooms, auditoriums, offices with variable occupancy level DCV is an appropriate method. Several research studies such as [3], [4], [5] have studied the CO_2-based DCV and stated its noteworthy energy saving potential.

This work comes in the sequence of a previously published article from the same authors [6] in which four occupancy and CO_2-based ventilation control strategies have been defined and simulated to assess the energy consumption and IAQ associated to each strategy. In this paper, a new CO_2-based DCV strategy has been developed and simulated in EnergyPlus in order to compare the results with the results of previously developed CO_2-based DCV strategies. This research has been developed under framework of Smart Window project at the University of Coimbra [7]. One of the tasks of this project is to develop and test DCV strategies for mechanical ventilation. These strategies can be used in spaces where occupants have difficulties in employing natural ventilation. Outdoor pollution and noise, as well as security and privacy purposes are the main reasons to employ solely mechanical ventilation.

2. MATERIAL AND METHOD

2.1. Case study overview

The Indoor Live Lab (I2L) [8], located in Mechanical Engineering Department (DEM) at University of Coimbra, with an area of 46.64 m^2 and 3 meters ceiling height, has been chosen as the test room to conduct simulations. Activity level of 1.2 met, average Du Bois body surface area of 1.8 m^2, infiltration rate of 0.2 h^{-1}, outdoor air flowrate of 24 m^3/h.person and main occupancy schedule, presented in table 1, has been considered for the simulation of all ventilation strategies.

Table 1. Main occupancy schedule

Weekdays Occupancy Schedule									
Time	00-09	09-10	10-13	13-14	14-18	18-19	19-20	20-21	21-24
Occupancy	0	2	5	0	5	3	2	1	0

2.2. Ventilation systems

Constant Air Volume (CAV) fans as well as Variable Air Volume (VAV) fans with different airflow rates have been considered during simulation of ventilation strategies. The fans power is obtained from the following equation: $P = (Q_{fan} \, . \, \Delta p)/\eta$ in which P represents the fan power in [Watts]; Q_{fan} represents the fan airflow rate in [m^3/s]; Δp represents the fan pressure rise in [Pa] (100 Pa is assumed); η represents the fan efficiency (0.7 is assumed).

2.3. Ventilation strategies

Figure 1 presents the new CO_2-based DCV as well as the two previously developed. In the new strategy the VAV fan operates proportional to the CO_2 concentration level and the minimum and maximum setpoints. In the other strategies, in single setpoint, a CAV fan operates only if the CO_2 concentration goes above the setpoint and stops, when it is below the setpoint and in double setpoint, the CAV fan operates when the CO_2 concentration goes above the maximum setpoint and only stops when CO_2 is below the minimum setpoint.

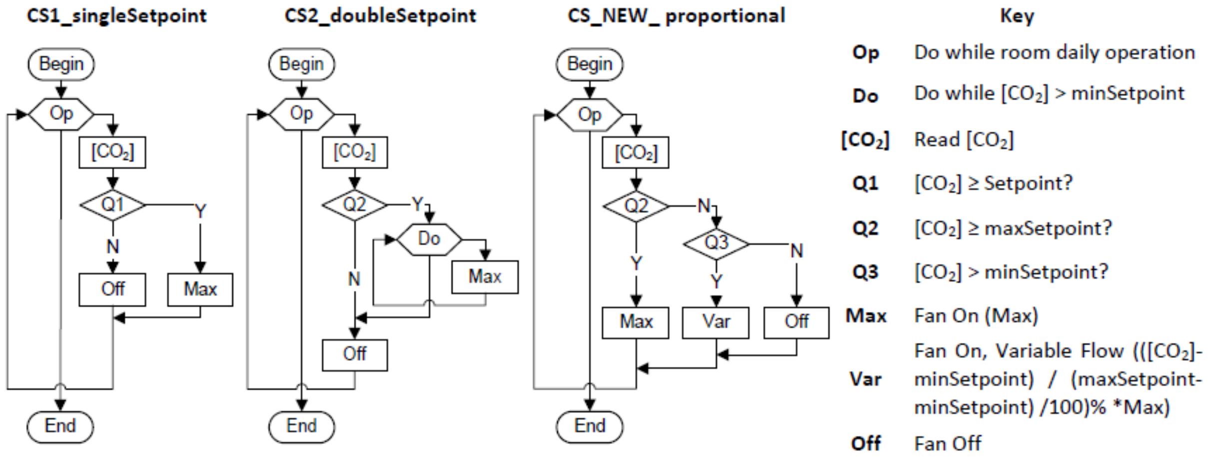

Figure 1. Ventilation strategies flowcharts.

All strategies have been simulated considering the setpoints presented in table 2. To see the influence of different minimum setpoints on the final results, four more strategies have been defined and simulated.

Table 2. CO_2 setpoints [ppm]

Control strategy		CS1	CS2	CS2.1	CS2.2	CS_NEW	CS_NEW1	CS_NEW2
Single setpoint		1000	--	--	--	--	--	--
Double setpoint	Minimum	--	800	900	950	800	900	950
	Maximum	--	1000	1000	1000	1000	1000	1000

3. SIMULATION RESULTS AND DISCUSSION

In this section the results have been presented and discussed. Moreover, comparisons between strategies considering the IAQ and energy consumption have been performed. Considering the base strategies, the CO_2 concentration in the CS_NEW never reaches the maximum setpoint while the other two does (see fig. 2, left part). Based on the monitored data, CS_NEW performed better for both IAQ and energy use. In energy consumption, 6% less than both CS1 and CS2, and in IAQ (average CO_2 concentration in the office), 3% better than CS1 and almost same as CS2 (see fig. 3).

Unnecessary ventilation -over ventilation- can be observed in CO_2 concentration and the fan airflow rate graphs, between 18:00 and 21:00 which causes more energy use. To avoid it, minimum setpoints closer to the maximum setpoint have been defined for CS2 and CS_NEW. From the graphs depicted in the right part of figure 2, it can be seen that the CO_2 concentration levels are slightly higher than the base strategies but still acceptable. The results showed that the fan energy consumption for all strategies is lower than the base strategies and the IAQ is suitable. As shown in figure 4, choosing a minimum setpoint closer to the maximum set point in CS_NEW reduces the energy use while the IAQ drop is negligible. Increasing the energy consumption in CS2.2 comparing with CS2.1 might be due to passing the optimal minimum setpoint for double setpoint strategy, but for the CS_NEW (proportional strategy) it did not happen. In the other word, it can be said that the closer the minimum setpoint to the maximum setpoint the higher the energy saving. Of course the IAQ will decrease but to still satisfactory level for the occupants.

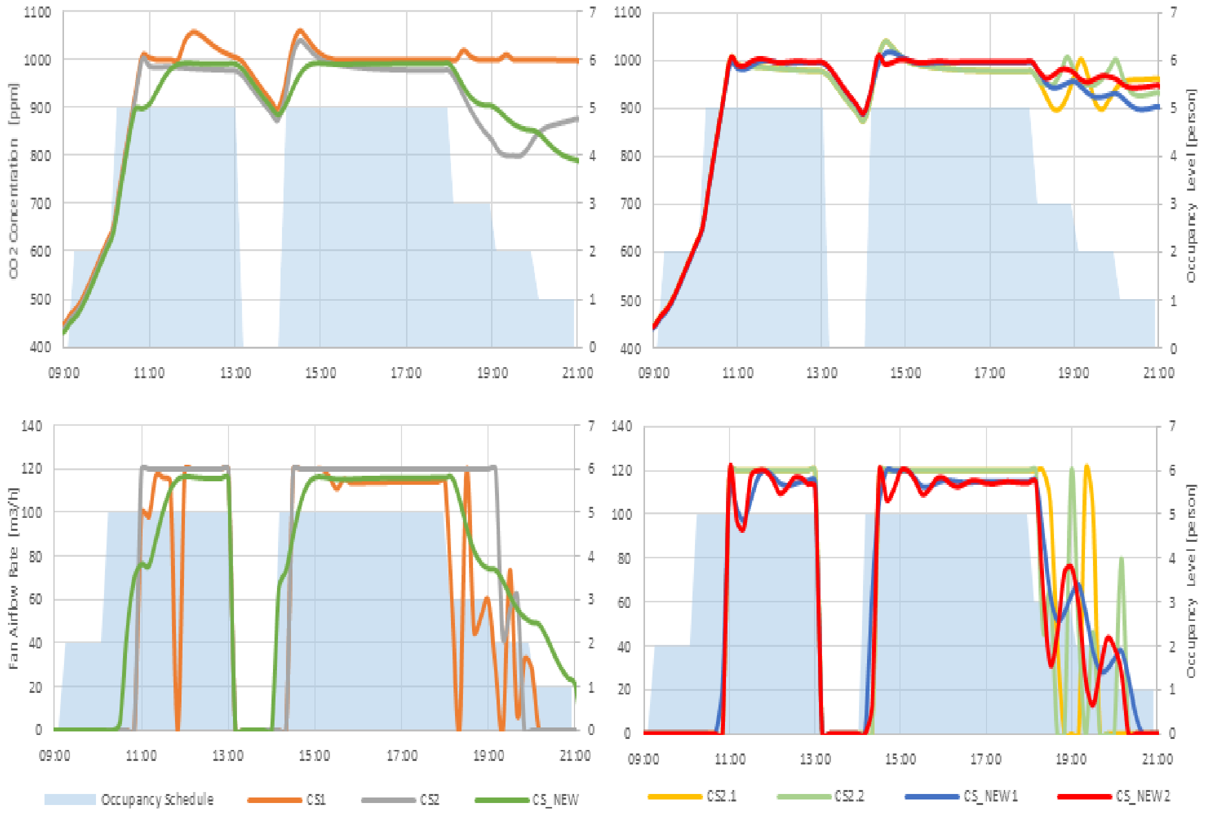

Figure 2. Variation of CO_2 concentration and fan airflow rate in all strategies.

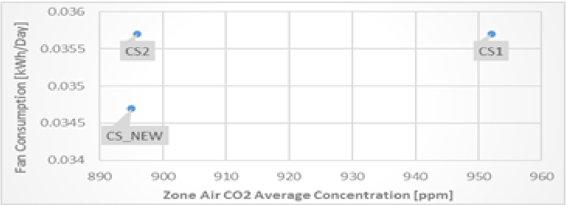

Figure 3. Room average CO_2 Level and fan energy consumption for base ventilation strategies.

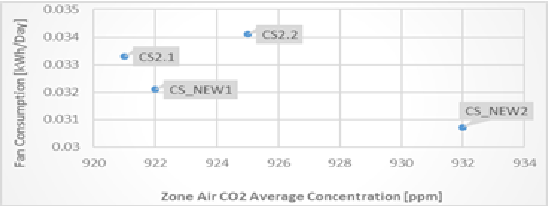

Figure 4. Room average CO_2 Level and fan energy consumption (modified minimum setpoints).

4. CONCLUSIONS

In this paper, a new CO_2-based DCV strategy has been developed and simulated with EnergyPlus. The IAQ and energy consumption associated to this strategy have been compared with the results of CO_2-based DCV strategies previously developed by the same authors. The comparison displayed that the new strategy performs better both in energy use and IAQ. The main findings of the present study can be listed as following:

- Proportional CO_2-based ventilation strategies have higher energy performance than simple strategies.
- In proportional strategies, the closer the minimum setpoint to the maximum setpoint the higher the energy saving.

ACKNOWLEDGEMENTS

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REFERENCES

[1] J. Laverge, N. Van Den Bossche, N. Heijmans, and A. Janssens, “Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies,” *Build. Environ.*, vol. 46, no. 7, pp. 1497–1503, 2011.

[2] B. Chenari, J. D. Carrilho, and M. Gameiro, “Towards sustainable , energy-efficient and healthy ventilation strategies in buildings : A review,” *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1426–1447, 2016.

[3] Y. Fan, K. Kameishi, S. Onishi, and K. Ito, “Field-based study on the energy-saving effects of CO 2 demand controlled ventilation in an office with application of Energy recovery ventilators,” *Energy Build.*, vol. 68, pp. 412–422, 2014.

[4] S. Emmerich and A. Persily, *State-of-the-Art Review of CO2 Demand Controlled*

Ventilation Technology and Application. Diane Publishing, 2001.

[5] Z. Sun, S. Wang, and Z. Ma, “In-situ implementation and validation of a CO2-based adaptive demand-controlled ventilation strategy in a multi-zone office building,” *Build. Environ.*, vol. 46, no. 1, pp. 124–133, 2011.

[6] B. Chenari, F. B. Lamas, A. R. Gaspar, and M. Gameiro da Silva, “Simulation of occupancy and CO2-based demand-controlled mechanical ventilation strategies in an office room using EnergyPlus,” in *CONECT 2016, Conference on Environmental and Climate Technologies*, 2016.

[7] L. D. Pereira, J. D. Carrilho, N. S. Brito, M. R. Gomes, M. Mateus, B. Chenari, and M. Gameiro, “Teaching and researching the indoor environment: From traditional experimental techniques towards web-enabled practices,” *Sustain. Cities Soc.*, 2016.

[8] J. D. Carrilho, B. Chenari, M. R. Gomes, G. Botte, M. Mateus, and M. Gameiro da Silva, “Development of a live laboratory for research and technology demonstration in indoor environment assessment and control,” in *the 2nd EfS Conference*, 2015.

5.4. Conclusion

Whole building dynamic simulation was performed using *EnergyPlus* software on the modeled case study, the I2L. Different ventilation control strategies have been developed and analyzed in this chapter, with the objective of maintaining the IAQ in a standard level while minimizing the energy consumption of the mechanical ventilator.

The results once again proved the importance of control and smartness in energy saving and in providing a good IAQ. The first ventilation control strategy, let's say the most basic strategy, if being used in an office, reduces the consumption as avoids ventilation during non-occupancy period. The second one, which is one step smarter can reach an energy saving of about 30% comparing to the first control strategy. Going further smart and developing the control strategies based on both occupancy and indoor CO_2 concentration would lead to a better performance in terms of energy while still provided a good IAQ.

The results from the double set-point control strategies reported overventilation during the low occupancy periods, which has been avoided by the performed sensitivity analyses. Therefore, it seems crucial to consider the minimum set point quite close to the maximum one or even develop strategies in which the minimum set-point would be adjusted. It was also pointed out by the results from the double set-point proportional control strategy that the closer the minimum set-point to the maximum set-point the higher the energy saving.

All in all, the research carried out in this chapter emphasizes the significance of using control in energy consumable building services such as ventilation. As natural ventilation is not predictable, presence and use of mechanical ventilation can compensate this drawback. Therefore, for mechanical ventilation, as a service that uses energy, the control strategies developed and analyzed in this chapter are recommended to be considered for it.

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Chapter 6

SMART READINESS INDICATOR

6.1. Introduction

As energy has become a core issue for the European Union (EU), in November 2016, a package of proposals called the “Clean Energy for All Europeans” has been presented by the EC to revise and adjust several directives in the field of energy efficiency, renewable energy, electricity market design, security of electricity supply and energy governance. The building sector, that contributes to 40% of the EU’s final energy use, has been considered as an essential driver of this energy transition. Moreover, around 75% of the current EU housing stock is energy inefficient and both renovation rate and depth are too low. Therefore, there is certainly an obvious need to finance building renovation by considering smart and energy-efficient technologies [106]. During the recent years, with the developments in the field of smart buildings, there is a strong link between the field of energy efficiency and the smartness of the built environment. At the same time, the digitization of the built environment with the utilization of Internet of Things (IoT) based automation tools even strengthen this requirement. Smart buildings integrate cutting edge information and communication technology (ICT) based solutions to optimize energy-efficient control of building systems and enable energy flexibility as a part of their daily operation. Such smart capabilities can also effectively assist creation of healthier and more comfortable buildings, which adjust to the needs of both the user and the energy grid while reducing building energy use and its environmental impacts.

The potential of smart technologies in the building sector was heavily emphasized in the 2018 revision of the European Energy Performance of Buildings Directive (EPBD) and the concept of a Smart Readiness Indicator (SRI) was introduced. This indicator allows rating the smart readiness of buildings, i.e. the capability of buildings (or building units) to adapt their operation to the needs of the occupant, also optimizing energy efficiency and overall performance, and to adapt their operation in reaction to signals from the grid (energy flexibility) [107]. The smart readiness indicator will raise awareness amongst building owners and occupants of the value behind building automation and electronic monitoring of technical building systems and should give confidence to occupants about the actual savings of those new enhanced functionalities. Figure 6.1 represents the main functionalities of smart readiness in buildings required by the revised EPBD as well as the target audience for the SRI.

Figure 6.1 – Three key functionalities of smart readiness in buildings and SRI's target audience [108].

Two technical support studies have been conducted in order to support the establishment of the SRI. The first one started in the beginning of 2017 with the objective of studying the possible scope and characteristics of such an indicator. The first study introduced the concept of smart ready buildings, gathered a catalogue of smart ready services and proposed a methodological framework for assessment these smart ready services to calculate the SRI score. Counting on the knowledge acquired from the first study and aiming to refine and finalize the definition and calculation methodology for the SRI, a second technical support study launched in December 2018. Throughout this second study, several progress reports have been delivered exploring the implementation of the SRI. Finally, in summer 2020, the final report [108] from the second technical support study has been published.

One of the main challenges to develop SRI methodology is to ensure charting of the smart ready services and their potential impacts to the building, the users and the energy grid. In this method, impact criteria are evaluated, but scores can potentially be aggregated along the three key functionalities mentioned in the EPBD.

In the next sections more details about the SRI and its improvements have been presented.

6.2. Contribution in Smart Readiness Indicator

In this section two articles communicated to an international conference have been presented.

6.2.1. Paper VI: Smart Readiness Indicator Part I An Overview

Right after the SRI was introduced, taking into account the importance of smart ventilation in smartness of buildings, it was decided to include it in this PhD research. Therefore, all improvements of SRI until June 2019 have been studied, mostly based on the “Support for setting up a Smart Readiness Indicator for buildings and related impact assessment - Second progress report” [101] as one of the key deliverable of the second SRI technical support study and also rarely available research in the topic. The outcome has been summarized in an article communicated in Energy for Sustainability International Conference 2019, titled “Smart Readiness Indicator Part I: An Overview”.

Author Contributions: Behrang Chenari as the main author, has conducted the research, gathered and collected data and information, and wrote the papers; Ehsan Asadi and M. Gameiro da Silva reviewed the contents and contributed to enhancing their quality.

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SMART READINESS INDICATOR PART I
AN OVERVIEW

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Keywords: Smart Readiness Indicator, Smart Ready Technology, Energy Efficiency.

Abstract *Buildings are the main sector in accomplishment of the EU energy and climate targets as well as the long-term sustainability goals by 2050 as they consume 40% of EU's final energy (read: the largest single energy consumer in Europe). Therefore, EU policies and strategies aim to not only improve the efficient use of energy in existing buildings and encourage the use of renewable energy sources, throughout their renovation process, but also reinforce the energy performance of new buildings, integrating smart technologies. The revised Energy Performance of Buildings Directive requires the development of an optional Common Union scheme for rating the smart readiness of buildings, so called the Smart Readiness Indicator. The Smart readiness indicator is an EU project proposed to raise awareness about the advantages of integrating smart technologies in buildings. This paper briefly presents the smart readiness indicator and its improvement so far.*

1. INTRODUCTION

As mentioned by European Commission [1], around 75% of the current EU housing stock is considered to be energy inefficient; annual renovation rates are low, between 0.4% and 1.2%, and the renovation depth is generally considered too shallow. Thus, the need to quicken and finance building renovation investments and leverage intelligence, energy-efficient technologies in the building sector is highly required and leads to significant energy saving and reduction of CO_2 emission. As a part of Clean Energy for All Europeans [1], the Commission proposed an update to the Energy Performance of Buildings Directive (EPBD) to help promote the use of smart technology in buildings, to streamline existing rules and accelerate building renovation. Smart buildings integrate Information and Communication Technology (ICT)-based solutions for effectively control and monitor the energy efficiency and energy flexibility as part of their daily operation. Smart buildings have also been recognized and accredited as the key influencers of future energy systems for which there will be a larger share of renewables, distributed supply and energy flexibility on the demand side. A greater commitment of smart technologies is expected to lead to significant energy savings in a cost-effective manner, while also helping to enhance indoor comfort in a manner that empowers the building to adjust to the needs of the users. Finally, in the revised Energy Performance of Buildings Directive [2]- which was published on 19 June 2018 - one of the crucial points is to improve the realization of this potential of Smart Ready Technologies (SRT), including automation, in the building sector. Therefore, the revised EPBD requires the development of an optional common European scheme for rating the smart readiness of buildings: The Smart Readiness Indicator (SRI). The SRI aims to acquaint the building users, owners, tenants and smart service providers to the added value of building smartness and assist them to well notice this value by providing data on the technological readiness of buildings to interact with their occupants and the energy grid.

This paper aims to present SRI and its methodology in a simple way. To do so, the authors use the final report from the first SRI technical support study carried out by the project partners as the main reference [3]. Meanwhile, the second SRI technical support study has been launched recently aiming to provide further technical input to feed the establishment of the SRI scheme. The objective of this paper is to make the audience acquainted with the concept of SRI and its progress so far.

2. SMART READINESS INDICATOR

The SRI is supposed to raise awareness about the profits of integrating smart technologies and ICT in buildings from an energy perspective, motivate consumers to accelerate investments in smart building technologies and support the application of technology innovation in the building sector. The indicator can also improve policy linkages between energy, buildings and other policy segments, in particular in the ICT area, and thus contribute to the integration of the buildings sector into future energy systems and markets. Smart buildings need to go beyond being energy efficient and healthy by recognising and reacting to users’ and occupants’ needs to optimise comfort, indoor air quality, wellbeing and operational requirements. Such smart capabilities can effectively contribute in creating healthier and more comfortable living environment with less energy consumption and carbon impact.

As proposed by the SRI technical support study [3], “Smartness of a building refers to the ability of a building or its systems to sense, interpret, communicate and actively respond in an efficient manner to changing conditions in relation the operation of technical building systems or the external environment (including energy grids) and to demands from building occupants.” Thus, an SRI for buildings shall provide information on the technological readiness of buildings to interact with their occupants and the energy grids, and their capabilities for more efficient operation and better performance through ICT technologies and electronic systems. The SRI is expected to become a cost-effective measure which can effectively assist in creating healthier and comfortable buildings with a lower energy use and carbon impact, and can facilitate the integration of Renewable Energy Sources (RES) by using smart ready services throughout available SRT.

Smart ready services satisfy a need from the user (occupant/owner) of a building or the energy grid it is connected to. Smart Ready Services are delivered to the building user or the energy grid through the use of SRT.

One of the main objectives of the SRI project was to compile the full list (or catalogue) of smart ready services that can be found in buildings and that could be considered in the calculation of the SRI. Three key functionalities of smartness in buildings have been taken into account when selecting the smart services for the catalogue:

- The ability to adapt its operation mode in response to the needs of the occupant paying due attention to the availability of user-friendliness, maintaining healthy indoor climate conditions and ability to report on energy use;
- The ability to maintain energy efficiency performance and operation of the building through the adaptation of energy consumption for example through use of energy from renewable sources;
- The flexibility of a building's overall electricity demand, including its ability to enable participation in active and passive as well as implicit and explicit demand-response, in relation to the grid, for example through flexibility and load shifting capacities.

The SRI service catalogue is structured based on services that belong to a given domain and can be provided with different functionality levels (the higher the level, the better the smartness). Services and functionality levels are then represented to impact scores.

2.1. SRI Domains

In the SRI service catalogue, services are structured along 10 domains: Heating, Cooling, Domestic Hot Water, Controlled Mechanical Ventilation, Lighting, Dynamic Building Envelope, On-site Renewable Energy Generation, Demand Side Management, Electric Vehicle Charging, Monitoring and Control as well as one extra domain so called various.

2.2. Smart Ready Services

The full catalogue of the SRI technical study currently lists 112 Smart Ready Services. The reader is referred to Annex A of this study [3] and the accompanying Excel spreadsheet for the full catalogue of services.

2.3. Functionality Level

For each of the services several functionality levels are defined. the higher functionality level generally reflects the “smarter” service. The number of functionality levels varies from service to service, the maximum level can be as low as 2 or as high as 5. The functionality levels are ordinal numbers, indicating that ranks cannot be compared in between different services. The functionality levels of the service, ranging from level 0 up to level 4, depending on the service.

2.4. Impact Criteria

The services translate into different impacts for buildings, building users and the energy grid. At this stage, the following eight impact categories are considered:

- Energy savings on site: refers to the impacts of smart ready services on energy saving capabilities.
- Flexibility for grid and storage: refers to the impacts of services on the energy flexibility potential of the building.
- Self-generation: refers to the impacts of services on the amount and share of renewable energy generation by on-site assets and the control of self-consumption or storage of the generated energy.
- Comfort: refers to the impacts of services on occupants’ comfort.
- Convenience: refers to the impacts of services on convenience for occupants.
- Well-being and health: refers to the impacts of services on the well-being and health of occupants.
- Maintenance and fault prediction, detection and diagnosis: Automated fault detection has the potential to significantly improve maintenance and operation of the TBS.
- Information to occupants: this refers to the impacts of services on provision of information on building operation to occupants.

Impacts of smart ready services (and related functionality levels) are expressed on a nine-level ordinal scale: ----, ---, --, -, 0, +, ++, +++, ++++. It then might be converted into a corresponding numerical or nominal score (i.e. -4, -3, -2, -1, 0, 1, 2, 3, 4). Figure 1 presents main actors of SRI by illustration of the structure of the smart ready services catalogue.

2.5. SRI Methodology

The project final report developed a generic SRI methodology based on Multi-Criteria Decision Making (MCDM). In MCDM there is no exclusive solution to a problem without inclusion of preferred information. Thus considering the framework of SRI, this method will help the decision makers to choose the best suited solution for the problem.

This SRI methodology receives the inputs (smart services) and analyse them based on the defined functionality levels to provide the outputs, the SRI score, which represent how smart the building is.

As all multi-criteria assessment methodologies which result in a single score or indicator, the following approach is taken:

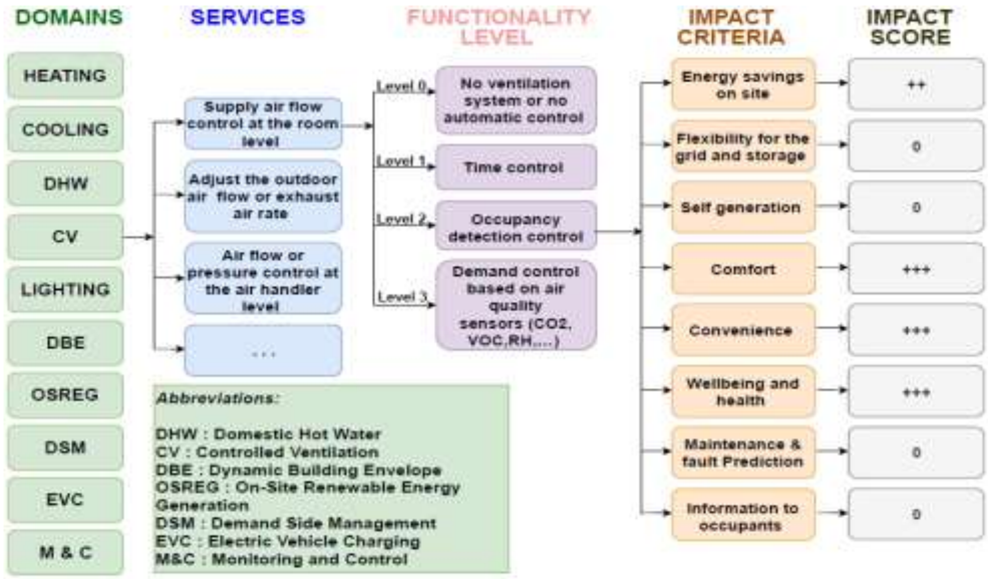

Figure 1. illustration of the structure of the SRI smart ready services catalogue

- Identify the relevant impact criteria to be used in the assessment;
- Develop a methodology to determine the effect that sub-elements have on each impact criteria and thereby allow scoring per impact criteria;
- develop a system of weightings to determine an overall score across the impact criteria.

Considering the impact criteria, the indicator can be expressed as a weighted sum as follows:

$$N = A \times a + B \times b + C \times c + D \times d + E \times e + F \times f + G \times g + H \times h$$

where a, b, c, d, e, f, g and h are the relative weightings given to the impact criteria scores A, B, C, D, E, F, G and H and N is the overall score. Normally, a to h would add up to 1 (to normalize the outcome) and A to H would be scored on a scale that corresponds to the final scale for N (e.g. it could be on a scale of 0 to 100, in which case A, B, C, D, E, F, G and H would also each be scored on a scale of 0 to 100).Having the services, the functionality levels and the ordinal ranking scales (possible to be mapped in nominal scores), mentioned in the catalogue, for any given service a maximum SR score can be obtained. If the maximum possible ordinal score to attain for the service/impact criterion/domain combination in question is ++++ and the score attained by the particular building is + then the maximum nominal score is 4 and the actual score is 1, thus the normalized score will be 1/4 or 25%. Then these maxima scores can be used to arise a normalized score by dividing the sum the nominal impact scores by the sum of maximum possible impact scores to achieve the overall SRI score for a building. The generic methodology can be applied either by equal weightings or differentiated weightings.

In equal weightings case each all impact criteria will receive similar weightings, say that 12.5% each, as we have got 8 impact criteria, while in differentiated weightings each domain will get a weighting based on its importance on a specific impact criterion. In the other word, those domains with higher importance will get higher weightings, those with lower importance will receive less weightings and even for those with no importance on the impact criterion, the weighting will be set on 0%.

Always the weightings of the domains for each impact criterion will be add up to 100%. Generally, the weighting decision has to be made on the impact criteria, the domains, the services considered and the functionality levels. In equal weightings, all actors will be equally weighted. In differentiated weighting the first two will be weighted considering their importance and those latter will be equally weighted. In order to carry out the assessment, first the domains and services that are relevant and present in the building have to be determined. Secondly, the functionality level associated to each service has to be obtained. Thirdly, the impact scores have to be counted and weightings, either equally or differentiated, have to be applied. Finally, based on the maximum obtainable scores, the normalized SRI score will be calculated.

3. CONCLUSIONS

The Smart readiness indicator is an EU project proposed to raise awareness about the advantages of integrating smart technologies in buildings. This paper briefly presents the smart readiness indicator and its improvement so far. The second technical support study of SRI has been recently launched. Considering the outcomes of the first technical study, this study will provide the technical inputs needed to improve and complete the definition of the SRI and the associated calculation methodology. The second part of this paper aims to provide an example of SRI calculation based on a previous research developed by the authors.

ACKNOWLEDGEMENTS

The presented work is framed under the Energy for Sustainability Initiative of the University of Coimbra (UC). This research is developed under the framework of LAETA project, RETROSIM - Development of an online tool for multi-objective optimization of energy efficiency in buildings” (POCI-01-0145-FEDER-032503). The first author also wishes to acknowledge Fundação para a Ciência e a Tecnologia (FCT) for supporting his research through the PhD research Grant SFRH/BD/131481/2017.

REFERENCES

[1] A. Clean Energy For All Europeans, “COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL,THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK,” 2016.

[2] E. THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION, “amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency,” *Off. J. Eur. Union*, pp. 75–91, 2018.

[3] J. S. Stijn Verbeke, Yixiao Ma, Paul Van Tichelen, Sarah Bogaert, Virginia Gómez Oñate, Paul Waide, Kjell Bettgenhäuser, John Ashok, Andreas Hermelink, Markus Offermann, Jan Groezinger, Mathias Uslar, “SUPPORT FOR SETTING UP A SMART READINESS INDICATOR FOR BUILDINGS AND RELATED IMPACT ASSESSMENT FINAL REPORT,” 2018.

6.2.2. Paper VII: Smart Readiness Indicator Part II Assessing Different Demand-Controlled Ventilation Strategies

The domain “controlled ventilation” covers services for air flow control and indoor environment control. The ventilation rate is an important driver for the energy demand of a building, and is equally important in relation to human health and comfort. It is well proven that smart controlled-ventilation based on parameters such as occupancy and indoor CO_2 concentrations may lead to better energy performance as well as comfortable indoor environment. Therefore, another study has been carried out to evaluate the SRI score associated to five ventilation strategies and to compare the results with those from the energy performance and IAQ in previous simulation studies. Comparing the obtained scores with those results from the previous studies showed the potential of SRI methodology to be used as an indicator of assessing building energy performance as well as its occupants’ comfort. The outcome of this research has been also communicated as an article in Energy for Sustainability International Conference 2019, titled “Smart Readiness Indicator Part II: Assessing Different Demand Controlled Ventilation Strategies”.

Author Contributions: Behrang Chenari as the main author, has conducted the research, gathered and collected data, carried out the calculations and wrote the papers; Ehsan Asadi and M. Gameiro da Silva reviewed the contents and contributed to enhancing their quality.

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SMART READINESS INDICATOR PART II ASSESSING DIFFERENT DEMAND CONTROLLED VENTILATION STRATEGIES

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Keywords: Smart Readiness Indicator, Smart Ready Technology, Energy Efficiency.

Abstract *Building sector is responsible for a large proportion of global energy consumption. Among all building services, Heating, Ventilation and Air Conditioning (HVAC) systems are significantly in charge for building energy use. In HVAC, ventilation is the key issue for providing suitable Indoor Air Quality (IAQ), while it is also responsible for energy consumption. Therefore, enhancing ventilation systems with integrating smart ready technologies not only improves energy efficiency, but also provides better indoor climate for the inhabitants and lowers the possibility of health issues in buildings. As mentioned in the first part of this article, the revised Energy Performance of Buildings Directive requires the development of an optional Common Union scheme for rating the smart readiness of buildings, so called the Smart Readiness Indicator. The Smart readiness indicator is an EU project proposed to raise awareness about the advantages of integrating smart technologies in buildings. This paper presents an assessment of Smart readiness indicator for five different ventilation strategies which were previously developed and simulated by the authors. The results show the potential of smart readiness indicator methodology to be used as an indicator for assessing building energy performance as well as its occupants' comfort while there are still some shortcomings that have to be covered during the second support study.*

1. INTRODUCTION

Buildings are responsible for a large sharing of energy consumption worldwide. Among all energy services in buildings, ventilation systems are not only accountable for a significant part of energy consumption but they are also highly influential on indoor climate and occupants' satisfaction in consequence. Thus, improving the ventilation systems using the available smart technologies helps to foster energy efficiency as well as indoor climate.

In the last decade, several efficient ventilation methods such as natural or hybrid ventilation have been presented in various research projects. Moreover, Demand-Controlled Ventilation (DCV) strategies which employ these methods have been discussed in various research studies. As mentioned in [1], implementing DCV strategies has shown significant effects on improving energy efficiency of ventilation systems because in DCV, supply is continuously matched with demand, so it results in having acceptable IAQ accompanied by notable energy and cost savings. Using DCV method, the space is ventilated based on its occupancy level or concentration of contaminants. DCV is a suitable method for ventilation of spaces where the occupancy level varies frequently, such as restaurants, canteens, lecture halls, shopping malls and offices. For instance, office buildings are mostly ventilated based on constant air volume systems, which causes wasting of energy for ventilating empty offices or those with fewer occupants. In many cases the actual level of occupancy is much lower than the design level which causes over ventilation of the buildings. In other words, in DCV systems, the demand of a space for air exchange is always being measured by IAQ sensors and the outside flowrate is being attuned to match the real demand.

The Smart Readiness Indicator (SRI), proposed by the revised Energy Performance of Buildings Directive [2]- which was published on 19 June 2018 – is an optional common European scheme for rating the smart readiness of buildings. The SRI aims to acquaint the building users, owners, tenants and smart service providers to the added value of building smartness and assist them to well notice this value by providing data on the technological readiness of buildings to interact with their occupants and the energy grid. Moreover, apart from ensuring the building's effective operation and helping improve its energy performance, SRI would further respect occupants' needs towards a healthy, comfortable and productive indoor environment. In the other word, unlike many energy efficient methods which result in energy saving with the expense of the occupants wellbeing and comfort, SRI would have an integrated assessment which will not neglect these vital issues.

In two separated research articles [2, 3], five demand-controlled ventilation strategies based on occupancy schedule period, occupancy level and indoor concentration of CO_2 in an office room had been studied. The results showed the best suited ventilation strategies for the office room that can provide acceptable level of indoor air quality with the least energy use.

The authors of the present paper, have assessed the SRI score of the same ventilation strategies to compare the energy performance and IAQ results from the simulation study with those from SRI assessment.

2. MATERIAL AND METHODS

2.1. Case study overview

The Indoor Live Lab (I2L) [5], located in Mechanical Engineering Department (DEM) at university of Coimbra has been chosen as the test room to conduct simulations. The I2L is equipped with several instruments and sensors which monitor Indoor Environmental Quality (IEQ) indices (see Fig. 1).

Figure 1. (a) Aerial view of the Mechanical Engineering Department of the University of Coimbra; I2L office with the instruments and sensors.

2.2. Ventilation systems:

Constant Air Volume (CAV) fans as well as Variable Air Volume (VAV) fans with different airflow rates have been considered during simulation of ventilation strategies.

2.3. Ventilation strategies:

Five occupancy and CO_2-based ventilation strategies have been defined and simulated.

- Control strategy 1 (Occupancy period based):

In this strategy, regardless the number of occupants, a CAV fan is used that operates only during occupancy period.

- Control strategy 2 (Occupancy level based):

Unlike the previous strategy, this is an occupancy-based DCV in which a VAV fan is used to provide a specific amount of airflow rate per occupant.

- Control strategy 3 (Single setpoint CO_2-based):

A maximum setpoint for indoor CO_2 concentration (1000 ppm) is defined. In this case, a CAV fan that operates only if the CO_2 concentration goes above the setpoint and stops, when it is below the setpoint, is used.

- Control strategy 4 (Double setpoint CO_2-based):

A maximum setpoint for indoor CO_2 concentration (1000 ppm) is defined as well as a minimum setpoint (500 ppm). Similar to the strategy 3, a CAV fan that operates when the CO_2 concentration is above the maximum setpoint is used. The fan only stops when CO_2 is below the minimum setpoint during occupancy time.

- Control strategy 5 (Proportional CO_2-based):

In this strategy, the VAV fan operates proportional to the CO_2 concentration level and the minimum and maximum setpoints.
Fig. 2 demonstrates the flowcharts of the simulated ventilation strategies.

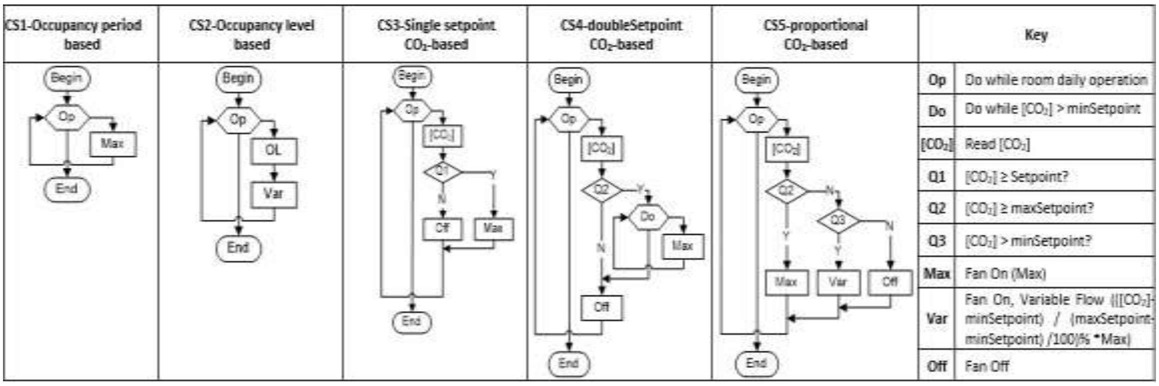


Figure 2. Ventilation strategies flowcharts.

2.4. SRI assessment

As all multi-criteria assessment methodologies which result in a single score or indicator, the following approach is taken:

- Identify the relevant impact criteria to be used in the assessment;
- Develop a methodology to determine the effect that sub-elements have on each impact criteria and thereby allow scoring per impact criteria;
- Develop a system of weightings to determine an overall score across the impact criteria.

Considering the aforementioned steps, four impact criteria which is being affected by the ventilation strategies were considered, namely, energy savings on-site (ESOS), comfort (COMF), convenience (CONV) and well-being and health (WBAH). Moreover, three services that are relevant to the ventilation strategies in the ventilation domain have been chosen from the catalogue. Afterward, two weightings systems (equal and differentiated) have been applied. In equal weightings, 25% attributed to the four chosen impact criteria and 33% to each of the three services. In differentiated weightings, 30% were attributed to ESOS, COMF and WBAH, and 10% to CONV while similar to equal weightings, the services have received equally 33% each. Later, considering the impact criteria, the indicator can be expressed as a weighted sum as follows:

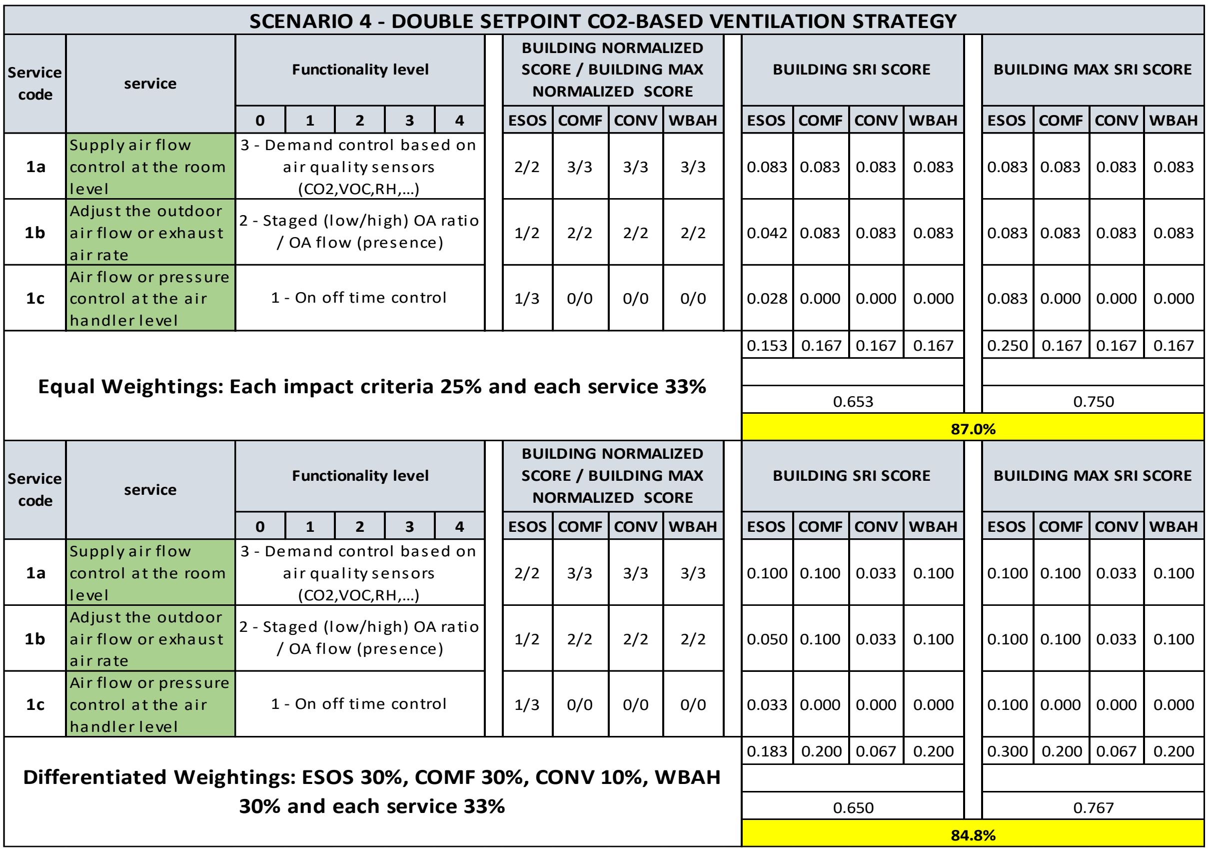
$$N = A \times a + B \times b + C \times c + D \times d$$

where a, b, c and d are the relative weightings given to the impact criteria scores A, B, C and D and N is the overall score. Normally, a to d would add up to 1 (to normalize the outcome) and A to D would be scored on a scale that corresponds to the final scale for N.

3. RESULTS

In this section the SRI scores obtained for each strategy are presented and discussed. Fig. 3

shows the SRI score obtained by the ventilation control strategy 4 (as reference to show how the SRI scores have been calculated), both for equal and differentiated weightings.



SCENARIO 4 - DOUBLE SETPOINT CO2-BASED VENTILATION STRATEGY																		
Service code	service	Functionality level					BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0	1	2	3	4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	3 - Demand control based on air quality sensors (CO2,VOC,RH,...)					2/2	3/3	3/3	3/3	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083
1b	Adjust the outdoor air flow or exhaust air rate	2 - Staged (low/high) OA ratio / OA flow (presence)					1/2	2/2	2/2	2/2	0.042	0.083	0.083	0.083	0.083	0.083	0.083	0.083
1c	Air flow or pressure control at the air handler level	1 - On off time control					1/3	0/0	0/0	0/0	0.028	0.000	0.000	0.000	0.083	0.000	0.000	0.000
Equal Weightings: Each impact criteria 25% and each service 33%											0.153	0.167	0.167	0.167	0.250	0.167	0.167	0.167
											0.653				0.750			
											87.0%							
Service code	service	Functionality level					BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0	1	2	3	4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	3 - Demand control based on air quality sensors (CO2,VOC,RH,...)					2/2	3/3	3/3	3/3	0.100	0.100	0.033	0.100	0.100	0.100	0.033	0.100
1b	Adjust the outdoor air flow or exhaust air rate	2 - Staged (low/high) OA ratio / OA flow (presence)					1/2	2/2	2/2	2/2	0.050	0.100	0.033	0.100	0.100	0.100	0.033	0.100
1c	Air flow or pressure control at the air handler level	1 - On off time control					1/3	0/0	0/0	0/0	0.033	0.000	0.000	0.000	0.100	0.000	0.000	0.000
Differentiated Weightings: ESOS 30%, COMF 30%, CONV 10%, WBAH 30% and each service 33%											0.183	0.200	0.067	0.200	0.300	0.200	0.067	0.200
											0.650				0.767			
											84.8%							

Figure 3. Calculation of SRI Score for ventilation control strategy 4.

Furthermore, table 1 presents the SRI score for all the ventilation control strategies.

Table 1. SRI score for all ventilation strategies

Ventilation Strategies		**CS1**	**CS2**	**CS3**	**CS4**	**CS5**
SRI Score	Equal	20.4%	83.3%	87.0%	87.0%	100.0%
	Differentiated	21.0%	83.3%	84.8%	84.8%	100.0%

According to the results, the CS5 ventilation strategy attained the best SRI score. Similarly, in the simulation studies, CS5 presented the best performance both for energy use and IAQ. In the simulation study, CS4 performed slightly better than CS3 but here they got the same SRI score. That is the matter of choosing single or double (min/max) set points for the CO_2 concentration in ventilation strategies, while in the SRI service catalogue, it has not been foreseen.

3. CONCLUSIONS

The Smart Readiness Indicator is an EU project proposed to raise awareness about the advantages of integrating smart technologies in buildings. This paper evaluates the SRI score of five ventilation strategies and compares the results with the energy performance and IEQ results from the previous simulation studies.

Comparing the obtained scores with those results from the previous studies shows the potential of SRI methodology to be used as an indicator of assessing building energy performance as well as its occupants' comfort. Moreover, it has to be noted that the SRI methodology is still under development during the second technical support study so it makes sense if there are some shortcomings in the first support study's outcomes. As such, the qualitative assessment of the scores for almost all functionality levels as well as the method (MCDM) which is based on weightings can be mentioned.

ACKNOWLEDGEMENTS

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REFERENCES

[1] B. Chenari, J. Dias Carrilho, and M. Gameiro da Silva, "Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1426–1447, Jun. 2016.

[2] E. THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION, "amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency," *Off. J. Eur. Union*, pp. 75–91, 2018.

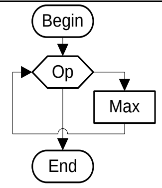
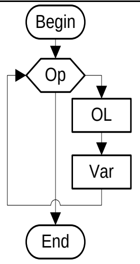
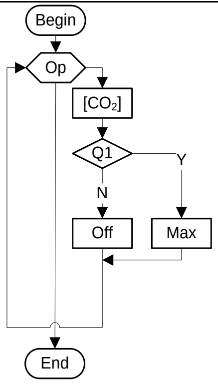
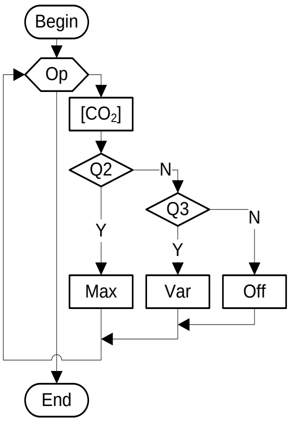
[3] B. Chenari, F. Lamas, A. Gaspar, and M. Gameiro da Silva, "Simulation of occupancy and CO_2-based demand-controlled mechanical ventilation strategies in an office room using EnergyPlus," in *International Scientific Conference "Environmental and Climate Technologies – CONECT 2016*, 2016.

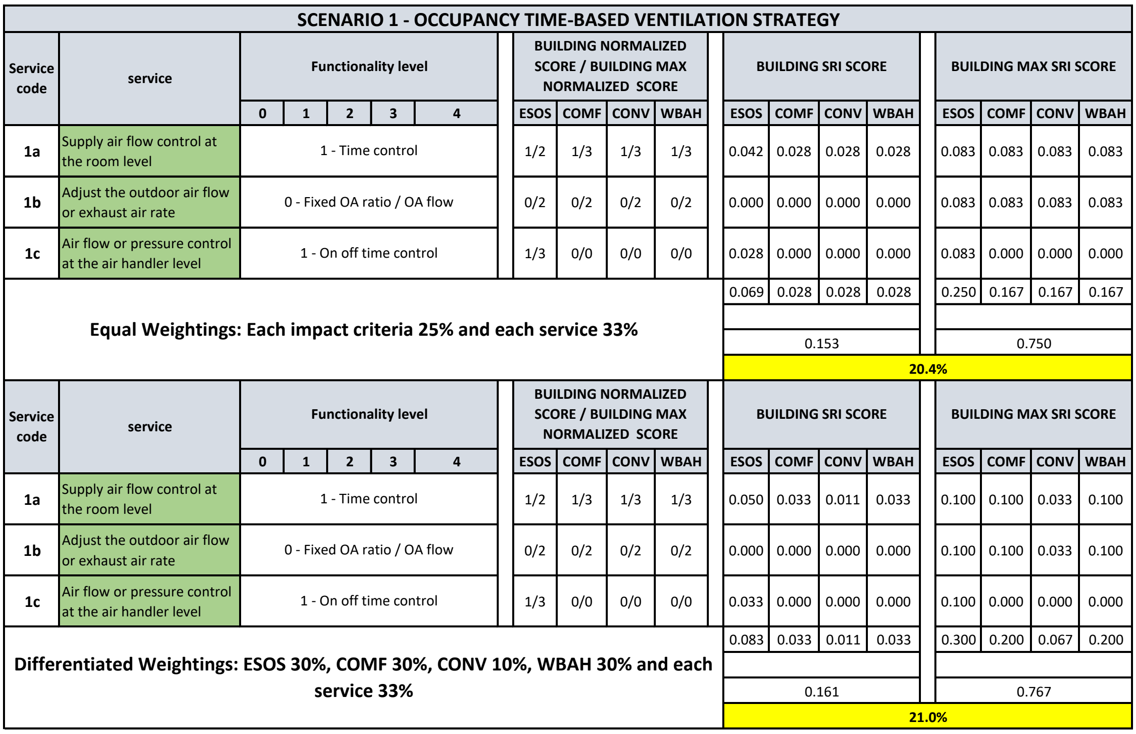
[4] B. Chenari, F. B. Lamas, A. R. Gaspar, and M. G. da Silva, "DEVELOPMENT OF A NEW CO_2-BASED DEMAND-CONTROLLED VENTILATION STRATEGY USING ENERGYPLUS," in *the EfS Conference*, 2017.

[5] J. D. Carrilho, B. Chenari, M. R. Gomes, G. Botte, M. Mateus, and M. Gameiro da Silva, "Development of a live laboratory for research and technology demonstration in indoor environment assessment and control," in *the 2nd EfS Conference*, 2015.

As in the article, only the SRI calculation sheet for control strategy 4 was presented (because of limitation in page numbers), figures 6.2, 6.3, 6.4 and 6.5 illustrate those regarding the ventilation strategies 1, 2, 3 and 5 respectively. Also table 6.1 represents the ventilation control strategies flowcharts.

Table 6.1 – Ventilation control strategies flowcharts.

CS1-Occupancy period based	**CS2-Occupancy level based**	**CS3-Single setpoint CO_2-based**	**CS5-proportional CO_2-based**	**Key**	
				**Op**	Do while room daily operation
				Do	Do while $[CO_2]$ > minSetpoint
				$[CO_2]$	Read $[CO_2]$
				Q1	$[CO_2] \geq$ Setpoint?
				Q2	$[CO_2] \geq$ maxSetpoint?
				Q3	$[CO_2]$ > minSetpoint?
				Max	Fan On (Max)
				Var	Fan On, Variable Flow $(([CO_2]$-minSetpoint) / (maxSetpoint-minSetpoint) x100)% *Max)
				Off	Fan Off

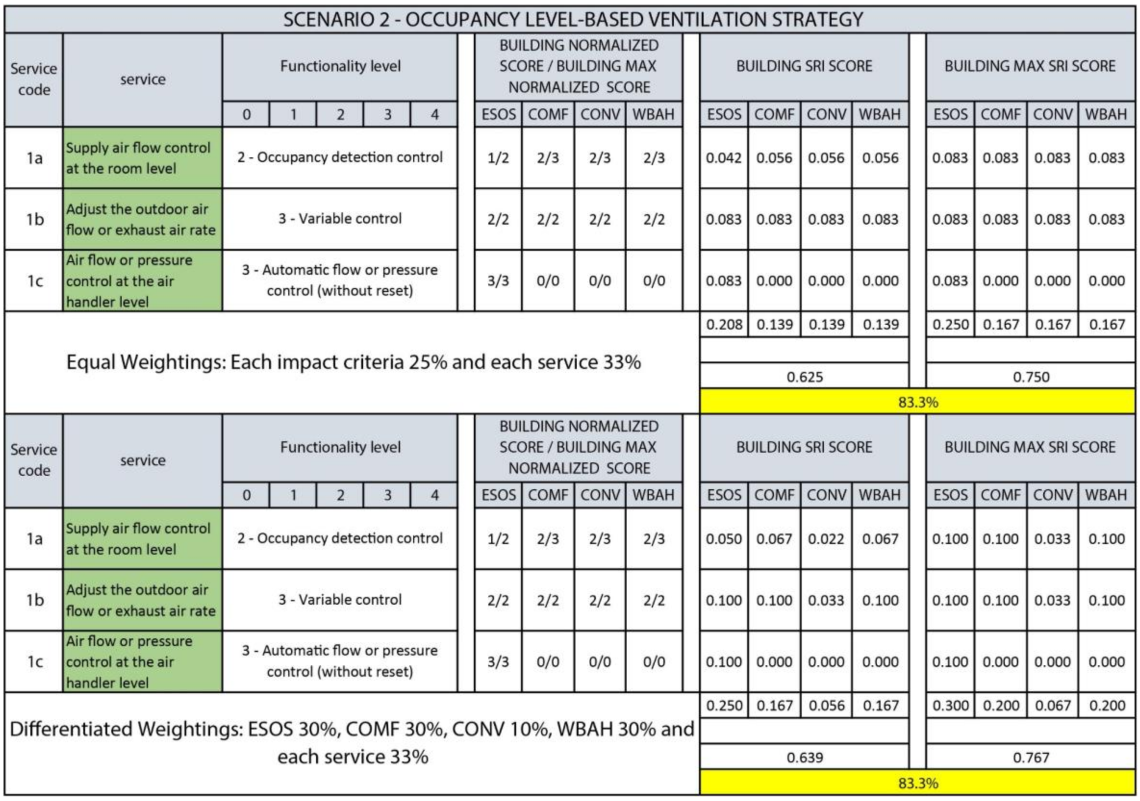


SCENARIO 1 - OCCUPANCY TIME-BASED VENTILATION STRATEGY

Service code	service	Functionality level					BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0	1	2	3	4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	1 - Time control					1/2	1/3	1/3	1/3	0.042	0.028	0.028	0.028	0.083	0.083	0.083	0.083
1b	Adjust the outdoor air flow or exhaust air rate	0 - Fixed OA ratio / OA flow					0/2	0/2	0/2	0/2	0.000	0.000	0.000	0.000	0.083	0.083	0.083	0.083
1c	Air flow or pressure control at the air handler level	1 - On off time control					1/3	0/0	0/0	0/0	0.028	0.000	0.000	0.000	0.083	0.000	0.000	0.000
Equal Weightings: Each impact criteria 25% and each service 33%											0.069	0.028	0.028	0.028	0.250	0.167	0.167	0.167
											0.153				0.750			
											20.4%							

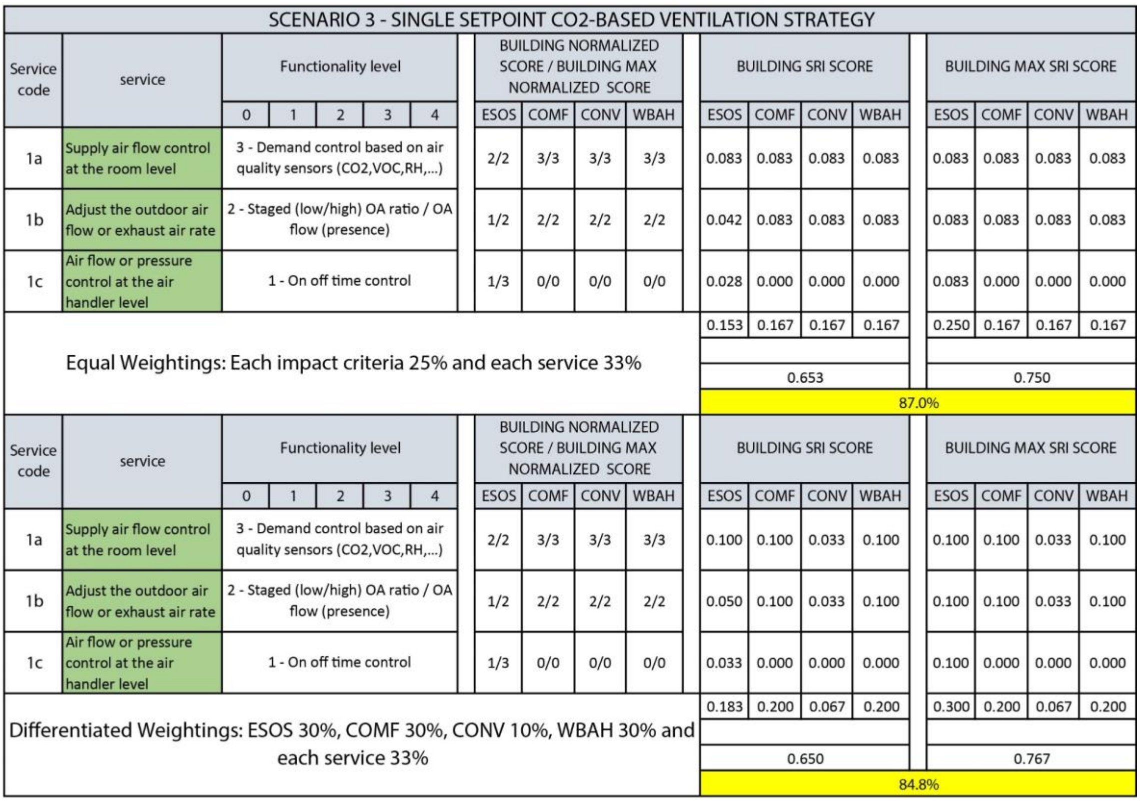
Service code	service	Functionality level					BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0	1	2	3	4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	1 - Time control					1/2	1/3	1/3	1/3	0.050	0.033	0.011	0.033	0.100	0.100	0.033	0.100
1b	Adjust the outdoor air flow or exhaust air rate	0 - Fixed OA ratio / OA flow					0/2	0/2	0/2	0/2	0.000	0.000	0.000	0.000	0.100	0.100	0.033	0.100
1c	Air flow or pressure control at the air handler level	1 - On off time control					1/3	0/0	0/0	0/0	0.033	0.000	0.000	0.000	0.100	0.000	0.000	0.000
Differentiated Weightings: ESOS 30%, COMF 30%, CONV 10%, WBAH 30% and each service 33%											0.083	0.033	0.011	0.033	0.300	0.200	0.067	0.200
											0.161				0.767			
											21.0%							

Figure 6.2 – SRI score calculation for CS1.



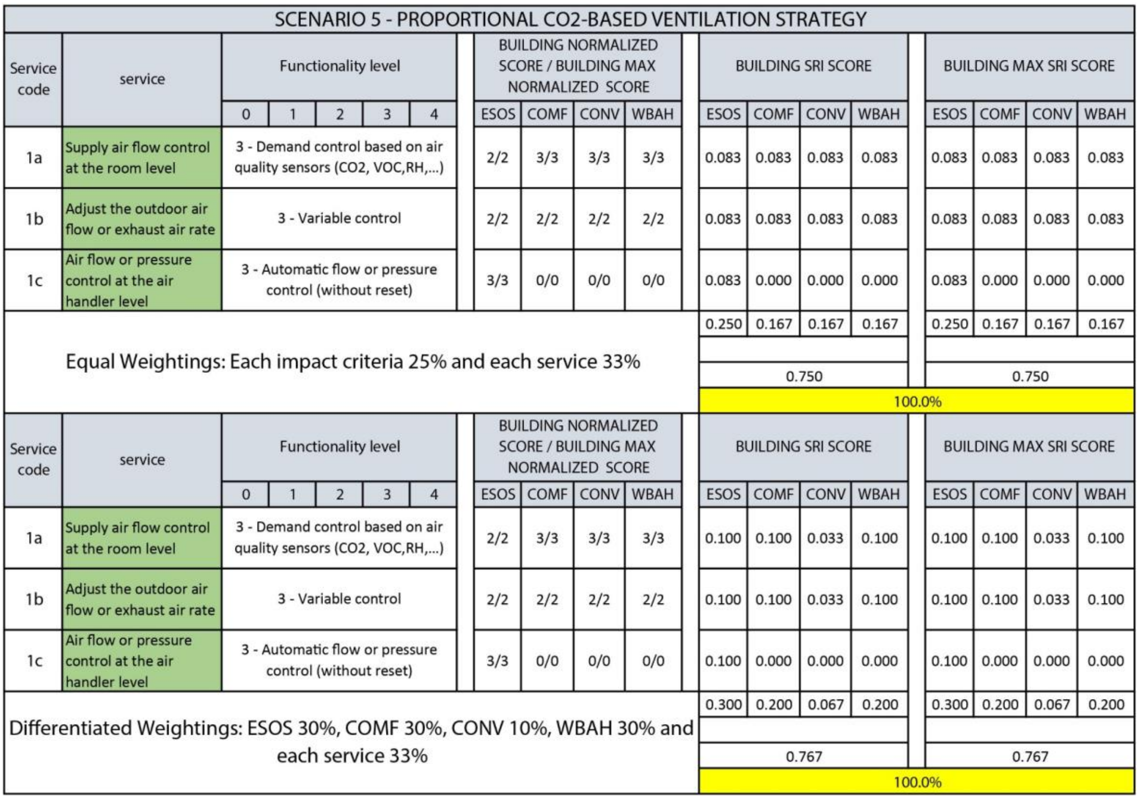
SCENARIO 2 - OCCUPANCY LEVEL-BASED VENTILATION STRATEGY														
Service code	service	Functionality level	BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0 1 2 3 4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	2 - Occupancy detection control	1/2	2/3	2/3	2/3	0.042	0.056	0.056	0.056	0.083	0.083	0.083	0.083
1b	Adjust the outdoor air flow or exhaust air rate	3 - Variable control	2/2	2/2	2/2	2/2	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083
1c	Air flow or pressure control at the air handler level	3 - Automatic flow or pressure control (without reset)	3/3	0/0	0/0	0/0	0.083	0.000	0.000	0.000	0.083	0.000	0.000	0.000
Equal Weightings: Each impact criteria 25% and each service 33%							0.208	0.139	0.139	0.139	0.250	0.167	0.167	0.167
							0.625				0.750			
							83.3%							
Service code	service	Functionality level	BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0 1 2 3 4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	2 - Occupancy detection control	1/2	2/3	2/3	2/3	0.050	0.067	0.022	0.067	0.100	0.100	0.033	0.100
1b	Adjust the outdoor air flow or exhaust air rate	3 - Variable control	2/2	2/2	2/2	2/2	0.100	0.100	0.033	0.100	0.100	0.100	0.033	0.100
1c	Air flow or pressure control at the air handler level	3 - Automatic flow or pressure control (without reset)	3/3	0/0	0/0	0/0	0.100	0.000	0.000	0.000	0.100	0.000	0.000	0.000
Differentiated Weightings: ESOS 30%, COMF 30%, CONV 10%, WBAH 30% and each service 33%							0.250	0.167	0.056	0.167	0.300	0.200	0.067	0.200
							0.639				0.767			
							83.3%							

Figure 6.3 – SRI score calculation for CS2.



SCENARIO 3 - SINGLE SETPOINT CO2-BASED VENTILATION STRATEGY														
Service code	service	Functionality level	BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0 1 2 3 4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	3 - Demand control based on air quality sensors (CO2,VOC,RH,...)	2/2	3/3	3/3	3/3	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083
1b	Adjust the outdoor air flow or exhaust air rate	2 - Staged (low/high) OA ratio / OA flow (presence)	1/2	2/2	2/2	2/2	0.042	0.083	0.083	0.083	0.083	0.083	0.083	0.083
1c	Air flow or pressure control at the air handler level	1 - On off time control	1/3	0/0	0/0	0/0	0.028	0.000	0.000	0.000	0.083	0.000	0.000	0.000
Equal Weightings: Each impact criteria 25% and each service 33%							0.153	0.167	0.167	0.167	0.250	0.167	0.167	0.167
							0.653				0.750			
							87.0%							
Service code	service	Functionality level	BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0 1 2 3 4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	3 - Demand control based on air quality sensors (CO2,VOC,RH,...)	2/2	3/3	3/3	3/3	0.100	0.100	0.033	0.100	0.100	0.100	0.033	0.100
1b	Adjust the outdoor air flow or exhaust air rate	2 - Staged (low/high) OA ratio / OA flow (presence)	1/2	2/2	2/2	2/2	0.050	0.100	0.033	0.100	0.100	0.100	0.033	0.100
1c	Air flow or pressure control at the air handler level	1 - On off time control	1/3	0/0	0/0	0/0	0.033	0.000	0.000	0.000	0.100	0.000	0.000	0.000
Differentiated Weightings: ESOS 30%, COMF 30%, CONV 10%, WBAH 30% and each service 33%							0.183	0.200	0.067	0.200	0.300	0.200	0.067	0.200
							0.650				0.767			
							84.8%							

Figure 6.4 – SRI score calculation for CS3.



SCENARIO 5 - PROPORTIONAL CO2-BASED VENTILATION STRATEGY

Service code	service	Functionality level					BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0	1	2	3	4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	3 - Demand control based on air quality sensors (CO2, VOC,RH,...)					2/2	3/3	3/3	3/3	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083
1b	Adjust the outdoor air flow or exhaust air rate	3 - Variable control					2/2	2/2	2/2	2/2	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083
1c	Air flow or pressure control at the air handler level	3 - Automatic flow or pressure control (without reset)					3/3	0/0	0/0	0/0	0.083	0.000	0.000	0.000	0.083	0.000	0.000	0.000
Equal Weightings: Each impact criteria 25% and each service 33%											0.250	0.167	0.167	0.167	0.250	0.167	0.167	0.167
											0.750				0.750			
											100.0%							

Service code	service	Functionality level					BUILDING NORMALIZED SCORE / BUILDING MAX NORMALIZED SCORE				BUILDING SRI SCORE				BUILDING MAX SRI SCORE			
		0	1	2	3	4	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH	ESOS	COMF	CONV	WBAH
1a	Supply air flow control at the room level	3 - Demand control based on air quality sensors (CO2, VOC,RH,...)					2/2	3/3	3/3	3/3	0.100	0.100	0.033	0.100	0.100	0.100	0.033	0.100
1b	Adjust the outdoor air flow or exhaust air rate	3 - Variable control					2/2	2/2	2/2	2/2	0.100	0.100	0.033	0.100	0.100	0.100	0.033	0.100
1c	Air flow or pressure control at the air handler level	3 - Automatic flow or pressure control (without reset)					3/3	0/0	0/0	0/0	0.100	0.000	0.000	0.000	0.100	0.000	0.000	0.000
Differentiated Weightings: ESOS 30%, COMF 30%, CONV 10%, WBAH 30% and each service 33%											0.300	0.200	0.067	0.200	0.300	0.200	0.067	0.200
											0.767				0.767			
											100.0%							

Figure 6.5 – SRI score calculation for CS5.

Although in this article the SRI score regarding different ventilation strategies and models available in an office room have been calculated and presented, but in a broader view, it shows the importance of availability of smart services in buildings. Especially for those that are going under retrofit or renovation process, knowing that the presence of controlled ventilation would lead to an improve in their SRI score.

6.3. Recent Updates of the SRI

As mentioned earlier, the articles presented in the previous section were prepared based on the “Support for setting up a Smart Readiness Indicator for buildings and related impact assessment - Second progress report” in 2019. Reviewing the “Final report on the technical support to the development of a smart readiness indicator for buildings” published in summer 2020, it was found that some changes and updates have been applied, which are briefly summarized in this section. The study group has decided to omit the Demand-Side Management (DSM) which may facilitate the communication, as the DSM term is quite unknown among public. It should be mentioned that this rearrangement does not lower the significance of DSM and grid control as it has been considered in the updated detailed service catalogue. Moreover, the final report discovered an overlap between energy flexibility and storage and self-generation and has decided to omit the self-generation impact criterion. It should be also noted that the benefits of energy storage towards the grid are covered by the energy flexibility and storage impact criterion, and the advantages of autonomy are taken into account by the convenience impact criterion. Therefore, the final study report has listed the nine smart readiness technical domains and the seven smart readiness impact criteria as illustrated in figure 6.6.

Figure 6.6 – The SRI domains (top) and impact criteria (bottom).

Moreover, and unlike the first technical support study, two catalogues of smart ready services have been compiled, a simplified assessment method (method A) and a detailed assessment method (method B) in which relevant services have been listed and their potential impacts on building users and the energy grid have been described. The service catalogues considered the known and widely marketed technologies. Once again it should be mentioned that according to the requirements from the revised EPBD, three key functionalities of smart readiness in buildings have been taken into account when defining the smart ready services in the SRI catalogues. Also unlike the first study in which 112 services were included in the catalogue, the final report presented 27 simplified services for method A and 54 detailed service for method B. In addition to smart services, some modifications and updates in functionality levels and impact scores have been reported, which are all available in ref. [108].

6.4. Conclusion

The Smart Readiness Indicator is an EU project proposed to raise awareness about the advantages of integrating smart technologies in buildings. The smart readiness score of a building (building unit) is communicated as a percentage that points out the ratio between the smart readiness of the building under study compared to the maximum smart readiness that it might have. In this chapter, the SRI has been studied and the SRI domains, impact criteria and assessment methodology have been presented. Moreover, the methodological framework for its calculation has been implemented and investigated.

According to the findings, in spite of some shortcomings of the proposed methodology in forecasting the energy use, the potential capability of the SRI methodology to be used as an indicator for assessing building energy performance as well as its occupants' comfort has been well observed. Also, still some weaknesses such as the qualitative assessment of the scores for almost all functionality levels as well as the method, multi-criteria decision analysis, which is based on weightings that increases the subjectivity can be mentioned. Furthermore, improving the building smartness without considering the energy efficiency improvement does not necessarily provide an added value for the building users[109].

The following conclusions also have been revealed by some recent research studies [[103], [110]–[116]] on the SRI and its implementation:

The current SRI methodology is not completely capable to identify the influence of all implemented actions on energy performance and IEQ improvements and also some of the influential domains and smart ready services are likely to be underestimated; As the proposed SRI methodology measures the smart capability of buildings, it might be unsuccessful to convert into actual performance of building; The two separate methodologies that exist might lead to inconsistent certifications and lack of clear guidelines and subjective decisions during the evaluation, may lead to unreliable assessments. These conflicts can make misperception among users and threaten the reliability and realization of the SRI framework. It is therefore important to address these issues at the early stages of the scheme's adoption in the member states and the presented methodological framework of SRI requires more research and development to study all potential aspects and resolve the current concerns.

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Chapter 7

CONCLUSION, LIMITATIONS AND FUTURE WORK

Energy demand has been increasing worldwide, therefore, the environmental impact resulting from energy production and consumption has become a major public concern. Building sector is one of the biggest contributors to energy consumption and is responsible for 40% of EU final energy consumption. Energy consumption in buildings refers to many factors such as lighting, domestic and commercial appliances as well as HVAC systems.

Many research focused on development of methods to improve energy efficiency in buildings. However, less attention has been paid dealing with energy-efficient ventilation methods in buildings. Thus, this research has been focused on developing, implementing and testing various ventilation control strategies to improve energy efficiency in buildings and maintain the IAQ in a good level.

7.1. Summary

Throughout this thesis, a background of the research topic has been presented in chapter 2. Chapter 3 presented a comprehensive literature review of various ventilation aspects such as natural ventilation, demand-controlled ventilation, energy-efficient ventilation strategies, the correlation between ventilation and occupants' health and productivity as well as the recently introduced Smart Readiness Indicator (SRI). Chapter 4 focused on development, implementation and analyzing of ventilation control strategies while presented the contribution of this research to the Smart Window research project and the I2L showcase project. Chapter 5 presented the results from simulation studies of the ventilation control strategies using building energy simulation software, *EnergyPlus*. Chapter 6 presented the SRI which was introduced in 2018 revision of the European Energy Performance of Buildings Directive (EPBD).

In summary, this thesis contributes to the study of indoor air quality and energy consumption in buildings via development of ventilation control strategies that can be applied to either new building or those existing going under renovation process. After the extensive literature review in the field of study and finding the research gaps, several ventilation control strategies have been defined, developed, implemented and tested in a real office room to evaluate their functionality and performance. Furthermore, the building energy simulation software, *EnergyPlus*, has been used to simulate the ventilation strategies and perform some sensitivity analyses to find out the factors that are more influential on IAQ and energy consumption. Finally, the smart readiness indicator score of these ventilation control strategies has been calculated which can be useful for building smart services in early-design decisions.

7.2. Responses to the Research Questions

Although the core research chapters have already addressed the research questions, the main responses and related findings deriving from the research questions are discussed and presented below:

- ***How to implement ventilation control strategies in order to improve energy efficiency and maintain indoor air quality in a good level?***

Ventilation is one of the key elements for providing suitable indoor air quality as it is the process of replacing stale indoor air by fresh outdoor air, which highly contributes to energy use and the well-being, comfort and productivity of the building occupants. This process can be done either using mechanical equipment such as fans or blowers, being called mechanical ventilation (active), or without interaction of any mechanical means, known as natural ventilation (passive). In order to implement ventilation control strategies, the first step is to find out the critical factors affecting the indoor air quality and the energy consumption. For energy consumption, the mechanical ventilation and for indoor air quality the indoor concentration of CO_2 have been considered as the influential factors. Also, the building occupancy, as people are the source of indoor CO_2 generation, has been considered. Then, the ventilation control strategies have been defined based on these influential factors. As presented in chapter 4 and 5, the developed ventilation control strategies are either CO_2-based or occupancy based or both. Later, in order to assess the performance of these ventilation control strategies, experimental and simulation methods have been used.

- ***Can smart window be a suitable product for improving building's energy efficiency while maintaining suitable indoor air quality?***

Although this thesis developed and analyzed the mechanical ventilation control strategies for the Smart Window project, it is well proved that, as it utilizes both natural and mechanical ventilation (hybrid ventilation), it employs the advantages from both methods while excludes their drawbacks resulting in lower energy use and providing a good IAQ. Also, considering the quite low social awareness about ventilation and IAQ, occupant window opening behavior to employ natural ventilation varies a lot. Therefore, this product, as a smart ready service for buildings, provides the required ventilation rate without interaction of the occupants with the lowest energy use.

- ***What are the best control strategies to mitigate energy consumption while providing good indoor air quality?***

The experimental and simulation results of the mechanical demand-controlled ventilation strategies proved the influence of control and smartness in lowering energy consumption and providing good IAQ. Several ventilation strategies have been developed and analyzed in this research. The simplest and most basic strategy, occupancy period based, which ventilate the space only if it is occupied uses more energy than other strategies while using occupancy level based strategy, the fresh air will be supplied to the space based on the number of the occupants and will cause noticeable energy saving. Considering the CO_2-based ventilation control strategies, different single, double and triple set-points strategies, as well as modulation or proportional strategy, have been developed and tested. Based on the results, the triple set-point (leveling) and proportional strategies performed better than the others and also the sensitivity analysis proved that the closer the minimum set-point to the maximum one, the lower the energy consumption, while maintaining a good IAQ. Of course depending on the building application, its occupancy model and the activity level of its occupants, other strategies may perform better.

- ***Can SRI be a suitable framework to assess human beings' adaptation with modern digitalization?***

The SRI methodology has been developed considering the ability to adapt the operation of the building according to the occupants' needs, considering their comfort conditions and providing them with information about energy consumption. There are still some weaknesses in the SRI framework such as the qualitative assessment of the scores for almost all functionality levels as well as the method, multi-criteria decision analysis, which is based on weightings and that increases the subjectivity. According to the findings, in spite of some shortcomings of the proposed methodology in forecasting the energy use, the potential capability of the SRI methodology to be used as an indicator for assessing building energy performance as well as its occupants' comfort has been well observed.

7.3. Recommendations

The outcome of the present thesis can be valuable for real-life applications by helping building designers, stakeholders (e.g., owners, operators), or policy makers to reduce energy consumption, and to improve the IAQ.

Considering the outcome of this thesis and based on the obtained results, some recommendations can be provided to enhance the energy performance of ventilation systems in office building. As office buildings are spaces where the occupants need to be productive, it is important to provide suitable indoor environment for them. Using smart systems to control indoor environment condition is highly recommended and seems to be a necessity in the era of digitalization, which enables the building services to provide good indoor environment with lowest energy use. In this way, the ventilation control strategies developed in this research can be used for office spaces to minimize the energy consumption and the period that occupants might face weak IAQ.

7.4. Limitations and Future Work

The work developed in this thesis presents some limitations from which several can be developed in future research:

The results from this thesis are valid for a single zone office building. Future work can follow the approach hereby presented in other type of buildings and in multiple zones. Moreover, assumption for a constant reference outdoor air CO_2 concentration can be reconsidered in future work and real outdoor concentration might be used. Also, based on this assumption, the results are valid for non-polluted regions and in case of polluted areas other factors and methodologies, like filtering, air cleaning and localized extraction may be considered. Furthermore, this research developed and implemented several mechanical demand-controlled ventilation strategies and assessed the energy performance and IAQ resulted by them, while in future work, not only natural ventilation but also heating and cooling condition can be considered. This enables to evaluate the thermal comfort along with the IAQ and the energy consumption.

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BIBLIOGRAPHY

[1] L. Pérez-Lombard, J. Ortiz, J. F. Coronel, and I. R. Maestre, “A review of HVAC systems requirements in building energy regulations,” *Energy Build.*, vol. 43, no. 2–3, pp. 255–268, Feb. 2011.

[2] “Energy statistics - an overview - Statistics Explained.” [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Final_energy_consumption. [Accessed: 03-Dec-2021].

[3] B. Tofield and M. Ingham, “Refurbishing Europe—An EU strategy for energy efficiency and climate action led by building refurbishment,” *Build with CaRe, Norwich*, 2012.

[4] “COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN COUNCIL A European Economic Recovery Plan,” Brussels, 2008.

[5] K. Melton, “RESEARCH PRIORITIES FOR RENEWABLE ENERGY TECHNOLOGY BY 2020 AND BEYOND,” 2010.

[6] “ENERGY-EFFICIENT BUILDINGS PPP MULTI-ANNUAL ROADMAP AND LONGER TERM STRATEGY.”

[7] B. Chenari, J. D. Carrilho, and M. Gameiro, “Towards sustainable , energy-efficient and healthy ventilation strategies in buildings : A review,” *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1426–1447, 2016.

[8] *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Published in Official Journal of the European Union, L 153/13, 18 June 2010.* .

[9] M. W. LIDDAMENT, “A Review of Ventilation and the Quality of Ventilation Air,” *Indoor Air*, vol. 10, no. 3, pp. 193–199, 2000.

[10] E. Gruber *et al.*, “Deliverable D26: Report on the project results. Technical report, EL-TERTIARY project, Intelligent Energy - Europe.”

[11] “DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010,” 2010.

[12] E. THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION, “amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency,” *Off. J. Eur. Union*, pp. 75–91, 2018.

[13] “DIN EN 16798-1 - European Standards.” [Online]. Available: https://www.en-standard.eu/din-en-16798-1-energy-performance-of-buildings-ventilation-for-buildings-part-1-indoor-environmental-input-parameters-for-design-and-assessment-of-energy-performance-of-buildings-addressing-indoor-air-quality-thermal-environment-lighting-and-acoustics-mod/. [Accessed: 24-Dec-2021].

[14] “ANSI/ASHRAE Standard 55-2010. Thermal Comfort Conditions for Human

Occupancy. American Society of Heating, Air-Conditioning, and Refrigeration Engineers, Inc., Atlanta, GA, 2010.”

[15] “International Standard ISO 7730:2005. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Organization for St.”

[16] “European standard EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. European Committee for Standardization, Bruss.”

[17] P.O. Fanger, *Thermal comfort : analysis and applications in environmental engineering*. Danish Technical Press, 1970.

[18] L. Fang, G. Clausen, and P. O. Fanger, “Impact of temperature and humidity on the perception of indoor air quality,” *Indoor Air*, vol. 8, no. 1983, pp. 80–90, 1998.

[19] “WHO guidelines for indoor air quality: selected pollutants,” Copenhagen, 2010.

[20] P. Op’t Veld, “Introduction to EC RESHYVENT–EU cluster project on demand controlled hybrid ventilation for residential buildings,” *Build. Environ.*, vol. 43, no. 8, pp. 1342–1349, Aug. 2008.

[21] K. J. Lomas and Y. Ji, “Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards,” *Energy Build.*, vol. 41, no. 6, pp. 629–653, 2009.

[22] G. Cao *et al.*, “A review of the performance of different ventilation and airflow distribution systems in buildings,” *Build. Environ.*, vol. 73, pp. 171–186, 2014.

[23] Hazim B. Awbi, *Ventilation of Buildings*, 2nd editio. New York: Spon Press, 2003.

[24] M. W. LIDDAMENT, “A Guide to Energy Efficient Ventilation,” *Air Infiltration Vent. Cent.*, 1996.

[25] P. S.P. Corgnati, M. Gameiro da Silva, R. Ansaldi, E. Asadi, J.J. Costa, M. Filippi, J. Kaczmarczyk, A.K. Melikov, B.W. Olesen, Z. Popiolek, Wargocki, *Indoor Climate Quality Assessment/REHVA Guidebook No. 14*. Brussles: REHVA, 2011.

[26] ASHRAE 62.1, “Ventilation for Acceptable Indoor Air Quality,” 2010.

[27] P. O. Fanger, “Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors,” *Energy Build.*, vol. 12, no. 1, pp. 1–6, Apr. 1988.

[28] CEN REPORT, “EN CR 1752 Ventilation for buildings - Design criteria for the indoor environment,” 1998.

[29] ECA (European Collaborative Action), “Indoor Air Quality & Its Impact on Man - Report No. 11 - Guidelines for Ventilation Requirements in Buildings,” *Office*, 1992.

[30] N. R. M. Sakiyama, J. C. Carlo, J. Frick, and H. Garrecht, “Perspectives of naturally ventilated buildings: A review,” *Renew. Sustain. Energy Rev.*, vol. 130, p. 109933, Sep. 2020.

[31] J. Chen, G. S. Brager, G. Augenbroe, and X. Song, “Impact of outdoor air quality on the natural ventilation usage of commercial buildings in the US,” *Appl. Energy*, vol. 235, pp. 673–684, Feb. 2019.

[32] H. Park and D. Y. Park, “Comparative analysis on predictability of natural ventilation rate based on machine learning algorithms,” *Build. Environ.*, vol. 195, p. 107744, May 2021.

[33] M. Fordham, “Natural ventilation,” *Renew. Energy*, vol. 19, pp. 17–37, 2000.

[34] J. Cheng, D. Qi, A. Katal, L. (Leon) Wang, and T. Stathopoulos, “Evaluating wind-driven natural ventilation potential for early building design,” *J. Wind Eng. Ind. Aerodyn.*, vol. 182, pp. 160–169, Nov. 2018.

[35] H. Zhang *et al.*, “A critical review of combined natural ventilation techniques in sustainable buildings,” *Renew. Sustain. Energy Rev.*, vol. 141, p. 110795, May 2021.

[36] N. R. M. Sakiyama, L. Mazzaferro, J. C. Carlo, T. Bejat, and H. Garrecht, “Natural ventilation potential from weather analyses and building simulation,” *Energy Build.*, vol. 231, p. 110596, Jan. 2021.

[37] N. Pesic, J. R. Calzada, and A. M. Alcojor, “Natural ventilation potential of the Mediterranean coastal region of Catalonia,” *Energy Build.*, vol. 169, pp. 236–244, Jun. 2018.

[38] N. Z. Ghalam, M. Farrokhzad, and H. Nazif, “Investigation of optimal natural ventilation in residential complexes design for temperate and humid climates,” *Sustain. Energy, Grids Networks*, vol. 27, p. 100500, Sep. 2021.

[39] A. Figueroa-Lopez, A. Arias, X. Oregi, and I. Rodríguez, “Evaluation of passive strategies, natural ventilation and shading systems, to reduce overheating risk in a passive house tower in the north of Spain during the warm season,” *J. Build. Eng.*, vol. 43, p. 102607, Nov. 2021.

[40] C. Liu, J. Yang, S. Ji, Y. Lu, P. Wu, and C. Chen, “Influence of natural ventilation rate on indoor PM2.5 deposition,” *Build. Environ.*, vol. 144, pp. 357–364, Oct. 2018.

[41] T. Ahmed, P. Kumar, and L. Mottet, “Natural ventilation in warm climates: The challenges of thermal comfort, heatwave resilience and indoor air quality,” *Renew. Sustain. Energy Rev.*, vol. 138, p. 110669, Mar. 2021.

[42] G. Carrilho da Graça and P. Linden, “Ten questions about natural ventilation of non-domestic buildings,” *Build. Environ.*, vol. 107, pp. 263–273, Oct. 2016.

[43] J. M. Alessandrini, J. Ribéron, and D. Da Silva, “Will naturally ventilated dwellings remain safe during heatwaves?,” *Energy Build.*, vol. 183, pp. 408–417, Jan. 2019.

[44] J. Wang, S. Wang, T. Zhang, and F. Battaglia, “Assessment of single-sided natural ventilation driven by buoyancy forces through variable window

configurations," *Energy Build.*, vol. 139, pp. 762–779, Mar. 2017.

[45] Z. Lei, C. Liu, L. Wang, and N. Li, "Effect of natural ventilation on indoor air quality and thermal comfort in dormitory during winter," *Build. Environ.*, vol. 125, pp. 240–247, Nov. 2017.

[46] D. Gupta and V. R. Khare, "Natural Ventilation Design: Predicted and Measured Performance of a Hostel Building in Composite Climate of India," *Energy Built Environ.*, vol. 2, no. 1, pp. 82–93, Jan. 2021.

[47] Y. Tao, H. Zhang, D. Huang, C. Fan, J. Tu, and L. Shi, "Ventilation performance of a naturally ventilated double skin façade with low-e glazing," *Energy*, vol. 229, p. 120706, Aug. 2021.

[48] T. Srisamranrungruang and K. Hiyama, "Balancing of natural ventilation, daylight, thermal effect for a building with double-skin perforated facade (DSPF)," *Energy Build.*, vol. 210, p. 109765, Mar. 2020.

[49] Y. Choi and D. Song, "How to quantify natural ventilation rate of single-sided ventilation with trickle ventilator?," *Build. Environ.*, vol. 181, p. 107119, Aug. 2020.

[50] Y. Tao, X. Fang, S. Setunge, J. Tu, J. Liu, and L. Shi, "Naturally ventilated double-skin façade with adjustable louvers," *Sol. Energy*, vol. 225, pp. 33–43, Sep. 2021.

[51] D. H. Han *et al.*, "Experimental study on thermal buoyancy-induced natural ventilation," *Energy Build.*, vol. 177, pp. 1–11, Oct. 2018.

[52] P. Saadatjoo, M. Mahdavinejad, G. Zhang, and K. Vali, "Influence of permeability ratio on wind-driven ventilation and cooling load of mid-rise buildings," *Sustain. Cities Soc.*, vol. 70, p. 102894, Jul. 2021.

[53] X. Meng, Y. Wang, X. Xing, and Y. Xu, "Experimental study on the performance of hybrid buoyancy-driven natural ventilation with a mechanical exhaust system in an industrial building," *Energy Build.*, vol. 208, p. 109674, Feb. 2020.

[54] J. Kim, F. Tartarini, T. Parkinson, P. Cooper, and R. de Dear, "Thermal comfort in a mixed-mode building: Are occupants more adaptive?," *Energy Build.*, vol. 203, p. 109436, Nov. 2019.

[55] J. Chen, G. Augenbroe, and X. Song, "Lighted-weighted model predictive control for hybrid ventilation operation based on clusters of neural network models," *Autom. Constr.*, vol. 89, pp. 250–265, May 2018.

[56] J. C. Salcido, A. A. Raheem, and R. R. A. Issa, "From simulation to monitoring: Evaluating the potential of mixed-mode ventilation (MMV) systems for integrating natural ventilation in office buildings through a comprehensive literature review," *Energy Build.*, vol. 127, pp. 1008–1018, Sep. 2016.

[57] G. Guyot, M. H. Sherman, and I. S. Walker, "Smart ventilation energy and indoor air quality performance in residential buildings: A review," *Energy Build.*, vol. 165, pp. 416–430, Apr. 2018.

[58] X. Du, R. Bokel, and A. van den Dobbelsteen, "Using spatial indicators to predict

ventilation and energy performance-correlation analysis for an apartment building in five Chinese cities," *Front. Archit. Res.*, vol. 8, no. 2, pp. 175–190, Jun. 2019.

[59] J. Kim and R. de Dear, "Is mixed-mode ventilation a comfortable low-energy solution? A literature review," *Build. Environ.*, vol. 205, p. 108215, Nov. 2021.

[60] L. Ledo Gomis, M. Fiorentini, and D. Daly, "Potential and practical management of hybrid ventilation in buildings," *Energy Build.*, vol. 231, p. 110597, Jan. 2021.

[61] S. Omrani, S. Matour, K. Bamdad, and N. Izadyar, "Ceiling fans as ventilation assisting devices in buildings: A critical review," *Build. Environ.*, vol. 201, p. 108010, Aug. 2021.

[62] S. S. Y. Lau, J. Zhang, and Y. Tao, "A comparative study of thermal comfort in learning spaces using three different ventilation strategies on a tropical university campus," *Build. Environ.*, vol. 148, pp. 579–599, Jan. 2019.

[63] A. Malkawi, B. Yan, Y. Chen, and Z. Tong, "Predicting thermal and energy performance of mixed-mode ventilation using an integrated simulation approach Article History," *Build. Simul.*, vol. 9, no. 3, 2016.

[64] D. Sánchez-García, C. Rubio-Bellido, J. J. M. del Río, and A. Pérez-Fargallo, "Towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change," *Energy Build.*, vol. 187, pp. 173–185, Mar. 2019.

[65] E. Barbadilla-Martín, J. Guadix Martín, J. M. Salmerón Lissén, J. Sánchez Ramos, and S. Álvarez Domínguez, "Assessment of thermal comfort and energy savings in a field study on adaptive comfort with application for mixed mode offices," *Energy Build.*, vol. 167, pp. 281–289, May 2018.

[66] A. Yang, S. B. Holøs, M. O. Resvoll, M. Mysen, and Ø. Fjellheim, "Temperature-dependent ventilation rates might improve perceived air quality in a demand-controlled ventilation strategy," *Build. Environ.*, vol. 205, p. 108180, Nov. 2021.

[67] C. R. Ruivo, M. Gameiro da Silva, and E. E. Broday, "Study on thermal comfort by using an atmospheric pressure dependent predicted mean vote index," *Build. Environ.*, vol. 206, p. 108370, Dec. 2021.

[68] P. Jafarpur and U. Berardi, "Effects of climate changes on building energy demand and thermal comfort in Canadian office buildings adopting different temperature setpoints," *J. Build. Eng.*, vol. 42, p. 102725, Oct. 2021.

[69] J. Park, H. Choi, D. Kim, and T. Kim, "Development of novel PMV-based HVAC control strategies using a mean radiant temperature prediction model by machine learning in Kuwaiti climate," *Build. Environ.*, vol. 206, p. 108357, Dec. 2021.

[70] L. Schibuola, M. Scarpa, and C. Tambani, "CO2 based ventilation control in energy retrofit: An experimental assessment," *Energy*, vol. 143, pp. 606–614, Jan. 2018.

[71] S. Taheri and A. Razban, "Learning-based CO2 concentration prediction: Application to indoor air quality control using demand-controlled ventilation,"

Build. Environ., vol. 205, p. 108164, Nov. 2021.

[72] E. J. Herrera-López *et al.*, “A control approach to regulate formaldehyde concentrations indoors a gross anatomy laboratory via a switched fuzzy logic system,” *Build. Environ.*, vol. 188, p. 107492, Jan. 2021.

[73] A. Schieweck, “Very volatile organic compounds (VVOC) as emissions from wooden materials and in indoor air of new prefabricated wooden houses,” *Build. Environ.*, vol. 190, p. 107537, Mar. 2021.

[74] N. Fu, P. Wei, Y. Jia, X. Zheng, and J. Guan, “Indoor volatile organic compounds in densely occupied education buildings of four universities: Target list, concentration levels and correlation analysis,” *Build. Environ.*, vol. 191, p. 107599, Mar. 2021.

[75] T. Zhang, Y. Zhang, A. Li, Y. Gao, Y. Rao, and Q. Zhao, “Study on the kinetic characteristics of indoor air pollutants removal by ventilation,” *Build. Environ.*, p. 108535, Nov. 2021.

[76] I. S. Walker and M. H. Sherman, “Effect of ventilation strategies on residential ozone levels,” *Build. Environ.*, vol. 59, pp. 456–465, 2013.

[77] W. O’Brien *et al.*, “An international review of occupant-related aspects of building energy codes and standards,” *Build. Environ.*, vol. 179, p. 106906, Jul. 2020.

[78] J. D. Clark, B. D. Less, S. M. Dutton, I. S. Walker, and M. H. Sherman, “Efficacy of occupancy-based smart ventilation control strategies in energy-efficient homes in the United States,” *Build. Environ.*, vol. 156, pp. 253–267, Jun. 2019.

[79] S. Chen, G. Zhang, X. Xia, Y. Chen, S. Setunge, and L. Shi, “The impacts of occupant behavior on building energy consumption: A review,” *Sustain. Energy Technol. Assessments*, vol. 45, p. 101212, Jun. 2021.

[80] S. Pan *et al.*, “A study on influential factors of occupant window-opening behavior in an office building in China,” *Build. Environ.*, vol. 133, pp. 41–50, Apr. 2018.

[81] H. Cho, D. Cabrera, S. Sardy, R. Kilchherr, S. Yilmaz, and M. K. Patel, “Evaluation of performance of energy efficient hybrid ventilation system and analysis of occupants’ behavior to control windows,” *Build. Environ.*, vol. 188, p. 107434, Jan. 2021.

[82] X. Chen and H. Yang, “Sensitivity analysis and optimization of a typical passively designed residential building with hybrid ventilation in hot and humid climates,” *Energy Procedia*, vol. 142, pp. 1781–1786, Dec. 2017.

[83] S. Yuan, C. Vallianos, A. Athienitis, and J. Rao, “A study of hybrid ventilation in an institutional building for predictive control,” *Build. Environ.*, vol. 128, pp. 1–11, Jan. 2018.

[84] C. Vallianos, A. Athienitis, and J. Rao, “Hybrid ventilation in an institutional building: Modeling and predictive control,” *Build. Environ.*, vol. 166, p. 106405, Dec. 2019.

[85] J. M. Rey-Hernández, J. F. San José-Alonso, E. Velasco-Gómez, C. Yousif, and F. J. Rey-Martínez, “Performance analysis of a hybrid ventilation system in a near zero energy building,” *Build. Environ.*, vol. 185, p. 107265, Nov. 2020.

[86] J. Fernández-Agüera, S. Domínguez-Amarillo, C. Alonso, and F. Martín-Consuegra, “Thermal comfort and indoor air quality in low-income housing in Spain: The influence of airtightness and occupant behaviour,” *Energy Build.*, vol. 199, pp. 102–114, Sep. 2019.

[87] A. Monge-Barrio *et al.*, “Encouraging natural ventilation to improve indoor environmental conditions at schools. Case studies in the north of Spain before and during COVID,” *Energy Build.*, vol. 254, p. 111567, Jan. 2022.

[88] A. Y. Lim, M. Yoon, E. H. Kim, H. A. Kim, M. J. Lee, and H. K. Cheong, “Effects of mechanical ventilation on indoor air quality and occupant health status in energy-efficient homes: A longitudinal field study,” *Sci. Total Environ.*, vol. 785, p. 147324, Sep. 2021.

[89] Y. Yuan, Z. Luo, J. Liu, Y. Wang, and Y. Lin, “Health and economic benefits of building ventilation interventions for reducing indoor PM2.5 exposure from both indoor and outdoor origins in urban Beijing, China,” *Sci. Total Environ.*, vol. 626, pp. 546–554, Jun. 2018.

[90] “Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/31/EU on the energy performance of buildings. COM(2016) 765 final.” .

[91] Z. Yang and B. Becerik-Gerber, “Assessing the impacts of real-time occupancy state transitions on building heating/cooling loads,” *Energy Build.*, vol. 135, pp. 201–211, Jan. 2017.

[92] K. Ben Jemaa, P. Kotman, and K. Graichen, “Model-Based Potential Analysis of Demand-Controlled Ventilation in Buildings,” *IFAC-PapersOnLine*, vol. 51, no. 2, pp. 85–90, Jan. 2018.

[93] C. Wang, K. Pattawi, and H. Lee, “Energy saving impact of occupancy-driven thermostat for residential buildings,” *Energy Build.*, vol. 211, p. 109791, Mar. 2020.

[94] M. Krarti, “Evaluation of occupancy-based temperature controls on energy performance of KSA residential buildings,” *Energy Build.*, vol. 220, p. 110047, Aug. 2020.

[95] L. Nikdel, K. Janoyan, S. D. Bird, and S. E. Powers, “Multiple perspectives of the value of occupancy-based HVAC control systems,” *Build. Environ.*, vol. 129, pp. 15–25, Feb. 2018.

[96] B. Merema, M. Delwati, M. Sourbron, and H. Breesch, “Demand controlled ventilation (DCV) in school and office buildings: Lessons learnt from case studies,” *Energy Build.*, vol. 172, pp. 349–360, Aug. 2018.

[97] L. Schibuola, M. Scarpa, and C. Tambani, “Performance optimization of a demand controlled ventilation system by long term monitoring,” *Energy Build.*, vol. 169, pp. 48–57, Jun. 2018.

[98] S. Zhang, Z. Ai, and Z. Lin, “Novel demand-controlled optimization of constant-

air-volume mechanical ventilation for indoor air quality, durability and energy saving," *Appl. Energy,* vol. 293, p. 116954, Jul. 2021.

[99] S. Haddad *et al.*, "On the potential of demand-controlled ventilation system to enhance indoor air quality and thermal condition in Australian school classrooms," *Energy Build.*, vol. 238, p. 110838, May 2021.

[100] H. C. de Rochefort, "EU Smart Readiness Indicator for buildings," *Assoc. Decent. Energy,* 2019.

[101] et al. S. Verbeke, Y. Ma, P. Van Tichelen, S. Bogaert, V. Gómez Oñate Waide Strategic Efficiency, P. Waide ECOFYS, "Support for setting up a smart readiness indicator for building and related impact assessment Final report," 2018.

[102] J. Al Dakheel, C. Del Pero, N. Aste, and F. Leonforte, "Smart buildings features and key performance indicators: A review," *Sustain. Cities Soc.*, vol. 61, p. 102328, Oct. 2020.

[103] B. Ramezani, M. G. da Silva, and N. Simões, "Application of smart readiness indicator for Mediterranean buildings in retrofitting actions," *Energy Build.*, vol. 249, p. 111173, Oct. 2021.

[104] D. B. Crawley *et al.*, "EnergyPlus : creating a new-generation building energy simulation program," *Energy Build.,* vol. 33, pp. 319–331, 2001.

[105] D. B. Crawley, J. W. Hand, M. Kummert, and B. T. Griffith, "Contrasting the capabilities of building energy performance simulation programs," *Build. Environ.*, vol. 43, pp. 661–673, 2008.

[106] "Smart finance for smart buildings: investing in energy efficiency in buildings | European Commission," *European Commission*, 2018. [Online]. Available: https://ec.europa.eu/info/news/smart-finance-smart-buildings-investing-energy-efficiency-buildings-2018-feb-07_en/. [Accessed: 21-Nov-2021].

[107] J. S. Stijn Verbeke, Yixiao Ma, Paul Van Tichelen, Sarah Bogaert, Virginia Gómez Oñate, Paul Waide, Kjell Bettgenhäuser, John Ashok, Andreas Hermelink, Markus Offermann, Jan Groezinger, Mathias Uslar, "SUPPORT FOR SETTING UP A SMART READINESS INDICATOR FOR BUILDINGS AND RELATED IMPACT ASSESSMENT FINAL REPORT," 2018.

[108] S. Verbeke, D. Aerts, G. Reynders, Y. Ma, and P. Waide, "Final report on the technical support to the development of a smart readiness indicator for buildings," 2020.

[109] R. Kosonen, *Smart Readiness Indicator (SRI): a tool to prove smartness of building services ?* 2019.

[110] T. Märzinger and D. Österreicher, "Supporting the Smart Readiness Indicator—A Methodology to Integrate A Quantitative Assessment of the Load Shifting Potential of Smart Buildings," *Energies 2019, Vol. 12, Page 1955,* vol. 12, no. 10, p. 1955, May 2019.

[111] I. Vigna, R. Pernetti, G. Pernigotto, and A. Gasparella, "Analysis of the Building Smart Readiness Indicator Calculation: A Comparative Case-Study with Two Panels of Experts," *Energies 2020, Vol. 13, Page 2796,* vol. 13, no. 11, p. 2796,

Jun. 2020.

[112] P. A. Fokaides, C. Panteli, and A. Panayidou, “How Are the Smart Readiness Indicators Expected to Affect the Energy Performance of Buildings: First Evidence and Perspectives,” *Sustain. 2020, Vol. 12, Page 9496*, vol. 12, no. 22, p. 9496, Nov. 2020.

[113] L. Canale *et al.*, “Estimating the Smart Readiness Indicator in the Italian Residential Building Stock in Different Scenarios,” *Energies 2021, Vol. 14, Page 6442*, vol. 14, no. 20, p. 6442, Oct. 2021.

[114] V. Varsami and E. Burman, “An Evaluation of the Smart Readiness Indicator proposed for Buildings,” *Build. Simul. 2021 Conf. 1-3 Sept. 2021, Bruges, Belgium.* , Sep. 2021.

[115] I. Martínez, B. Zalba, R. Trillo-Lado, T. Blanco, D. Cambra, and R. Casas, “Internet of Things (IoT) as Sustainable Development Goals (SDG) Enabling Technology towards Smart Readiness Indicators (SRI) for University Buildings,” *Sustain. 2021, Vol. 13, Page 7647*, vol. 13, no. 14, p. 7647, Jul. 2021.

[116] T. Märzinger and D. Österreicher, “Extending the Application of the Smart Readiness Indicator—A Methodology for the Quantitative Assessment of the Load Shifting Potential of Smart Districts,” *Energies 2020, Vol. 13, Page 3507*, vol. 13, no. 13, p. 3507, Jul. 2020.

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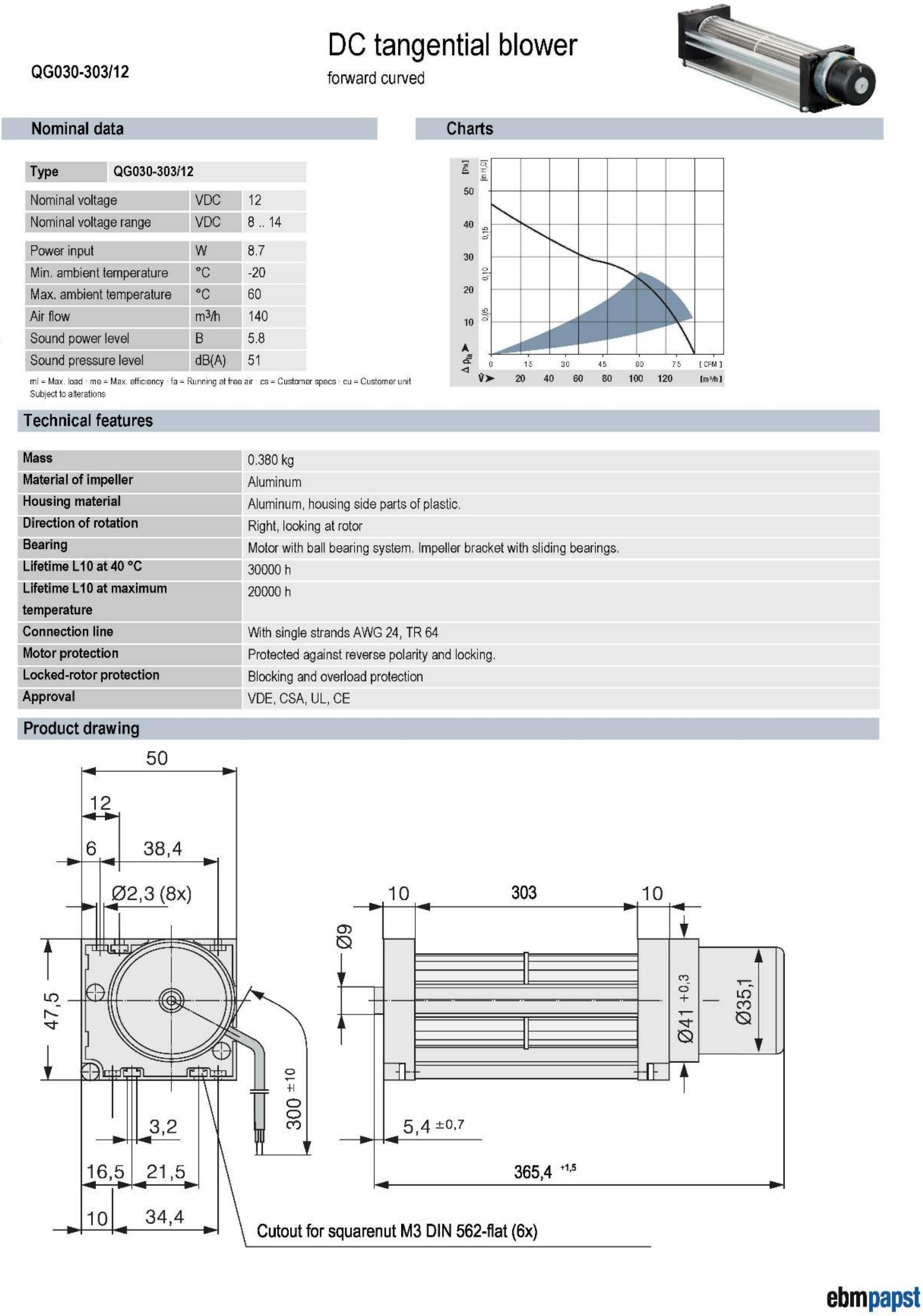
APPENDICES

A. Smart Window Final Prototype Development

Figure A. 1 – Smart Window final prototype.

B. Linear and Centrifugal Fan Datasheets



QG030-303/12

DC tangential blower

forward curved

Nominal data

Type	QG030-303/12	
Nominal voltage	VDC	12
Nominal voltage range	VDC	8 .. 14
Power input	W	8.7
Min. ambient temperature	°C	-20
Max. ambient temperature	°C	60
Air flow	m³/h	140
Sound power level	B	5.8
Sound pressure level	dB(A)	51

ml = Max. load · me = Max. efficiency · fa = Running at free air · cs = Customer specs · cu = Customer unit

Subject to alterations

Charts

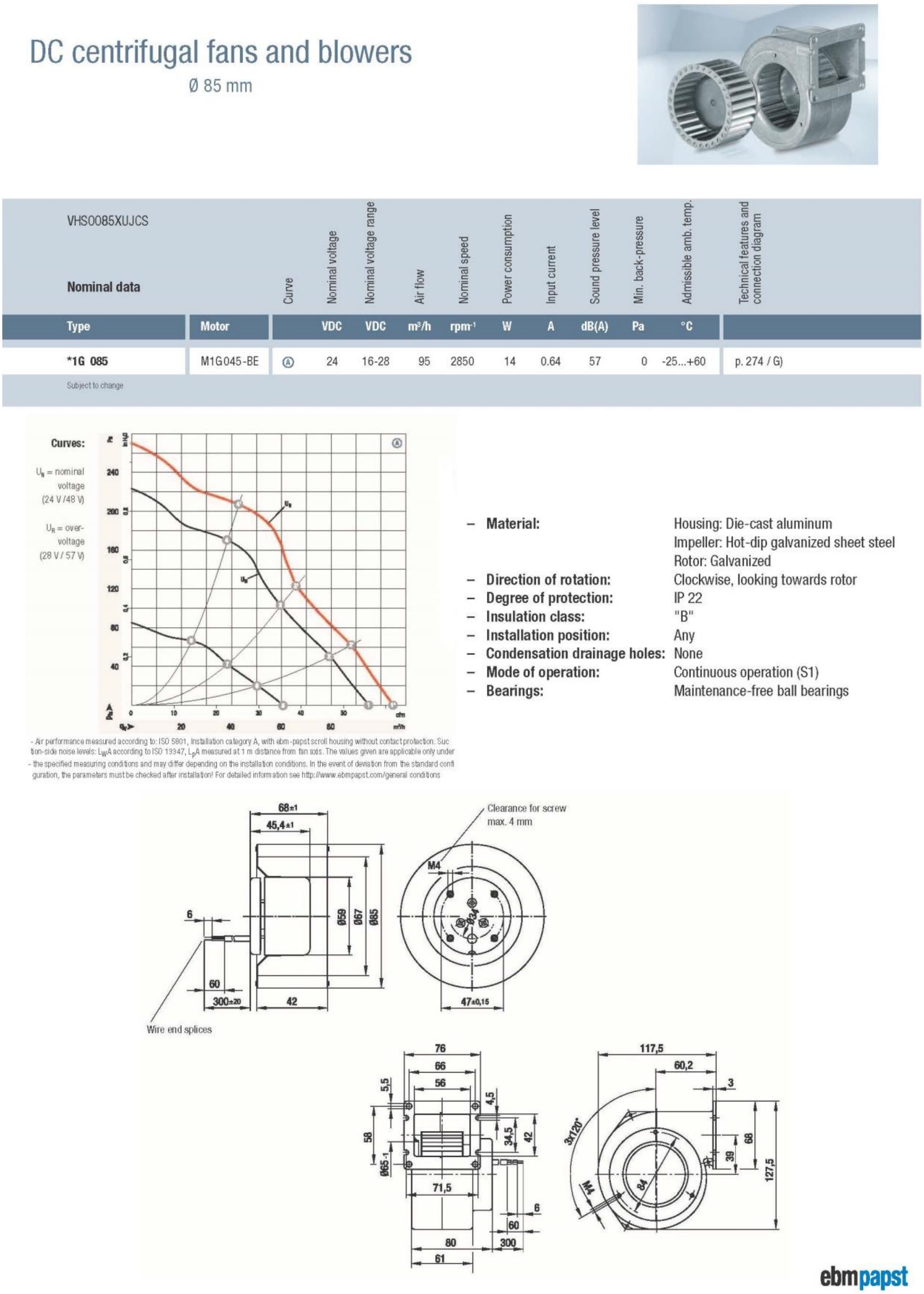
Technical features

Mass	0.380 kg
Material of impeller	Aluminum
Housing material	Aluminum, housing side parts of plastic.
Direction of rotation	Right, looking at rotor
Bearing	Motor with ball bearing system. Impeller bracket with sliding bearings.
Lifetime L10 at 40 °C	30000 h
Lifetime L10 at maximum temperature	20000 h
Connection line	With single strands AWG 24, TR 64
Motor protection	Protected against reverse polarity and locking.
Locked-rotor protection	Blocking and overload protection
Approval	VDE, CSA, UL, CE

Product drawing

ebmpapst

Figure B. 1 – Tangential (Linear) fan datasheet.



DC centrifugal fans and blowers

Ø 85 mm

VHS0085XUJCS

Nominal data

Type	Motor	Curve	Nominal voltage VDC	Nominal voltage range VDC	Air flow m^3/h	Nominal speed rpm^{-1}	Power consumption W	Input current A	Sound pressure level dB(A)	Min. back-pressure Pa	Admissible amb. temp. °C	Technical features and connection diagram
***1G 085**	M1G045-BE	Ⓐ	24	16-28	95	2850	14	0.64	57	0	-25...+60	p. 274 / G)

Subject to change

Curves:

U_N = nominal voltage (24 V / 48 V)

U_R = over-voltage (28 V / 57 V)

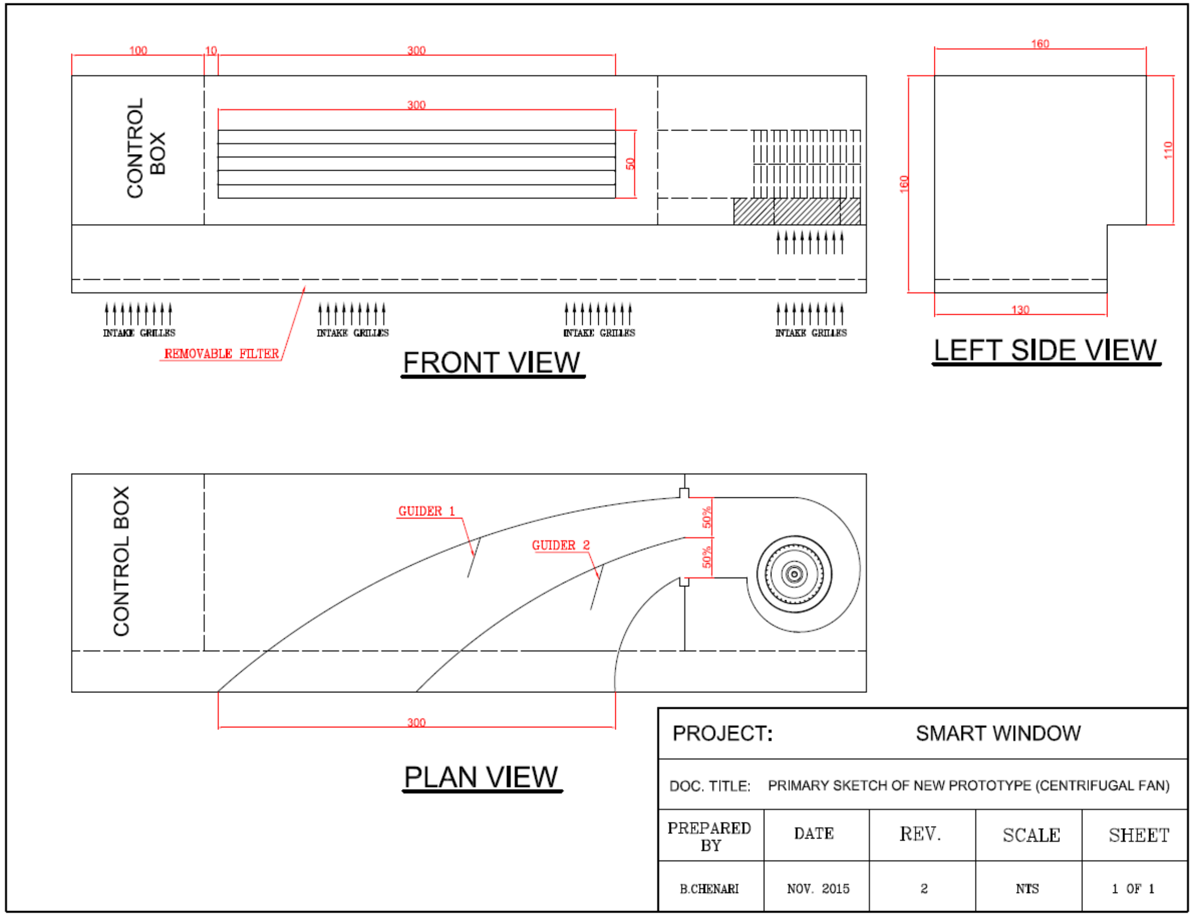
- Air performance measured according to: ISO 5801, Installation category A, with ebm-papst scroll housing without contact protection. Suction-side noise levels: L_WA according to ISO 13347, L_pA measured at 1 m distance from fan axis. The values given are applicable only under
- the specified measuring conditions and may differ depending on the installation conditions. In the event of deviation from the standard configuration, the parameters must be checked after installation! For detailed information see http://www.ebmpapst.com/general conditions

– **Material:**	Housing: Die-cast aluminum Impeller: Hot-dip galvanized sheet steel Rotor: Galvanized
– **Direction of rotation:**	Clockwise, looking towards rotor
– **Degree of protection:**	IP 22
– **Insulation class:**	"B"
– **Installation position:**	Any
– **Condensation drainage holes:**	None
– **Mode of operation:**	Continuous operation (S1)
– **Bearings:**	Maintenance-free ball bearings

ebmpapst

Figure B. 2 – Centrifugal fan datasheet.

C. Ventilator Boxes Drawings

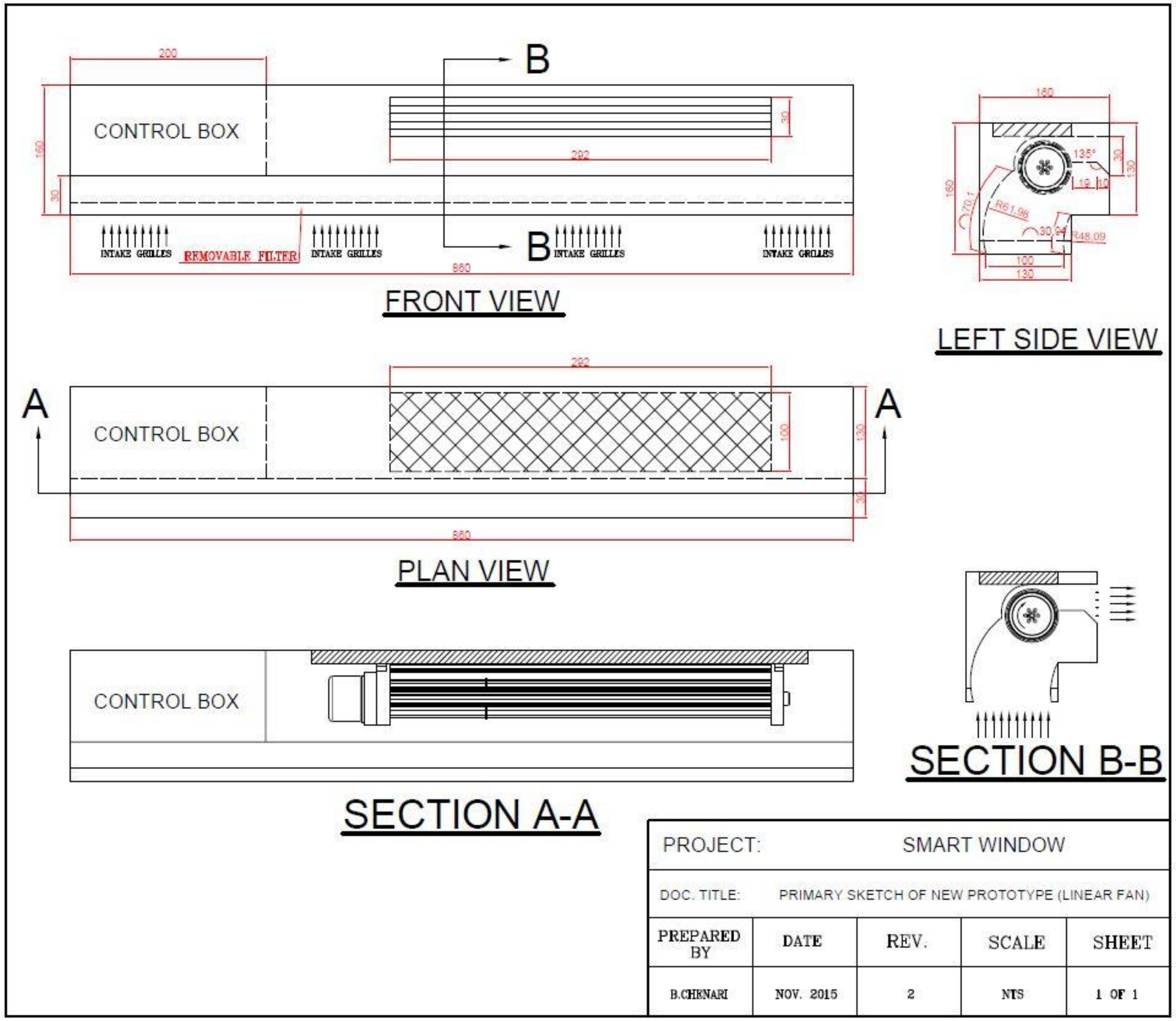


PROJECT: SMART WINDOW

DOC. TITLE: PRIMARY SKETCH OF NEW PROTOTYPE (CENTRIFUGAL FAN)

PREPARED BY	DATE	REV.	SCALE	SHEET
B.CHENARI	NOV. 2015	2	NTS	1 OF 1

Figure C. 1 – Centrifugal ventilator box sketch.



PROJECT:	SMART WINDOW			
DOC. TITLE:	PRIMARY SKETCH OF NEW PROTOTYPE (LINEAR FAN)			
PREPARED BY	DATE	REV.	SCALE	SHEET
B.CHENARI	NOV. 2015	2	NTS	1 OF 1

Figure C. 2 – Linear ventilator box sketch.

D. Noise Measurement at the I2L

Acoustic comfort is one of the elements of IEQ, so the noise level in different parts of the I2L has been measured, especially at the workplaces when the fans were working. In order to assess the noise generated by the ventilators, the centrifugal fan box has been chosen as the worst scenario (comparing to the linear fan box). According the datasheets of the fans, the centrifugal fan noise level has been mentioned 57 dBA and linear fan 51 dBA.

The measurements performed in a weekend to reduce the background noises. Figure D.1 depicts the test room plan in which the measurements have been performed in six work places in a seated ears level +1.15 m and four middle points in the room in a standing posture ears level +1.60 m. The measurements have been done using a sound level meter, CESVA SC310, based on OCTAVE BAND 1/1 method (See figure D.2). During the measurements the specific sound pressure levels as well as the frequency analyses have been performed.

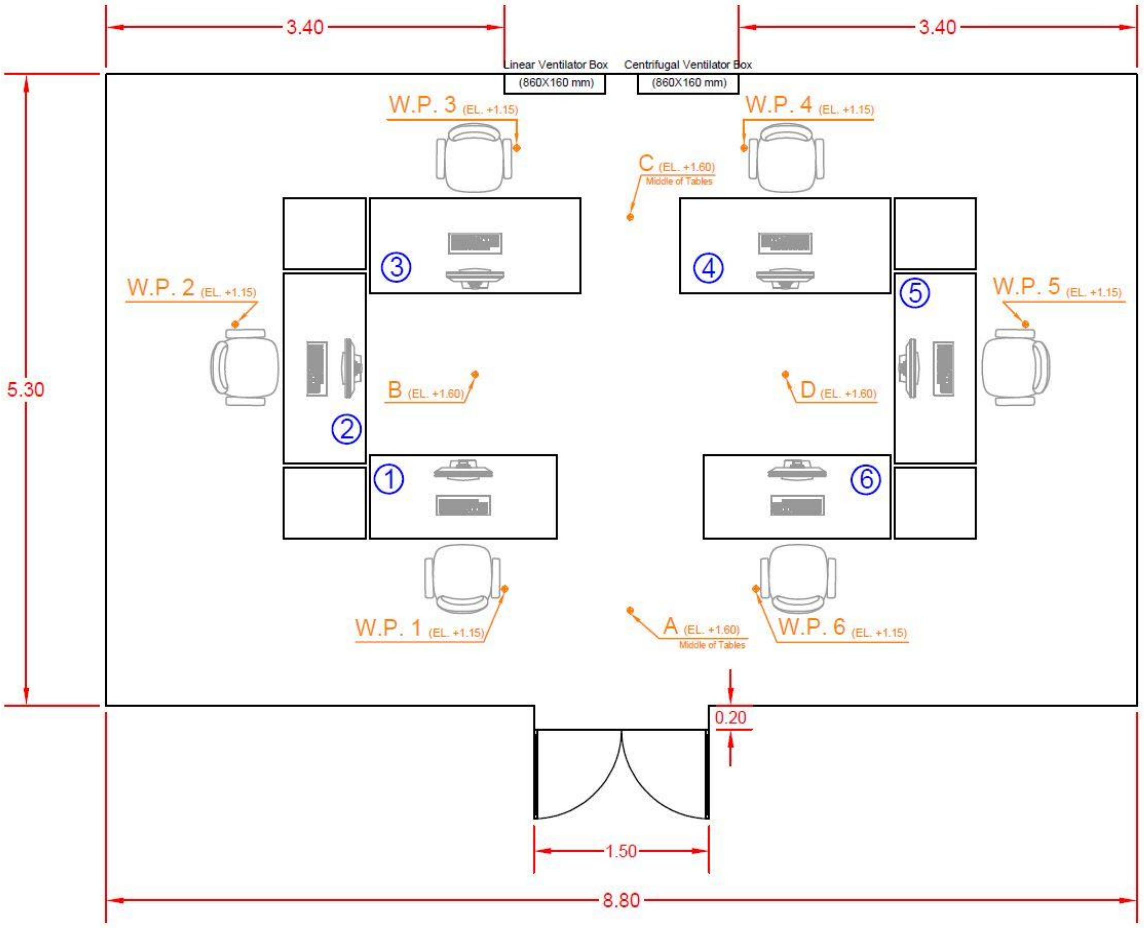


Figure D. 1 – Test room plan and measurement points.

Figures D.3 and D.4 depict the specific sound pressure level in all work places and intermediate points in different percentage of fan power that enables us to compare the intensity of the noise in each point and Fan power.

Moreover, as shown in figures D.5 and D.6, the average sound pressure level is calculated based on the following equation.

$$Average\ Sound\ Pressure\ Level = 10\log\left(\left(\frac{1}{n}\right)\sum_{k=1}^{n} 10^{\frac{L_k}{n}}\right)$$

Also, using the same equation, the average value of the sound pressure level in the room in different fan powers has been calculated (see figure D.7). Moreover, for each work place and intermediate points the sound pressure level and the frequency analysis has been performed. Figures D.8 and D.9 present variation of the sound level by altering the percentage of the fan power for the work place 1.

Figure D. 2 – Noise measurement device and setup.

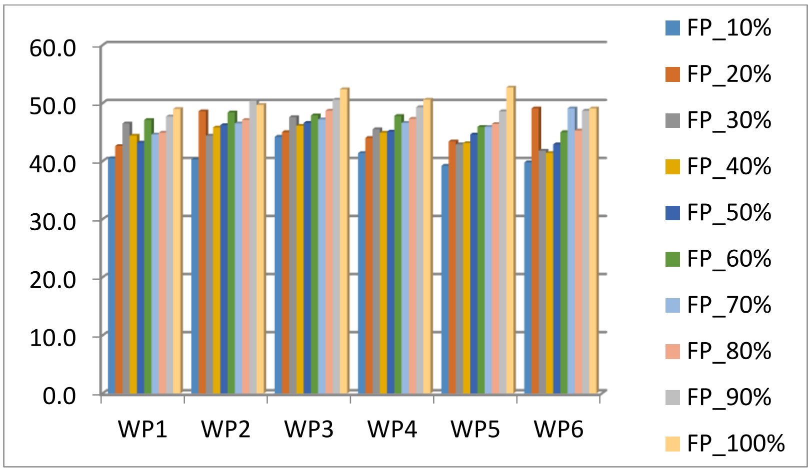


Figure D. 3 – Specific sound pressure level in each work place and fan power.

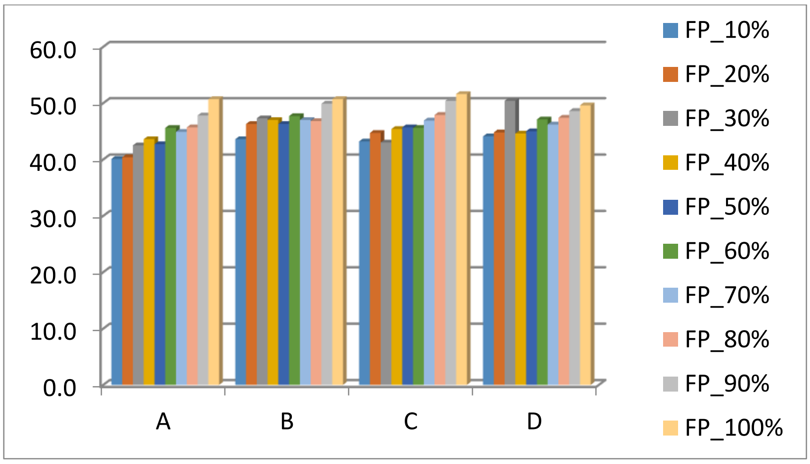


Figure D. 4 – Specific sound pressure level in each intermediate point and fan power.

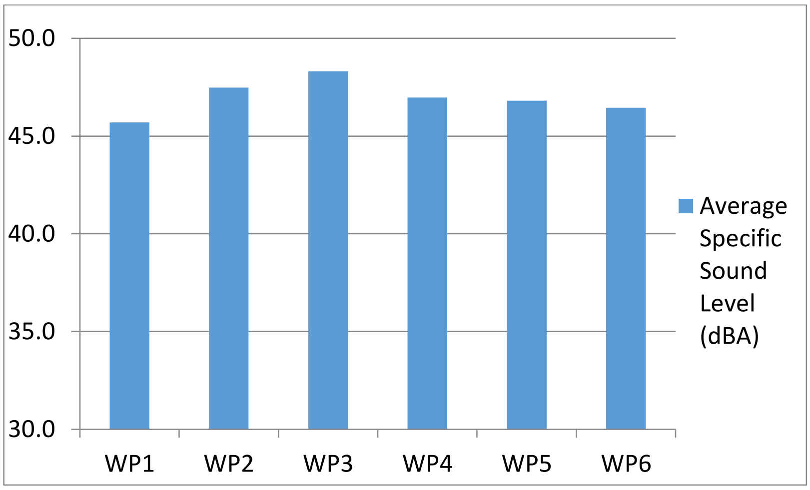


Figure D. 5 – Average sound pressure level in each work place.

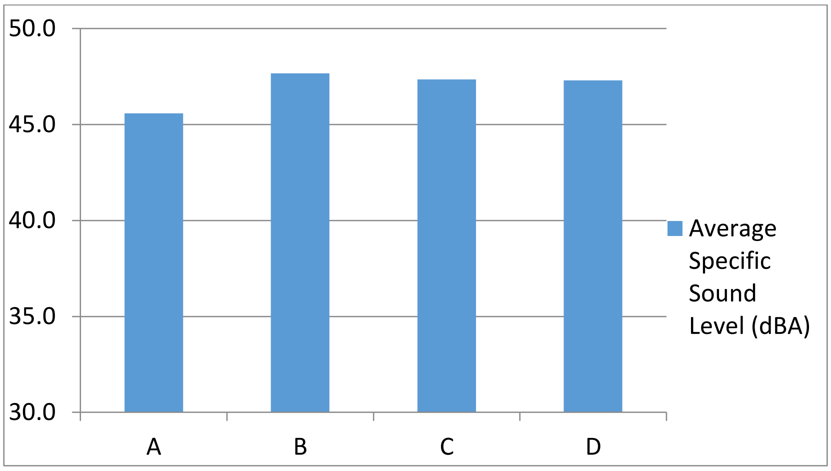


Figure D. 6 – Average sound pressure level in each intermediate point.

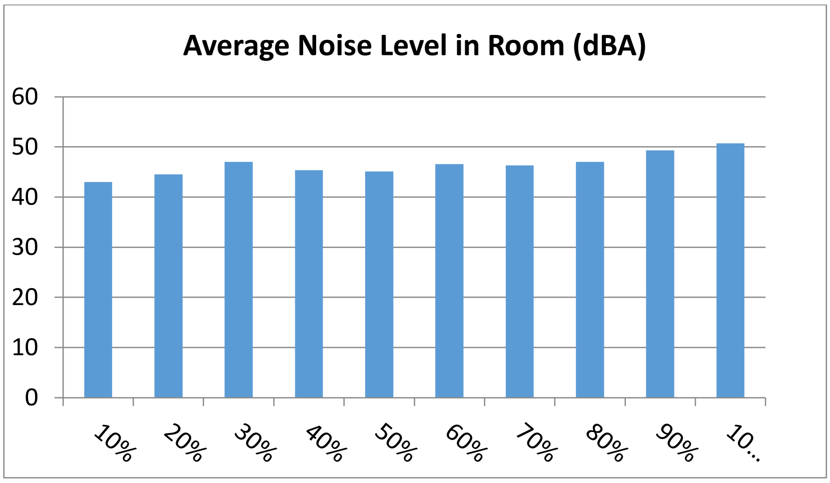


Figure D. 7 – Average sound pressure level in different fan powers.

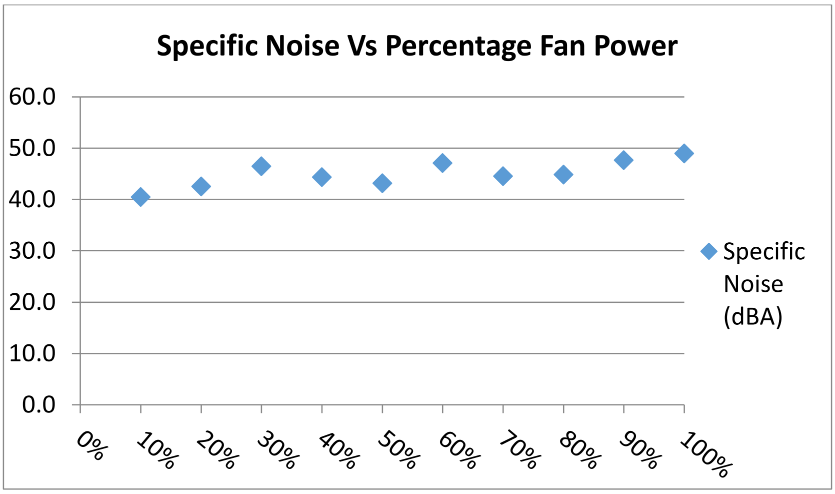


Figure D. 8 – Specific noise in work place 1 in different fan powers.

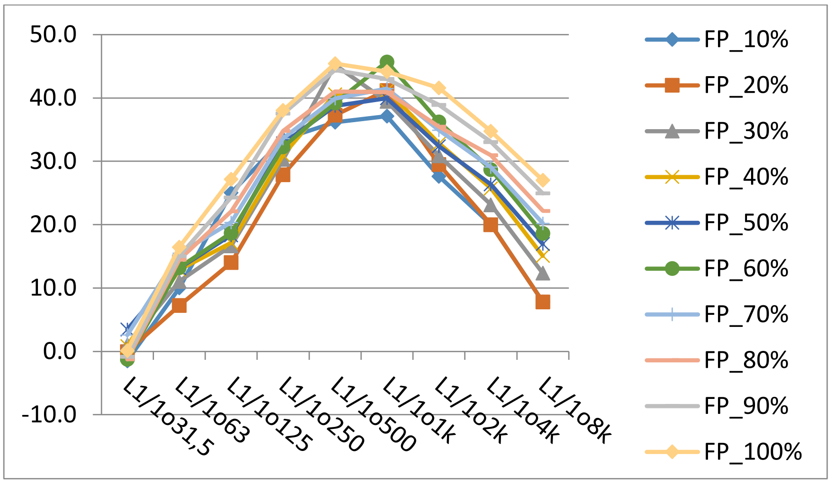


Figure D. 9 – Frequency analysis in work place 1 in different fan powers.

E. Air Velocity and Airflow Rate Tests

During the performance evaluation of the testing prototypes, air velocity and airflow rate tests for each ventilation box have been performed using an air measurement tool, Fluke 975 AirMeter Test Tool. As shown in Figure E.1, the device is capable to measure the air velocity and airflow rate using the velocity meter probe.

Figure E. 1 – FLUKE 975 AirMeter Test Tool.

The tests have been performed while ventilator boxes were controlled by the computer in order to adjust the power. The air velocity and air flow rate have been tested on various speeds, from 10% to 100%. The air velocity has been recorded in 90 nodes in the air discharge opening of the ventilator boxes to calculate the average air velocity.

Based on the following equation, using the air velocity and the cross section area of the discharge opening, the air flow rate has been also calculated.

$$Q = v..A$$

where Q is the airflow rate in m^3/h, v is the air velocity in m/s and A is the cross section area in m^2.

Figures E.2, E.3, E.4 and E.5 show the variation of air velocity and airflow rate by altering the fan power for both linear and centrifugal ventilator boxes.

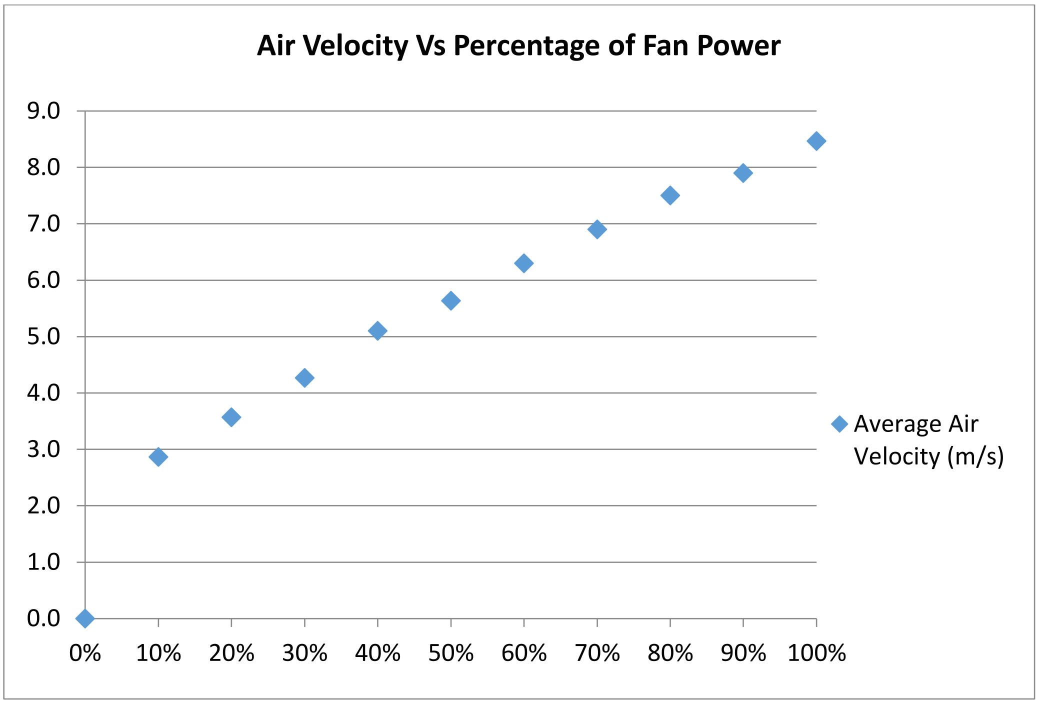


Figure E. 2 – Air velocity variation in different percentage of fan power.

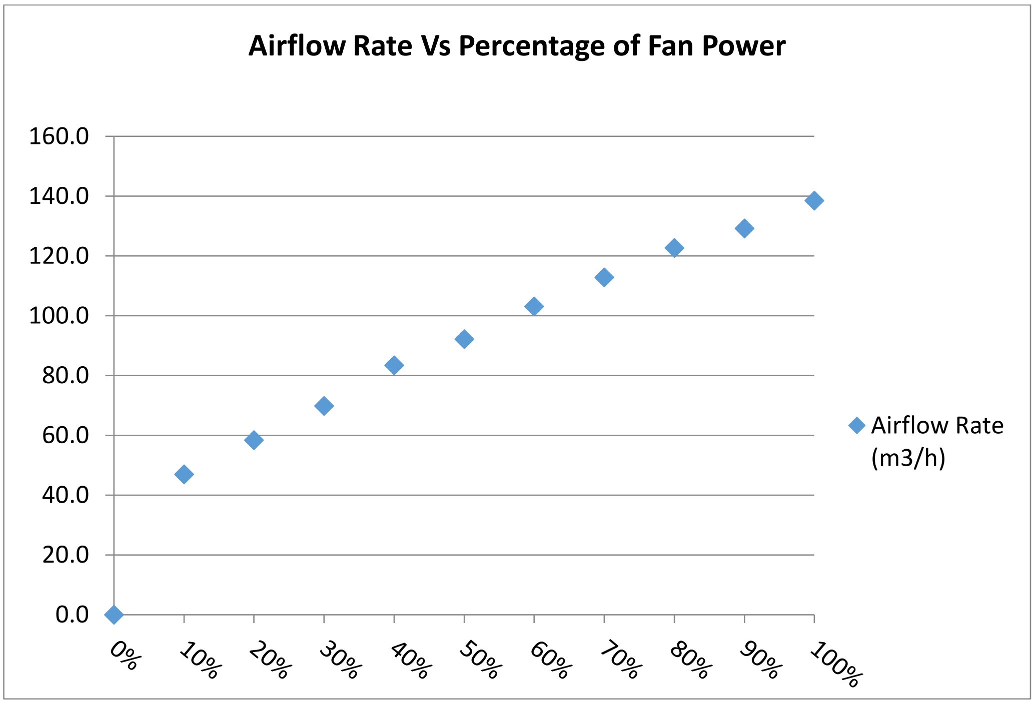


Figure E. 3 – Airflow rate variation in different percentage of fan power.

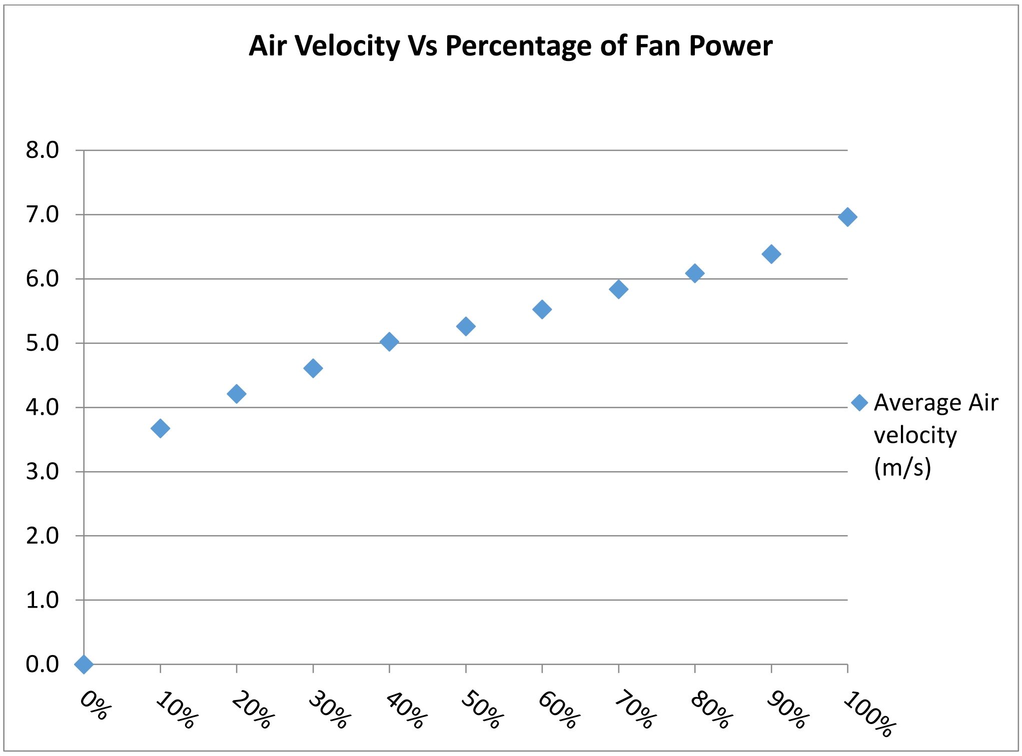


Figure E. 4 – Air velocity variation in different percentage of fan power.

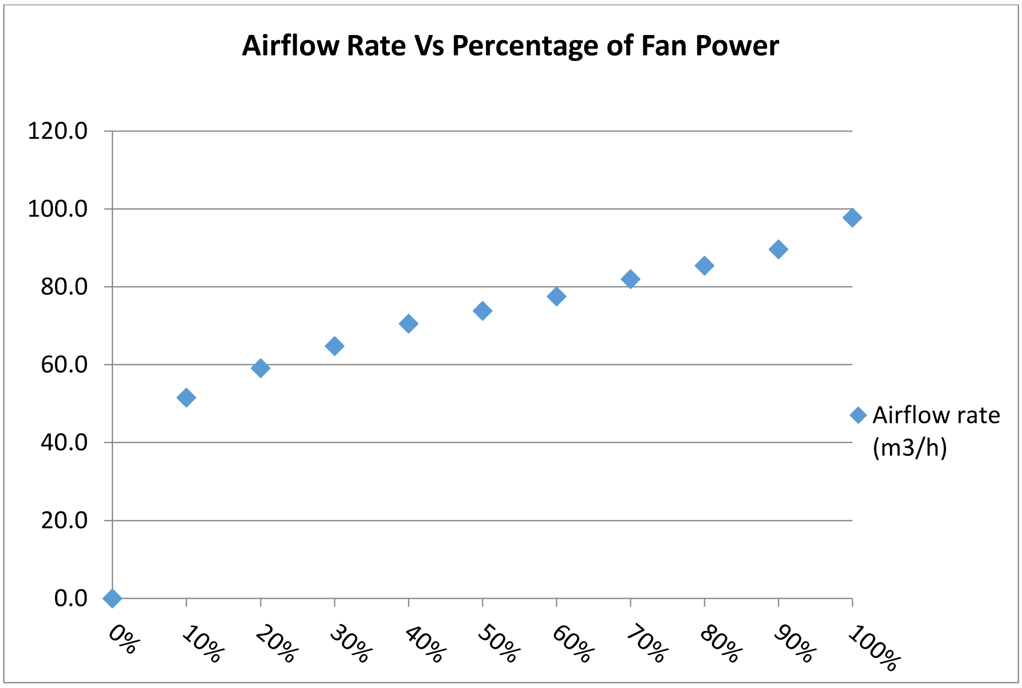


Figure E. 5 – Airflow rate variation in different percentage of fan power.

F. LabVIEW Front Panels and Block Diagrams for Testing Ventilation Control Strategies

- ***Ventilation Control Strategies 1 and 2***

Figure F. 1 – Front panel for ventilation control strategies 1 and 2.

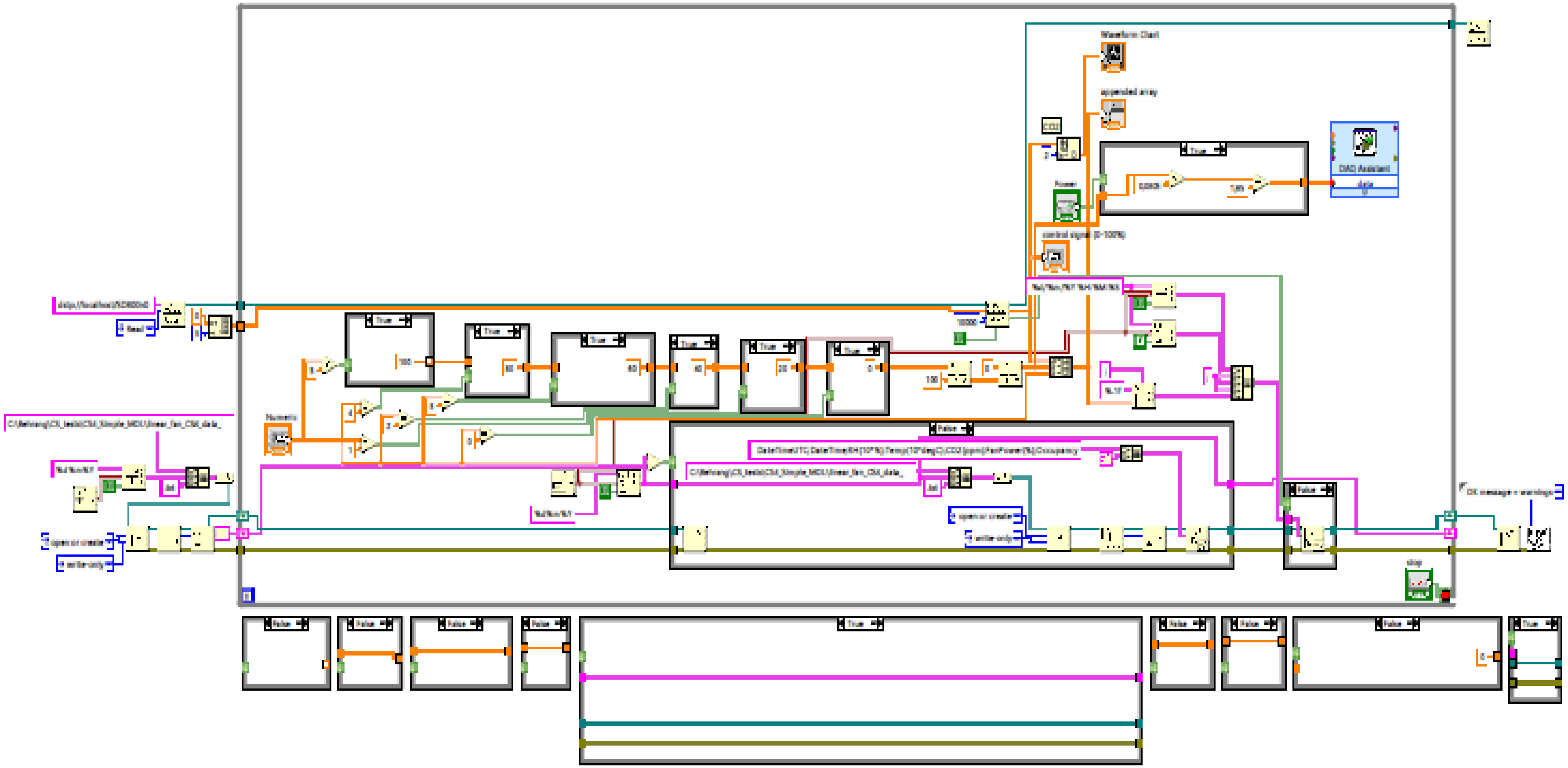


Figure F. 2 – Block diagram for ventilation control strategies 1 and 2.

- ***Ventilation Control Strategies 3, 4 and 5***

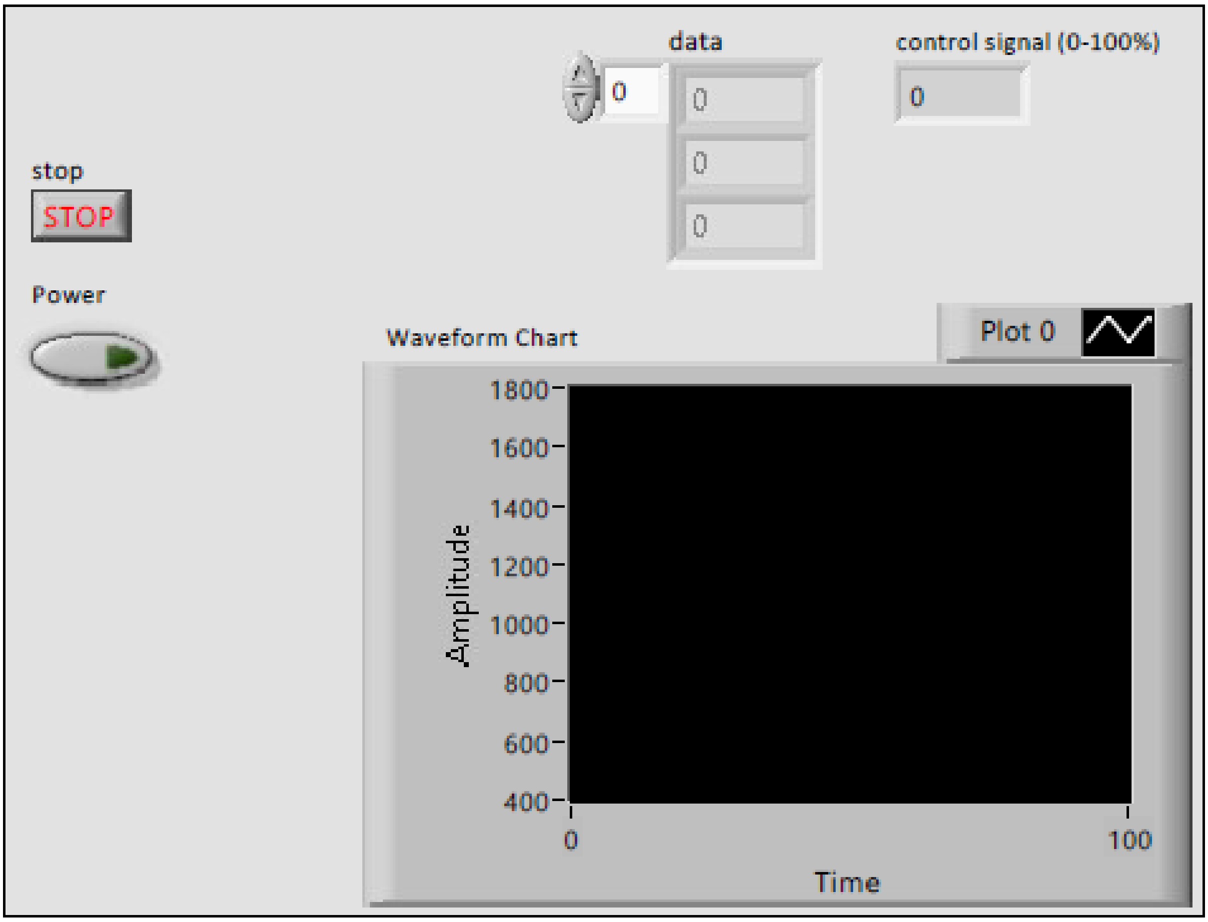


Figure F. 3 – Front panel for ventilation control strategies 3, 4 and 5.

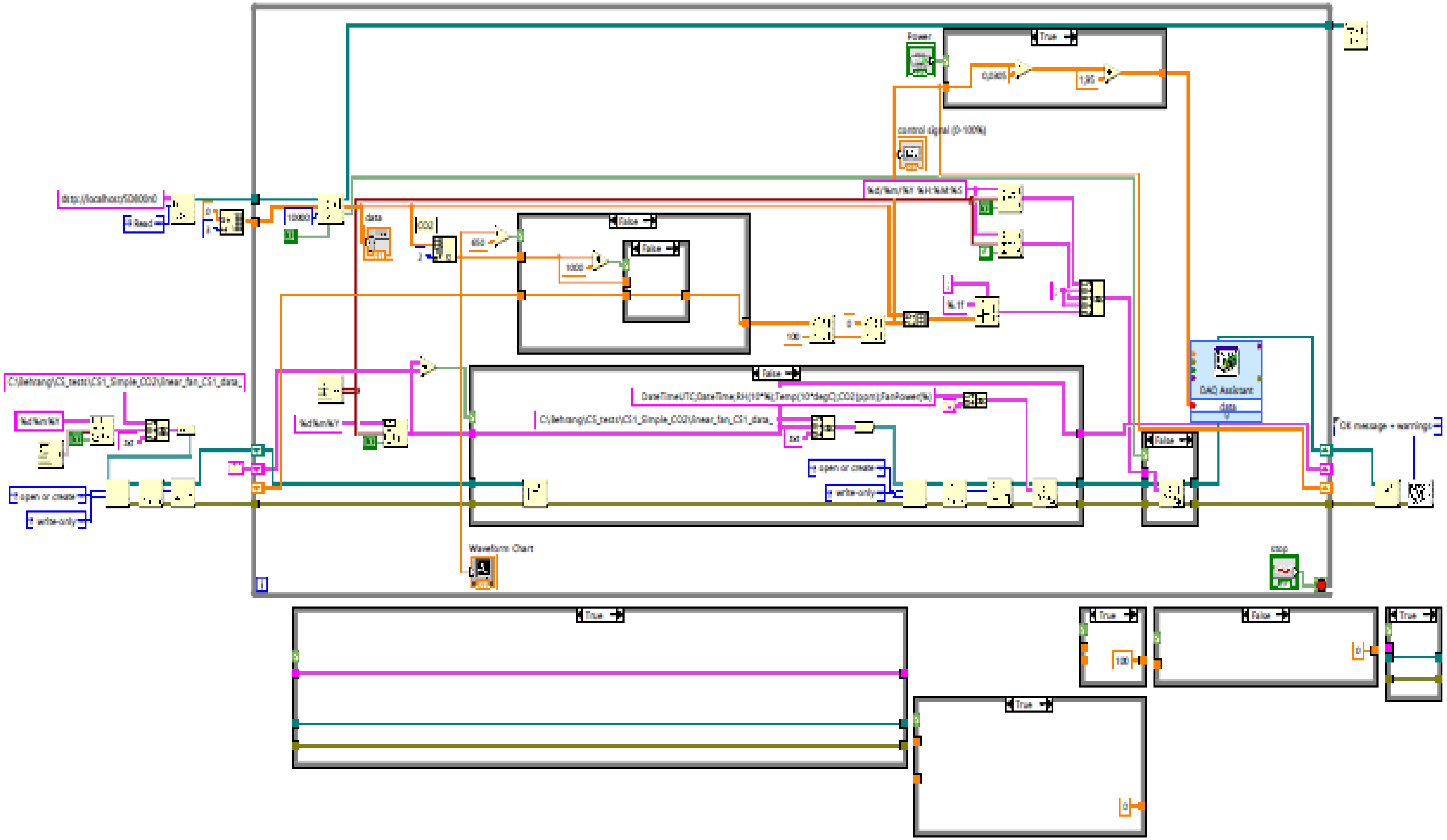


Figure F. 4 – Block diagram for ventilation control strategy 3.

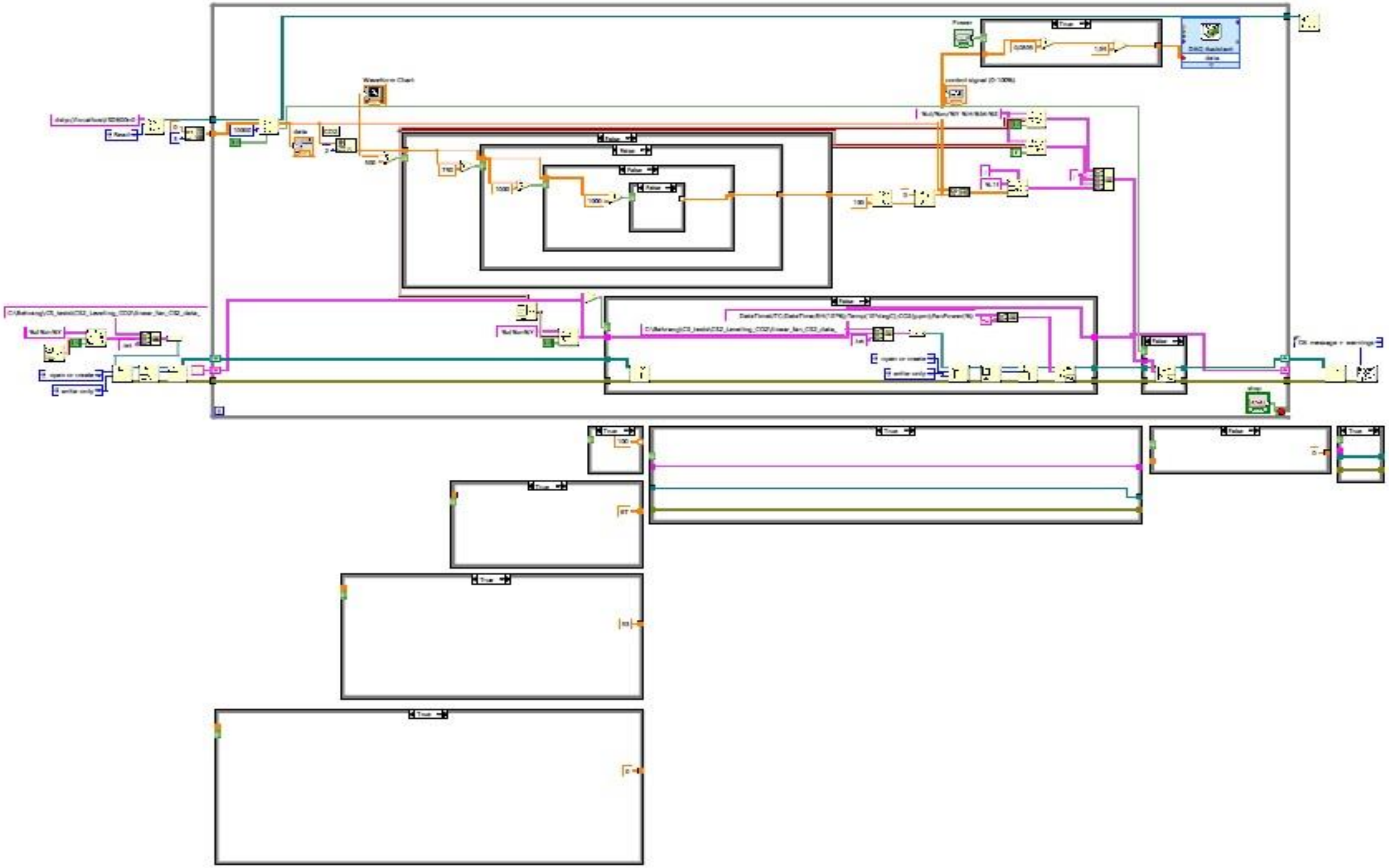


Figure F. 5 – Block diagram for ventilation control strategy 4.

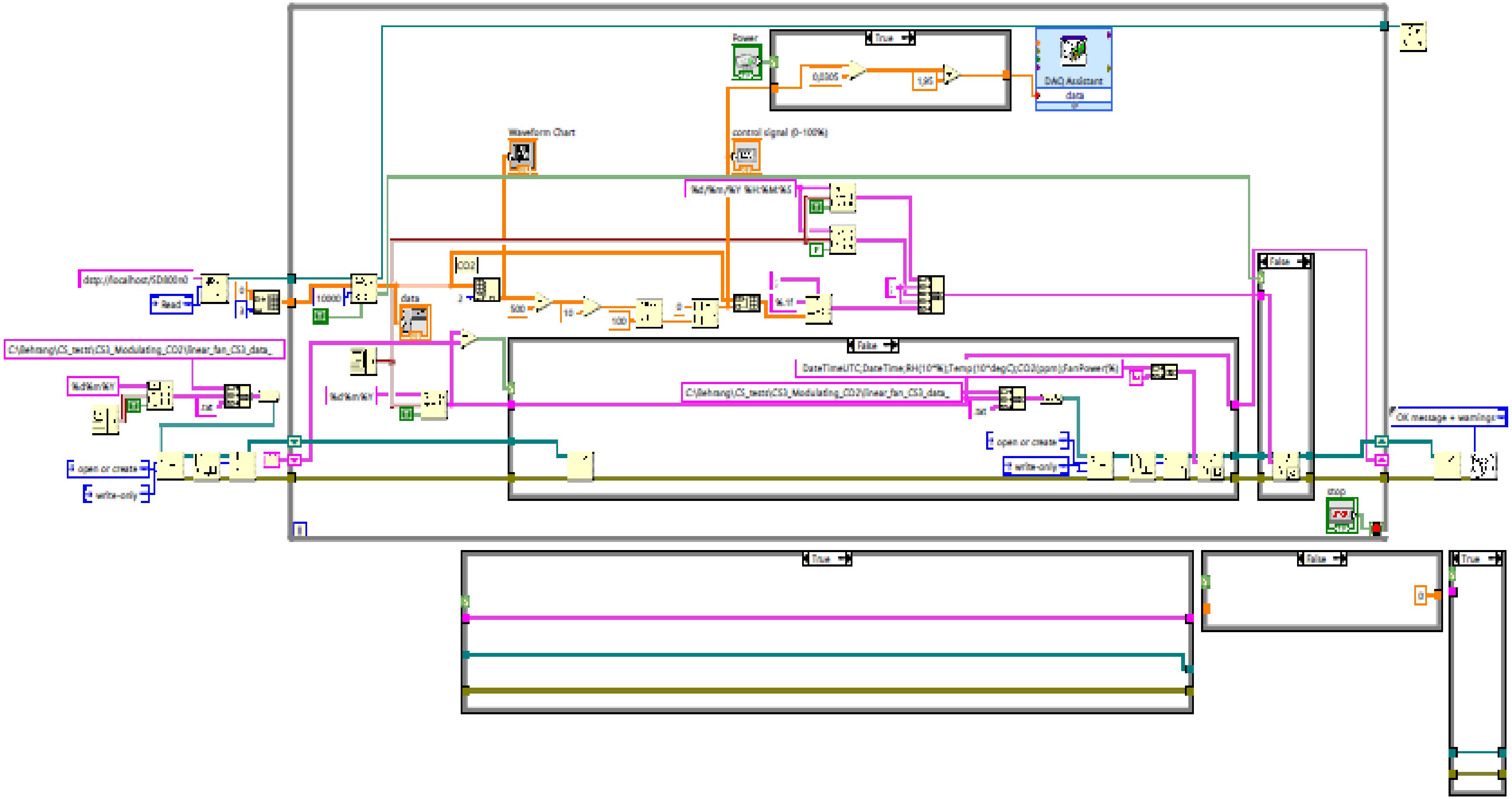


Figure F. 6 – Block diagram for ventilation control strategy 5.