Atefeh Salehi

NATURAL VENTILATION IN OLD BUILDINGS: RECOMMENDATIONS FOR ITS IMPROVEMENT

PhD Thesis in Sustainable Energy Systems
Supervised by Professor Maria Isabel Morais Torres and Professor Ana Teresa Vaz Ferreira Ramos
Submitted to the Faculty of Sciences and Technology of the University of Coimbra

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Professor Maria Isabel Morais Torres, Professor at University of Coimbra, Portugal.

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"A path is only a path, and there is no affront, to oneself or to others, in dropping it if that is what your heart tells you . . . Look at every path closely and deliberately. Try it as many times as you think necessary. Then ask yourself alone, one question . . . Does this path have a heart? If it does, the path is good; if it doesn't it is of no use."

Carlos Castaneda

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Dedicated to

I dedicate this thesis to

*My beloved father, **Mahmoud,***

You have successfully made me the person I am becoming.

*The loving memory of my mother, **Mehrangizh,***

You will always be remembered.

And to

*My darling husband, **Jahed.***

Abstract

Currently it is recognized that residential building sector is one of the largest energy consumers in the worldwide. The 70s´ energy crises was important to draw attention to the energy performance subject. Reinforcing thermal insulation is one of the usual solutions to improve energy efficiency of buildings. However, this thermal insulation reinforcement normally leads to a decrease of the natural ventilation of the building. The reduction of natural ventilation and infiltration in the old existing building, due to rehabilitation works, has been causing a reduction in indoor air quality and an increment of relative humidity levels in the indoor environment compared with that observed before rehabilitation.
Therefore, it is important to find a balance between the thermal performance of the building and an acceptable quality of indoor air in term of ventilation effectiveness.
Providing optimal indoor condition is not only related to the renewal of the air but also with its distribution. Hence airflow patterns in historical buildings influence interior conditions.
The aim of this work is to develop solutions that will enable an increment of natural ventilation of old buildings that have/have not already been rehabilitated, taking into account its architectural characteristics and constraints due to the fact that we are dealing with old buildings with some conservation and preservation limitations. With these solutions it will be possible to increase the indoor air quality of the buildings and to improve its thermal characteristics and thus the life conditions of its inhabitants will be also improved.
To achieve the proposed objective, the research was developed resorting to in-situ measurements and simulations. The in-situ measurements were achieved by using Blower Door Test/ Fan pressurization method. Energy and airflow simulation was performed on Design-Builder software with the main goal of answering to some questions, such as:
- What are the existing conditions of the buildings?
- How effective are the suggested solutions toward the improvement of natural ventilation in buildings?
The results of this research can be interesting for architectures, engineers and persons which are working on retrofit and renovation of the old existing buildings in order to find the best solution before starting the process.

Keyword: natural ventilation, indoor air quality, air circulation, architectural solutions, infiltration rate, air permeability, old buildings, rehabilitation.

Resumo

É correntemente reconhecido que o sector dos edifícios residenciais é um dos maiores consumidores mundiais de energia. A crise energética dos anos 70 foi importante para chamar a atenção para o conceito de desempenho energético. O reforço do isolamento térmico é uma das soluções mais usuais nos edifícios para melhorar a sua eficiência energética. No entanto, o reforço do isolamento térmico leva, normalmente, a uma diminuição da ventilação natural do edifício. A redução da ventilação natural e da infiltração nos edifícios antigos, causada por trabalhos de reabilitação, tem levado a uma redução da qualidade do ar interior e do aumento da sua humidade relativa num ambiente interior comparando com o que se observava antes da intervenção. Neste sentido, é importante estabelecer um equilíbrio entre o desempenho térmico do edifício e uma qualidade do ar interior aceitável em termos de eficácia de ventilação.

A obtenção de condições interiores ótimas não está apenas relacionada com a renovação do ar interior, mas também com a sua distribuição. Assim, os padrões de fluxo de ar existentes nos edifícios históricos influenciam a sua condição interior.

O objetivo deste trabalho centra-se no desenvolvimento de soluções que irão permitir o aumento da ventilação natural, em edifícios que já foram reabilitados e tendo em atenção as suas características arquitetónicas e restrições existentes devido ao fato dos edifícios serem antigos e terem algumas limitações de conservação e preservação. Pretende-se também estudar o mesmo tipo de soluções para aplicação em futuras intervenções. Ao longo do trabalho são sempre tidas em consideração as. Com estas soluções será possível melhorar a qualidade do ar interior dos edifícios e as térmicas e consequentemente as condições de vida das habitantes serão melhordas.

Para atingir o objetivo proposto a investigação foi desenvolvida recorrendo a medições in-situ e simulações. As medições in-situ foram conseguidas usando o Blower door test. As simulações do desempenho energético e do fluxo de ar foram realizadas com software Design-Builder com objetivo principal de se responder às seguintes perguntas:

- Quais são as condições existentes dos edifícios?
- Quão eficazes são as soluções sugeridas para a melhoria da ventilação natural nos edifícios?

Os resultados desta investigação podem ser interessantes para arquitetos, engenheiros e para os profissionais das áreas de reabilitação e renovação de edifícios antigos a fim de encontrar a melhor solução antes de iniciar o processo.

Palavras-chave: ventilação natural, qualidade do ar interior, circulação de ar, soluções arquitetónicas, taxa de infiltração, permeabilidade ao ar, edifícios antigos, reabilitação.

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Abbreviations

ACCREDIA	**-**	**Italian National Accreditation Body**
ACE	-	Air Change Effectiveness
ACH	-	Air Change per Hour
ASHAE	-	American society of Heating and Air Conditioning Eng.
ASHRAE	-	American Society of Heating, Refrigerating, and Air conditioning Engineers
ASRE	-	American Society of Refrigerating
AVIC	-	Air Infiltration and Ventilation Center
AV-T	-	Air-Vent at Top of the window
AV-B	-	Air-Vent at Bottom of the window
BBRI	-	Belgium Building Research Institute
BDT	-	Blower Door Test
BLAST	-	Building Load Analysis and System Thermodynamics
B-O	-	Bigger Outlet
CETE de Lyon	-	Centre d'Etudes Techniques de 1 Equipment de Lyon
CFD	-	Computational Fluid Dynamic
cfm	-	Cubic Feet per Minute
CMV	-	Centralized Mechanical Ventilation
CO	-	Carbon Monoxide
CO2	-	Carbon dioxide
DB	-	Design Builder
ELA	-	Effective Leakage Area
EPBD	-	Energy Performance of Building Directive
ERDA	-	Energy R&D Administration
ETS	-	Environmental Tobacco Smoke
EU	-	European Union
GHG	-	Green House Gas
HVAC	-	Heating, Ventilation and Air Conditioning
IAQ	**-**	**Indoor Air Quality**
IEA	-	International Energy Agency
IRC	-	International Residential Code
LCC	-	Life Cycle Cost
LNEC	-	Laboratoria Nacional de Engenharia Civil (National Laboratory for Civil Engineering
NL	-	Normalized Leakage
NPL	-	Neutral Pressure Level
NPP	-	Neutral Pressure Plane
NO_2	-	Nitrogen Dioxide
O-B	-	Opening with Bottom hung
O-N	-	Opening with New configuration
O-T	-	Opening with Top hung
O-S	-	Opening with Side hung

OSHA	-	Occupation Safety and Health Administration
PDEs	-	Partial Differential Equations
PMV	-	Predicted Mean Vote
PPD	-	Predicted Percentage of Dissatisfaction
RANS	-	Reynolds-Averaged Naiver-Stokes
RCCTE	-	Regulation of Characteristics of thermal performance of buildings
REHVA	-	European Heating, Ventilation and Air Conditioning Associations
RH	-	Relative Humidity
RSECE	-	Regulations of Energy Systems in Buildings Climate
RW	-	Bigger skylight (Roof Window)
SARS	-	Sever Acute Respiratory Syndrome
S-B	-	Opening with Bottom hung and side-fin
SBS	-	Sick Building Syndrome
SCE	-	Energy Certification System
S-N	-	Opening with New configuration and side-fin
S-T	-	Opening with Top hung and side-fin
S-S	-	Opening with Side hung and side-fin
SWOT	-	Strengths, Weaknesses, Opportunities, and Threats
TEC	-	The Energy Conservatory
TNO	-	Netherland Organization for applied scientific research
TSV		Thermal Sensation Vote
WHO	-	World Health Organization
WWR	-	window to wall ratio
ZEB	-	Zero Energy Building

List of Units

A	-	area of an opening	m^2
Ac	-	Floor area	m^2
AE	-	Envelope area of the building	m^2
A_e	-	total effective area of the inlet openings	m^2
A_s	-	total effective area of the outlet openings	m^2
C	-	Pressure coefficient	-
C	-	Heat loss by convection from the outer surface of the clothed body.	W/m^2
C_{env}	-	airflow coefficient	-
CL	-	air leakage coefficient	$m^3/(h.pa^n)$
C_{pe}	-	pressure coefficient of input	-
C_{ps}	-	pressure coefficient of output	-
E_d	-	Heat loss by water vapor diffusion through the skin	W/m^2
E_{sw}	-	The heat loss by evaporation of sweat from the surface of the skin	W/m^2
E_{re}	-	The latent respiration heat loss respectively	
ELA_{50}	-	Effective leakage area at 50 pa	cm^2
$EQLA_{50}$	-	Equivalent leakage area at 50 pa	cm^2
H	-	Internal heat production in the human body	-
H	-	vertical distance between the two surfaces measured between midpoints	m
h	-	height	m
K	-	Dry respiration heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing).	W/m^2
L	-	Dry respiration heat loss from the skin to the outer surface of the clothed body (conduction through the clothing).	W/m^2
n_{50}	-	ventilation rate (air change rate) at 50pa	$m^3/h/m^2$
n_{50}	-	ventilation rate (air change rate) at 50pa	h^{-1}
n_{50}	-	ventilation rate (air change rate) at 50pa	$l/s.m^2$
n_{50}	-	ventilation rate (air change rate) at 50pa	m^3/h
n_{50}	-	ventilation rate (air change rate) at 50pa	vol/h
n_{50}	-	ventilation rate (air change rate) at 50pa	l/s
n_{50}	-	ventilation rate (air change rate) at 50pa	l/(s.p)
n_{50}	-	ventilation rate (air change rate) at 50pa	ac/h
n_{50}	-	ventilation rate (air change rate) at 50pa	cfm
n_{50}	-	ventilation rate (air change rate) at 50pa	dm^3/s
n_{50}	-	ventilation rate (air change rate) at 50pa	$dm^3/s/m^2$
n_{50}	-	ventilation rate (air change rate) at 50pa	cm^2/m^2
n	-	airflow exponent	-
NLA_{50}	-	Normalized leakage area at 50 pa	cm^2/m^3
q_{50}	-	air permeability at pressure 50 pa	l/sm^2, $m^3/h.m^2$
q_{env}	-	air tightness of the building	m^3/s
RPH	-	hourly average annual renovation	h^{-1}

$\boldsymbol{RPH_{50}}$	-	hourly renovation obtained by pressurization test at 50 Pa	h^{-1}
$\boldsymbol{U}$	-	wind speed	m/s
$\boldsymbol{V}$	-	building volume	m^3
$\boldsymbol{V_{50}}$	-	Air Flow at 50 pa	m^3/h
$\boldsymbol{V_{env}}$	-	airflow rate through building envelope	m^3/h
$\boldsymbol{V_r}$	-	airflow rate measuring system	m^3/h
$\boldsymbol{V_m}$	-	measured airflow rate	m^3/h
$\boldsymbol{W}$	-	width	m
$\boldsymbol{w_{50}}$	-	specific leakage rate at pressure 50 pa	$m^3/h.m^2$
$\Delta \boldsymbol{T_{int-ext}}$	-	mean temperature difference between the outside environment and the interior	°C
$\boldsymbol{\Delta P}$	-	induced pressure difference	pa
$\boldsymbol{\rho_0}$	-	density of the air temperature correction	kg/m^3
$\boldsymbol{\rho_e}$	-	air density outside temperature	kg/m^3
$\boldsymbol{\rho_i}$	-	density of air at indoor temperature	kg/m^3

Chapter 1:

Introduction

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*"**There is no subject directly connected with life on which there is so large an amount of popular ignorance as ventilation**".*

Andrew Jackson Downing

1.1 Background of research and motivation

The subjects of energy and thermal comfort are very important ones as they have a strong effect on the worldwide as well as in human life. Therefore, they have been an important field of science and research. So that, many researchers are working and studying them and there is also a broad industry sector which is developing and executing new materials by improving solutions and materials quality. Hence, optimizing and minimizing building energy consumption are the most important challenges of the global warming and environmental concerns.

Besides of thermal comfort, Indoor Air Quality (IAQ) has become a critical concern due to the fact that its poor quality influences the occupants' health. This negative effect has been studied by several researchers like Jaakkola et.al. (1989) [1].

The problem of poor quality of indoor air was triggered in the 70´s, the same decade of the energy crisis when energy saving became a topic of extreme importance. In order to have energy saving in the building, its envelope was constructed with better insulations layers and sealed against air leakage [2].

Ventilation is one of the ways to improve indoor air quality and to provide healthy air through diluting the pollutants from the building, which can be achieved by two ways: mechanical ventilation, that consumes energy and natural ventilation.

Due to the increment of energy used worldwide in the past decades and since ventilation is responsible for 30-50% of building energy consumption through the heating and cooling loads, natural ventilation plays an important role in Zero Energy Building (ZEB) approach.

In order to realize this approach, investigations in the field of ventilation must include studies on the airflow distribution, ventilation rate regulation and passive solutions. In ZEB buildings, it is important to find a balance between two main areas: the thermal performance of the building envelope and an acceptable quality of the indoor environment in terms of thermal comfort, ventilation effectiveness and indoor air quality [3]. This idea can be helpful in the process of intervention and retrofit of old buildings.

Ventilation rate is one of the fundamental factors in the field of IAQ and building energy performance. On the other hand, estimating over-ventilation rate is another factor which should be concerned in the decrement of energy consumption related to the ventilation and IAQ.

Based on Brown [4], to solve/prevent problems of built environment related to IAQ after the intervention, the characteristics of airflow and aspects of natural ventilation must be studied. However, providing optimal indoor conditions is not only related to the amount of air entering the building but also to its distribution. Airflow patterns in old buildings influence the distribution of air, the flow speed and the temperature distribution [5]. The infiltration rate depend on the air tightness of the building, indoor and outdoor temperatures and the wind pressure. Since an airtight building has less airflow transfer through the envelope, it is important to plan intervention and retrofit actions so that the retrofitted building does not became too tight. Fan pressurization test is a way of estimating the building leakage, being also possible to figure it out by the simulation method and especially by Computational Fluid Dynamic (CFD).

1.2 Research objective

Thermal rehabilitation of old buildings has been achieved, mainly, by the reinforcement of the thermal insulation of its facades which has led systematically to decrease of natural ventilation of interior spaces.
This reduction of natural ventilation has led to the emergence of new problem non-existent before such as the molds and reduction of indoor air quality, namely through the increase of relative humidity in the indoor environment. Hence, the effectiveness of ventilation in old buildings and also retrofitted buildings is the main gap of this research field.
The work that was developed aims to study solutions that will enable to improve the natural ventilation of old buildings already rehabilitated and that can combine improved natural ventilation with architectural features and that may be applied in other future interventions.
So the aim of the work is to propose some solutions for retrofitting that will improve the quality of natural ventilation in interior spaces, with respect to the existing constraints due to the fact that we are dealing with old buildings that present architectural limitations. With these solutions, we intend to improve the quality of the air inside buildings with improved thermal characteristics and thus improve the conditions of the old buildings of our cities. Therefore, we are going to use the ventilation and infiltration rate of the building in order to find its IAQ.
The primary purpose of this research is to investigate the effect of ventilation rate on IAQ. To do so, the following aspects need to carry out:

- To apply the simulation for finding the indoor airflow characteristics of optimal ventilation in term of thermal comfort;
- To determine the IAQ parameters;
- To define the optimal configuration of inlets/outlets (air supplier/extractor) in order to improve IAQ and air distribution.

1.3 Research questions

Before undertaking any investigation on ventilation in old residential buildings, it is important to identify main goals of the project and some questions should be asked based on them. The list below presents some of the questions which will be answered during this research:
What are the ventilation requirements to grant an interior healthy environment?

- How much is the minimum/maximum air change rate to keep a good air quality and to avoid pathologies based on the regulation in the tested buildings?
- Is there any relationship between house characteristics and the need of ventilation?
- What practical intervention actions must be changed to solve the indoor air quality of the building?
- Do the buildings receive adequate ventilation (based on the regulation) for the health and comfort of the occupants in the existing condition and also after recommendations?
- How large is the possible the variation in supply-exhaust ventilation between different buildings?

1.4 Structure of research

This research intends to give a contribution to solve the problem of reducing natural ventilation in old buildings after interventions for thermal rehabilitation that normally leads to the appearance of new pathologies and decrease of interior air conditions. It consists of seven chapters, which the first one is the introduction and the last one is the conclusion.

To do this research, in the second chapter, as the literature review, the main characteristics of ventilation, ventilation principles, and natural ventilation requirements are presented. An introduction about thermal comfort will also be presented. This chapter is intended to be the framework of this thesis.

The third chapter is divided into two parts. The first part presents some of the finalized researches which have already been done in several countries. With this section, it is possible to make a comparison between different systems and methods. The second part is devoted to the analysis of different existing regulations worldwide, including Europe and also Portugal.

In the fourth chapter, initially, the analysis of different existing methodologies in this research field is carried out. Then, the characterization of construction in the selected area of the case studies is presented. This section has been divided into two parts in which the first one is a general approach to the main traditional construction in Coimbra and the second one is the characterization of the case studies with an analysis of the existing living conditions. Finally, in the last part of this chapter the selected methodology based on the condition of the case study in order to develop this research and achieve its aim is presented. The general methods of this research focus on measurement and simulation techniques. Therefore, this chapter contains the procedures of the selected analysis methods.

The fifth chapter presents the analysis of the thermal comfort and airflow distribution in the selected buildings based on the existing conditions. The aim of this chapter is to examine the existing condition of the buildings as a starting point to figure out the ventilation effectiveness. The first part of this chapter present the results of the in-situ tests with the use of the Blower Door Test (BDT) that allowed the measurement of airtightness of the buildings. The second part is related to the analysis of thermal comfort and indoor air quality of buildings with numerical simulations. With this global analysis, it will be possible to know exactly what are the conditions of thermal comfort of the existing buildings is. After that, the analysis of airflow distribution of the building at urban environment and buildings level is done.

The main aim of simulations is to determine the most appropriate ventilation asset for the building. This scenario should be able to guarantee a suitable microclimate by reducing energy consumption and discomfort condition. With this aim, temperature and air velocity are visualized. To do the simulations for analyzing natural ventilation *Design Builder (DB)* was selected as the best tools for modeling.

With the help of the in-situ measurements and the numerical simulations, and always having in mind all constraints that exist in historical center of the cities, several recommendations to improve the natural ventilation and its behavior in buildings are studied in the sixth chapter.

Both chapters, fifth and sixth, were developed based on the Portuguese regulation, especially REH, and on these two chapters is possible to check the building conditions with their analytical results. At the end of sixth chapter, a discussion is made with a comparison between the results of the existing and suggested conditions. The most important discussions and conclusions are summarized in Chapter seventh. Furthermore, possible future works are indicated also at the end.

Chapter 2:

State of the Art, Literature review of the ventilation in housing

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*"**Man is a funny creature. When it is hot, he wants it cold. When it is cold, he wants it hot. Always wanting what is not. Man is a funny creature**".*

ASHRAE Journal, Feb. 1999, p49.

2.1 Introduction

The world population is growing to more than 7.3 billion, half of this population lives in urban areas and it is expected that this urban population increases to more than 9.7 billion by 2050 [6]. However, this fast growing of urban population can cause various problems such as increment of the energy consumption and CO_2 emissions which influence both human life and environment [7]. Actually, it has been stated that 40% of the energy consumption and CO_2 emission in Europe will be devoured by construction, which is expected to follow this pattern of energy consumption to the year 2050 [8] [9]. But, as stated by *Asadi* et.el [10], this current needs of energy consumption will not decrease even if all new buildings are built on the idea of low energy building. Besides the new buildings, there are many existing buildings which have significant effects on the current energy consumption for a long time. As it is considered in the roles of conservation and energy efficiency of the building by *Energy Performance of Building Directive* (EPBD) 2002/91/EC [9] and its recast EPBD - 2010/31/EU [8] in the European energy policy, the conservation and the use of the energy in buildings are very important.

Due to the human requirements of thermal comfort, an increment of the energy consumption for cooling and heating is considered as one of the main current challenges of building sector [11]. Generally, after the first oil crisis, there was a developing concern around energy proficiency in the housing sector [12]. Thus, the question is, what will happen tomorrow? The answer to this question depends on the viewpoint of the researchers.

As stated by *Händel* [13] in the research of *federation of European Heating, Ventilation, and Air Conditioning* Associations (REHVA), ventilation gives or takes 30-40 % of the energy expended for heating of the building [14], while this rate in Portugal is around 30-45%.

Due to the importance of the IAQ issue and growing attention to the environmental and economic impacts of the energy usage, natural ventilation has been selected as an interesting method to provide an acceptable indoor air environment and to decrease the economic and environmental impacts of the energy usage. Based on the latter information about the energy consumption condition in the worldwide and in Portugal and due to the scope of the research, the following sections present different information about the characterization of the ventilation, especially in the old residential buildings.

Hence, this chapter is organized as follows: in sections 2.2 and 2.3 the importance of the ventilation and the concept and application of the natural ventilation is presented; principles of the natural ventilation are illustrated in Section 2.4; consequently, the different types of the natural ventilation will be explained in Section 2.5; section 2.6 is devoted to the advantage and disadvantage of the natural ventilation; since there are some requirements for ventilation systems, section 2.7 states these requirements; section 2.8 and 2.9 illustrate the human comfort and IAQ as two of the most important factors associated with the ventilation.

Consequently, section 2.10 explains the natural ventilation based on the building characterization according to two conditions: interior and exterior ventilation. After that, natural ventilation and its correlation with energy sector are presented in Section 2.11. Finally, Section 2.12 clarifies the natural ventilation retrofit in the old residential buildings.

2.2 The importance of ventilation

Ventilation is a key point of human well-being and comfort. Based on the *American Heritage Dictionary* [15], “it is the process of replacement of noxious air with the fresh air”. It is also the main factor of the existence of a qualified living condition in the building and has been studied for a long time as a part of building construction system. It is undoubtable that building ventilation specifically influences the IAQ, which needs to be comprehensively clarified [16]. The necessity of the ventilation is associated with the human comfort because clean air makes people feel better and healthier. Ventilation also has a positive effect on the quality of human actions inside the building.

The history of the indoor ventilation goes back to the time when the open fires for cooking and heating became available in the buildings. The oil crisis in the 1970s which led to high consumption of energy for heating/cooling when the building sector, as a part of the crisis, consumed a high amount of energy for heating/cooling. Due to the lack of insulation/sealing layer in the construction, after the oil crises, in order to decrease the energy consumption by building sector the way of ventilation has been changed. In Portugal, with the publication of the first thermal regulation in 1990s´, it became mandatory to build insulated and airtight buildings. During the time, in order to have better results, the application of different modern techniques for the air circulation, shading and evaporating were developed based on the adoption of modern techniques with current standards and regulations.

The presence of ventilation is one of the main requirement of the buildings in order to keep the level of oxygen in the air at an acceptable level, to remove the pollutant, odors, and moistures, and also to balance the indoor temperature for providing a comfortable environment which caused by building thermal mass [17]. As mentioned by *Putra* [18], the human satisfaction in a space is related to some factors that impact the air quality of the space. These factors include air velocity, humidity, temperature, and air pollution.

Thus ,natural ventilation is considered as a notable concern with different aspects which, some of them, are presented in the following [19]:

A: Conservation of ventilation solutions in the old buildings as a part of building identity.

B: The presence of the ventilation to control IAQ [20].

2.3 Concept and applications of natural ventilation

The presence of ventilation, especially the natural ventilation in a building, is absolutely necessary. Due to the flexibility of ventilation that is linked to different factors (from climate changes to the building construction), we think that all of them should be taken into account to realize its concept. Comprehension of natural ventilation needs an understanding of the concept of ventilation. Based on the research done by *Klevien* [19], generally, the concept of natural ventilation is related to three different aspects: the first one is a natural force, the wind or buoyancy-driven forces, which is an important factor needed to drive the ventilation system; the second one are the ventilation principles, single-side, cross and/or stack ventilation, to activate the driven forces for ventilating the building; the last one refers to the properties of the ventilation components like a window, wind tower, chimney, double-faced, atria, ducts and etc.

Natural ventilation aims to satisfy three different goals which are discussed by *Allard and Alvarez* [21]. The first goal is the cooling of the building by natural ventilation assuming that the interior temperature is higher than the exterior one. In other words, the cooling of the indoor air is the objective of the first goal. The second one is devoted to the cooling of the building structure and construction components, while the last one considers the cooling of the human body based on the evaporation and convention methods. The evaporation rate and cooling sensation will be expensed with an increment of the air velocity. In another word, by an increment of the air movement in a space, the human tolerance threshold will increase, which results in tolerating higher air temperature by human (residents). Thus, the level of thermal comfort will also increase. Therefore, without energy usage and just by using the air movement through natural ventilation, the thermal comfort level can be increased, though this increment of air movement should be controlled.

As stated by *Yeang* [22], natural ventilation enhances the comfort in two ways, direct and indirect. The direct way depends on the occupants of the building, meaning that the occupants feel cooler by more wind influx and increment of interior air speed. *Yeang* entitles this methodology as “comfort ventilation” [22] [23]. The second method, the indirect way, is in the view of night ventilation of the building. It removes the heated thermal mass of the construction throughout day-time which has been called “nocturnal ventilate cooling” [17] [24]. *Allard* [25] also carried a deep examination of the strategies of the natural ventilation to enhance the comfort. *Allard* proposed that the speed of air should be 0.8 m/s at maximum as the velocity, higher than this rate might provoke discomfort.

Since the information concerning the provision of the ventilation and/or natural ventilation might have been picked up in steps inside different areas of studies, some of the most important historical events, which have direct or indirect effects on the evolution of the ventilation are presented in Table 1. Each one of the events was an achievement on its time about the technique and application.

Table 1: Hierarchy of attention to the development of ventilation in the Worldwide [26]

Year	**Name**	**Event**
1895	The American Society of Heating and Ventilation Eng. (ASHVE) was formed	
1905	The American Society of Refrigerating (ASRE) was established	
1907	William Napier Shaw	First idealized buildings as single control volumes which links to the outdoor environment via flow- limiting orifices.
1910	Lewis Fry Richardson	Presented a paper on the first FDM solution for the stress analysis of a masonry dam.
1913	Sharman Kingsley	Suggested that open –air school would be a good prophylactic measure for healthy children.
1919	American Society of Heating and Ventilation Eng.	Established a comfort chart that quantified the environmental determinants of comfort.
1922	Harvard School of Public Health	Constructed a psychrometric chamber to refine the standards for human comfort.
1936	Constantin Yaglou	Established a paradigm for using ventilation as a means of achieving odor and thermal comfort in the living environment.
1950s	Iterative method were employed leading to the eventual development of computational fluid dynamics (CFD) in the late 1960s to early 1970s.	
1951	James B. Dick	Laid out key principles of the macroscopic building airflow analysis.
1954	ASHVE changed name to the American society of Heating and Air Conditioning Eng. (ASHAE)	
1959	ASHAE merged with ASRE and become the American Society of Heating, Refrigerating and Air Conditioning Eng. (ASHRAE)	
1960s	Building simulation began with studies of fundamental theory and algorithm of load and energy estimation.	
1970s	Network airflow model were introduced	
1978	Lawrence Berkeley National laboratory	DOE-2 energy Analysis program was released evolving from previous that were developed in the public sector.
1980s	Multi –Zone network models started as a research and design tool for air distribution analysis, smoke control, etc.	

***Continued** Table 1: Hierarchy of attention to the development of ventilation in the Worldwide [26]*

Year	Name	Event
1981	ASHRAE Standard 62-1981	Reduced minimum outdoor airflow rates and introduced IAQ procedure.
1988	Povl Ole Fanger (late world renowned professor)	Suggested at least 15 cfm per person was needed to dilute occupant odors.
1989	ASHRAE standard 62-1989	Tripled and quadrupled the minimum non-smoking ventilation rate of 1981.
1990s	Methods to integrate multi-zone airflow analysis with building thermal and contaminant- dispersal analysis were prosed.	
1999	ASHRAE standard 62-1999	Made several minor changes and clarification that did not impact the minimum required outdoor airflow rates.
2000s	Coupling airflow network model and CFD model became popular in building natural ventilation studies.	
2001	ASHRAE standard 62-2001	Converted from standard 62-1999, a little more change in minimum outdoor airflow rate.
2003	Outbreak of sever acute respiratory syndrome (SARS) caused a total of 8098 people worldwide to become sick: 813 of these died.	
2004	ASHRAE Standard 62.1-2004	new ventilation rate procedure and many lower rates were prescribed
2004	Yuguo Li and co-workers	Found evidence that the SARS virus was transmitted by air who studying the infection spread in hospital.
2006	ASHRAE standard 2006 supplement	Contained new requirements for separation of environmental tobacco smoke (ETS) spaces from ETS-free space.
2007	ASHRAE standard 2.1-2007	Increase in ventilation rate for high –rise residential occupancies.
2009	Outbreak of swine influenza killed over 700 people worldwide in one month, WHO advised taking adequate infection control precaution (e.g. natural ventilation) at home.	

2.4 Principles of the ventilation

Ventilation in a construction, which replaces interior polluted air with fresh air, is associated with the generated airflow by temperature or pressure difference through the windows, doors, or other building components that separate the interior and exterior environments according to presented information in section 2.3.

Natural ventilation based on the pressure difference between two spaces causes the air mass movement from higher pressure zone to the lower pressure zone. It happens on various scales, from the macro scale, the surfaces of the earth with a large amount of air movement, to the micro scale, the interaction of wind and building [27].

In natural ventilation, wind and buoyancy effect are considered factors that cause the pressure difference between two areas [28]. The process of using wind and temperature driven forces to generate the natural ventilation is demonstrated in Figure 1.

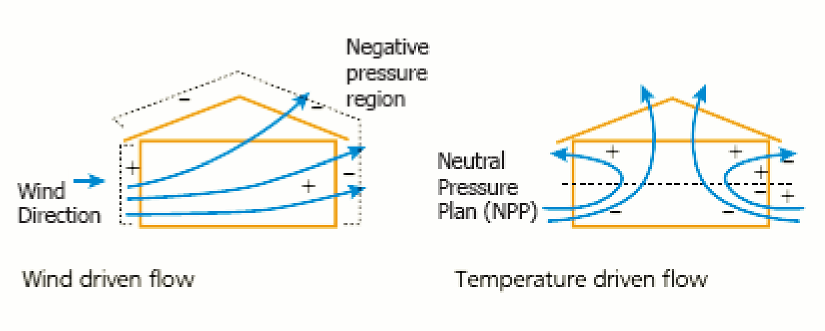


Figure 1: Illustration of the wind and temperature driven forces in the natural ventilation [28]

As it is shown in Figure 1, the role of wind-driven forces in natural ventilation is linked to the position of the openings with respect to the wind direction and also positive pressure region. The wind can enter the spaces through the openings on the windward side (positive pressure) and stack out the building from the roof and the leeward side (negative pressure). The temperature-driven forces arise based on temperature difference between higher and lower air temperature. This temperature difference causes the air entrance into the room from down openings and increases the air changes (air renovation) in the room and leaves it from upper openings or ceiling [29].

Ghiaus [28] mentioned that the buoyancy effect arises due to the humidity difference which causes that the cooled and dense air enters from the bottommost part of the wall and spreads in the room while the warm and humid air leaves from the highest part of the wall [28]. The effect of the pressure difference on the natural ventilation is also associated with the height of the building. The flow direction is linked to the air temperature. More precisely when the outside temperature is higher than the inside (in the warm season), the flow direction is reversed. To assess the ventilation in the building, it is also necessary to understand the airflow standards [19][30]. In summary, the existence of natural ventilation in a building is associated with three main factors, i.e. wind pressure (velocity and direction), temperature difference, distribution and pattern of the airflow which are briefly explained in the following.

2.4.1 Wind pressure

Wind is a phenomenon which changes in time and space. Hence, it is really hard to predict its intensity, velocity, and direction. As explained by *Hartog* [31], the prediction of the wind depends on a set of factors such as building form, building orientation, placement, and location of the building associated with the urban area and topography. All these factors influence the pressure coefficient and exposure of the airflow over the building. The maximum pressure is over the building envelopes, where the flow of air is discontinued and the presence of obstruction increases the wind pressure over the facades and at the same time avoids the wind incidence. However, this increment of wind pressure on the windward side increases the wind velocity along the sides and top of the building (Figure 2)[32].

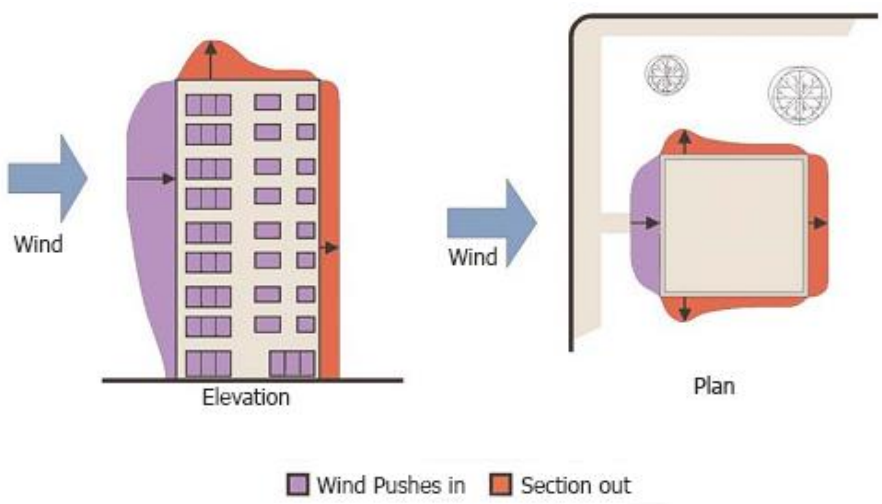


Figure 2: Illustration of wind pressure around the building [32]

The interior pressure changes based on the wind velocity, depending on the properties of the openings in the building envelope (location and number of openings). For example, if the openings are uniformly distributed on the sides of the buildings, the resultant indoor pressure is marginally lower than the outdoor pressure [28], which causes an increment in the pressure difference on the windward side and a decrement in the leeward side as well as on the roof of the building. In other words, as mentioned by *Quirouette* [32], the pressure difference would be positive on the windward side and negative on the leeward side. Summarizing, the position of the building envelopes with respect to the wind direction defines the condition of pressure over the exterior envelopes and this pressure difference over the envelopes results in the air leakage. The orientation of the envelope against the wind direction is not the only cause of the pressure difference. Actually, the pressure difference can also be seen on a multi-story building between upper and lower levels. It means that the height of the building also influences on the pressure difference. The reason of this pressure difference is the pressure coefficient which depends on the geometry of the building. Hence, the European standards present an equation which is called *Bernoulli´*s equation to figure out this pressure coefficient.

$$\frac{v^2}{2} + h + \frac{p}{\rho} = C \qquad \text{Eq. 1}$$

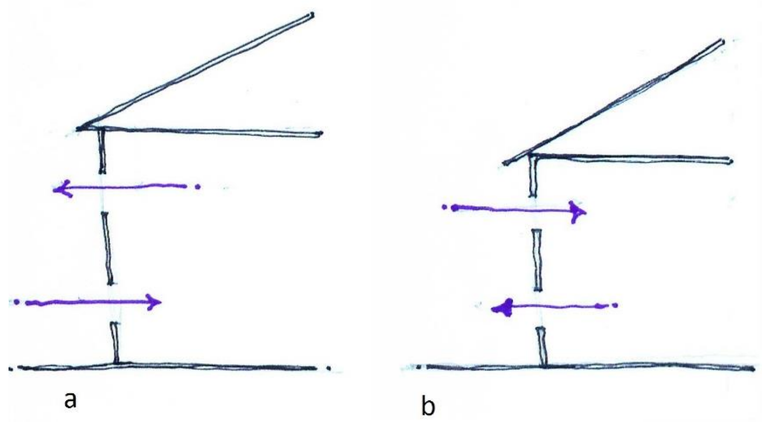
Where;
C is the pressure coefficient.
v stands for the wind speed (m/s).
h is the dimension of a given frame.
ρ is the specific mass.
p is the air pressure (pa).

2.4.2 Temperature differences

Temperature difference is another factor which affects natural ventilation. The presence of openings with different dimensions between interior and exterior areas is one of the reasons of temperature difference and consequently pressure difference. Eq. 2 illustrates the relation between the pressure difference and interior and exterior temperatures.

$$\Delta_{ph} = T_0 . g . h . \rho_0 . \left(\frac{1}{T_{ext}} - \frac{1}{T_{int}}\right) \qquad \text{Eq. 2}$$

Where:
h is the difference in the elevation between the center lines of the openings (m).
ρ_0 is the air density at 273K (k).
g is the gravity.
T_{int}, T_{ext}, and T_0 are indoor, outdoor and reference temperatures respectively (°C).
As *J. Botelho da Silva* [33] quoted from *Liddament* [34], the direction of the air mass movement in natural ventilation depends on the air temperature. If the temperature of the inside is higher than the outside, the airflow enters the room from the lower part and leaves from the upper part. But if the temperature of the inside is lower than outside, the airflow direction is reversed. (See Figure 3).



a): the air flow direction when Tint ≥ T ext., b) : the air flow direction when Text ≥ Tint

Figure 3: The direction of airflow based on the air temperature [33]

Meanwhile, the ex-filtrated air from the upper level of the building generates a reverse pressure at the lower level of the building which induces air infiltration. These movements are caused by the temperature difference occurring in the openings and construction components [25] [35]. Based on the pressure difference in the exterior wall, there is a hypothetical plane called *Neutral Pressure Plane* (NPP) in exterior walls. This plane is the limit level where the pressure difference varies from infiltration to ex-filtration. Figure 4 presents different NPP level [32].

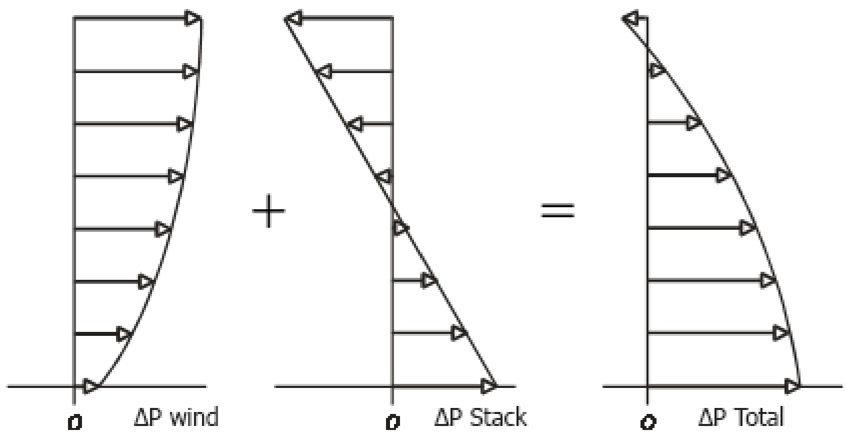


Figure 4: The effect of the neutral pressure plane (NPP) on infiltration and exfiltration process [35]

Taking into account what *Quiroette* mentioned [32], the placement of NPP is dictated on the light of the distribution and the size of leakage sites on the vertical envelope of the building. It is characterized as the point of the building facade, where there is no pressure difference between indoor and outdoor on the calm condition [32].

2.4.3 Airflow patterns and distribution

As mentioned in the beginning of section 2.4, the wind and thermal buoyancy cause the pressure difference which influences on the airflow and its distribution. In order to measure the airflow induced by wind and stack effects, the rate of pressure difference caused by this mechanism should be also added. The rate of the airflow is neither linearly proportional to the pressure difference, the final pressure is nor the overlap of the wind and stack pressure. Figure 5 shows this process with more details.

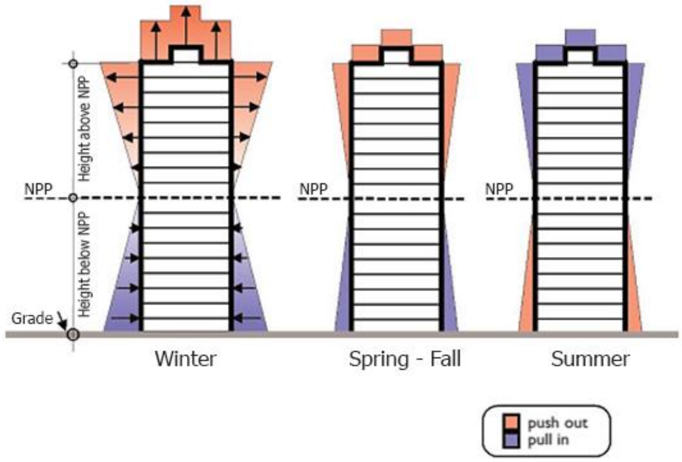


Figure 5: Overlap of the wind and stack pressure on the windward side of a building [1] [36]

Besides of the location of NPP and properties of the airflow pattern and its distribution which are illustrated by *Rebuild America* [36], there are some other physical factors that affect the airflow properties. These physical factors are building design, building height, position of the openings in the envelope, and etc. The occupants' action have also a direct effect on the pressure difference and indirect effect on the airflow distribution. Thereafter to understand the principles of the ventilation and the effect of each one of the above-mentioned factors on the ventilation, a brief study of the different types of ventilation based on these principles is presented.

2.5 Types of natural ventilation

Concerning the properties of each one of the effective variables, there are different types of ventilation such as single-side ventilation, wind-driven cross ventilation, buoyancy-driven stack ventilation, wind-driven stack ventilation, and hybrid ventilation. Figure 6 presents the three main types of natural ventilation namely single-side, cross, and stack ventilation.

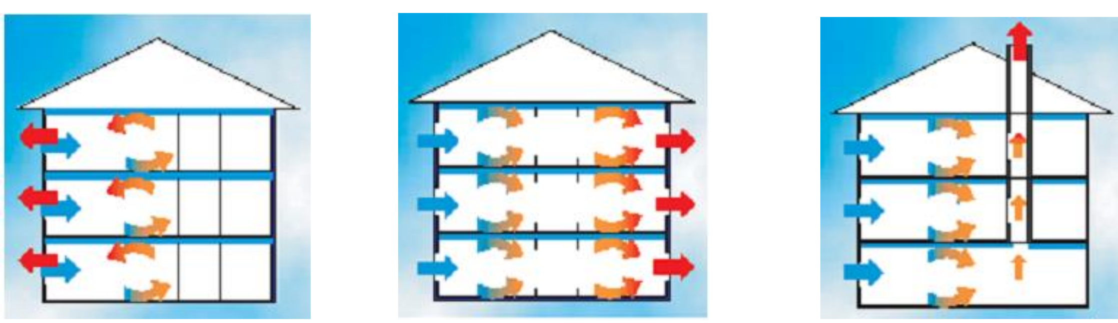


Figure 6: Single side, cross, and stack ventilation [37]

The single-side ventilation is the simplest type of the natural ventilation in which the supply and extract openings are located on the same side of the building. In this type of ventilation, which is the least efficient one, the opening area should be at a minimum 4% of the floor area. The cross ventilation is the second type of ventilation which is associated with the placement of supply and extraction openings in different directions. The openings can be located at the same or different heights which effect the airflow distribution

[1] The length of arrow in the presented figure is the amount of pressure difference at different height of the building.

in addition to increasing the efficiency of the ventilation in the interior space. This type of the ventilation has better performance when it works based on the wind driven effect.
The stack ventilation is the third type of ventilation which has a different characteristic from the other two. It is based on the air-supply through the louvers and the extraction through chimneys. Owing to the attributes of temperature difference, the stack ventilation is an additional type of natural ventilation which arises based on the thermal buoyancy properties. It is a temperature-driven phenomenon, in which the warmer indoor air is more buoyant than the colder outdoor air [38]. Due to a pressure difference between inside and outside of the building at the top of the wall and roof [39] air is pushed out through the cracks and openings. However, according to the mentioned *Magyer* by [37], it is associated with the wind-driven ventilation through a roof termination in the zones with negative pressure.
Different sorts of indices for effectiveness and efficiency of the ventilation have been proposed and discussed since 1980. In order to determine the performance of the ventilation system, different indicators which have some influences on the effectiveness of the ventilation system should be evaluated. These indicators are classified in four main fields, namely air change, air diffusion, heat removal and pollution removal.

2.6 Advantage and disadvantage of natural ventilation

Magyar [37] enumerates some advantages and disadvantages of the natural ventilation which are summarized in Table 2.

Table 2: Advantages and disadvantages of the natural ventilation [37]

Advantages	**Disadvantages**
The 'open window' environment associated with natural ventilation is often popular, especially in pleasant locations and mild climates.	Heat recovery from exhaust air is technically feasible but not generally practicable.
Natural ventilation is usually inexpensive when compared to the capital, operational and maintenance costs of mechanical systems.	Fresh air delivery and air distribution in large, deep plan and multi-roomed buildings may not be possible.
Better control of their environments and less restrictive comfort criteria.	Lack of filtration capabilities particularly urban, with high outdoor particle.
High airflow rates for cooling and purging are possible if there are plenty of openings.	Unable to control humidity especially in hot and humid climates (risk of draughts).
No need for space that conventional mechanical systems demand.	Airflow rates and the pattern of air flow are not constant.
A greater physical and psychological connection to the Outdoor area.	Ventilation rate is likely to be at its lowest in summer, just when it need to be at its greatest.

Continued *Table 2: Advantages and disadvantages of the natural ventilation [37]*

Advantages	**Disadvantages**
No fan energy and system noise.	Inadequate control over ventilation rate could lead to indoor air quality problems and excessive heat loss. Difficult to control when natural driving forces are small.
Suitable for many types of buildings located in mild or moderate climates.	Natural ventilation is unsuited to noisy and polluted locations.
Easy to operate.	Occupants must normally adjust openings to suit prevailing demand.
Minimum maintenance.	

Considering the above-mentioned advantages and disadvantages of natural ventilation, the most important advantages due to objectives of this research are user-controllability (having better control on the environmental condition) and no need of energy. On the other hand, the most important disadvantages are associated with the level of RH, ventilation rate and airtightness in the winter period.

2.7 Requirements of ventilation

Due to the importance of ventilation, especially in old buildings and as it is a part of building's identity besides of its functionality, it is necessary to keep it in the intervention process. According to *Rebuild America* (1999) [36], in order to have an efficient ventilation, it is required to have an integrated approach in design, installation, and operation phases, to know the relation between all integrated factors from the wind and temperature to ventilation system and to identify their relation to the airflow distribution. Therefore, an efficient ventilation retrofit strategy needs to take into account all conditions of the ventilation planning in the building. Some actions that are required to be performed to an efficient ventilation strategy are listed below.

- Necessity of energy efficiency in ventilation.
- Planning for the existence and distribution of the ventilation system.
- Necessity of occupant comfort and well-being in the building.
- Finding the interaction between ventilation and climate.
- Identifying the air pollutions which are produced in the building (from moisture, cooking, smoking and etc.) or at the urban level.
- Compering of the relation between building construction and building airtightness and air permeability.
- Designing ventilation strategies for different types of buildings.

In order to have an efficient ventilation system, the adoption of ventilation retrofit strategies according to the building type and construction method should be considered. The properties of the building design (interior design) also should be analyzed in this process.

2.8 Human thermal comfort

Comfort in an environment is one of the key factors of human well-being as it creates an agreeable condition for the human life. The inhabitants appreciate the indoor environment basically toward its air quality and thermal condition [37]. The thermal comfort may be promptly recognized as too hot or too cold, which more directly affects the human's comfort. So the temperature should consent for prerequisites to attain the minimum level of dissatisfaction [40][41]. The satisfaction of comfort zone is linked to different factors which the climatic factors being the most important ones. According to *Olgyay* [42], these climatic factors include air temperature, radiation temperature, air velocity and humidity. On the other hand, the activity level of people and their clothing are among other factors which affect the human comfort. According to *Olgyay* [42], quoted by *Aldy* et.al. [43], "the man´s physical strength and mental activity are at their best within a given range of climatic condition and that outside this range efficiency lessens while stress and the possibility of disease increase".

Donaldson and Nagengast [44] and also *Banham* [45] have investigated the discomfort theory presented by *Hermans* in 1883 which is associated with the poor ventilation based on the body heat loss mechanism. *Banham* [45] has quoted that: "*Hermans* proving that the thermal, rather than the chemical properties of air are of vital importance in connection with ventilation, insofar as normally spaces are concerned". This hypothesis had been expounded on the twentieth century and formed the current comfort requirements associated with the thermal condition and ventilation, i.e. thermal comfort.

Thermal comfort based on the *ASHRAE standards* (ASHRAE 1992 [46], ISO 1984 [47]) is characterized as "the mental condition that expresses satisfaction with the thermal environment". The prediction of thermal comfort has been standardized with different models, especially with the ones that have been determined by *Fanger* (1972 and 1988) [48] [49] which are presented/discussed in the following. Subject to the different available models for thermal comfort, and physiological and psychological characteristics of human being, two main fields of thermal comfort in which other available models are categorized based on them are explained in the following.

1- The heat balance approach: a technique for calculation of the steady states thermal comfort based on climate chamber research [48].
2- The adaptive approach: due to ASHRAE 55-2013 [50], "it is a relation for steady state thermal comfort which determined from investigations in this field. It assumes the people will have adapted to the indoor thermal condition".

2.8.1 Heat balance approach

Fanger [48] illustrated a well-known definition of heat balance approach. As stated by *Hartog* [31], *Fanger* assumed homogeneous climatological conditions around the human body and formulated a steady state heat balance equation for the human body. This heat balance equation is provided by:

$$H - E_d - E_{sw} - E_{re} - L = K \qquad \text{Eq. 3}$$

$$K = R + C \qquad \text{Eq. 4}$$

Where;

H is the internal heat production in the human body.

E_d is the heat loss by water vapor diffusion through the skin, while E_{sw} and E_{re} stand for the heat loss by evaporation of sweat from the surface of the skin, and the latent respiration heat loss respectively.

L and K respectively stand for the dry respiration heat loss and the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing).

R is considered as the heat loss by radiation from the outer surface of the clothed body.

C is devoted to the heat loss by convection from the outer surface of the clothed body.

As stated by *Hartog* [31], *Fanger* has developed an equation to predict the Mean Vote based on the thermal comfort. The *Predicted Mean Vote* (PMV) describes the thermal sensation based on 7 scales from -3 cold to +3 hot [46] [51]. PMV is a function of activity, clothing, air temperature, mean radiant temperature, air velocity and RH. *Predicted Percentage of Dissatisfaction* (PPD) which is another equation developed by *Fanger* [48] indicates the variance in the thermal sensation of a group of people at the same status. PPD is the percentage of human satisfaction/dissatisfaction from the indoor environment. It says that if 95% of the people are satisfied with the indoor conditions (5% dissatisfaction of the space), space has comfort condition.

2.8.2 Adaptive approach

After heat balance equation proposed by *Fanger*, *Humphreys* [52] developed another thermal model called adaptive approach. In order to develop this model, *Humphreys* considered the connection between thermal comfort and air temperature. He found that there is a huge amount of temperature differences in which a thermal comfort is felt by people. He realized that the thermal comfort level depends on people's feelings and this level can be higher for people who live in a hot climate compared to the people in a lower temperate or colder region. Based on this approach, comfort level varies on daily basis due to outdoor temperature. This difference is due to the adaptation of the body to the climate conditions which causes to bare higher interior air temperature. The comfort temperature band and limits based on this approach are presented in Table 3.

Table 3: Different level of comfort temperature based on adaptive approach [53]

Category	**Explanation**	**Suggested acceptable band**	**Suggested acceptable limits PMV**
I	Normal expectation (New and renovated Building)	±3	±0.5
II	Moderate expectation (existing building)	±4	±0.7

2.9 Indoor Air Quality (IAQ)

IAQ as a function of the air pollution has a high impact on human comfort. Thus, in order to have the maximum level of IAQ, the room should be ventilated with fresh air in order to remove the maximum level of chemical and biological components. *Fordham* [54] emphasizes that ventilation is adjusted to decrease the fresh air supply on structures by sacrificing the IAQ. As quoted by *Walker* [27] from *Yeang* [55], there are three significant sources of poor IAQ, namely “hermetically sealed buildings their synthetic furnishings, diminished ventilation, and also human bio-effluents” [27]. *Wargocki* [56] has argued that inadequate ventilation is the reason of more than 50% of low IAQ. He also has indicated that as most of the people spend around 90-95% of their time in the inner areas, their health, comfort, and performance are associated with the indoor environment in the buildings [56]. Therefore, it is absolutely necessary to provide adequate ventilation to guarantee an agreeable and healthy indoor environment. *Wargocki* [57] has mentioned that ventilation is determinedly connected to the thermal comfort and health, and is a key element of maintaining agreeable IAQ for occupants. Due to the investigation on the effect of poor air quality on the well-being of human life, the interior pollutants are categorized into the following three groups [58]:

1- Dust, fumes, and smokes.
2- Mists and fogs.
3- Vapors and gasses.

Table 4 illustrates the individual pollutants emitted from fabricating material, furnishings, and also ventilation system.

Table 4:Indoor pollutants, sources and control methods [59]

Pollutant	Source	Control
Tobacco smoke	Cigarette and other tobaccos products.	Smoke free zones, rooms and ventilation
Nitrogen dioxide (NO_2)	Gas combustion: Appliances .e.g. stoves, water heater, unvented space heater, fumes, heaters, and kerosene.	Modify flame: Temperature, vent appliances, tandem combustion chambers and room ventilation
Carbon monoxide (co)	Same as No_2, plus fireplaces and wood stoves	Modify combustion parameters, vent appliance and room ventilation.
Formaldehyde	Building and insulating materials, furniture. Adhesive, consumer products and combustion.	Modify production process, substitute stable adhesive, and modify combustion appliances: room ventilation, cooling and dehumidification.
Carbon dioxide Co_2	Kerosene heaters, gas heaters and people.	Modify combustion parameters: ventilation
Asbestos	Ceiling and floor tiles, pipe insulation, thermal and acoustical insulation materials, concrete and spackling compound	Removal, encapsulation, enclosure and sealants, education of exposed individual's warnings.
Organic compounds	Building materials, consumer products, furnishings, polishes, waxes, maintenance materials pesticides and room deodorants.	Substitute stable, nontoxic materials, room ventilation
Particulate matter	Combustion source, wood stoves, fireplace, biological agents, e.g. microorganisms, molds, pollens and animal dander	Air cleaning, filters and ventilation, cleaning of ventilation systems.

2.10 Natural ventilation and building characterization

Based on what was stated in sections 2.8 and 2.9 about the human comfort and IAQ, it can be concluded that ventilation is one of the most important factors to maintain human comfort in buildings. As stated before, there are different ventilation systems and solutions. But natural ventilation has received more attention after energy crisis (1973) and increased the attention towards the energy conservation. The efficiency of the natural ventilation is associated with different factors from climate conditions to building construction. The effect of climate conditions (the wind, temperature difference, and pressure difference) in natural ventilation was presented in section 2.4. In the following section, the effect of building construction in the natural ventilation is presented. In order to have more precise studies, the section is divided into two sub-sections: interior ventilation (the effect of the interior form of the building in the ventilation and air distribution) and exterior ventilation (the effect of the exterior form of the building in airflow distribution and pattern).

2.10.1 Interior ventilation

Interior ventilation is based on the interior design of the building as well as the placement of the openings and their effect on the interior air distribution. As stated by *Watson* [60], the characteristics of ventilation not only relies on the wind direction but also on the position of the openings, the presence of vegetation and also on the details of the building design. Since the wind speed and temperature differences are classified as the climatic properties and cannot be controlled by the location of the building, as stated by *Ferreira* [61], the design and management of a natural ventilation solution focuses more on the building design and location and size of the openings.

Therefore, the interior design of the building and especially the position of the interior wall influences the airflow pattern in the interior spaces. Consequently, by choosing the optimal arrangements and location of the building and also by controlling the openings operation, the pressure difference and buoyancy forces will be controlled as well. It is also possible to control the effect of the air movement of urban scale in the interior areas by an appropriate design of the openings in the building [30]. Figures 7 and Figure 8 indicate the airflow pattern in the interior space of the building due to the building design and opening conditions.

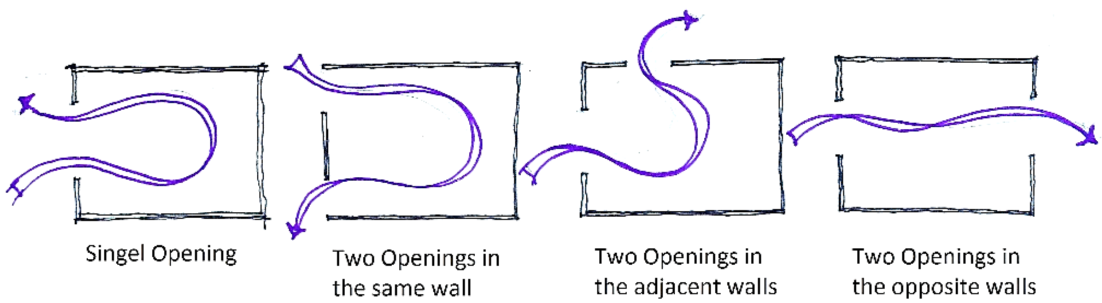


Figure 7: Air flow pattern in the interior space of the building

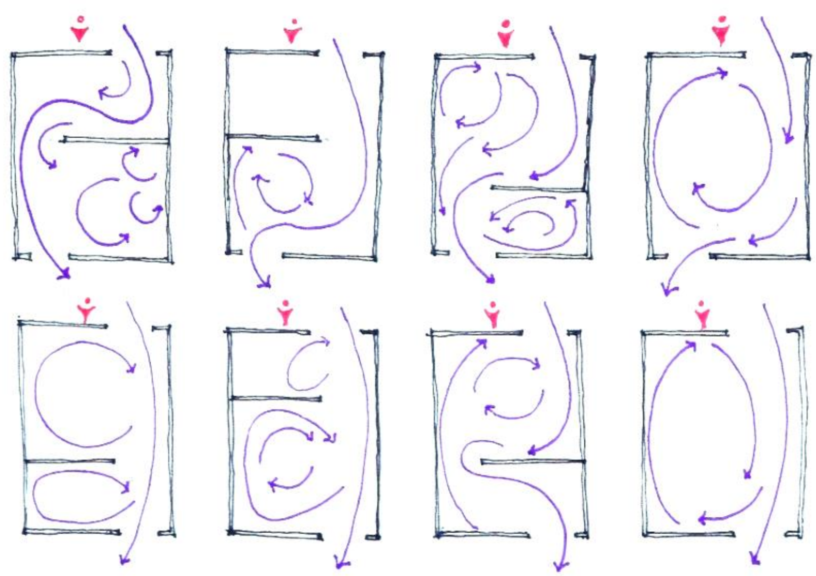


Figure 8: The effect of the interior partition location on the airflow pattern

More information about the effect of building construction and components on the natural ventilation is presented in Table 5.

Table 5: Affected factors of building and environment (building components and characterization factors) on the natural ventilation (adapted from [62])

Issue	Influenced Factor	Comment
location	Adjacent building	Large adjacent buildings can adversely affect wind patterns and greater opening areas are required.
	Surrounding trees. Land formation	On proper location of the building, the surrounding trees, structures and land formations are essential to the success of a natural ventilation system.
	Properties of ground	Locating on high ground is best, because it permits necessary drainage as well as exposing the building to the effects of wind.
Orientation	Wind direction and angel	Wind direction relative to the building orientation determines the sides of the building that are exposed to the wind and the angle which the wind will hit the surface. This will in turn affect the magnitude of the differential pressure across the building.
	Position of buildings´ surface	- Facing the open side to the south also minimizes the effect of the prevailing north and northwest winter winds. A modified open-front unit is usually narrow enough that orientation has little effect on ventilation. - Solar heat load on the roof of a north-south oriented building is greater than east-west oriented structure, modified open-front swine buildings are usually well enough insulated that this is not a major concern.
Form	Building depth	At building depths greater than 15 m the ventilation strategy becomes more complex; the limit for daylighting and single sided natural ventilation is often taken as 6 m. (But is probably higher.)
	Ceiling height	Adequate floor to ceiling heights are required for displacement ventilation and buoyancy driven natural ventilation. A minimum floor to ceiling height of 2.7 m is recommended [62].
Wall	Height of wall	- Wall height becomes more important as building width increases, if enough sidewall vent area is to be available for summer airflow [27]. - Sidewall height can also affect natural ventilation. For instance, if walls are not high enough, mechanical bunks can disrupt proper airflow through the building in summer.
Interior space	Position of partition	Minimum interior walls, partitions and other obstructions to airflow are desirable.
	Interior design	The building should be planned with a single loaded corridor and minimal interior partitions in the naturally ventilated rooms. Bathrooms should be provided and these spaces should be placed on the lee-side of the building [63]

***Continued** Table 5: Affected factors of building and environment (building components and characterization factor) on the natural ventilation (adapted from [62])*

Issue	Influenced Factor	Comment
Roof	Type of roof	Roof is one of the passive cooling techniques that it can have different construction and characterization which will be explained. There are different kinds of roof as passive cooling system such as Ventilated Roofs, Naturally Ventilated Roofs, Artificially Ventilated Roofs, Micro-Ventilated Roofs, High Roof, Double roof, Roof slope.
Shading	Position of shading	The appropriate use of external planting or other features can reduce solar gain. These need to be external, not internal and it is important to consider making the windows smaller rather than relying on shading as this will also reduce heat losses.
Window	Size of window	Since the wind can be toward either side of the building, the intake or vent opening on each side should be at least as large as the ridge vent opening on top [14].
	Type of window	There are different window opening which Horizontal pivot windows have more ventilation capacity than vertical pivot windows [64]. Open-able areas must be controllable in both summer and winter, e.g. large openings for still summer days and trickle ventilation for the wintertime.
	Shape of window	Window shape can affect ventilation performance: Single sided ventilation provided by top or bottom hung windows is rarely effective except in domestic situations where gains and occupancy levels are low.
	Height of window	Height difference between the top and bottom of the window muse be maximize to have high gain situation.

2.10.2 Exterior ventilation

This section is devoted to analyzing the effect of exterior conditions (topography of the area, urban conditions) on the natural ventilation. More precisely the exterior ventilation is associated with the analysis of the natural ventilation in the macro scale (urban level). Factors such as size and form of the building, free-space between the buildings, urban topography and street orientation in front of the prevailing wind, which influence natural ventilation in the interior spaces, are some effects of the macro scale in the exterior ventilation. The effect of each one of these factors is illustrated in the following:

One of the effective factors in exterior ventilation is the orientation of the building in the urban scale. The importance of this factor is due to the direction of the prevailing wind, as it makes a negative and positive pressures around the exterior shell of the building. Figure 9 presents the distribution of the wind around the building at the urban scale.

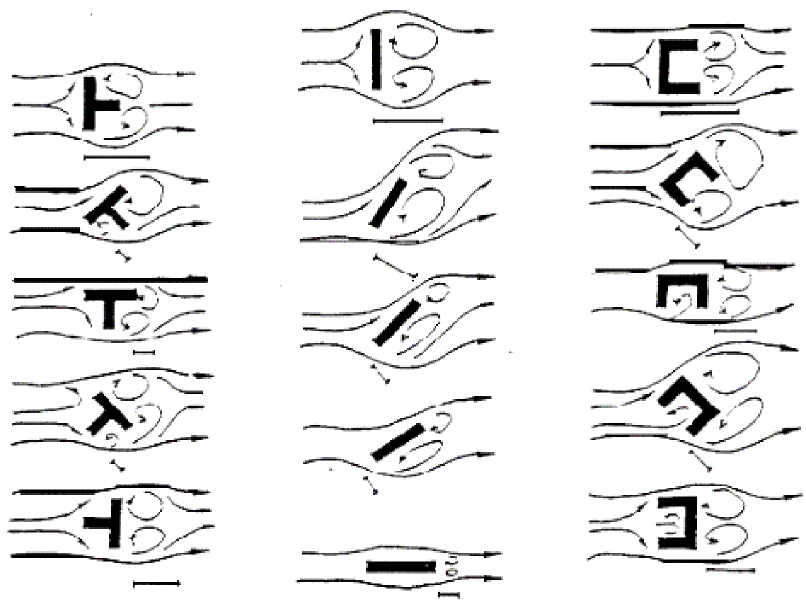


Figure 9: The effect of wind incidence angle, the length, and shape of obstructions on the downwind wake [63]

Figure 10 also presents the distribution of negative and positive pressure around the building.

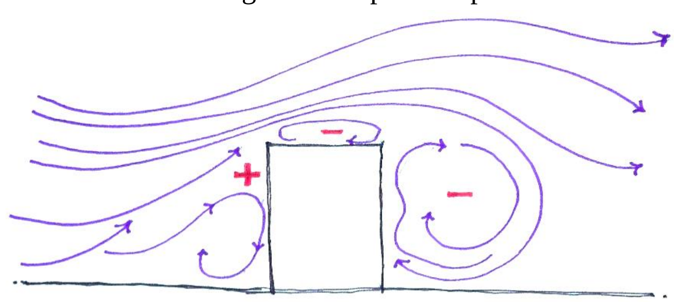


Figure 10: The pressure zones and wake cavity

The orientation of the street against the prevailing wind is another factor that affects natural ventilation in the building. For example, the formation of wind funnels if the street is in the same direction of the prevailing wind. This case influences configuration over building envelopes [63].
Topography is another factor which has an impact on the shape of the wind flow. Because when the wind passes over the land/ground, the shape of the land/ground changes the shape of the wind flow. The topography can also cause a wind channel in the urban area [65]. This type of channeling happens mainly when the environment is stable and the depicted flow extends roughly to the height of the surrounding terrain [60]. Figure 11 presents the flow channeling in the urban canyon according to the urban topography.

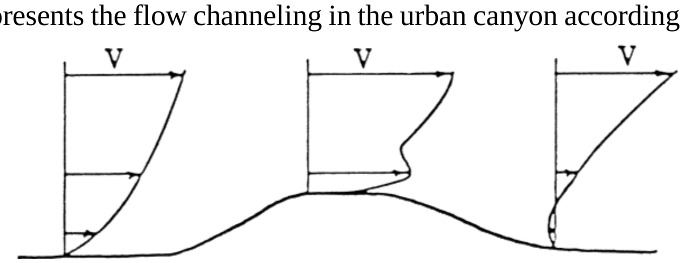


Figure 11: Velocity profile of the wind near a ridge [60]

Dekay and Brown [66] present the best approaches to the interaction between the wind and building's form. They state that velocity and direction of the wind could be evaluated using three main principles of the air movement. The first principle is an output of friction that indicates that the air velocity is slower close to the ground surface and faster in the higher altitudes. Therefore, the wind velocity profiles would be different due to the urban topography (see Figure 12).

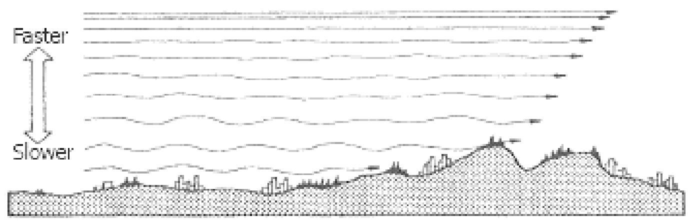


Figure 12: Variation in the air velocity according to the ground roughness [66]

The distance between buildings in urban area is also an important factors that influences exterior ventilation. *Priolo* [67] quoted from Allard [35] states that "buildings´ location should be at a distance from other buildings, that is greater than the depth of their wake. So that, they will not shelter it from summer winds". Thus, the street and other open spaces with narrow and long forms channel the wind. It happens if the relation between the length of the street to the height of the buildings that have bounded the street is less than 3 m [63] [60]. Figure 13 fairly clarifies this situation.

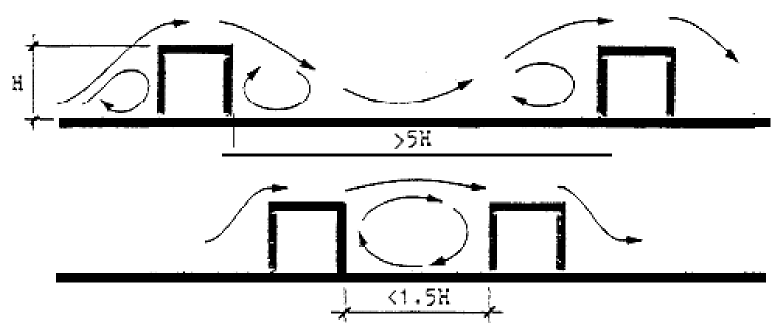


Figure 13: The building wakes and inter-building spacing [68]

2.11 Natural ventilation and building energy performance

In 2011, the building sector was responsible for 42.6% of the total energy consumption in *EU* and the *USA* [69]. The heating and ventilation systems consumed 48% of the total energy in *EU* and 57% in the *USA* [69]. Energy consumption in the service sector like heating and ventilation is also the largest part of the total energy consumption in the construction sector [70]. Therefore, natural ventilation is applied to achieve the aim of *Nearly Zero Energy Building* (NZEB) beside of using it for thermal comfort and IAQ. In order to reduce the energy consumption in this sector, the building should not over-ventilate which results in a reduction of the rate of energy consumption and its cost.

Most of the existing buildings are over-ventilated especially by infiltrations [71], while its acceptable rate for new buildings has been determined to be 0.35 ACH at 50 pa pressure based on the ASHRAE standards [58]. In Portugal in the light of REH [72], the rate of air-change per hour is 0.4 ACH in the winter time and 0.6 ACH in the summer time. The Canadian building code [73] and the Swedish building code [74] indicate that the ventilation rates should be different in each space due to its application. Thereby they use a multi-zone regulation for the infiltration rate. For example in the Canadian code, the infiltration rate is 10 cfm (cubic feet per minute) (5 l/s) for each room except bedroom and bathroom, while the required rate for bedroom and bathroom is 20 cfm (10 l/s) [73]. In the Swedish code, the average of the infiltration rate is 8 cfm per square foot (3.5 l/s per square meter) of the floor area in the occupied rooms, whereas the rate should be 8.5 cfm (4 l/s) per bedroom [74]. Since the energy performance is critical to minimize the uncontrollable infiltration and to supply sufficient ventilation [75], in the following more information about these concepts are explained.

2.11.1 Natural ventilation and building airtightness

As stated by *Magyar* [37], the airtightness illustrates the resistance of the building envelope to the airflow and is influenced by airflow's paths in the building. These paths are classified into two different sectors:

1- Leaks in the interstitial spaces (spaces between floors and walls).
2- Leaks in the building envelope.

The airtightness and air leakage in the buildings appear because of the architectural design solutions (like location of the windows, balconies, elevators, and materials), existence of crack and leakage in the junctions of the construction, penetration (elevator shaft, garbage shutting, and crack in plumbing) and also connections between floors. Therefore, in order to have an energy efficient ventilation system, the appropriate attention should be devoted to the building airtightness [17].

2.11.2 Building air infiltration

Ventilation is influenced by the uncontrolled air leakage (i.e. airtightness) crosswise the building envelope that can allow excessive energy consumption subject to the air infiltration from the outside [76]. Therefore, ventilation is a real issue to the new and also existing buildings which can improve the "comfort" environment. On the other hand, it can cause various problems such as: moisture development, pollution problems, increasing the humidity level in winter, dry air in summer, etc.

Generally, infiltration is the air penetration through the building construction, building components, cracks and unintentional openings in the building construction by the pressure difference of the wind and/or temperature driven [77]. The air also circulates between inside and outside of the building through openings in the building envelopes (for ventilation, access, and other purposes) [78]. As a result, infiltration is one of the fundamental sources of ventilation in the housing sector. Air infiltration is a neglected factor in the design of the natural ventilation while more attention should be devoted to it. However, this is included in the air-change rate in designing the mechanical ventilation system.

Air leakage of the building envelope is associated with three main categories. The first one is the building typology, material, components as well as age and maintenance of the building [79]. The second one is the exterior climate such as air velocity and temperature difference. The last one deals with the interaction between building and environment (wind direction, exposure, and shielding) [80]. Due to the role of the air infiltration of the building envelope in the natural ventilation and energy performance of the building, it is necessary to identify different paths of the air leakage and infiltration in the building in order to control them efficiently. Figure 14 presents different paths of the air infiltration in the housing sector.

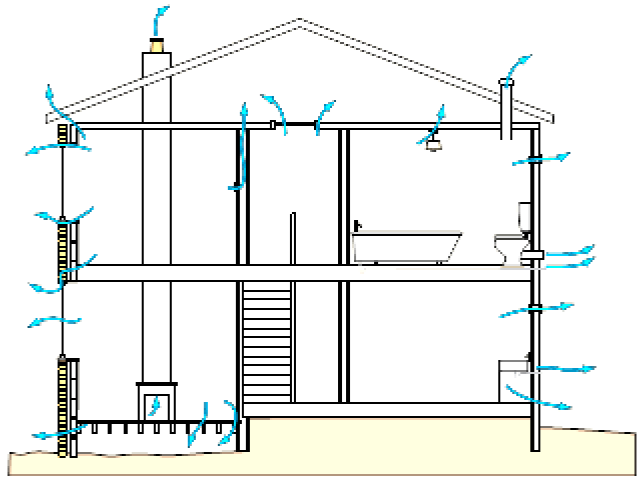


Figure 14: Different paths of air leakages in building [17]

2.12 Renovation of natural ventilation in old residential buildings

Considering all information presented in previous sections, we can say that natural ventilation is the main and even the only solution for building ventilation in old constructions. Beside of the functionality of the natural ventilation solution, it is also part of buildings´ identity. Therefore, it is necessary to conserve it in the intervention process. The best conservation action happens when we have appropriate knowledge about the ventilation properties in old buildings. Hence, the building retrofit process and properties of the existing natural ventilation solutions are illustrated in the following section.

2.12.1 Building's retrofit

Although, a necessity exists for the revitalization of the natural ventilation in old buildings as a way of conservation of the building characteristics and their heritage value, the retrofit methods require a proper consideration of the building physics and a careful approach about the moisture level on air and construction materials [81]. In most of the existing buildings, that suffered rehabilitation works, the transfer of moisture between the indoor and outdoor environment has been changed. In most of them, the traditional solid walls act like the breathing ones [3]. Hence, the property of the breathing performance should be taken into consideration.

Intervention and retrofit process are amongst the critical stages in the lifespan of the buildings and sometimes can introduce some new problems. For example, as stated by *Kunzel* [82], by decreasing the air leakage of a retrofitted building, the internal moisture, and condensation in the interior surfaces of the building increases which causes the lowering of IAQ and mold growth problems. Therefore, it is necessary to pay attention to the humidity problem in the process of the building retrofit, as well as considering the comfort, health, and durability of the building. Finding the paths of humidity penetration is an important factor to keep in mind.

2.12.2 Building ventilation element in the past

Old buildings have ancient natural ventilation technology. In particular, some of the recent investigations on the natural ventilation in these types of buildings are focused on the reactivation of the natural mechanisms [19]. Since most of the old buildings are naturally ventilated, in the following some details and construction elements which are used as part of the natural ventilation solution are explained.

- Open fireplaces

The ventilation and heating systems are generally associated with each other. Fire generates a negative pressure in the building and causes the output of the smoke based on the stack effect. Since the air moves between the spaces through the walls and doors to create a ventilation system, thus the fireplace and its smoke were used, to create natural ventilation in the winter period.
Usage of an open fireplace, unsealed window and doors, develop/creates some major problems like air currents. However, as the building is not heated in the summer time, the stack effect is decreased [83]. Therefore, the open fireplaces are one of the construction elements of the old buildings which are used as a ventilation solution.

- Duct space for ventilation

The presence of bathrooms and heating systems in buildings dates back to 1920s´. Due to the system of the bathroom, the air enters the bathroom through the ground floor by a duct or a brick flue and it exhausts through air vents based on the idea of stack effect.
Since the stack effect is the easiest way of air change in the winter and summer times, the ducts of the building act as a chimney stack and in the summer time the top of the duct is warmer than the bottom and therefore the duct intakes the fresh air [83]. Hence, duct components and chimney effect are another part of natural ventilation solutions in the old buildings.

- Interior design of the building

The interior design of the building is one of the factors of natural ventilation. The height of the building creates a big distance between inflow and outflow of the building. The openings and interior walls position affect the air circulation of the building, for example, the air streaming in the “right way” from bedrooms and lounge room to the bathroom and kitchen [83].

- Supply and exhaust air systems

Usage of supply and exhaust air system in the building construction has started since the 1970s´. By using these heat exchange system, the standards of heat recovery could be easily achieved, but based on the maintenance problems, high operation costs, and energy crises, the researchers had to find an alternative method which started around 1975-1980s´ [83].

2.12.3 Sick Building Syndrome (SBS)

The reduction of the ventilation rate to conserve the energy after the oil crisis of 1973, increased the contamination of toxic substances indoors and decreased the IAQ. These changes in the quality of the air might appear by the economic motivation of the building design, planning, construction, furnishing, and operation. This condition led to an increase of complaints caused by psychological and health problems associated with indoor contamination [84]. Natural ventilation is a promising method to improve the IAQ while reducing SBS. It is also a method to eliminate or decrease the energy consumption of the air conditioning systems, particularly structures that are spotted for mild climate areas [85]. *Levin* [86], argues that SBS will be basically an issue of modern buildings. ASHARE (2011) [84] quotes from *Levin* [86] that “many investigations of building occupants’ complaints in the new or remodeled buildings have determined that the occurrence of these symptoms is significantly higher than in a normal building.” [84].
As stated by *World Health Organization* (WHO), 30% of the structures in the worldwide have the potential to prompt the well-being issues. Based on *Levin* [86] quoted from WHO, a temporarily or permanently sick building based on ASHRAE [84] would have properties as following:

- They almost have forced ventilation systems.

- They need a relatively light construction.
- The indoor surfaces covered frequently with textile, carpets, and other materials with a high surface to the volume ratio.
- They are portrayed by airtight building envelopes.

Therefore, it seems that the SBS is mainly a configuration problem where physical features of indoor environment play a critical role.

2.13 Conclusions

Generally, natural ventilation is a way for cooling the air, occupants, and also building components. It is associated with three main factors: ventilation forces (wind and buoyancy driven), principles, and components.

The ventilation system of the building is related to two different parameters of climate and construction. The wind, air temperature, air pressure and airflow pattern are some of the climate factors. In what concerns to construction parameters, they are divided into two groups of interior and exterior. In the interior part, the building design, placement, and sizing of the opening, form of the building, location are important. On the other hand, the exterior factors are at the urban level and they are related to the placement of the building, building orientation, urban topography, and etc.

Concerning to the problem of the energy consumption worldwide, natural ventilation is one of the best ways to decrease the amount of energy consumption in the construction sector. Therefore, infiltration and air permeability of the building are important as infiltration is one of the ways of ventilating the building in the natural ventilation. However, the problem of over-ventilating by infiltration should be fairly considered. To do so, identifying different paths of the air leakage and infiltration in order to control the problem of over-ventilation is necessary.

Chapter 3:

Ventilation in Old Buildings: A review of previously finalized projects, existing regulations, and standards worldwide

*"**If there is a pile of manure in a space, do not try to remove the odor by ventilation. Remove the pile of manure**".*

Max von Pettenkofer, 1858

3.1 Introduction

Existing old residential buildings have interesting ancient natural ventilation strategies. In particular, some recent studies on the natural ventilation in these buildings are oriented to the reactivation of this natural mechanisms. Some architectural solutions in old buildings are often interpreted as a ventilation method, which has been neglected in rehabilitation actions. In the following sections, we attract the attention towards the topics of naturally ventilated buildings, their energy efficiency, IAQ, and ventilation effectiveness in some of the existing finalized projects as a guidance and recommendations which could be further developed by research centers and funded government agencies worldwide. Hence, the chapter is organized as follows: section 3.2 is devoted to the literature review of the natural ventilation where different aspects of natural ventilation are reviewed. In section 3.3, are explained some adapted methodologies as national recommendations in different countries. In section 3.4, some recommendations and regulations at the international level are presented. Finally, section 3.5 concludes the chapter.

3.2 Literature review of natural ventilation

Considering the fact that there is an extensive diversity of studies in the literature about natural ventilation, it was attempted to classify the existing researches on the basis of ideas and strategies. These classifications can help the researcher to obtain a good background knowledge about this research topic, to understand what has been done so far and what remains to be done. Several approaches have taken place over the years in the process of analyzing/studying natural ventilation. Ohba [87] has presented the new tendency of natural ventilation which is demonstrated in Figure 15. According him, the basic tendency in the field of natural ventilation was the conventional approach (experimental, statistical and theoretical), whereas the next generation was the computational approach (Building simulation, airflow model, Computational Fluid Dynamic (CFD) model).

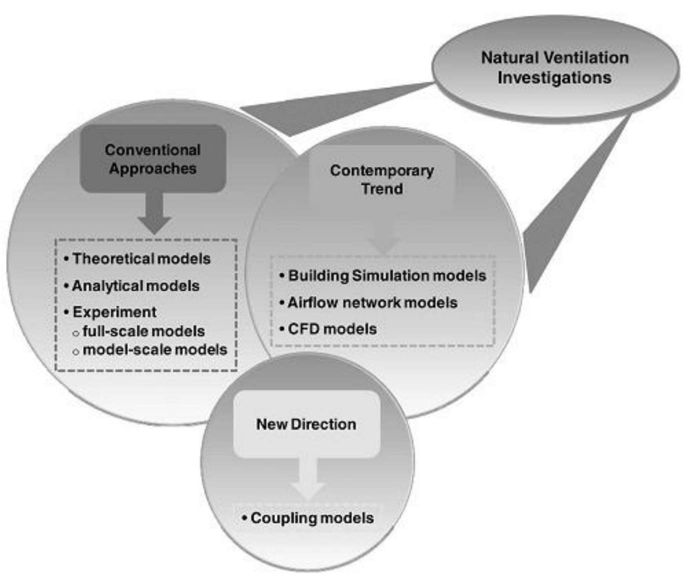


Figure 15: General trends of the natural ventilation [87]

By using computational approach, it is possible to find problems of the buildings in a specific point like energy or airflow and also develop a solution to figure them out. Nowadays, there is a new direction for the investigation of the natural ventilation which is called coupling approach. This approach needs a balance between computational and experimental approach to present the existing conditions and propose realistic solutions due to the problems.

3.2.1 Review of natural ventilation studies by the conventional, computational and coupling approach

There is a huge number of finalized researches based on different approaches of conventional, computational, and coupling. Table 6 shows the classification of some of these studies which have been used in this research.

Table 6: The summary of finalized research in natural ventilation (adapted from [87])

Approach	Methodology	Title	Author	Main Scope
conventional	Experimental	Natural ventilation through large openings- measurements at model scale and envelope theory.	Etheridg (2004)	Analysis of the natural ventilation in buildings with large openings by the modeling of envelop flow.
		- Impact of open windows on room airflow and thermal comfort. - Characteristics of airflow through windows	Heiselberg et al. (1999, 2001, 2002)	Study of the side and bottom-huge windows. The results show that by changing the opening porosity, based on the configuration of openings, the discharge coefficient is also changed.
		Turbulence effect on the discharge coefficient and mean flow rate of wind-driven cross ventilation	Chu, et al (2009)	Study of turbulence effect on discharge coefficient and mean flow rate.
		Local similarity model of cross ventilation : part 2, application	Ohba et al (2002)	Evaluation of the ventilation performance of several types of openings by using the local dynamic similarity model.
		A fundamental study of the airflow structure of outflow openings	Endo et al (2004)	Analysis of discharge coefficient due to the airflow condition around the outlet opening in a cross ventilation.
		Airflow through large openings- a catchment problem?	Sandberg (2002)	Prediction of airflow through the pressure distribution in a building.
		Study of the airflow structure in cross-ventilation rooms based full-scale model experiments.	Nishizawa et al. (2007)	Study of the importance of changing flow direction, deflected flow, surface flow, and circulating flow for cross ventilation.
		Characteristic of airflow as the effect of balcony, opening design and internal division on indoor velocity- A case study of traditional dwelling in urban living quarter in tropical humid region.	Prianto and Depecker (2002)	Investigation on the combined effect of balcony, opening and internal division on indoor airflows pattern of a two-story building.
		The influence of wind flows on thermal comfort in the Daechung of a traditional Korean house	Ryu et al. (2009)	Analysis of the effect of wind characteristics on the thermal comfort, a Korean house as the case study.
		Effect of ventilation opening level on thermal comfort status of both animal and husbandman in a naturally ventilated rabbit occupied building.	Ogunjimi et al (2007)	Analysis of the effect of the opening area and the building orientation on the thermal comfort level of a building.

***Continued**, Table 6: The summary of finalized research in natural ventilation (adapted from [87])*

Approach	Methodology	Title	Author	Main Scope
conventional	Experimental	Ventilation performance measurement using constant concentration dosing strategy.	Chao et al (2004)	Indication of a good natural ventilation system to provide an air-exchange efficiency.
		Characteristics of airflow from open windows	Heiselberg et al (2001)	Discovery of bottom-hung window as the best type of window for single-side ventilation in winter.
		Single-side natural ventilation measurments	Eftekhari (1995)	Obtainment of the air velocities and temperatures in a single –side ventilated office building.
		Case studies of natural ventilation in high rise residential building in Hong Kong.	Lam et al (2005)	Discovery of the air-change/hour in buildings with natural ventilation on different orienttaion and height.
		Field measurment of performance of roof solar collector.	Khedari et al (2000)	Indication of large opening effect on a high rate airflow.
		The lee side ventilation induced air movement in a multi –span glasshouse	Wang and Deltour (1999)	Investigation on the effect of leeward side ventilation on the air movement in a multi –span glasshouse.
		Detailed observation of cross ventilation and airflow through large openings by full scale building model in wind tunnel	Sawachi (2002)	Realization of the prediction of cross ventilation rate in wind-driven by using the quantitative method of wind tunnel.
		Natural ventilation for passive cooling: Measurement of discharge.	Flourentzou et al (1998)	Study on the measurement of ventilation performance in an existing building to find the flow coefficient.
		Infiltration of outdoor air in two newly constructed high rise residential buildings	Lam et al (2006)	Discovery of the building orientation effect on the air change rate.
		A case study on natural ventilation characteristics of the Diyarbakir Surici (Old City) in Turkey.	Aluclu and Dalagic(2005)	Discovery of hourly ventilation in order to obtain necessary airflow rate for comfort condition.
		Influence of ventilation on indoor radon level.	Chao et al (1997)	Investigation on the natural ventilation rate effect on the radon level in interior space in residential units.
		The effect of human behavior on natural ventilation rate and indoor air environment in summer, - a field study in southern Japan	Iwashita and Akasaka(1997)	Analysis of air change rate of eight apartment buildings.
		Airflow and thermal efficiency in solar chimneys and tromb walls	Burek and Habeb (2007)	Analysis of the effect of solar intensity and the channel depth on mass flow rate through the channel.
		Application of passive cooling systems in the hot and humid climate: the case study of solar chimney and water roof in Thailand.	Chungloo and Limmeecheckai (2007)	Investigation on the effect of solar chimney and water spraying over a roof on natural ventilation.
		Enhancement of natural ventilation in high-rise residential buildings using stack system.	Priyadarsini et al (2004)	Study on the application of passive and active stack systems to enhance natural ventilation in public housing and gave a conclusion on the energy efficiency of the stack system used in a hot and humid climate region.

***Continued**, Table 6: The summary of finalized research in natural ventilation (adapted from* [87]*)*

Approach	Methodology	Title	Author	Main Scope
	Theoretical	Local dynamic similarity of cross ventilation, part 1: theoretical framework.	Kurabuchi et al (2002-2004)	Discovery of the local similarity model of cross ventilation by using dynamic similarity around openings.
		Theoretical study of natural ventilation flux in a single span greenhouse.	Wang and Deltour (1998)	Analysis of the natural ventilation flux in a single greenhouse with roof opening and side wall openings
		Ventilation in a European dwelling: A review	Dimitroulopoulou. C, (2011)	Investigation on the ventilation in different countries based on the building conditions, health, regulations and standards.
		Experimental investigation on solar chimney for room ventilation.	Mathur et al (2006)	Evaluation of the possibility of using solar radiation to induce room ventilation in a hot climate.
		Natural ventilation	Fordham, M. (2000)	Study on the effectiveness of natural ventilation in the existing building.
	Analytical	Solar chimney for enhanced stack ventilation.	Bansal et al (1993)	Application of an analytical model to study the effect of stack ventilation on building.
		A study of solar chimney assisted wind tower system for natural ventilation in buildings	Bansal et al (1994)	Study about a wind tower coupled with a solar chimney design.
		Multi – objective methods for determining optimal ventilation rate in dwellings	Das, P. (2008)	Investigation on the optimal ventilation rate in residential building based on the multi-objective optimization approaches.
	Experimental and Analytical	Direct wind tunnel modeling of natural ventilation for design purposes	Carey and Etheridge (1999)	Investigation on the measurement of ventilation rates in a wind tunnel by different ventilation strategy.
		Natural ventilation of a building with heating at multiple levels	Livermore and Woods (2007)	Development of some theoretical models to explore the conditions of each flow regime validated by using a small-scale analogue experimental system.
Computational	**Simulation**	Application of night cooling concept to social housing design in dry hot climate.	Macias et al (2006)	Investigation on the passive night ventilation in social housing by applying the solar chimney concept.
		Study of natural ventilation in building by large eddy simulation	Jiang, Y. chen, Q. (2001)	Study on the simulation of indoor and outdoor airflow characterization of natural ventilation.
		A study of natural ventilation of public housing in Singapore using CFD simulation	Wong, N.H. and Loke, A. (2001)	Study on the natural ventilation by CFD approach.
		Natural ventilation design: an analysis of predicted and measure performance.	Belleri, A. et al. (2014)	Prediction of ventilation performance by effective design parameters.
Coupling	**Experimental and numerical simulation**	Wind tunnel test on velocity pressure field of cross-ventilation with open window.	Shinsuke and et al. (1992)	Analysis of the pressure and velocity of the air flow in and around an opening in cross ventilation.
		On the improvement of natural ventilation models	Ferrira, R. et al (2013)	Study on the validation and improvement of the models of ventilation in buildings with single-side and cross- ventilation.

Continued *Table 6: The summary of finalized research in natural ventilation (adapted from [87])*

Approach	Methodology	Title	Author	Main Scope
Coupling	**Experimental and numerical simulation**	Solar chimneys: simulation and experiments.	Afonso and Oliveira (2000)	Analysis of the effect of height of a solar chimney on the average flow rate.
		Effect of fluctuating wind direction on cross natural ventilation in building, from large eddy simulation.	Jiang, Y. chen, Q. (2002)	Analysis of across ventilation by large eddy simulation and on-site measurement (wind tunnel).
	Building Simulation/ airflow model and Analytical model	Multiple steady states in stack ventilation.	Chenvidayakarn,T. Woods, A. (2005)	Analysis of the ventilation and thermal comfort of occupants due experimental results.
		Coupling building energy simulation and CFD: application to a two-storey house in a temperate climate.	Barbason, M. and Reiter, S. (2014)	Study on the improvement of overheating prediction of the building.
		Control natural ventilation for energy efficient buildings	Schulze, T. eicker, U.(2012)	Analysis of opening configuration and typologies on the airflow network by building simulation in the design phase.
	Energy simulation and CFD simulation	Natural ventilation simulation with coupling program between building simulation and cooptation fluid dynamic simulation program for accurate prediction of indoor thermal environment.	Lipin, W. and Hein, W. (2006)	Prediction of natural ventilation effectiveness by coupling approach.
		Coupled Energy plus and CFD simulation for natural ventilation	Zhang, R. and Lam, KH. (2012)	Comparison of the airflow rate in different openings by simulation software.

As revealed in relevant literature, there are different factors such as ventilation rate, infiltration rate, air leakage and building air permeability that influence the efficiency of natural ventilation.
On the other hand, some physical factors such as building construction, building envelope and building components like windows, ceiling affect the ventilation, especially natural ventilation. Thus, the analysis of ventilation effectiveness based on the building´s components, properties and building performance is an active field of research in this area.
Therefore, the literature review will be based on two classes: The first class is about different theoretical parameters such as airtightness, air change rate, air permeability and air leakage which are associated with ventilation effectiveness.
Although the second class is the physical parameters like the airtightness of envelopes and its components as an effective factor it should be further investigated in different fields such as airflow, air change rate at different standard pressure and Effective Leakage Area (ELA).

- **Analysis of the literature based on the theoretical parameters**

Research literature infers that the efficiency of ventilation is related to the improvement of the airtightness of the building, which thus causes a reduction in the uncontrolled airflow through the cracks, infiltration, exfiltration, and etc. A research entitled "Improvement of airtightness in dwellings" about this matter has been developed in the UK in the framework of the project of *GPG224* and by *Energy Saving Trust* [88]. The last explained how it is possible to catch a high rate of airtightness in a new building.

There are also some recommendations about existing buildings. The study was developed in 100 new residential buildings with different construction techniques.

The conclusion of the research shows that only 20% of the selected buildings, in England and Wales, achieved the good rate of air permeability 7 $m^3/h/m^2$ in buildings with natural ventilation system. However, the best rate of 3 $m^3/h/m^2$ has been achieved for buildings with mechanical ventilation system. After that, the researchers proposed some recommendations such as sealing of windows, sealing of cracks, improvements of mortar joints to improve the building conditions for the remained 80% of the analyzed buildings.

Sherman [89] accomplished an important research on the air change rate and airtightness in buildings, based on the tracer gas method. The research involves the basic principle of mass conservation (air and tracer gas) which was shown in the continuity equation. He developed a study (2014) [90] about the application of BDT method. They have analyzed different techniques of BDT to find the total leakage of the structure based on the single zone or multi-zone.

Papaglastra [91] also has done a research about the airtightness of buildings in different European countries. According to this research, the value of air change rate in pressure of 50 pa (n_{50}) varies from 1.09 (h^{-1}) in Norway to 6.38 (h^{-1}) in Greece.

The results of the research show that the Norwegian buildings are "tighter" due to their cold climate, and that buildings in Greece have more "leakage". However, this air leakage is used in Greece as a way of building ventilation. Table 7 presents the value of n_{50} in different countries based on this research.

Table 7: Summary of n50 for 7 European countries [91]

Country	Sources	Number of available n_{50} values (h^{-1})	Types of building tested	Mean N_{50}	Min N_{50}	Max N_{50}	St. dev.	St. dev. mean	median
Belgium	Belgium building research institute (BBRI)	21	18houses, 1 industry, 2 offices	4.99	0.5	22.50	2.10	1.02	3.70
Greece	National and Kapodistrain university of Athens, group of building environment research (NKUA)	39	39 houses	6.38	1.87	13.10	3.15	0.49	2.64
The Netherlands	Netherland organization for applied scientific research (TNO)	218	110 houses, 108 apartments	1.48	0.06	6.20	1.03	0.70	1.26
France	Centre de Etudes Techniques de 1 Equipmet de Lyon (CETE de Lyon)	644	327 houses, 242 apartments, 10 industries, 5 offices, 4 hotels, 5 information, 7 multiple use halls, 4 sports, 4 whole apartment building, 46 others	3.38	0.04	60.96	4.42	1.31	2.55
Norway	Striftelsen SINTEF (Tampere university of Technology)	17	17 houses	1.09	0.17	2.79	0.86	0.79	0.74
Finland	Department of Civil Eng. Helsinki university of technology, HVAC laboratory	128	70 houses, 58 apartments	2.54	0.3	16.20	2.33	0.92	2.05
Germany	Blower Door GmbH Energia und Umweltzentrum (EUZ)	27	13houses, 3 industries, 2 offices, 2 homes for elderly people, 2 shops, 1 hospitals, 1 school, 1 library, 2 others.	1.21	0.01	4.70	1.07	0.88	1.00

Kalamees (2007) [92] has also presented a value of n_{50} in the worldwide in order to compare the condition of the building in Europe with other non-European countries. Table 8 presents the results of his research.

Table 8: Comparison of n50 value around the world [92]

Country	**Measurement time**	**Number of houses**	**Air change rate at 50pa, n_{50}, (h^{-1})**		**Remarks**
			average	**Min-Max**	
Belgium	1995-98	51	7.8	1.8-25	--
Canada	1985-95	222	3.1	0.4-11	New conventional houses
		47	1.2	0.13-2.6	low energy houses
Estonia	1999-2000	19	9.6	4.9-32	--
	2003-05	31	4.9	0.7-14	Built in 1993-2004
Finland	1979-81	16	6.0	2.2-12	Common pre-fabricated timber framed wall elements houses
		28	3.5	1.0-7.5	Special attention is paid for the air tightness
	1981-98	171	5.9	1.6-18	Mostly reclamation cases
	2002-04	100	3.9	0.5-8.9	Timber framed envelope
Norway	1980	61	4.7	2.0-8.0	--
	1984	10	4.0	3.3-5.4	Built in 1980, low energy houses.
Sweden	1978	205	3.7	St. dev. 1.24	Built during 1960s-1970s
	-	44	1.02		Timber framed envelope
UK	-	471	13.1	2-30	--
USA	1850-1993	12,902	29.7	0.5-84	--

- **Analysis of the literature based on the Physical parameters**

The second classification of the literature review is related to the building physics and components and their effects on the ventilation effectiveness. Therefore, the analysis of the envelope performance has also been targeted.

Pinto et.al. (2011) has also done a research involving the measurement of the air permeability of a dwelling and its components in Portuguese housing stock [93]. The research showed that the rate of air permeability has wide ranges due to the building component properties (Table 9).

Table 9: The air permeability of building´s components [93]

Component	**Test date**	**Flat**	**Flow rate for 50pa (m^3/h)**
Roller shutter boxes	8th and 21st Feb. 2006	1 and 3	586.3
Windows	8th and 21st Feb. 2006	1 and 3	64.0
Main entrance door	14th Mar. 2006	5	269.8
Kitchen external door	8th Feb. 2006	1	95.2
		Total airflow rate (m^3/h)	1015.3
		ACH_{50} (h^{-1})	6.3

Based on the *European Directive of Energy Performance* of Building (EPBD- 2002/91/CE) [94], assessing the air permeability of the building and its components is one of the most important ways to optimize building energy performance.

The thermal conductance of envelope elements (opaque and transparent) which are indicated by R-value, is an important factor in the performance of the envelope. It is also related to the U-value of the envelope. Hence, the main parameters of U-value such as location, thickness, density, and type of insulation, are extra factors which are associated with the envelope conductance [95] [96].
The window is one of the most important elements in natural ventilation because its opening area has an effect on the air leakage and ventilation rate of the building. Generally, the reason for the importance of the window is due to the flow which passes through it. Thus, the area of the window is an important factor in the calculation of the ventilation effectiveness. On the other hand, the discharge coefficient is another important factor in the effectiveness of ventilation and the window configuration has an effect on the discharge coefficient. For example, a window with a larger side measurement has a bigger discharge coefficient compared to a window with large bottom measurement. The discharge coefficient in a naturally ventilated opening is associated with the type of window, wind pressure, and wind direction. Since natural ventilation solution is necessary based on the wind and buoyancy driven forces, the position and size of the opening are important in the effectiveness of natural ventilation. The height of the window also affects the amount of the airflow through the window which in turn influences the effectiveness of ventilation. The building containing driven ventilation, the airflow movement based on the height of the opening is presented in Figure 16 [97].

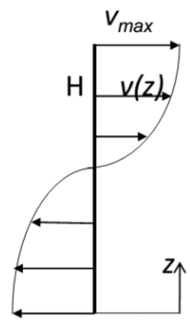


Figure 16: The airflow distribution through an opening with buoyancy driven ventilation

However, this curve changes based on the height of the building, as the airflow varies along the opening height. Generally, the airflow through the building is related to the type of ventilation system. For example, the shape of the airflow when passing through the window by a wind-driven ventilation system is different from the stack driven ventilation system. This is indicated in Figure 17.

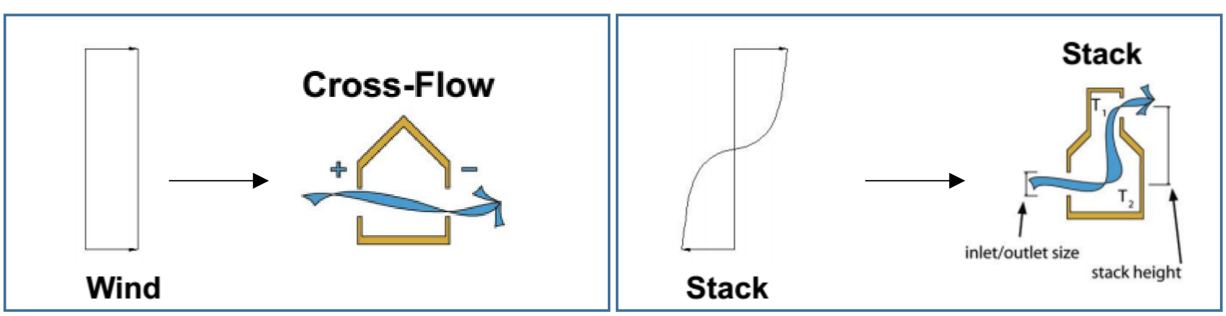


Figure 17: The shape of airflow passing through the window [97]

The window configuration is a factor that has an effect on the shape of the airflow and also on the ventilation area. According to *Breezway* [98], the configuration of a window, its ventilated area and a IAQ are

connected together. According to this research, the best relation among the window configuration and ventilation area belongs to the louver window with 80% , followed by the casement windows with 30% and the worst case belong to the fixed window with 0%.
Besides the different window configurations, windows with the same hung position have different airflows distribution based on the type of the ventilation strategy. This difference is presented in Figure 18.

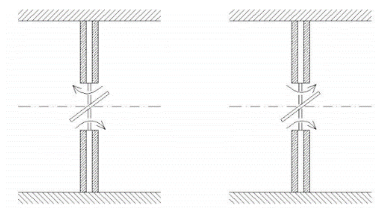


Figure 18: Window configuration and airflow distribution [97]

The geometry of the window is another important factor in the airflow distribution. As it was mentioned above, the opening configuration is very important in the model of airflow in the interior spaces. Although a huge number of studies have been done on this topic, there are still many gaps that are not yet fulfilled. According to the literature, a passive cooling method is another important factor in the effectiveness of the ventilation through the window configuration and its orientation based on pressure over the envelope. This method relies on any temperature difference within the building and also pressure difference over the envelopes.
Among all technological aspects of the envelope performance, the economic factor is also an interesting research field. *Kraus* et. al. [99] analyzed the airtightness of the energy efficient buildings by studying the advantages and disadvantages of building airtightness process in order to catch the energy efficiency in the building. The research was developed according to the *Strengths, Weaknesses, Opportunities, and Threats* (SWOT) analysis as a strategy for quality management. The economic parameters like type of construction and year of construction were investigated as external factors which affect the process of energy efficiency by the building airtightness. According to this research, mixed construction buildings have the higher air change rate, while the masonry construction is the tightest one.
The influence of moisture in the performance of the building envelope has also been investigated. A large part of the research in this field is about the degradation of interior or exterior finishes and structural components. This degradation manifests itself by the appearance of mold and fungal growth, condensation effect on the finishing surfaces, and etc. Ham et.al [100] investigated on the moisture condensation and material degradation in existing buildings. They explained that "the primary cause of energy inefficiency in the existing buildings is building deterioration by material degradation and moisture intrusions based on thermography method".
Lstiburek [101] also studied the moisture problem in the building envelope. He explained that "the energy efficient tight envelope is part of the solution for the healthy building when interior humidity, temperature, and pressure are controlled simultaneously" [101]. However, by using the tight envelope, the natural ventilation system of the building will face bigger problems of condensation in the interior area after a period. This problem is related to the infiltration and air leakage rate of the building because in the naturally ventilated building(s), infiltration is a part of their ventilation system. Therefore, it is necessary to make a balance among the envelope tightness and performance and also the efficiency of their ventilation system.

3.2.2 Technical aspects of building performance analysis based on the literature review

According to the technical standards for evaluating the performance of the building envelope which are often described in the literature review, the simplest technique is the visible inspection (thickness measurements, sample extraction of the insulation to assess its density and condition, and etc.). This technique can be used for some ceilings and floors after construction while more complex techniques are needed after construction to avoid disassembly of envelope components like a wall, as it faces environmental problems such as pressure and wind when it is compared with other building components.

In order to know the complex technique of a construction, the combination of measurement methods such as infrared camera and BDT (together) as experimental techniques and/or the simulation techniques are useful.

CFD is one of the most popular tools for analyzing the natural ventilation and airflow simulation [102] [103]. Based on *Ohba* [87], many ventilation- related studies [104], [105], [106], [107], [108] and etc. have been done based on the application of CFD to model the fluid dynamic as well as internal and external flow. An important CFD based research has been done by *Awbi* [109] [109] in which all equations and factors associated with CFD are presented.

As it is mentioned in the literature, building energy simulation (BES) is also an appropriate tool for analyzing the energy efficiency of the building configuration [110]. BES makes it possible to survey that how much energy is consumed in the buildings. How can this be controlled? How can we improve building energy performance based on methods which are related to the building configuration?

Generally, BES programs are divided into two main groups of design program and detail program. They are associated with two main modules to predict and simulate the building´s thermal condition and also airflow network. As there are plenty of simulation programs in this field, *Hand* et.al [110] investigated the capability of each one of these programs and concluded that all of them has their own advantages and disadvantages and none of them is absolutely perfect to be solely used for a research.

Masiac [111] studied the improvement of night ventilation based on the idea of solar chimney based on BES. They used a solar chimney on the exterior surfaces of the building on the west side. The exterior surface of the chimney is covered with vertical grills. After the simulation of the passive night time cross ventilation condition of the building, it was discovered that by using this solar chimney without having to open the window at the night time, cross ventilation system is works better than the primary condition.

Rashwan [112] has also analyzed the application of nanomaterial to improve the energy efficiency of building envelopes. This research made a comparison of energy performance of a building with two different materials: the first one is a traditional material and the second one is the nanomaterial. This new material is used for the painting, coating, insulation and also window. This energy performance comparison was done using the *Autodesk Ecotect Analysis* software. The final results of the research show that the heat exchange of the envelope will decrease up to 40% by using the nanomaterial painting. Also, the heat transfer of nanomaterial as the insulation layer in the exterior wall has a better performance than traditional material. Its U-value is 8 times less than the traditional one, which causes an improvement in the heat transfer up to 45%.

The coupling of the building simulation and CFD with the analytical or experimental methods is a new research direction. However, each one of these methods solely is able to provide some information about the thermal and airflow configuration of the building but, the results are not absolutely accurate. By coupling mentioned methods, it is possible to have a precise prediction of the condition of the building and thus the results are more trustworthy. However, computational cost increases.

The combination of the infrared thermography camera and blower door pressurization test to evaluate the location of leaks and also homogeneity of insulations is one of the complex techniques of building leakage evaluation.

For example, *Eric* et.al. [113] investigated building energy performance by the infrared imaging. The research was developed using Infrared thermography and BDT method for visualization of crack position in the building.

Tracer gasses, smoke, draft sensation and anemometry are other methods of complex techniques to identify the crack´s location. *Sherman* [89] has researched the technique of using tracer gas for measuring ventilation rate and building air tightness. *Pinto* [114] investigated the measuring of building air infiltration rate using the tracer gas in Portugal.

BDT is a technique to determine the buildings´ airtightness. For example, *Persily and Grot* [115] used pressurization test on federal buildings in which a whole building test was done by the method of pressurization. Another research was done by *The Energy Conservatory* (TEC) [116] to analyze the building airtightness based on the method of multi-fan. The literature also describes the use of balancing fan (with blower door operated simultaneously) or leakage variations to outline series and inter-zone leakages such as leaks between living spaces and attic or between adjoining dwellings [90].

Hult [90], used the blower door techniques to establish the boundaries of the pressure over the envelopes. More information about the details of each one of these models and their specific requirements are presented in Chapter 4.

Plenty of research projects in the framework of the research associations can be found in the literature. For example, *International Energy Agency* (IEA) has published different reports about the ventilation challenges which deal with simulation (its annexes 25, 34) [117], [118], control and commissioning (its annexes 18, 40) [119] [120], and ventilation system (its annexes 26, 27) [121] [122].

The next section is devoted to different research projects carried out by governments in the *European Union* (EU) and the *USA* while their results have been used as a recommendation or code in the national levels.

3.3 Adapted methodology as a national recommendation in different countries

Part of the literature of this topic is related to the studies in which their results were used as the recommendation at the national level. This section has been divided into two categories: the first category involves studies that became recommendation or rule in the country. The second category involves studies which are applied to a real case and it is possible to observe their results. Examples of these two categories are presented in the following subsections.

3.3.1 Recent developments on the quality frameworks for airtightness, Belgian Case

The research project " *ETANCH´AIR"* has been done in Flemish, Brussels and Walloon regions of Belgium in order to make a new role for energy efficiency of their buildings [123]. According to this new role, the airtightness of the building should be tested by fan pressurization test. They have tried to make a database based on the last declaration of energy performance in their country to monitor and evaluate the effect and application of the new rule. Based on the published information about this database and application of the new role, the usage of fan pressurization test in 2006 was around 2% while after the new role it increased to 58% in 2012 (Figure 19). Thus, based on its new role, they have better control on the measurement of the air leakage of the buildings and on the improvement of their energy efficiency.

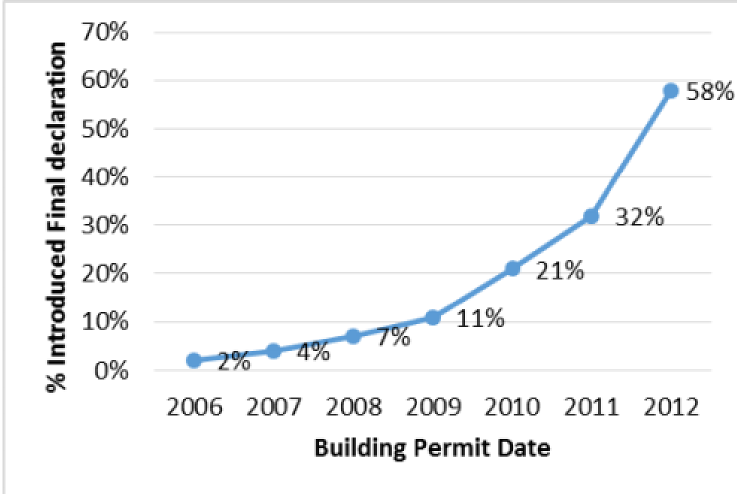


Figure 19: Percentage of increment on the air permeability measurement of buildings in the Flemish Region [123]

3.3.2 Proposal for updating French regulation concerning airtightness measuring equipment's calibration

The existing standard for airtightness in France is NF-EN 13829 2 which was completed in 2010 by French application guide of *GA P50-784 3* [124]. Due to the identified weakness of this regulation, the achieved experience of airtightness and also ISO-9972, France government decided to update the regulation. This project was done in 2011 by *CETE de Lyon* 4. As *Boithias* [125] mentioned, "the research was in charge of updating French philosophy about calibration rules by optimizing the compromise between calibration´s precision and cost". They tried to find the most precision of the airtightness measurement and also existing and upcoming technologies for it. This research specific that GA P50-784 regulation presents the indicators for airtightness and its uncertainty. This new guide has tried to make a comparison between the cost and precision of the calibration in order to find the optimized relation. They have also improved the required precision for the measurement of the low airflow.

3.3.3 The observatories BBC [5] examines airtightness measured air permeability of individual houses, France case

Sébastien Lefeuvre, Effinergie, France Effinergie is a French association which was created with the aim of studying comfort and energy efficiency of the construction in this country since 2006. One of the finalized projects in this center is observatories BBC [126]. This project aimed to examine the airtightness of 2500 low-energy residential buildings. The results of measurements showed that the average air permeability in individual houses was 0.4 $m^3/h.m^2$ at 4 pa which is 40% better than normal individual houses (Table 10). The air permeability of 50% of the houses was between 0.31-0.5 $m^3/h.m^2$ at 4 pa and 1.7-2.7 $m^3/h.m^2$ at 50 pa. The standard deviation drop was from 9.0 - 0.7 $m^3/h.m^2$at 50 pa. The average of air permeability was 0.54 $m^3/h.m^2$ at 4 pa and 2.9 $m^3/h.m^2$ at 50 pa, which is 34% lower than current building

[2] Adapted version of French norm based on EN13829.
[3] French regulation for thermal performance of buildings- Determination of air permeability of buildings- Fan pressurization method.
[4] Center of Studies and Expertise on Risk, Environment, Mobility and Development.
[5] Batiments Basse Consommation which it means Low Energy Building.

conditions. This project showed that it is possible to decrease the air permeability and air leakage of buildings by applying low energy regulation.

Table 10: The summary of the results of the project [126]

Measured air permeability	**Individual houses BBC $m^3/h.m^2$ at 4 pa**	**Samples CETE (1792 houses - May 2011) $m^3/h.m^2$ at 4 Pa**
Average	0.4 (2.17 at 50 Pa)	0.68 (3.69 at 50 Pa)
Standard deviation	0.12 (0.65 at 50 Pa)	1.65 (8.69 at 50 Pa)

3.3.4 Defects and moisture problems in buildings of old city centers, Portugal case

This research has been done within a collaboration between Uppsala University and some Portuguese Universities and is about the intervention processes and its moisture problems [127]. Conservation of ancient buildings is a major issue for modern societies, both from economic and cultural viewpoints. Information about the ancient built heritage is vital to plan adequate corrective measures. Historic centers of Portugal were selected as case studies. It surveys the building typology, material, problems of envelopes, and indoor space.

According to *Lourenco* et.al [127], the investigation was sequentially carried out in consecutive steps by using three levels of interventions: the first level was using the general plan of the area, available from the Municipality and visual observation from the exterior. The second level of the improvement was the damage survey in the building envelope, because of the large size of the historical center and the available resources. Finally, the third level was considered aiming the analysis of the indoor conditions of the building stock. To assess and predict the long-term heat and moisture performance of building envelope systems, researchers have used simulation tools or experimental investigations.

In this study, typical air leakages and their locations were determined from the field - measurement data reported by *Kalamees* [128]. Full-scale laboratory measurements were carried out to determine the moisture convection performance through the joints between the external wall and attic floor. Based on laboratory measurements, the simulation model built according to the CHAMPS-BES program (Coupled Heat, Air, Moisture and Pollutant Simulation in Building Envelope Systems) was validated for future analysis.

There was also another research on the quality of housing projects with respect to intervention solutions entitled "*Processo de recuperação e renovação urbana e social da baixa de Coimbra –(2005-2008)"* [129]. The study was conducted in the metropolitan area of Coimbra and the survey was conducted in 800 buildings with 2000 inhabitants. The research has focused on the rehabilitation and urban renewal of the existing buildings based on the construction, social and economic viewpoints. The construction phase was developed to find the sustainable rehabilitation solutions based on the detected pathologies in the buildings.

3.3.5 Experimental analysis of different building typologies, Italian Case

This research was developed by *Alfano* [76] to investigate the airtightness of 20 different residential building typologies in order to evaluate the air permeability of the buildings in different building typologies. To do so, a list of effective parameters and criteria was designed and researchers have tried to find the relation between these parameters and building air permeability. Figure 20 illustrates these parameters.

All the measurement devices have been calibrated by the Italian National Accreditation Body (ACCREDIA) [130] and the class of airtightness of windows has been defined based on the EN-12207

Standard [131]. The results show that the contribution of the airtightness of the windows ranges from 3.64% to 37.4%, with an average value 15%, higher than the ASHRAE one. This result confirms the higher influence of the windows in the investigated Italian buildings and the possibility of significantly reducing ventilation heat losses with a simple retrofit of the frame. Also, the inefficiency of the windows is linked to the unsealed rolling-shutter box and assembling of the frame.

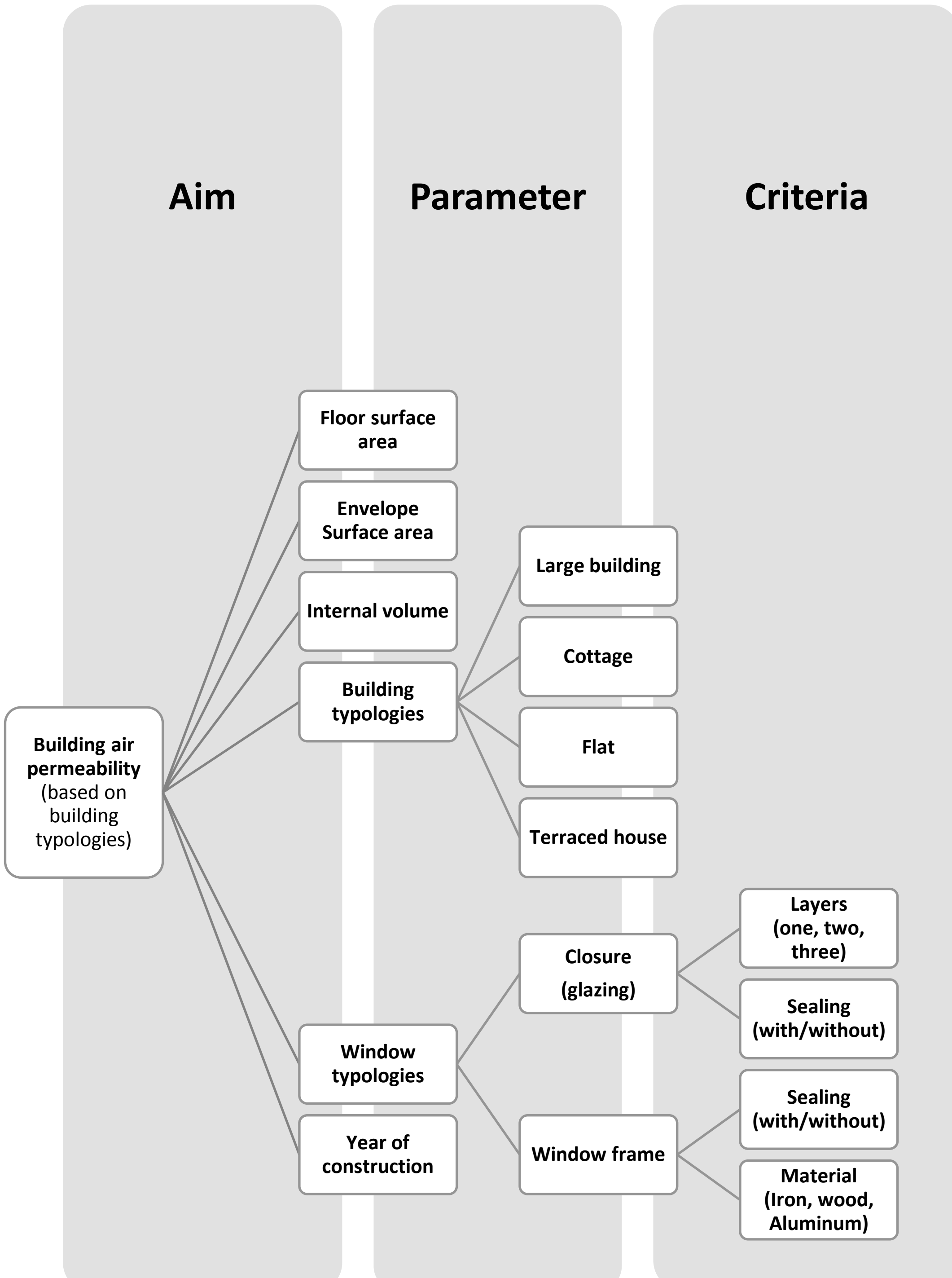


Figure 20: The effective parameters and criteria on the building air permeability

3.3.6 Building air leakage databases in energy conservation policies

The research uses the existing envelope air leakage databases on the envelope air leakage in the UK, the USA, France, Germany and the Czech Republic in order to find the relation of construction and airtightness rate. This project was developed in *Tight Vent Center* with the collaboration of *Air Infiltration and Ventilation Center (AVIC)* about the airtightness of buildings in Europe and the USA [132]. It showed that the air permeability of the buildings strongly depends on the building characterization. As it is explained in this research [132], the important building characteristics which affects the air permeability of the building are location, construction year, physical dimensions (floor area, volume, numbers of floors), foundation type, envelope materials, insulation types and/or ratings, construction methods, and ventilation system.

3.3.7 Domestic sector airtightness of the communities and local government, the UK case

There is a finalized project in the UK [133] named "*Domestic sector Airtightness of the Communities and Local Government*" in which the idea was the airtightness performance of residential buildings in UK, subject to current and future legislations. The research was developed in 25 dwellings whose construction belonged to two groups of masonry cavity and steel frame. The research was developed to find the number of factors which are known to influence the airtightness of dwellings. These factors are the age of dwellings, construction type, size and the complexity of the buildings, longevity, seasonal ventilation, number of floors, and quality of workmanship.

3.3.8 Indoor air quality (IAQ), thermal comfort, and daylight: An analysis of residential building regulations in 8 member states, European Union case

The research was developed by *Building Performance Institute Europe (BPIE)* in order to analyze the existing regulation of residential buildings in term of IAQ, thermal comfort and daylight in eight EU member states [134]. The aim of this research was to highlight the importance of the regulation in these fields.

The general idea of *BPIE* was to minimize the energy requirements of the buildings as well as having appropriate indoor climate though there are not any specific frameworks in EU legislation for it. Thus, this research has attempted to understand the role of national indoor climate regulations and compare them with European technical standards. The research was developed in Belgium, Denmark, France, Germany, Poland, Sweden, and United Kingdom in both new and existing buildings.

The report provides some recommendations for further policy development relevant to indoor climate. The research examines the improvement of indoor air climate in related to the improvement of building airtightness, air exchange in buildings, appropriate ventilation conditions. The difference between the latter mentioned quantities in each one of the countries will be explained in Section 3.5. Hence, the evolution towards meeting the requirements for energy performance in existing buildings should impose appropriate minimum requirements to assure a good IAQ for the occupants.

3.3.9 Airtightness measurements data from the USA single family dwellings

This research was developed in approximately 13000 single family houses in Alaska, Alabama, Vermont, and the Rhode Island [135]. BDT was used to check the building airtightness rate. The tested buildings had one or two floors of which 56% were multi-floors dwellings and the remaining were single floor dwellings. The results showed that the multi-floors are 11% leakier than single-floor houses because *Normalized Leakage* (NL) in multi-floors houses is 1.8 and in single-floor houses is 1.6. According to the presented information, the buildings which were built after the 1980s' do not have any trend to increase air leakage with an increment of the age while this tendency is high in buildings built before the 1980s', this can be related to the building regulations and the rate of application of these building regulations in the two periods.

3.3.10 Airtightness measurement data, Finland case

Due to the importance of the building airtightness and energy efficiency of the buildings in Finland, two research projects were done in this country in 2002-2009. The results of this two projects were presented by *Vinha* [136] which presented the results of airtightness measurement in 170 single-family detached houses and 56 apartments for multi-family houses. All buildings were analyzed based on different variables (envelope structures, wall, floor and ceiling structures, floors, age, insulation material, ventilation, and construction technology) (Table 11).

Table 11: Air change and air leakage rates at 50 pa (h^{-1}) on one-floor and multi-floors houses [136]

Type of house	One – floor houses			Multi-floors houses		
	Amount of houses	Average n_{50} value (h^{-1})	Average q_{50} value (l/sm^2)	Amount of houses	Average n_{50} value (h^{-1})	Average q_{50} value (l/sm^2)
Autoclaved aerated concrete	3	2.0	1.8	7	1.3	1.6
Lightweight aggregate concrete	2	4.4	4.6	8	2.9	3.5
Brick	4	2.7	2.5	6	2.8	3.2
Shuttering concrete block	2	2.4	2.2	8	1.4	1.8
Concrete element	4	3.3	2.9	6	2.2	2.6
Concrete and masonry houses in total	15	2.9	2.7	35	2.1	2.5
Log	8/7	7.3	6.0	12	5.1	5.6
Timber framed	46	3.8	3.4	48/47	4.4	4.8

The results show that the buildings with Log (traditional wooden house in the north of Europe) are the leakiest ones because their n_{50} value is 7.3 h^{-1} for one-floor and 5.1 h^{-1} for multi-floors houses while the value of n_{50} for timber- wooden buildings are 3.8 h^{-1} and 4.4 h^{-1}. On the other hand, the difference value of q_{50} in Log and timber-wooden houses with one-floor is smaller while this difference is bigger in concrete buildings. The project explains that this difference arises because the ratio between volume and envelope area of concrete houses is higher than Log and timber-wooden frame houses. Figure 21 presents the results of air change rate of single-family houses and their difference with the standard rates.

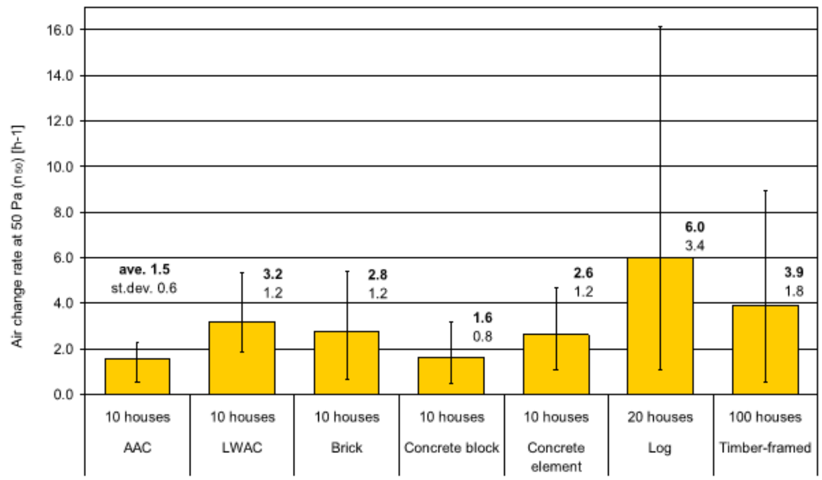


Figure 21: Air change rate of single-family detached houses normalized by indoor volume (n_{50}) [136]

The presented figure shows two types of numbers above each column of which the bold numbers indicate the averages values and the regular ones beneath show standard deviations. The research concluded that in addition to the construction material, the construction method and a number of floors also influence the air change rate of the building. Also, the type of insulation and vapor barrier material have effect on this rate. For example, the building with polyurethane was tighter than the building with other types of insulation materials. Another important factor in this rate is the ceiling structure which is associated with the gaps and joint conditions in the connection between the wall, floor, and ceiling.

3.4 Related recommendation and regulation at the international level

Naturally ventilated constructions ought to be planned on the basis of providing thermal comfort, on accomplishing sufficient moisture and contaminant removal and to meet or exceed government energy conservation performance standards. Insomuch the EU aimed to reduce Green House Gas (GHG) emission and also energy saving up to 20% till 2020-30 [137] and due to the effect of natural ventilation in environmental and energy performance of the building, reclaiming the energy performance can be an important way to achieve the EU objectives for energy and environmental aspects.

At the moment, there are some regulations which contribute to the energy saving in buildings. According to BPIE [138], there is a list of regulations such as "Eco-design of the energy related products in the framework of 09/125/EC [139] (recast of Energy-using Directive 32/2005/EC [140]), the End-use Energy Efficiency and Energy Services Directive 32/2006/EC(ESD) [141], the Energy Performance of Building Directive 2010/30/EU (EPBD recast of 2002/91/EC) [142], and also the labelling framework directive 1998/11/EC (recast of 75/1992/EC) [143]" in which all of them are focuses on the energy efficiency subject.

Portugal like other European countries has its own energy regulations. The first energy regulation in Portugal was published in 1990 and was named RCCTE (Regulamento das Características de Comportamento Térmico dos Edifícios) for the housing sector. More information about the Portuguese regulation is presented in Section 3.4.3. Considering the fact that achievement of the energy efficiency in buildings requires some strategies and plans based on the regulations and standards, in the following, some of the important regulations and standards which are effective have presented.

3.4.1 International and national codes and standards

There are plenty of regulations and recommendations which are used in the international and national level, some of them are more important than others. The list of some of the most important national regulations is presented in the following:

- EN 13829:2011. Thermal performance of the building- determination of air permeability of building- Fan pressurization method. European committee for standardization [144].
- ISO 5725-1: 1994. The accuracy of measurement method and results part 1: general principles and definitions. International organization for standardization [145].
- Occupation Safety and Health Administration (OSHA): 1998, air contaminants: examines air contaminants- permissible exposure limits [27].
- Energy Protection Agency Indoor Air Quality Standard (proposed) [146].
- American Lund Association Health House [147].
- Energy Policy Act of 2005 [148].
- CAN/CGSB-149: 1986, determination of the airtightness of building envelopes by the Fan pressurization method. Canadian General Standard Board [149].
- Sweden: BFS 1998:38: Hygiene, health, and the environment [74].
- UK: the building regulation 1991, Document F:F1 Means of ventilation [150].
- France: Arrêtê du 24.03.82 relatif à l'aération des logements (relation to the ventilation of residence) [151].
- Denmark: DS 418:2002 Calculation of heat loss from buildings [152].
- Finland: D2 Finnish Code of building regulation, indoor atmosphere and ventilation of building, regulation, and guideline, 2003 [153].
- Australia: As 1668.2-2002: the use of ventilation and air conditioning in buildings [154].
- Canada: Residential mechanical ventilation system CAN/CSA- F326 or alternatively the Canadian national building code, section 9- ventilation [73].

Besides all of the existing standards and regulations in EU and also worldwide, EN regulations are amongst the most important ones in the field of ventilation and IAQ. Since some of the EN regulations are the root of the others, and due to the importance of EN regulations for this research, the existing EN regulations and their connections and roots are presented in the following table (Table 12).

Table 12: List of EN Regulation and their variables [155]

From	To	Information Transferred	Variables
15251	15243	Indoor Climate requirements.	Heating and cooling set points.
13779-15251	15242	Airflow requirement for comfort and health	Required supply and exhaust airflow.
15242	15241	Airflows	Airflows entering and leaving the building.
15241	13792	Airflows	Airflow for summer comfort calculation.
15241	15203-15315-15217	Energy	Energies per energy carrier for ventilation.
15241	13790	Data for heating and cooling calculation.	Temperature, humidifies, airflows entering the building.
15243	15243	Data for air systems	Required energies for heating and cooling.
15243	15242	Data for air heating and cooling systems	Required airflows when of use.
15243	13790	Data for heating and cooling calculation.	Set point, emission efficiency, distribution recoverable losses, generation.
13790	15243	Data for system calculation	Required energy for generation.

Due to the presented list of EN regulations for ventilation and IAQ, the following figure (Figure 22) presents the relation between these regulations and how these regulations have affected each other in the revision phases.

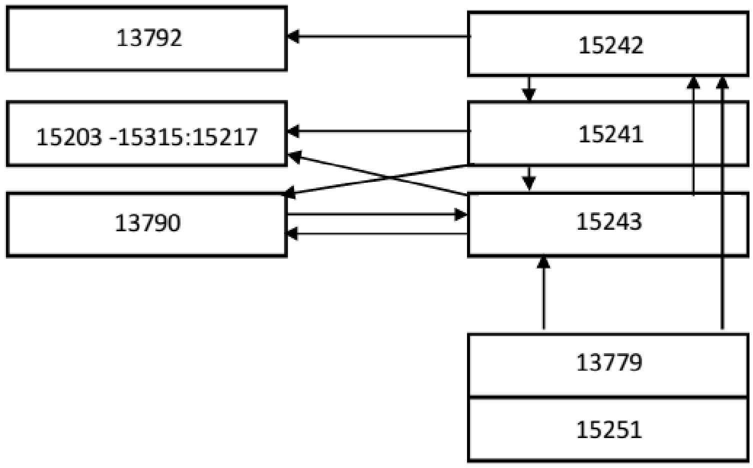


Figure 22: Scheme of relationship between standards [155]

Beyond the consideration of regulations in EU, in this section, the list of existing regulations for building performance in the USA are presented:
- ASHRAE 62.2-2004: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings [156].
- ASHRAE 62.1-2004: Ventilation for Acceptable Indoor Air Quality [58].
- ASHRAE 90.2-2003: Energy Efficiency for Design of Low-Rise Residential Buildings [157].
- Uniform Building Code (1994) [158].
- International Residential Code (2003)[159].
- International Energy Conservation Code(2003) [160].

Amongst all above listed regulations and standards, the main standards for energy efficiency of the building are ASHRAE 62.1 and 62.2 [58] [156] as well as EN-15251 which is a part of the European Directive 2002/91 [94]. Due to these standards, the minimum ventilation rate is guaranteed based on the intended use of the building, air quality, and environmental pollution. In the previous ASHRAE standards (before 1996), the residential building was counted as a small part of its broader ventilation standards. After 1996, ASHRAE discovered that it is a necessity to have separate standards for the ventilation of the residential buildings and, therefore, ASHRAE presented the first approved regulation for the residential ventilation in 2004. It is applicable for both new and existing buildings including all single-family houses and small multi-family houses. As a conclusion, it is necessary to mention that, due to the diverse range of documents, many of them address similar aspects of the problem and consider similar types of requirements.

3.4.2 Building code requirements for existing buildings in the EU

Based on the existing standards and regulations, it is clear that each one of these documents presents a different rate for ventilation, airtightness, and energy efficiency while most of them are focused on the similar aspects of the problems and present the same type of requirements to solve the problems.

Thus in the process of research and analysis, it is important to select the most relevant standards based on the aim of the research as well as the location of the studies. According to the requirement of EPBD, each country should have a specific code in order to improve the energy performance of the buildings. By the way, some countries do not have their own code and some of them which have their own code, it only applies to big buildings. In Portugal as an example, there are specific regulations which are updated based on EPBD regulations. This regulation applies for buildings with floor area over $50m^2$.

Since some countries have prepared their national code, in the following some information is presented on these regulations based on different objectives.

- Ventilation Rate

Ventilation rate is one of the most important aspects of IAQ that can be analyzed according to different standards from different countries. This parameter is prescribed on per square meter basis, per person basis, and/or a combination of both units. The indicators and units of air change rate define the fresh airflow and air volume of the space.

The units include 1/h (h^{-1} (per hour) and ac/h (air change per hour)) which illustrate the number of times that indoor air volume is renewed in one hour. There is also another volume which is based on the fixed volume (m^3 or liter) per time (s or h) and it is related to the number of occupants, type of room, and floor area [134].

In some countries, there are different rates for different rooms, while in other countries there is only one rate for the whole building. Table 13 presents the ventilation rate of building in countries with national codes.

- Operable windows

Regarding the building´s windows in the building codes and regulations, there is a lack of specific rate and number for operable windows in the ventilation codes and standards in the majority of countries.

Only some countries have a specific rate for it. For example in CA-24 [161] in California-USA, due to the International Residential Code (IRC), all habitable rooms should have at least one window with a minimum area of 4% of the floor area or the rate of air change in the room should be 0.35 ac/h , or the whole house ventilation should supply 15 Cubic Foot per Meter (CFM) per occupant. Also in some specific spaces like bathrooms, the minimum area of the operable window is 1.5 square feet or should have a fan with 50 CFM capacity for ventilation [161].

However, an exception in IRC is that the room can have no window if it is ventilated properly. Due to the fact that operable windows and air change rate on the national codes and recommendations are different in the different countries and their characteristics are presented in the following table (Table 13).

- Airtightness

Airtightness is a rate that helps to understand the envelope resistance against air leakage. Measurement techniques like BDT and also quality management approach are ways of finding its value in the existing buildings. That is why in some countries like the UK there is a minimum value for building airtightness and in other countries like Germany, there is a maximum value for the leakage of the envelope [162]. Generally, the building air leakage expression is based on different criteria in different countries and a specific unit does not exist for it. For example, Netherland, USA, Norway, and Belgium have the unit of ac/h at the reference pressure (4, 10, 50 pa), and the unit of expression of air leakage in the UK, Switzerland, and France is $m^3/(h.m^2)$ at the reference pressure of 4 or 50 pa while this unit is $L/(s.m^2)$ in Sweden. It should be noted that besides all the different existing units for the airtightness, it is possible to have a comparison between them if the assumption is based on a specific volume, area or pressure. The following table (Table 14) presents the values of minimum airtightness in different countries.

Table 13: Ventilation flows standard for a dwelling (adapted from [134])

country and standard ref.	**Whole building ventilation rate**	**Living room**	**Bedroom**	**Kitchen**	**Bathroom +WC**	**Only WC**
Brussels(NBN D50-001) Requirement	3.6 $m^3/(h.m^2)$. floor surface area	Minimum 75 m^3/h should be limited to 150 m^3/h	Minimum 25 m^3/h should be limited to 72 m^3/h	Minimum 75 m^3/h	Minimum 50m^3/h should be limited to 75 m^3/h	Minimum 25 m^3/h. fixed value (i.e. independent of the area)
Denmark (BR10) Requirement	Min. 0.3 l/s.m^2 (supply)	Min 0.3 l/(s.m^2) supply		20 1/s (exhaust)	15 l/s (exhaust)	10 l/s (exhaust)
France (Arrete 24.03.82) Requirement	10-35 m^3/h (depending on room number and ventilation system)			Continuous: 20-45 m^3/h		15 m^3/h
Germany (DIN 1946-6) recommendation	15-285 m^3/h (details see chapter)			45 m^3/h (nominal exhaust flow)	45 m^3/h (nominal exhaust flow)	25 m^3/h (nominal exhaust flow)
Italy (legislative Decree 192/2005, UNL EN 15251) Recommendation	Naturally ventilated: 0.3-0.6 vol/h	0.11 m^3/s per person for and occupancy level of 0.04 persons/m^2			4 vol/h	
Poland (Art 149-1-journal of laws 2002, item 690. And PN-B-0340:1983/Az 3:2000) recommendation	20 m^3/h for each permanent occupant should be calculated according to the polish standard but not less than 20 m^3/h	20-30 m^3/h for each permanent occupant for public building for flats, it is a summary of flow from all rooms.		30 m^3/h to 70 m^3/h without window.	50 m^3/h	30m^3/h
Sweden (BFS2014:13-BBR21) Requirement	Supply: min 0.35 l/ (s.m^2) floor area or (8 cfm per square foot)	8.5 cfm (4 l/s) per bed space of supply capacity.				
Switzerland. (SIA 384/2, SIA 382/1)		80-120 m^3/h			30-60 m^3/h	
Norway (NBC. Ch 47-1987)		Supply operable window or inlet bigger that 100 cm^2 in external wall.		Mech. Extract 60 m^3/h or by natural extraction at least 150 cm^2 duct above roof	Mech. Extract 60 m^3/h or by natural extraction at least 150 cm^2 duct above roof	Mech. Extract 40 m^3/h or by natural extraction at least 100 cm^2 duct above roof
Netherlands (NEN 1087)		1.0 dm3/s/m^2 floor area.		21 dm^3/s	14 dm^3/s	7 dm^3/s
UK(approved Document F) recommendation	13-29 l/s (depending on bedrooms)			13-60 l/s (extract)	8-15 l/s (extract)	6 l/s (extract)
Finland (NBC-D2, 2003)		0.5 (l/s.m^2), 6.0 (l/s.p) or 0.35 l/s.m^2 floor area		Exhaust 8 l/s (cont), 25 l/s (boost)	Exhaust 10 l/s (cont), 15 l/s (boost)	Exhaust 7 l/s (cont), 10 l/s (boost)
Canada (CSA-F361-M1989, ASHRAE.62-1989)	>0.3 ac/h, 5 l/(s.p)(10cfm).	Master bedroom and basement 20 cfm (10 l/s).		Exhaust 50 l/s(inter), 30 l/s (cont.)	Exhaust 250 l/s(inter), 15 l/s (cont.)	
EN 15251-European standard	0.35-0.49 l/(s.m^2)	0.6-1.4 l/(s.m^2)		14-28 l/s	10-20 l/s	7-14 l/s

Table 14: Summery of international residential airtightness and ventilation standards [163]

Country	Building airtightness	Residential ventilation rate
Belgium	≤1.0 ACH_{50} recommended with balanced HRV. Otherwise ≤3.0 ACH_{50}.	≥1.0 l/(s.m^2) floor area. Plus exhaust in bathroom and kitchen.
Canada	≤1.5 ACH_{50} required new HUDAC and R 2000 homes	Require 5-10 L/s mechanical ventilation be distributed to/from individual room: typically amounts to ~ 0.3 ac/h
Finland	No requirement.	≥0.5 ac/h recommended.
France	No requirement for airtightness: requires calculation of ventilation heat loss	≥1.0 ac/h continuous required: must be supplied to living/ bedroom, exhausted from kitchen and bathroom.
Japan	Aggregated leakage per envelope area: ≤2.0 cm^2/m^2 (cold climate). ≤5.0 cm^2/m^2 (moderate climate).	≥0.5 ac/h recommended.
New Zealand	No requirement.	≥0.35 ac/h or 15 CFM (7.5 L/s) per person recommended.
Norway	≤4.0 ACH_{50} required for new single family detached homes. ≤ 3.0 ACH_{50} for other homes.	Supply openings and exhaust rates specified by room type.
Sweden	≤ 3.0ACH_{50} required for single-family. ≤ 2.0ACH_{50} required for other homes.	≥0.35 L/(s.m^2) floor. Must be continuous: -0.5 ac/h for 2400 ft^2 home.
Switzerland	≤1.0 ACH_{50} required with balanced ventilation systems: 20-30 ACH_{50} recommended for exhaust ventilation.	Recommended: ≥0.4 ac/h in single-family homes. ≥0.6 ac/h in multi-family homes.
United Kingdom	When mechanical ventilation is present, recommendation is for homes to be as tight as practicable.	Recommended: ≥8 L/s (17 CFM) per person. ≥ac/h in living and bedroom. ≥3.0 ac/h in kitchen and bathroom.
USA	Recommendation per ASHRAE Std. 136, but no requirement.	Recommended ≥0.35 ac/h or 15 CFM/person whichever is greater.

- Humidity

According to EN-15251 [164] and EN-14134 [165], humidity is one of the most important factors in the ventilation of the residential buildings and has an effect on protecting the building against SBS. In fact, it is not possible to control or influence some of the sources of the humidity by designer [134]. The rate of relative humidity in different national codes is presented in Table 15.

Table 15: The standard of humidity for a dwelling (Extracted from [134])

Humidity		
Sweden	Requirement and recommendation in place	Humidity difference indoor and outdoor is ≤ 3 g/m^3 in winter.
Denmark	Requirement and recommendation in place	--
UK (ENGLAND AND WALES)	Requirement and recommendation in place	Less than 65% per month and less than 85% per day
Germany	Requirement and recommendation in place	30-70%
Poland	Requirement and recommendation in place	40-60 %
France	No reference in legislation	
Italy	No reference in legislation	

3.4.3 Portuguese regulation in ventilation

Due to Portuguese thermal regulation, an energy performance certificate must be issued for each building and this certificate assign an energy label to the building according to a specific energy efficiency scale [166]. *Brandão de Vasconcelos* (2016) [167], states that 50% of the total housing stock was built in 1960-1990 and more than 85% of them are classified with C or less energy label.

Due to the importance of energy aspects, the first energetic regulation in Portugal was written in 1991 which was named RCCTE (Decree-Law No. 40/90 1990) for housing sector[168]. After that in 1998, the second Portuguese code under the name of RSECE (Decree-Law No. 119/98 (for services and commercial buildings with HVAC) has been published.

Due to the EPBD directive of 2002, Portuguese government updated version of their national code on 2006 in three fields; Energy Certification System (SCE) - Decree-Law 78/2006 , Code of Energy Systems in Buildings Climate (RSECE)- Decree-Law 79/2006 [169] (commercial and services building with HVAC) , Regulation of characteristics of thermal performance of housing sector (RCCTE) - Decree-Law 80/2006 (for housing sector) [170] which it was available in 2008.

Subsequently, based on the EPBD (recast 2010), a new updated version of the Portuguese codes became available since 2013. This new and updated regulation is divided also into two parts of REH (for housing) according to the Decree law 118/2013 [171] and RECS for commercial and services building with HVAC. Besides these codes, there are some other regulations like Portuguese Standard NP 1037-1 and especially its Part 1 for residential buildings, natural ventilation [172], and Thermal Values regulation of DL, 234/2013 [72].

According to the Portuguese standard of DL 118/2013 [171], the ventilation of the residential buildings should adopt a maximum rate of renovation which is generally 0.4 h^{-1} in the Portuguese regulation and for the cooling season is 0.6 h^{-1}.

This rate considers the building as a zone with a value for the whole building. As it was already explained, all countries should have their own regulations for energy efficiency and also ventilation. In the following, the summary of ventilation requirement due to the regulation of different countries is presented (Table 16).

Table 16: Summary of ventilation requirements for residential buildings [114]

Source	**Global rate of ventilation**	**Living room**	**Bed room**	**Kitchen**	**WC with Bath**	**WC without bath**
EUA (ASHRAE 62.2.2007, applicable to housing and multifamily buildings up to three floors) [114]**,** [173]**.**	0.05 A_f +3.5 (number of room +1)+ infiltration 36m^3/h/100 m^2 A_f	A win> 4% $A_f > 0.5m^2$	A win> 4% $A_f > 0.5m^2$	V_{Mec}: 180 m3/h (inter), 5 RPH (cont.) + A win> 4% $A_f >$ 0.5m^2	V_M : 90 m^3/h (inter.), 36 m^3/h(cont.)	A win> 4% $A_f >$ 0.15m^2
Europe (EN 15251:2007) [164]	0.6 ac/h	Ad: 25.2 m^3/h.p or 3.6 m^3/h.m^2	Ad: 25.2 m^3/h.p or 3.6 m^3/h.m^2	Ex: ≥72 m^3/h	Ex: ≥54 m^3/h	Ex: ≥36 m^3/h
Portugal (NP 1037-1:2002) [174]		Ad: ($V_{Nat.}$): >30 m^3/h and 1 ac/h; with fire place >4 ac/h	Ad: ($V_{Nat.}$): >30 m3/h and 1 ac/h;	E_x. ($V_{Nat.}$): > 60 m^3/h and 4 ac/h	E_x. ($V_{Nat.}$): > 45 m^3/h and 4 ac/h	E_x. ($V_{Nat.}$): > 30 m^3/h and 4 ac/h
Portugal (RSECE-2006) [169]		30 m^3/h.P (non-mokers), 60 m^3/h.p (smokers)	30 m^3/h.P (non-mokers), 60 m^3/h.p (smokers)			
Portugal (REH-2013) [72]	0.4 ac/h in the winter period and 0.6 ac/h in the summer period.					

According to Table 16, some of the countries has the ventilation values based on different zones and spaces while this is not available for Portugal i.e. the Portuguese regulation considers the building as a whole for the ventilation.

3.5 Conclusion

In the past, natural ventilation was the main way of ventilating residential buildings. But with the development of the technology, the society have more tendency to use mechanical ventilation. However, with increased attention to the energy efficiency and sustainability measures, the natural ventilation has become more popular in the residential buildings.

Since there are several aspects in relation to the ventilation performance, most of the literature review of this topic is related to parameters such as ventilation efficiency, thermal comfort, IAQ, energy efficiency and quantitative impact of ventilation.

Due to the extensive existing literature, it should be concluded that the insufficient ventilation rate and IAQ are the same as the insufficient ventilation conditions. Subject to the literature review, there are different factors which effects on the ventilation conditions of the building.

Owning to the literature review with the existing information in different aspects of this topic, it is clear that this is an active research area and most of the existing methods and information are practical for the residential sector.

However, there are some gaps associated with the diagnosis of the effectiveness of the natural ventilation occurring significantly in existing buildings. Therefore, it is necessary to emphasize more on this topic and to develop some methods for evaluation of the efficiency of natural ventilation.

In conclusion, it is possible to classify the reviewed studies in different classes based on their main objects and importance for researchers. Amongst the reviewed studies for this chapter, most of them, as the first class, remarked the importance of the topics.

In the second class, residential buildings are considered as a system and ventilation is part of this system.

The third class belongs to the research which considered various important factors in this field such as building envelope air tightness, ventilation, air distribution, and ventilation performance, which are considered systematically.

The fourth class is devoted to the researches which are targeted to the relation between ventilation and air tightness with insulation performance or moisture problems and related studies.

The last class has considered the links between ventilation and airtightness with combustion problem in the building.

Considering these studies, there is a gap in the literature of the current topic relating to the efficiency of the natural ventilation based on the diagnostic method. Considering the aim of this research, the next chapter is devoted to the existing methodology and an appropriate criterion will be selected to develop this research.

Chapter 4:

Research Methodology

Index of chapter 4

*"**There is nothing like the cure of fresh air for cases of bladder infection, paranoia, and Cartesian thinking**".*

Rawi Hage

4.1 Introduction

As presented in previous chapters, the primary purpose of ventilation is to create optimal conditions, in terms of air quality and thermal comfort in indoor environments. So that people can live or work there, taking into account their health, comfort and productivity [175]. Face to the importance of air pollutant and the role of IAQ in the ventilation of residential buildings, the increment of the ventilation rate can reduce the pollutant concentration.

Building airtightness is a factor that affects building air change rates under normal conditions of weather and building operation. The air change rate through the airtightness has a strong effect on the heating and cooling load, occupant comfort, IAQ, and building durability [176], particularly in housing sector.

Due to the effect of *Relative Humidity* (RH) in the performance of the whole building, indoor humidity may also be too high at a low ventilation rate and/or a high moisture production rate. According to *Kalamees* et.al. [177], humidification and high indoor humidity impose a serious hydrothermal load on the building envelope that may cause serious problems for the building envelope and indoor climate because of condensation, the growth of microorganisms and house dust mites.

The ventilation rate of the house is calculated by determining the internal pressure for the house that balances the mass flow in and out [178]. Based on *Eskola* [179], the building air leakage is related to the envelope airtightness and also to the pressure difference over the building envelope. Therefore, airtightness measurements can be used to provide air leakage parameters for models that analyze natural infiltration. Such models can estimate average annual ventilation rates and the associated energy costs [176]. The main aim of this experimental research is to use the obtained results (measured and simulation), to improve the ventilation rate of the building according to the building characteristics.

Since the increase of ventilation rate causes the improvement of IAQ, decreases the pollutant concentration in interior space, as well as the moisture condensation and the energy consumption, the research is developed based on a multi-criteria approach (IAQ, energy, comfort, and pollution).

Since condensation is one of the biggest problems in the old and existing buildings, *Quirouette* [32] presented the idea of more openings in the envelope to balance the ventilation rate in the positive or neutral pressure and to decrease condensation. However, this solution causes the occurrence of others problems like the increment of energy consumption and the difficulty to keep an acceptable indoor temperature.

Based on the information of previous chapters and their review in above, this chapter is devoted to different existing methodologies related to the research topic that will be approached. After that, based on the existing methods and case studies characteristics, the appropriate methodology for the research will be selected and described.

There are different methods and solutions for natural ventilation and air infiltration which are related to the aim of the research and viewpoint of the researchers. Consequently, various models and tools can be used according to the type of required information.

Generally, there are three different approaches to study/analyze ventilation and air infiltration issues, namely, simulation, statistical methods and measurement methods. Since the procedures of measurement methods involve high costs, most researchers use statistical and simulation methods to develop their research. For this reason, the number of researchers using measurement methods is decreasing even though the results are more realistic and reliable than the other two methods. It should be noted that simulation and statistical methods have their own advantages and disadvantages. Due to the advantages and disadvantages of these three classified methods, this research was done using measurement and simulation methods to give the most realistic and reliable results. The research begins with simulation methods and after that, the measurement method was done to calibrate the results in order to have accurate results to begin the next phase of research. Since each of these two selected methods include different sub-methods, the following is a list of these sub-methods with a brief explanation in order to choose the appropriate methods to develop the work.

4.2 Building simulation methods (dynamic model)

As it was stated in the previous section, due to the high cost of measurement methods, recently, the simulation method has been substituting them as a new approach which is now used more than measurement methods. Building simulation is a popular method for studying naturally ventilated building design. Thermal simulation and airflow network are two fundamental modules in building simulation method [176]. Computer simulations can help to study the thermal comfort and IAQ in a room or in a building [180]. The differences between different simulation software are based on their basic model and the level of the model complexity. In the following, main modeling approaches including empirical models, multi-zone models, zonal models, CFD models are presented. All simulation tools are structured based on them.

4.2.1 Empirical models

The empirical models offer generally some correlations to calculate the rate of ventilation or the average speed in a zone [181]. This model combines the effect of the temperature difference with the wind speed to evaluate the ventilation rate or air speed inside a building.

The model, as a single-zone model, assumes that the structure (e.g. a room) can be described by a single and well-mixed zone. *Pinto da Silva Amaral* [114] citing *Etheridge* [182] states that empirical models can be separated into two groups:

1-Purely empirical models that result from measurements.

2- Semi-empirical models that attempt to simulate the physical processes and usually resolve the equation of continuity.

There are several models which are based on the Empirical model idea. The model of BS-5925, the model of *Aynsley*, the model of *De-Gibbs* and *Pfaff*, and the *Laboratório Nacional de Engenharia Civil* (National Laboratory for Civil Engineering –LNEC) model are some of them. Due to the importance of LNEC model and its relation to this research, in the following more information is presented about it.

4.2.1.1 The LNEC model

LNEC (Laboratório Nacional de Engenharia Civil) is the name of the center that developed this model in Portugal [183] which is based on researches undertaken in LNEC. In this model, the input or output flows due to the chimney effect, with two openings equal at different heights can be obtained by the following expression:

$$q = 0.16A\sqrt{\frac{h}{2}\,\Delta T_{int-ext}} \qquad \text{Eq. 5}$$

Where;

q is the volume flow [m^3/s].

A is the area of an opening [m^2].

H is the vertical distance between the two surfaces measured between midpoints [m].

$\Delta T_{int-ext}$ is the mean temperature difference between the outside environment and the interior [◦C].
The flow due to the chimney effect, for two sets of the openings with different heights, can be calculated by:

$$q = 0.16\sqrt{\frac{h\Delta T_{int-ext}}{\frac{1}{A_e^2}+\frac{1}{A_s^2}}} \qquad \text{Eq. 6}$$

Where;
A_e is total effective area of the inlet openings [m^2].
A_s is total effective area of the outlet openings [m^2].
The airflow due to wind effect for sets of apertures arranged in series, can be obtained by:

$$q = 0.6A_{eq}\, U\sqrt{C_{pe} - C_{ps}} \qquad \text{Eq. 7}$$

$$A_{eq}^2 = \left(\sum \frac{1}{A_i^2}\right)^{-1} \qquad \text{Eq. 8}$$

Where;
U is the wind speed [m/s].
C_{pe} is the pressure coefficient of input.
C_{ps} is the pressure coefficient of output.

4.2.2 Multi-zone models

A multi-zone airflow network model is developed from the single-zone model. This model can determine the airflows in a complex ventilated building subject to internal and external loads. Hence, it is extensively used in ventilation simulation [184].
Multi-zone modeling approach takes a room within a building as one node that is connected to others by openings between rooms and openings to the outside. The nodes are connected to each other through a line that is called element [7]. This model determines the pressure differences among zones by neglecting the flow velocity within the areas based on the application of the Bernoulli equation [13]. Based on *Pinto da Silva Amaral* [9], this type of model is capable of predicting airflow and pressure distribution within a building by dividing it into zones and airflow paths. Airflows and their distribution in a given building are caused by pressure differences that can be induced by the wind, buoyancy effect, mechanical force or a combination of these factors. Thus, this model requires extensive information for the flow characteristics and pressure distribution. This type of airflow network model is based on the mass balance equation. Figure 23 present the idea of the multi-zone model.

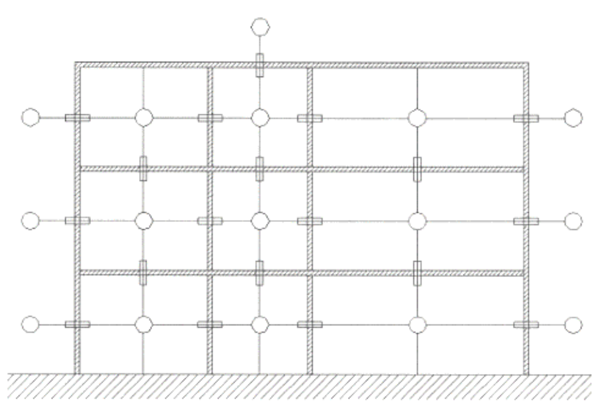


Figure 23: Multi–zone model [114]

The output data includes the pressure differences on each opening and/or internal pressures; flow rates in each opening (in both directions); *hourly renewals* (RPH = flow rate/volume) in all areas and the whole parts of the building.

4.2.3 CFD model

CFD models are capable of predicting two or three-dimensional airflow and thermal distribution patterns in a room [2]. The governing equations are the continuity, momentum, energy and mass diffusion. During the last years, the interest in developing software based on CFD to predict the flow in the components has increased [114]. As a macroscopic analysis of the distribution of the physical variables is required (ex. mass, speed, and temperature) for the determination of thermal comfort, ventilation, air quality and energy considerations, the equations take the form of *Partial Differential Equations* (PDEs). Each equation describes the con

servation of a dependent variable and is integrated for each controlled volume. With CFD models we can consider the following quantities at any location:

- Wind speed.
- Temperature and mean radiant temperature.
- Enhanced indices (PMV-PPD- and Draught risk (DR)) [185].

4.2.4 Zonal models

A zonal type model is an approach between the CFD and Multi-zone models. However, it is faster than CFD model to obtain the outputs of the research. So, it is a good alternative to make an annual or seasonal analysis. Similar to multi-zone models, the zonal model's space is divided into different areas. However, the areas corresponding to the flow that is located within each component.

As it is explained by *Pinto da Silva Amaral* [114], such models can be coupled with multi-zone and thermal simulation models. *Stewart* et.al [186] presented a type of a zonal model which is an adaptation of COMIS multi-zone model. Some examples of using the zonal model in the simulation are: prediction of moisture in the indoor air behavior model which is developed by *Mendonça* [187], thermal comfort modeling (PMB, PPD) developed by *Haghighat* et.al [188] and pollutant distribution like the research of Huang [189].

4.2.5 Comparison of airflow network and CFD models

As stated by *Ohba* and *Lun* [26], the zone and fluid flow equation is the difference between multi-zone and zonal models. In order to use the equation, the zones and connections between them and with the outside air should be described. Description of parameters like pressure and temperature in the multi-zone models are based on the average of each value. The multi-zone models predict the airflow pattern but cannot solve the problem of airflow distribution and concentration. The zonal model can describe the flow characteristics in a zone, but it is not as wide as CFD models. The comparison of CFD model and airflow model shows that CFD model presents a more detailed information when compared with airflow model. However, airflow model is useful to have information on different subjects. Both CFD models and airflow models have associated with the in and out airflow.

4.2.6 Coupling of the building energy simulation with CFD and airflow network models

The Coupling of CFD models and building energy simulation is a new trade of natural ventilation analysis. *Djunaedy* et al. [190], further extended the coupling program to external coupling between ESP-r (a thermal simulation program) and a CFD commercial code for mechanical ventilation. For natural ventilation, *Tan* and *Leon* [191] coupled a multi-zone airflow model with CFD by a static strategy. As it is explained by *Ohba* and *Lun* [87], in the process of building energy simulation, the temperature (buoyancy effect) has an effect on ventilation due to the stack effect and the airflow rates influence the heat balance equations. Therefore, different methods have been proposed to couple the airflow model with the thermal model [87]. Generally, the simulation software's that are coupled with the CFD models are categorized in two groups of single-flow and multi-flow elements. Therefore, the building simulation programs classify into two classes of design tools and detail simulation tools. Some common simulation programs are: *DOE-2, COMIS, ESP, TRNSYS, and Design-Builder*. *Crawely* et.al [192] analyzed the existing building simulation program and their properties. Prediction of thermal comfort by natural ventilation with CFD simulation is not easy because it needs to compute the building in two scales of macro (building) and micro (room). In these programs, the ambient temperature, solar radiation, wind, and humidity are considered by the climate condition to provide the boundary condition for CFD simulation. On the other hand, the indoor thermal environment provides the heat transfer and fluid dynamic. To do a research based on a simulation analysis, it is necessary to select one of these approaches and accordingly select one of the simulation software's which is accurate to develop our research, which will be presented in section 4.6.2.

4.3 Measurement methods

The measurement methods are one of the more accurate ways to analyze natural ventilation conditions in an existing building but its high cost causes a reduction in its use. However, the accuracy of the results of measurement methods are high and these methods present the results under real condition. Due to the idea of the research about the natural ventilation and building air leakage, the existing methods for measurement of airflow and air leakage are presented in the following:

4.3.1 Traced gas dilution method

The method of the *Tracer Gas* (TAG) aims to study the air movement across a boundary. This method measures the distribution of the flows through the spaces within the buildings. The assessment of the air change rate of the buildings in this method is possible by three different measurements of the gas concentration [76]: (i) the concentration decay; (ii) the constant injection; (iii) the constant concentration. Generally there are two ways to measure leakage with TAG: external detection with TAG (inside- out method), internal detection of TAG (outside- in method) [193]. The boundary condition of this method is building shell, or a zone inside of the building or room. This method is used to determine both temporal and spatial ventilation effectiveness. TAG method use *ASTM* standard E741-2000 based on decay, constant injection, and constant concentration measurement. The expected error of TAG results varies from 5% to 10% [194].

4.3.2 Fan pressurization method (Blower Door Test, BDT)

The most common technique to measure the air leakage of building envelope is "fan pressurization" method or *Blower Door Test* (BDT). BDT was first used in Sweden around 1977 and consists in mounting a fan in a window (or door) to test the tightness of the building envelope. Today, standardized test procedure for performing fan pressurization measurement is described in the European standard EN-13829 [195], which is implemented on most European countries, and will also be used in this research. In order to explain the reason of selecting BDT as the measurement of this research, a comparison of BDT with TAG method is presented in the following table (Table 17). After that, the main advantage of BDT will be explained in this research.

Table 17: Comparison of BDT method and TAG method

BDT	**TAG**
Determine the rate of air infiltration through a building envelope	Determine the rate of air infiltration through a building envelope
Simpler than TAG method	More expensive and complex
Annual average air infiltration rate	Seasonal variation in the air infiltration rate
Regardless of ambient weather conditions	Sensitive to the ambient weather conditions
The correlation results of ACH50/20 to Sherman's ACH/N is varies from 6% to 33%.	The correlation results of ACH50/20 to Sherman's ACH/N is varies from 4% to 38%.
Errors depend on the user assumptions	Errors depend on the user assumptions
It is performed at performed elevated pressure differentials across the building envelope	It conducted at near zero differential pressure at near normal building operating conditions.

According to the information of Table 17, and also based on the aim of the research, BDT has been selected as the measurement method of this research as it aims to find the annual average air infiltration through the building envelope regardless of the weather condition and season.

BDT is associated with EN-13790 [196] and EN-13829 [197]. EN-13829 [197] describes BDT procedure in order to evaluate airflows from cracks, leaks and openings of the building and define their airtightness. BDT evaluates the airflow under different pressures and especially at 50 pa pressure difference. One of the advantages of this method is that it is less affected by climate conditions [198]. The test uses a fan mounted on a temporary screen door to induce both positive and negative pressure differences across the building envelope while measuring the airflow through the fan [199]. Since there are two types of pressurization and depressurization method for BDT, the user will choose one of them or even both according to the aim of the research. As it is explained in the ASTM: E-1827 (2007) [200], "Combining the results of depressurization and pressurization measurements can minimize the wind and stack pressure effects on calculating airtightness but may overestimate air leakage due to backdraft dampers that open only under pressurization". This air leakage is the rate of leakage in/out the dwelling $m^3/h/m^2$. According to the obtained results from pressurization and depressurization of BDT, the air tightness of the building will be measured in q_{env} m^3/s which is the airflow rate of the building envelope under different pressure, Δp pa [201] [202]. According to ISO-9972 Standard [203], BDT methods is divided into three categories:

(i) Method A - a test of a building in use (i.e., during the cooling or heating season). The objective of method A is to measure the air leakage rate that contributes to the infiltration/exfiltration flow under real conditions and it is used to measure the airtightness from an energy point of view [204].

ii) Method B – a test of the building envelope in which any intentional opening shall be closed or sealed. The objective of method B is to measure the air leakage rate that flows only through the building envelope and not through the intentional openings in the envelope, it is thus used specifically for evaluating the quality of the envelope finishing. Within the context of the EPB-regulation, the airtightness measurements aim to quantify energy losses due to infiltration/exfiltration [204].

(iii) Method C – a test of the building in use (i.e. automatically regulating, externally mounted air transfer devices are sealed, other openings are handled in the same way as for method A) [76].

4.3.2.1 Procedures of BDT

To start the measurement, all doors and openings must be closed and sealed. The path of ventilation and damps must be also closed and sealed carefully. Since this measurement method consists in multiple steps for measuring and the measurement range is between 10-60 Pa, increments between 5 and 10 Pa should be done and measurements at least in 5 points shell be executed [205] [202]. Since the tests are influenced by the outside conditions, the ideal test conditions will be for wind speed between 0 and 2 m/s and outside temperature between 5 and 35 °C [205]. Temperature measurement is not required for most tests, but there are cases that testing protocols require temperature corrections that can be 1 - 2% in total. Some protocols require the volume of the building to be measured in order to calculate air-change rates. If normalized leakage areas or permeability is required, then the surface area of the building must be measured. In some cases, floor area must be measured in order to calculate specific leakage area that is required by some testing protocols. The floor area is generally measured to the outside walls and does not include the area of partition walls. Table 18 lists the procedures for testing and results for various protocols including the procedure for calculating building volume, normalize leakage area, floor area for different countries [206].

Table 18: Acceptable testing conditions, test setup requirements and results for several protocols of around the world [206]

Standards	**ASTM**	**CGSB**	**EN-13829**	**ATTMA**	**USACE**	**WE state**	**LEED**
Apply to	Residence	Residence	Residence	Residence and Large Building	Large Building	Large Building	Apartment
Origin	USA	CANADA	Europe	UK	USA	WA State	North America
Acceptable Condition	41 to 95 F < 5 mph wind	< 20 km/h wind	< 6m/s wind height × ΔT< 500 mc	< 6m/s wind height × ΔT< 25 mc	Bias< 10% of min. test or < 30% for both way	95% confidence interval	Same as ASTM
Baseline points	10 second average before and after measurem ent	Before each test measureme nt	30 second average before and after test	30 second average before and after flow measureme nt	20 second average 12 points before and after flow measureme nt	10 second average before and after flow measureme nt	10 second average before and after flow measureme nt
Induced pressure point range	10-60 Pa	15-50 Pa	10-50 Pa	10-60 Pa	25 -75 pa	25 -80 pa	10-60 Pa

***Continued** table 18: Acceptable testing conditions, test setup requirements and results for several protocols of around the world* [206]

Standards	ASTM	CGSB	EN-13829	ATTMA	USACE	WE state	LEED
Number of points	5-10	1-2- or 7	5	7	12	12	5
Test direction preferred	Both	depress	Both	Both	Both	Both	Both
Test direction acceptable	Either but usually depress.	Depress.	Usually depress.	Usually press.	Both unless building requires over 125.000 CFM	Both	either
Results	EfLA@ 4 pa , ACH50, CFM 50	EqLA @ 10 pa. ACH 50	$(m^3/h)/m^2$	$(m^3/h)/m^2$	CFm 75/ sq ft	CFm 75/ sq ft	EfLA@ 4 pa
Required results	None	None	None	2 to 10 $(M^3/h)/m^2$	0.25 CFm 75/ sq ft	0.40 CFm 75/ sq ft	125 sq in /sq ft EfLA @ 4 pa

4.3.2.2 BDT results

After the measurement phase, the collected data are combined with the equations which are provided in standard and then the results of the air change rate (n_{50}), air permeability (q_{50}), and specific leakage rate at pressure 50 pa (w_{50}), which are the objective of BDT measurement, will be collected. The BDT results can be used [207]:

a) To measure all permeability of a building or part thereof for compliance with a design airtightness specification.
b) To compare the relative air permeability of several similar buildings or parts of buildings.
c) To identify the leakage sources.
d) To determine the air leakage reduction resulting from individual retrofit measures applied incrementally to an existing building or part of a building.
e) To estimate the air leakage reduction after a retrofit (e.g. substitution of windows or doors) [76].

Generally, to use the equation and analyze the results of BDT, it is necessary to know some of the main parameters involved in those equations about the internal volume, envelope area, and etc. Definition of envelope area parameter will be explained in a brief way due to EN-13829 [208]:

The area of the building envelope in selected cases, A_e, is the total area of floors, walls, and ceilings of the internal volume. Generally, all internal dimensions should be used to calculate this area. Net floor area, A_f, is the total floor area of all floors belonging to the internal volume subject to the test. It is calculated according to the national regulation.
In order to find pressure difference, ΔP, it is necessary to subtract the average of the different pressure, $\Delta P_{0,1}$ $\Delta P_{0,2}$, obtained in the calibration process equipment, from each of the different pressures measures, ΔP_m, using Eq.9.

$$\Delta P = \Delta P_m - \left(\frac{\Delta P_{0,1} + \Delta P_{0,2}}{2}\right) \quad \text{Eq. 9}$$

According to EN-13829 (2000) [208] ,we use Eq. 10 to convert the reading airflow rate measuring system (V_r), the measured airflow rate (V_m) at the pressure and temperature of the flow measuring device, according to the specifications of the manufacturer.

$$V_m = F(V_r) \quad \text{Eq. 10}$$

Where in the case of using BDT, *Retrotec* model 1000, it is obtained by Eq. 11 for pressurization test and by Eq. 12 depressurization test as follows:

$$V_m = \left(V_r \times \sqrt{\frac{\rho_0}{\rho_e}}\right) \quad \text{Eq. 11}$$

$$V_m = \left(V_r \times \sqrt{\frac{\rho_i}{\rho_e}}\right) \quad \text{Eq. 12}$$

To convert the measured airflow rate (V_m) to airflow rate through the building envelope (V_{env}), we use Eq. 13 for pressurization tests and Eq. 14 for depressurization as follows:

$$V_{env} = V_m \times \left(\frac{\rho_e}{\rho_i}\right) \quad \text{Eq. 13}$$

$$V_{env} = V_m \times \left(\frac{\rho_i}{\rho_e}\right) \quad \text{Eq. 14}$$

Where;
ρ_0 is the density of the air temperature correction [kg/m^3].
ρ_e is density of air at outside temperature [kg/m^3].
ρ_i is density of air at indoor temperature [kg/m^3].

Which are obtained by Eq. 15.

$$\rho = \frac{P_{bar} - 0.37802\, P_v}{287.055(\theta + 273.15)} \quad \text{Eq. 15}$$

In which the corrected temperature is 20ºC.
To determine the airflow through the envelope based on the airflow coefficient (C_{env}), and the flow exponent (n), according to the following Eq.16.

$$V_{env} = C_{env} \times (\Delta P)^n \quad \text{Eq. 16}$$

Where:
V_{env} is the airflow rate through building envelope [m^3/h].
ΔP is the induced pressure difference [pa].
C_{env} is the airflow coefficient.

n is the airflow exponent which both of them should be calculated separately for pressurization and depressurization.
The air leakage coefficient (C_L), is obtained by correcting the value of (C_{env}) for the pattern conditions (20ºC and 1.1×10^5 Pa) using Eq. 17 for pressurization and Eq. 18 to depressurization as follows:

$$C_L = C_{env} \left(\frac{P_i}{P_0}\right)^{1-n} \quad \text{Eq. 17}$$

$$C_L = C_{env} \left(\frac{P_e}{P_0}\right)^{1-n} \quad \text{Eq. 18}$$

Where;
ρ_e is the outdoor air density [kg/m^3].
ρ_o is the air density at standard conditions [kg/m^3].
ρ_i is the indoor air density [kg/m^3].
The air leakage rate (V_L) can be calculated by Eq. 19.

$$V_L = C_L \times (\Delta P)^n \quad \text{Eq. 19}$$

Where;
C_L is the air leakage coefficient [m^3/ (h.pa^n)].
ΔP is the induced pressure difference [pa].
N is the airflow exponent.
Due to the rate of V_L, it is possible to obtain the values of air renovation rate, air permeability, and specific leakage rate. Since the reference pressure, $\Delta p_{r,}$ is always 50 pa, $V_{\Delta pr}$, is determined by the Eq. 20.

$$V_{50} = C_L \times (50)^n \quad \text{Eq. 20}$$

The air renovation rate at the reference pressure difference, e.g 50 Pa (n_{50}), the air permeability of 50 Pa (q_{50}), and the specific leakage rate (W_{50}), are obtained through the division of the airflow leakage by internal volume for the specific area and the useful area, using the Eq. 21, 22, and 23.

$$n_{50} = \frac{V_{50}}{V} \quad \text{Eq. 21}$$

$$q_{50} = \frac{V_{50}}{A_E} \quad \text{Eq. 22}$$

$$W_{50} = \frac{V_{50}}{A_u} \quad \text{Eq. 23}$$

At the end, in order to predict the mean value of infiltration rate, another possibility is the prediction average values of the infiltration rate (RPH).

$$RPH_{annual\ average} = \frac{RPH_{50}}{N}, \quad \text{Eq. 24}$$

Where;
Annual average RPH is an hourly average annual renovation [h^{-1}].
RPH_{50} is hourly renovation obtained by pressurization test at 50 pa,
N is a constant that depends in particular on the local climate, building type and deployment of the building. Internationally, there was obtained a significant sample of households with a value average of N equal to 0.66 [209].
Subjected to the research methodology, next section (4.4) presents the case studies and its properties.

4.4. General characterization of constructions in Coimbra

Taking into account the goal of this chapter and in order to select the appropriate method for the research, the characterization of the case studies is presented in this section. In the context of this section, it is necessary to ask the following question:

- What are the main characteristics of the existing constructions in the historical centers of Portuguese cities?

In this chapter, the construction characteristics of the Old Portuguese buildings will be presented. At the first step, a general framework will be made to characterize the building systems of traditional Portuguese construction in Coimbra. In the second step, the case studies of the research will be presented. This analysis will be based on data collected through the survey work which was done by the *University of Coimbra* (2005-2008) [129] , that are presented in the following works: thesis of *Ramos* from *University of Coimbra* [210], thesis of *Vicente* from *University of Aveiro* [211], and thesis of *Pinto da Silva* from *University of Porto* [114].

In order to have a precise analysis of the building construction in the downtown of Coimbra, besides of general studies on characterization of Portuguese constructions, it is necessary to study the urban structure and building construction properties in Coimbra. One of the zones of the old town of Coimbra is "*Almedina*", near the "*Mondego River*". The houses consist of poor masonry or in some cases, rammed earth and adobe. The center of the city which portrays the heart of city life, has been recently registered as a world historical heritage. Following below, the characterizations of urban structure and buildings in the downtown of Coimbra is made.

4.4.1 Urban structure

Coimbra was born on the right-side of the *Mondego River*. Its configuration makes it a symbol of converging paths, exposed, and open to the south. The urban structure of the downtown district has a specific configuration with narrow streets and high buildings. By analyzing the data from the research of *Vicente* [211], it can be concluded that 78% of roads/paths have a width less than 4 m and that most of them (60%) have the width between 2-4 m. In Figure 24 and according to *Ramos* [210] and *Vicente* [211], we can see some information about the height of buildings. It illustrates that about 60% of the buildings have between four and five floors. These three factors - deployment, building height, and width of the street - are the most important characterization aspects of the urban structure and the existing constraints to obtain the comfort inside the houses. The urban structure is totally compacted in this zone with buildings and pavement covering the entire area of land with a total absence of green spaces except where it is strictly necessary for circulation and accessibility of the area. Only a few of the building have an interior or exterior patio.

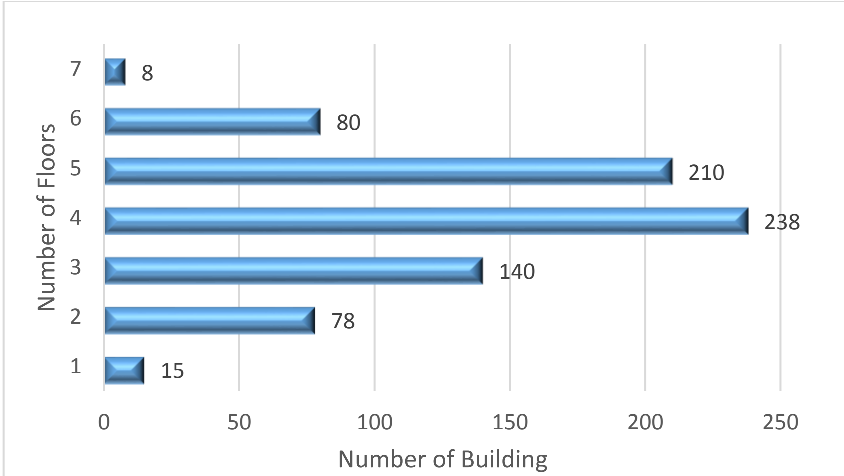


Figure 24: Number of floors above the ground floor [210], [211]

4.4.2 Type of facade and adaptability of buildings

As mentioned above, the urban typology is one of the main features and conditions of the spaces occupation, notably due to the implementation of the buildings. The position that the building takes on the building fabric constraint the arrangement of indoor spaces and occupancy possibilities. Based on the research of *Ramos* [210] and *Vicente* [211], approximately 80% of the total buildings have openings in one or two facades and only 154 of 770 buildings have opening in the three or four facades (about 20% of the cases). The number of the buildings faced is another important factor which should be considered (Figure 25).

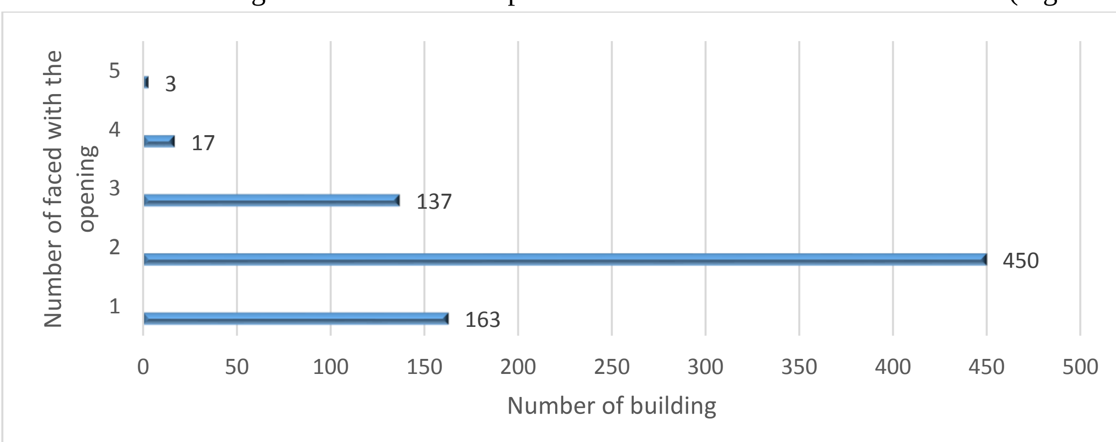


Figure 25: Analysis of number of building with faced and openings on them [213], [214]

4.4.3 Covering and roof

The geometry of coverage was assessed according to their shape, number, and water type. According to *Ramos* [210] and *Vicente* [211], we can see the existence of sloped cover in 96% of the analyzed constructions. Gabel roof was found in about 72% of the roofs with validated registration (714 buildings). In about 16% of the buildings, the existence of only one water-cover was verified. In 11% of the buildings, there are three or four water-covers, and in 1% of the cases, five or six waters exist.

Regarding the type of the coating material, there is a predominance of ceramic tiles, in about 83% of analyzed cases. The most used types of ceramic tiles are "*Lusa*" and "*Marselha*", which are recorded in

86% of buildings with ceramic tiles. In 17% of them, "*Canudo*" is applied. In some cases, there are two or three kinds of materials which are applied to the same coverage.
To ensure the structural safety, the replacement of wooden elements by other materials is a common practice in these cases and constitutes a mischaracterization of the traditional constructions.

4.4.4 Interior and exterior walls

The characteristics and conditions of the walls were analyzed according to the location, considering the use of two groups to study their particular properties: exterior and interior walls.

1- Exterior walls

The exterior walls of the buildings present variable thicknesses in the same housing, with a reduction of the thickness in the highest floors. About 40% of the analyzed walls feature a variable thickness from 0.6 to 0.7 m on the ground floor of the building. In almost 45% of the cases, the walls of the ground floor have the thickness greater than 0.7 m, the remaining 15% of the cases have the thickness of fewer than 0.4 m. Based on information in the literature, around 90% of facade walls are made of stone, 7% by hollow brick and brick, 0.6% by solid brick, and 0.48% by reinforced concrete.

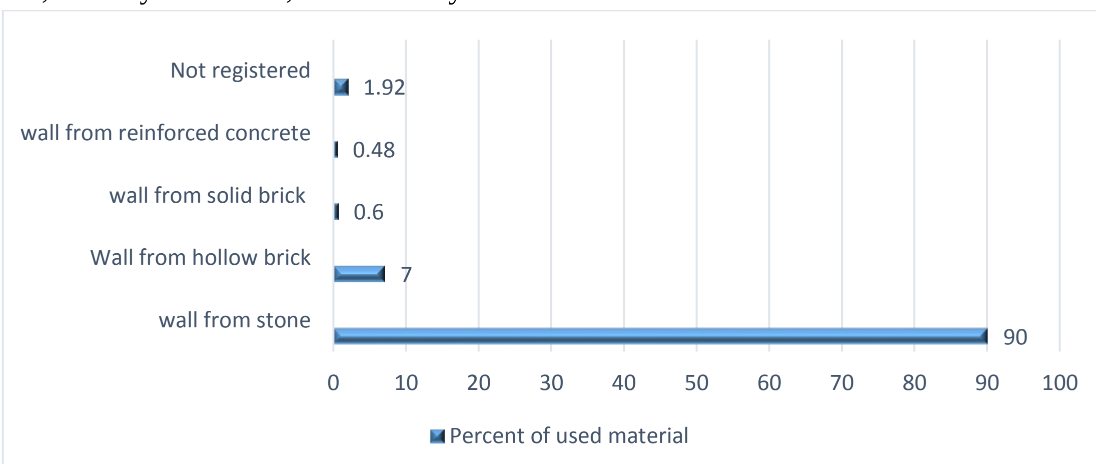


Figure 26: The distribution of wall construction made by different materials in the exterior wall [210]

Different types of coatings on the walls are available. Sometimes more than one coating exists in the same facade. Data extracted from previous studies indicates the existence of traditional materials such as lime-paint, mortar-lime, materials that reflect the time of construction. One of the main problems of the exterior wall is anomalies in their exterior layers. The anomalies of the walls were analyzed according to three anomalies caused by moisture phenomena, cracking and others. The reasons of cracking are associated with efforts towards which the material has no character to resist. The differential settlements of foundations generate cracks of 45° occurring in the current area of the wall or on the most susceptible points as spans of the openings. The resultant cracking of stress concentrations can occur due to increased load on the masonry, reducing its load bearing capacity due to its progressive deterioration or due to combined effects of these two. The position of the foundations, temperature variations or horizontal forces can also cause horizontal cracking in connection to the floor, vertical or orthogonal connections between the walls. The crushing normally occurs in the masonry singular points where there is a concentration of stresses resulting from the discharge of the beams in the walls. The anomalies resulting from moisture-related phenomena according to *Ramos* [210] are shown in Figure 27. The main reason of these anomalies consist of the runoff with 47% of instances of verified cases, surface condensation that has 30% of the cases and the rising damp and infiltration by coverage which consists of 20% of the cases. Infiltrations by frame or cover and the internal condensation represent less prevalent factors. The third group of anomalies includes degradation produced by pollution, moss, mold, and graffiti.

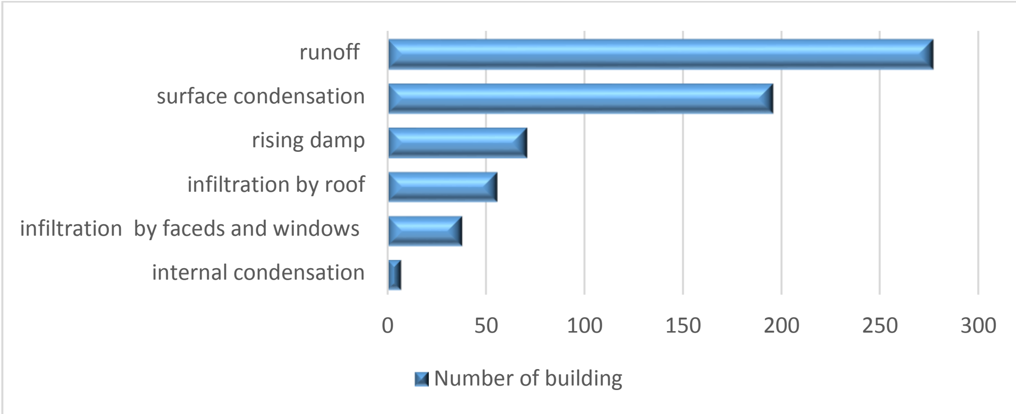


Figure 27: The reason of anomalies for humidity [210]

2- Interior walls

In what concerns to the constitution of the interior walls it can be said that there is a prevalence of lath partition (47.5% of the cases) and brick masonry (28.3% of the analyzed cases). The use of other materials is found in the remaining analyzed walls (18.1%), in which 7.3% belongs to the existence of stone walls, 5.1% to gypsum, and 5.7% to wood. In 6.2% of the cases, no interior wall exists. As described in section 4.4.1.1, the partition is made of timber frame and is covered by plaster, mortar and subsequently with around 1 cm which received painting. It has different configurations of a support structure which have been characterized. Based on the studies which were done in the area, the pathologies of the building are classified in Figure 28.

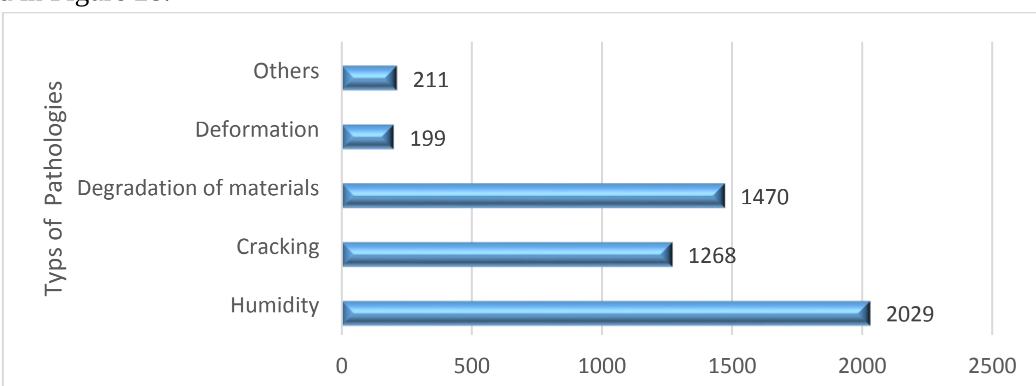


Figure 28: The classification of pathologies in the interior walls of existing building in the center of the city of Coimbra [210]

The prevailing conditions consist of problems with moisture which was detected in 39% of the cases. Degradation of materials and cracks were found respectively in about 28% and 25% of the cases. The interior walls deformations consist of 3.9% of the cases and the remaining 4% includes various pathologies. Moisture spots were observed in more than 50% of the walls, which can be caused by surface condensation or infiltration with the most diverse origins. The conservation and degradation of construction determine the possibility of leaks and general condition of the building tightness. This gives rise to about 14% of the conditions checked by runoff. The inner condensations are also presented in the form of molds which constitute almost 28% of the problem. The degradation of the materials is characterized by the peeling of ink or peel with the disintegration of the plaster.

The cracking is the third largest group of observed pathologies. The cracks of 45° exist in approximately 77% of the analyzed walls. The horizontal cracks occur in 11% of the walls and the interior facings cracks were seen in 12% of the cases.

4.4.5 Features and pathologies of windows

As a part of the characterization of the existing frames in the constructions of the studied area, the data about the material used and the glazing type were extracted from literature and is presented in Figure 29.

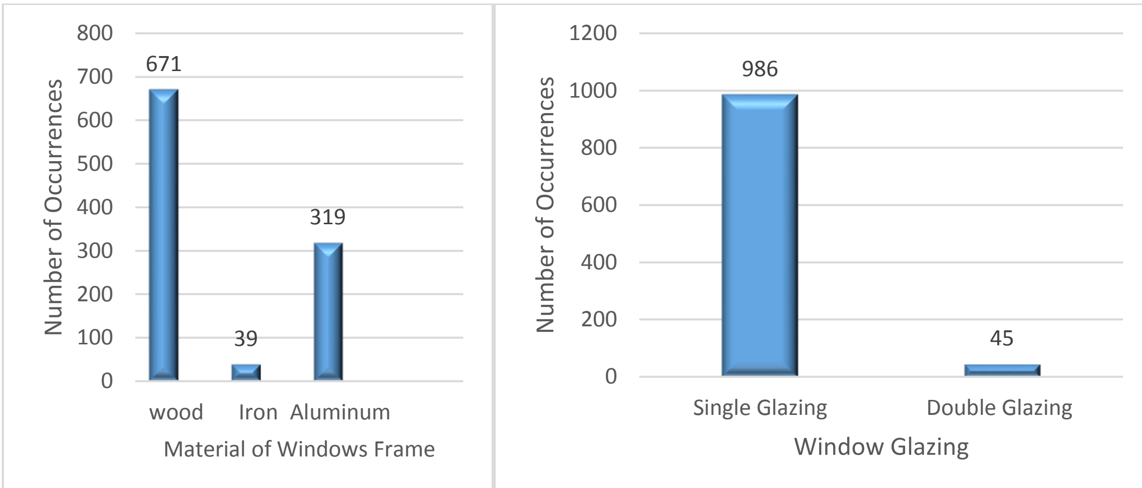


Figure 29: Analysis of the window´s frame and glazing type in the existing buildings [210], [211]

The predominance of wooden frames is recorded in 65% of the analyzed openings, iron is used in 4% of the cases and aluminum is employed in 31% of 1021 analyzed cases [211]. It should be noted that the usage of aluminum has started after the rehabilitation actions in this area and is not an original solution.

The observed pathologies in these constructive elements are very diverse and some of them do not directly affect its performance. More information about is referred by *Vicente* [211]. The glass fracture was recorded in about 11% of gaps, as well as warp and wood rotting were recorded in 10% and 8% of the cases respectively, and the excessive deformation occurs in 2.5% of the cases of the analyzed pathologies.

4.4.6 Characteristics and pathologies of the ceiling, floors

The pavement structure is used for fixing the ceiling that is made of wood and is attached to the support elements of the pavement.

According to the existing analysis of the pavement support structures and ceilings in the study area it is found that, in 73.52% of the cases, a wood support structure exists. In 25.24% of the cases, concrete is used, but those are cases where rehabilitation works have already taken place, and steel profiles are used in 0.81% of the cases to reinforce the existing structure of wood.

For the floor covering, there is a predominance of the wooden pieces in the lining of floors and its occurrence is registered in 28.91% of the examined cases. The use of ceramic tiles is verified in 18.03% cases and followed by the employment of plastic webs in 11.35% cases. The use of vinyl material and carpets were observed in 388 of the cases (10.72%) and in 325 of the cases (8.98%) respectively. The wooden floors provide problems related to lack of maintenance. They are the most registered pathologies in related to the deformation of the structure and cracks. The situation for the ceilings is almost the same and around 35% of the buildings are registered as having wooden ceilings.

The geometry of the roofs in this area is associated with the shape, number, and type of the waterway/canal. *Ramos* [210], analyzed the building´s roof according to the number and type of waterways. In 72% of buildings, there are just one or two slopes. The number of slopes varies till 6 slopes in a roof. The classification of roofs based on the shape of the coverage shows that in more than 96% of the cases, buildings have sloped roof and the rest have plane surface coverage. The use of ceramic tile as roof cover was verified in 86% of the cases. As it was explained in section 4.4.1.3, amongst different types of ceramic tile, "*Lusa*" and "*Marselha*" are the most popular types in this area which were used in more than 85% of the cases. In structural viewpoint, roofs are wooden in 59% of the case, while concrete or combinations of different types of materials were used in the rest of the cases.

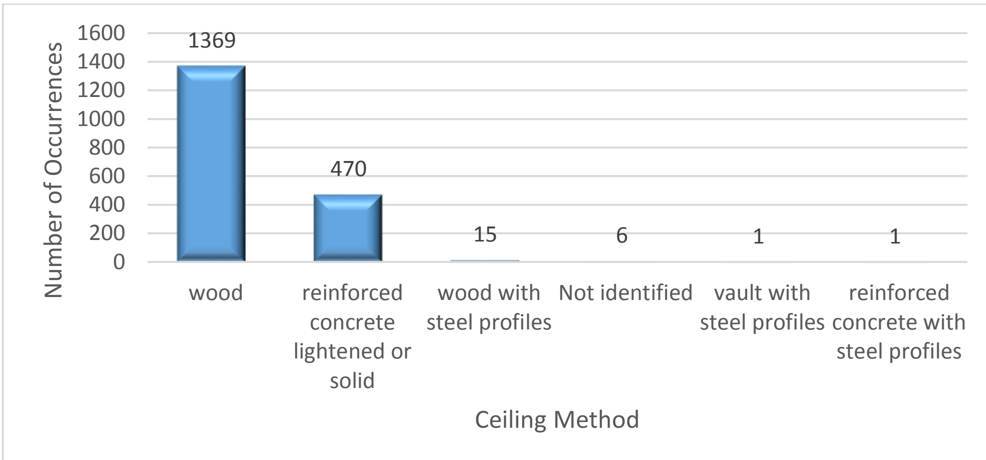


Figure 30: Analysis of the methods of ceiling construction in the center of the city of Coimbra [210]

4.4.7 *The* comfort level in old buildings

Given the previously disclosed characteristics, the comfort levels achieved inside the dwellings are conditioned by the degradation of materials, components, and existing systems. The health conditions are also compromised due to the connection among spaces and the lack of minimum levels of ventilation or lighting. The previous research which was carried out in the study area includes some data for the comfort and health of the spaces by identifying some weaknesses of existing buildings. Therefore, in the following existing information about the comfort level of the building in the area of the study is presented.

According to the ASHRAE standard, thermal comfort and human satisfaction in the indoor environment is divided into 6 categories: cold, cool, neutral, relatively, warm, and hot condition. In order to have information about the existing conditions of the buildings in the area, some questionnaires related to its comfort condition were filled by the occupants. The summary of these analyses is presented in Figures 31 and 32.

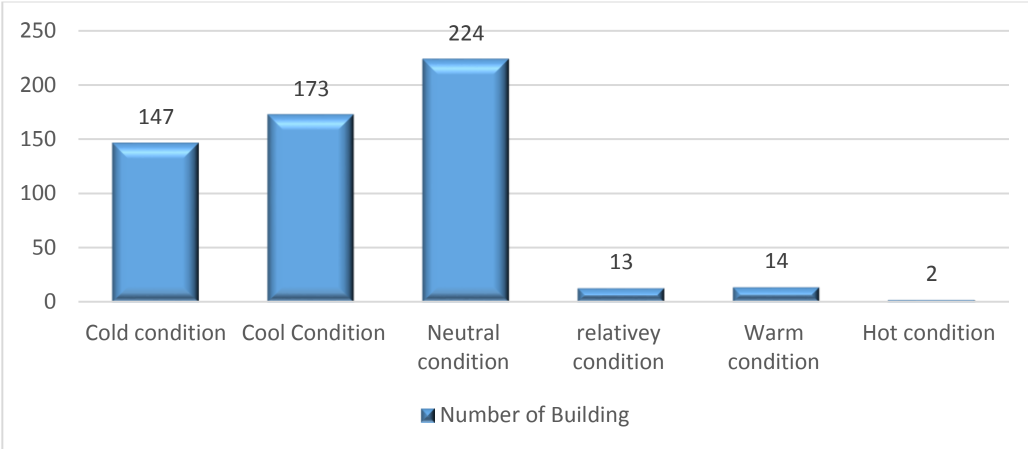


Figure 31: Analysis of the thermal comfort condition in the existing building in the winter period [210], [211]

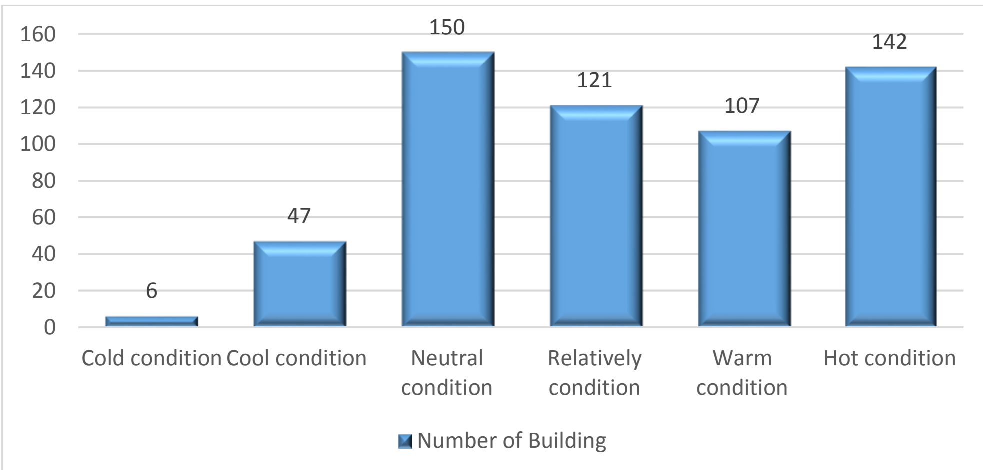


Figure 32: Analysis of the thermal comfort condition of the existing building in the summer period [210] [211]

The results show that the occupants feel cold in the winter period and warm in the summer period. It means that the existing buildings do not have sufficient thermal comfort conditions. According to the previous research, in 46.25% of the cases, there is no heating equipment, and in 63.78% of the cases there is no cooling equipment. The remaining cases reveal the existence of at least one device either for heating or cooling.

4.4.8 Ventilation

There are two types of ventilation in existing Portuguese construction and in the following a brief explanation about them, based on the research of *Pinto da Silva*, [114] will be presented.
In residential buildings, ventilation systems are intended essentially to ensure IAQ, to provide fresh air and the exhaustion of pollutions components. Also, the ventilation can minimize the energy consumption of the building. Generally, there are two types of ventilation systems in buildings: natural ventilation and mechanical ventilation. There is also a new hybrid system which is based on a combination of these two systems.

1- Natural ventilation systems

Pinto da Silva [114] has stated that there are different descriptions of well-known natural ventilation strategies:

- Infiltration /exfiltration: It uses cracks of the surrounding elements, especially in the doors and windows to provide inlet and exhaust air;
- Ventilation unique facade: inlet and exhaust air happening through vents, louvers or windows which are located in the same facade;
- Cross ventilation: inlet and exhaust air through vents, grates or windows, located on opposite surfaces or opposite sides of the same building;
- Ventilation through ducts: based on entering air through openings, and exhausting air through conducts located in bathroom, kitchen, and toilet.

2- Mechanical systems

When compared to natural ventilation mechanical ventilation systems allow better control of ventilation rates. However, in addition to other disadvantages, beside of energy consumption, it produces noise and requires maintenance. The most common types of mechanical ventilation systems are presented below:
- Mechanical insufflation: it intakes the air through ducts, fans and exhaust air through openings, slits, or louvers located in the envelope or natural ventilation ducts. The system allows the use of preheating and blowing air filtering;
- Localized mechanical extraction and individual: it intakes the air through openings, slits, or louvers located in the envelope and extracts the air through independent fans in kitchen and sanitary installation. The extraction is often discontinuous, covering only one of service spaces and is individualized for each dwelling;
- Centralized mechanical ventilation (VMC or simple flow): it intakes the air through openings (inlet), slits, or louvers located in the envelope and extracts the air through fans in bathroom, kitchen, and toilet. The exhaustion is often continuous to the whole building (centralized and controlled at a single point);
- Mechanical ventilation double flow (balanced systems): it works based on admission and extraction of air through ductwork and fans. The system is often controlled from a single point and allows the use of air filters and exchanges heat.

Often in Portugal, natural and mechanical ventilation systems are associated, using the individual mechanical extraction in the kitchen and the natural extraction in the sanitation spaces. The mechanical removal is usually discontinuous. However, in most of the existing buildings in Coimbra which belong to the decades before 1960s, 1970s, and 1980s, the natural ventilation is the only ventilation system of the building used for making comfort condition and air circulating.

Based on *Ramos* [210] 58.4% of total building in Coimbra have interior compartments. The number of interior compartments varies between the existences of an interior compartment (15.58% of the cases) till nine interior compartments (0.91% of the cases). It is important to analyze the relation between spaces with several features and usage. In 8.31% of the cases, there is a connection between the toilet and the kitchen, as well as in 10.14% of the cases the lack of sanitary facilities is recorded. Figure 33 shows the articulation of spaces with sanitary facilities.

Figure 33: Examples of articulation of spaces with sanitary facilities [210]

4.5 Specific characterization of case studies of the research

Since the research intends to analyze the ventilation effectiveness of the old residential building before and after rehabilitation and presents some solutions to improve the thermal comfort and air quality of the building based on the ventilation effectiveness, the research was carried out in four old residential buildings with different properties. In the following, characterization of each one of the buildings is exposed.

4.5.1 Localization of the case studies

As it was explained in the previous sections, the research was carried out in the downtown of Coimbra. Due to the topography of the city in this area, the downtown of Coimbra is divided into two zones: "*Baixa*" and "*Alta*". "*Alta*" is the area with higher altitude where the University of the Coimbra is the main point. The second part of the downtown "*Baixa*" is the lowest part and is near to "*Mondego River*". The case studies of the research are all located in "*Rua Fernandes Thomas*". This street is located in the middle of the downtown. The entrance of this street has a perspective of the "*Mondego River*" and it is influenced by blowing winds from the River side. The street is connected to "*Rua da Couraca Lisboa*" from the south and to "*Rua Quebra Costas*" and "*Torres da Almedina*" from the north. Figure 34 presents the location of the street in the city and its connection to other streets.

Figure 34: Location of "Rua Fernandes Thomas" as the case study of the research

The characteristics of the street are almost the same as other streets of the downtown. As it was already mentioned in the previous sections, the street is located in the old part of the city with narrow and tall buildings on both sides. The entrance of the street, the south side of the street, has a width of 6 m and has a view to "*Mondego River*". Buildings receive blowing winds from this side. Therefore, the width of this part of the street has an intensive effect on the air circulation in the urban area, specifically in "*Rua Fernandes Thomas*". Going further into the street, the width decreases to approximately 2.8 m in the middle of the street, with tall buildings on both sides. At the end of the street which is near to the "*Rua Quebra Costas*" the width is less than 2.1 m.

Figure 35 demonstrates the width of the street in different locations. As it is presented in this figure, the top left shows the entrance of the street on the south side with the widest width. The top right shows the middle of the street and the down shows the end of the street on the north side with the narrowest width.

In Figure 36 we can see tall buildings located on both sides of the street with 4 to 5 floors. It was already mentioned that the width of the street is relatively narrow and, therefore, the urban canyon in the street is deep and the rate of building height to the street width is from 1.87 in the widest part in the south to 7.2 in the narrowest part of the street. Based on the definition of urban canyon, the right figure has a deep canyon and the right one has a normal canyon. Figure 36 presents the urban canyon depth in the "*Rua Fernandes Thomas*".

Figure 35: Different sections of the street in the area of the case studies

Figure 36: The analysis of the urban canyon in the area of case studies

4.5.2 Construction characterization of the case studies

In this section, the selected buildings as the case studies are described.

1- **Multi-family house**

This building, a multi–family building with four floors, is the first and second case studies of the research. It is located in the widest part of "*Rua Fernandes Thomas*". A restaurant is located on the ground floor of the building while the other floors are residential with only one apartment in each floor. The research was developed on the third and fourth floors. The main structure and construction of the building are the original ones. The building is colored with some partial changes in appearance. The apartment which is located on the third floor has two rooms and is the first case study. More information about the plan, elevation, section, and also photo of the building is presented in Appendix 1.

The apartment is occupied and has a double-sided/cross ventilation. There are three main openings in the main building faced (the west side) and two small openings on the opposite side (the east side) which are located in the kitchen and bathroom. As explained in the previous sections, no cooling and heating systems exist in this old residential building. No mechanical ventilation system exists and the apartment uses natural ventilation system.

The apartment located on the fourth floor is also an apartment with two rooms, but unoccupied at the time of the research and is the second case study. The entrance of the apartment is connected to the corridor. As the other one, it does not have any cooling and heating systems. More information about the plan, section, elevation and also photos of the building are available in Appendix 1. The apartment has a double-faced ventilation system with the main windows on the west side. There are also two small windows on the east side of the building. Figure 37 presents the location of the building in the urban plan of the city.

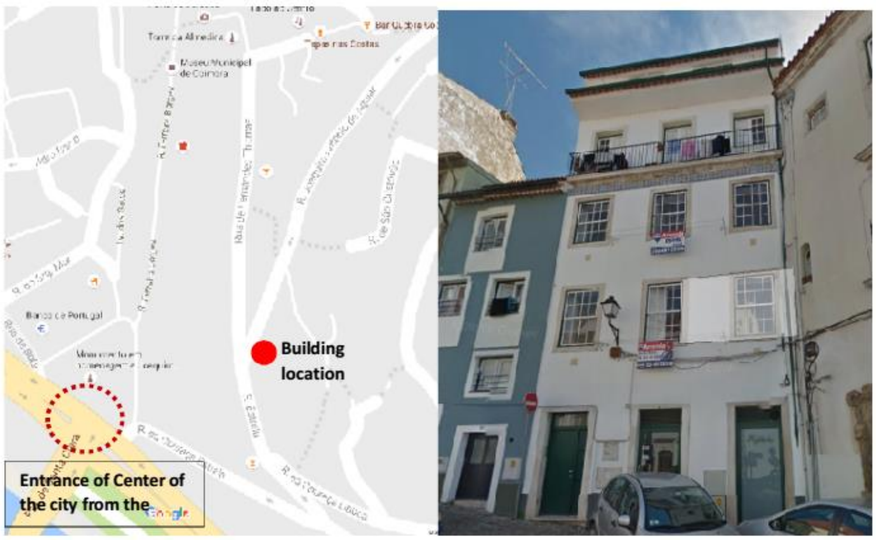


Figure 37: Location of the first and second case studies of the research

2- **Multi-family house**

The third case study of the research is an occupied flat which is located on the first floor of a multi–family house. This 4-floors building is located in the middle of the street "*Rua Fernandes Thomas*". Like the previous case study, it has no cooling and heating systems and it works based on the natural ventilation system. The flat has two big windows in the main facade of the building.

There is also another small window in another side of the room which is just connected to the inner spaces as well as to the outdoor through a corridor. Therefore, the flat profits from the cross ventilation system while one side connected to the outdoor air and the other side belongs to the inner spaces. The selected building was retrofitted four years ago. Due to the intervention which was done in the building, the walls have insulation layers and new windows with wooden frames. Figure 38 presents the location of the building in the city center. More information such as plan, section, elevation and also a photo of the building are available in Appendix 1.

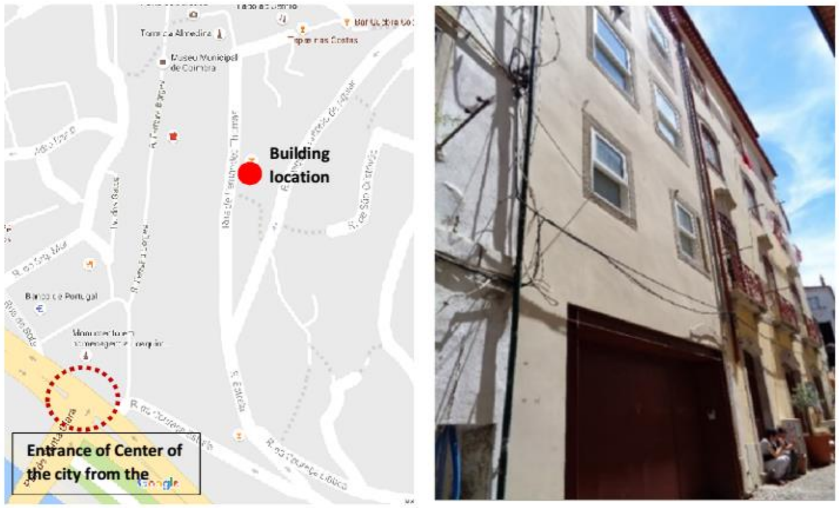


Figure 38: Location of the third case study of the research

3- **Single family house**

In order to evaluate the conditions and characteristics of the ventilation system in different types of the old residential buildings, another case study for this research was selected. This fourth case study is a single-family apartment which is located at the end of the street "*Rua Fernandes Thomas*". The house is divided into four floors. Like the other two cases, the building lacks the cooling and heating systems and benefits from natural ventilation. The building only has windows on one side with the view to "*Rua Fernandes Thomas*".

Floors are linked by a staircase which acts as a duct for the air circulation in the building. At the top of the last floor, a ceiling window exists to help the ventilation system as a stack ventilation. A simple intervention has been done in the building around 10 years ago. Figure 39 shows the appearance of the building and more information about photo, plan, section, and elevation is presented in Appendix 1.

Figure 39: Location of the third case study of the research

4.6 Methodology of the case study

This section is devoted to the methods which were selected to the development of the research. As it was previously explained, the research intends to improve the efficiency of natural ventilation based on the building properties. Hence, the research intends to find the energy performance condition and the qualification of interior air by air leakages, air permeability and the infiltration rate of the building. Subject to the aims of the research, the multi- criteria analysis has been selected.

As it was exposed, there are two main categories for a methodology according to the aim of this research, namely the simulation method and measurements method. The simulation method was the first procedure chosen for developing this research. There are four different models, i.e. Empirical model, multi-zone model, zonal model, and CFD model, in which simulation software was developed. Each model has their own advantages and disadvantages. Some of them may also be used together. This has been explained in section 4.2.

Regarding the measurements methods for the air leakage and ventilation effectiveness of the building, there are methods such as BDT and TAG methods which were explained in section 4.3. The case studies for the research are four residential buildings (apartments) in the center of the city of Coimbra.

As this section concludes, in order to realize the efficiency of natural ventilation based on building characteristics, it is necessary to analyze the building energy performance (thermal comfort and IAQ) and also infiltration rate.

Hence the framework of the research methodology is divided into three levels: building (in order to find the building characteristics), infiltration (in order to find the building air leakage and infiltration rate), and energy (in order to find the energy performance condition of the building). Subjected to the existing methods and models worldwide, the following figure (Figure 40) explains the sketched hierarchy of the research.

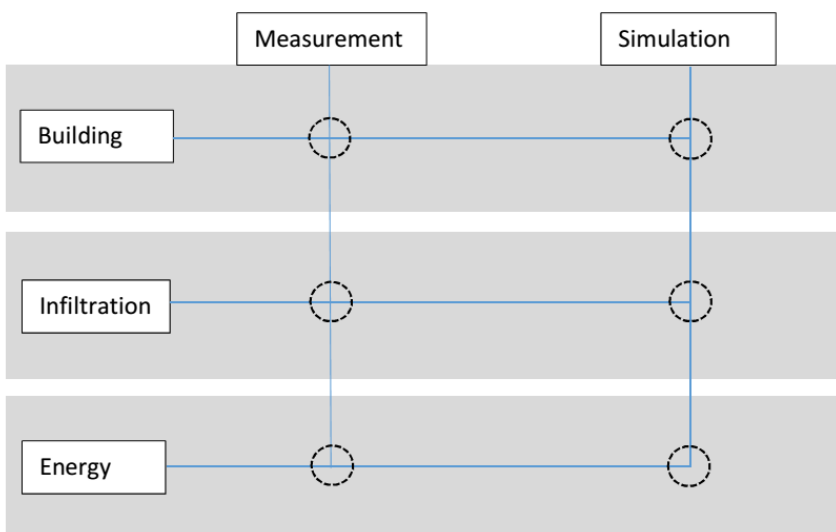


Figure 40: The procedures of the research methodology

The chart contains three rows and two columns. The rows present three main categories of the research, specifically building, infiltration and energy, while the columns stand for two methods of developing the research, simulation methods and measurement methods.

The following steps clarify different parts of presented chart in Figure 40:

- To understand the energy performance and ventilation effectiveness of the building, it is necessary to obtain the characterization of the building at the first step. Therefore the in-situ measurement of the building helps to find the properties of the building such as envelope area, opening area, percent of interior and exterior envelopes, existing opening configuration. Also, general properties of the building about the construction and pathologies in the cases studies should be considered.
- To estimate the infiltration rate of the building, according to the existing methods that were already presented, it is necessary to clarify that: 1- the existing models vary from the climate dependent infiltration model, which considers the airtightness and infiltration of the building envelope over a normal pressure (like TAG method), or 2- to a time-dependent climate-independent model in which the weather data (temperature, barometric pressure) should be measured continuously and the annual infiltration would be the sum of the infiltration calculated for each time step (like BDT).
- In regards to energy, it is possible to find the energy model of the building in three different ways. 1- The first is a simplified approximation of the energy model of the building, 2- the second is using the average of infiltration, and then find the energy model. 3- The third is a time-dependent energy model which is the most accurate one and is associated with the climate data. Figure 41 demonstrated this information.

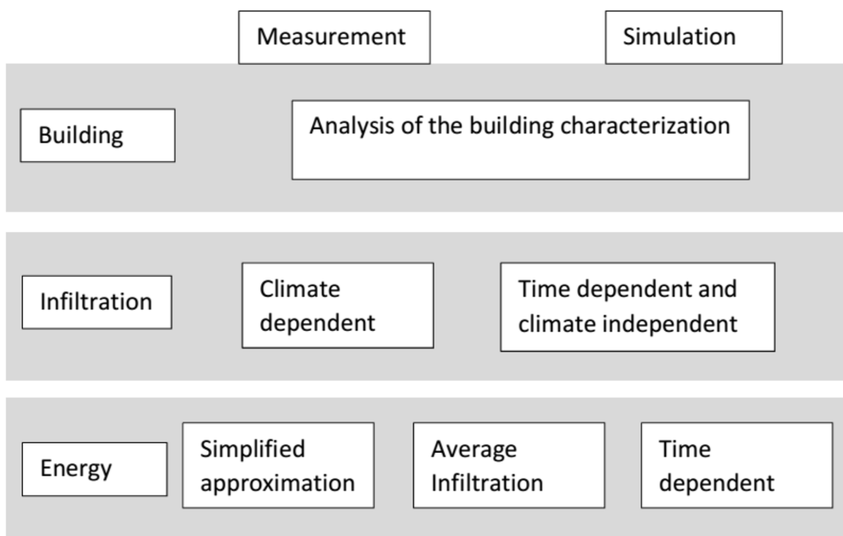
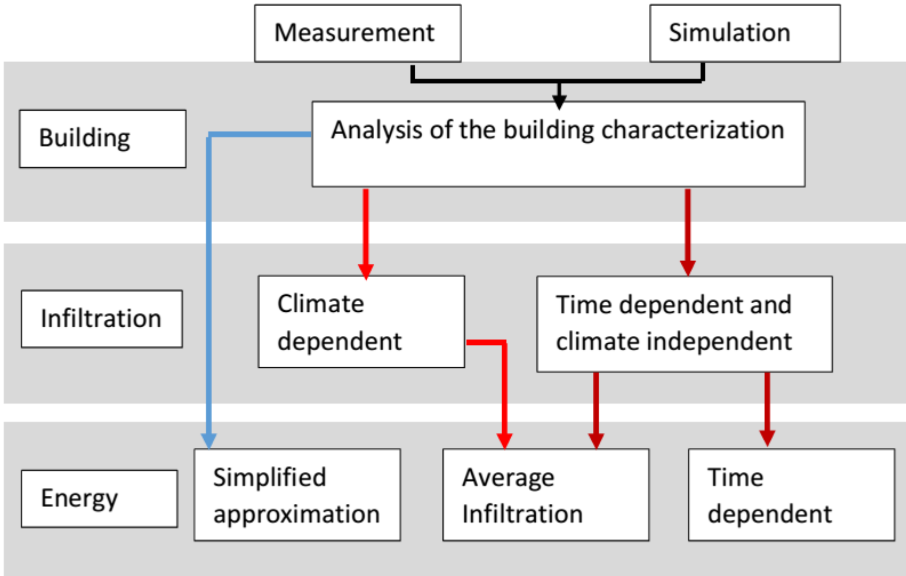


Figure 41: The explanation of the research methodology based on existing method

Each one of the models in each category has a relationship with the main methods (measurement, and simulation) which are presented in Figure 42.



The arrows show that there are different possibility of developing this research based on the resented information in this chart.

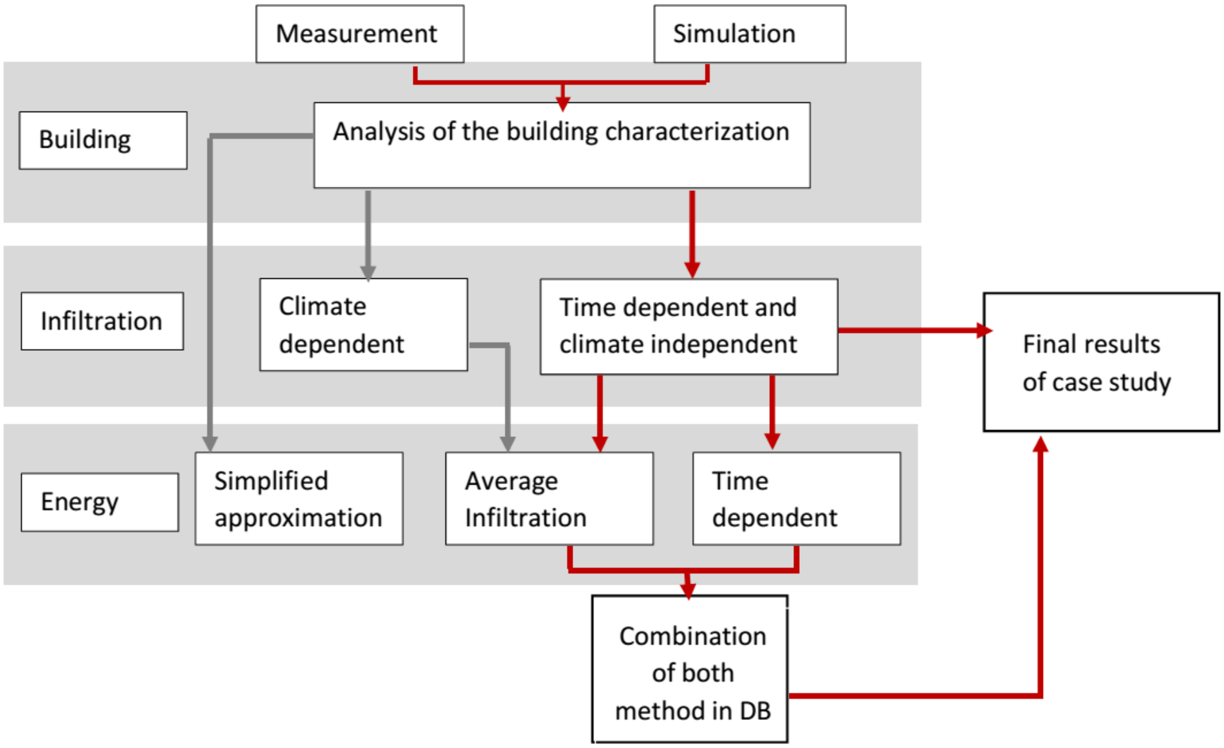
Figure 42: The hierarchy of the research methodology

Based on the figures presented above, in both methods of measurement and simulation, building characteristics will be considered first. After that, based on the obtained information from the building characteristics, the next steps come up.

To do so, there are three ways for the next steps which will be explained below:

1- The first way is simulating the building energy performance with the software which works by the simplified approximation, but it is not possible to obtain the infiltration properties (blue arrow).
2- The second way is, based on the climate-dependent method (TAG method), finding the infiltration rate of the building and consequently the simulation of the energy performance of the building will be followed by the software which works based on the average infiltration method (red arrow).
3- The third way is, based on the time-dependent and climate-independent method (BDT), considering the building infiltration condition, and after that, analyzing the building energy performance by the software which is working by two different ways of time-dependent or average infiltration method (dark red arrow).

Due to all presented information, the selected method to be followed is presented in Figure 43.



The red arrows shows the selected procedures for this research.

Figure 43: The final process of research methodology

After analysis of the existing models, the BDT method as a time-dependent and climate -independent model, as a measurement method was chosen to find the rate of infiltration and ventilation effectiveness in these buildings.

To do the measurement, the tests were done with a *Retrotec* Model 1000 Blower Door. As it was mentioned in section 4.3, the tested buildings were completely sealed and then the equipment starts to measure and calculate the building properties. At the end, the data gathered by Blower Door is implemented in *Fantestic* software and the final reports for each one of the tested building is obtained. At this point, the measurement phase is done and the results of measurement of building infiltration are available.

To analyze the building energy performance as the third step of the research, the simulation software Design Builder (DB) was selected. The further reasons for choosing this software are: firstly, it is a coupled simulation software which makes possible to simulate both energy and airflow; secondly, its structure is developed by coupling multi-zone and CFD models while its energy module is based on the Energy Plus software and a multi-zone model for energy simulation. It is also possible to analyze the airflow by its CFD module.

The CFD module of the DB software is based on the *Navier-Stokes* equation. According to DB-CFD, it is possible to calculate the results of the air velocity, airflow distribution in the building, PPD, PMV, and also ventilation effectiveness.

After finding the effective ventilation rate by each one of these methods (measurement and simulation), the results will be inserted in the new norm of ventilation in Portugal which has been organized by LNEC and that was developed based on EN15542. After that the condition of building air permeability and infiltration will be found. Up to now, the existing building conditions have been found.

Therefore, based on the obtained results and knowledge of the existing building conditions and also taking into account the case studies conditions and limitation of intervention in the area of study, the best solutions to improve natural ventilation and air quality of the buildings will be studied. The following figure (Figure 44) shows the continued process of the research.

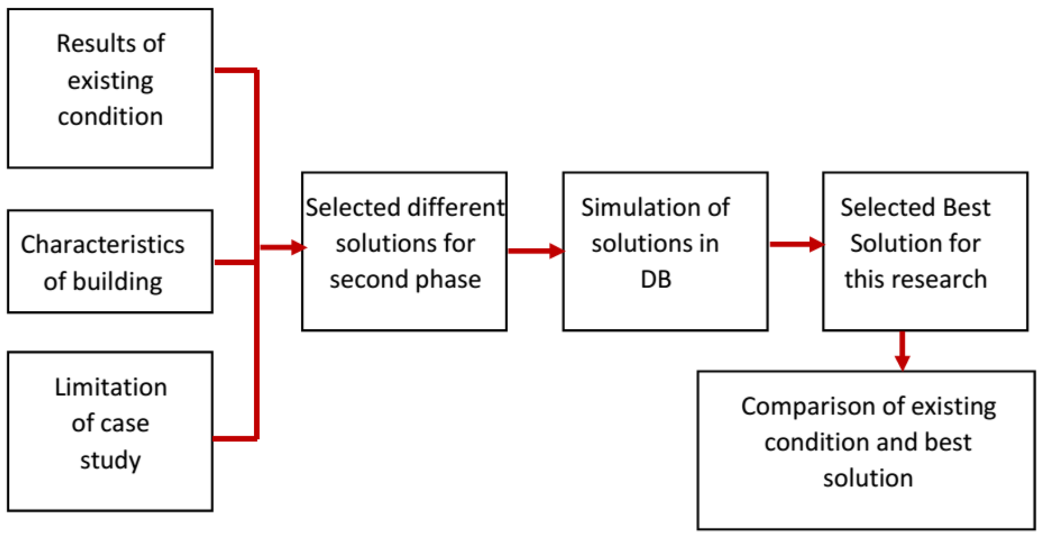


Figure 44: Second phase of research methodology

Based on all presented information about the methodology of this research, next chapter will present the analysis of thermal comfort and ventilation effectiveness of the cases studies in the existing condition.

Chapter 5:

Analysis of ventilation effectiveness results in four case studies

Index of chapter 5

*"**Take care to get what you like or you will be forced to like what you get. Where there is no ventilation fresh air is declared unwholesome**".*

George Bernard Shaw

5.1 Introduction

This chapter presents the airflow distribution, infiltration rate and also energy performance of the residential buildings selected as the case studies, to analyze the effectiveness of natural ventilation based on the building characterization. According to the structure of the research methodology presented in Chapter 4, this chapter intends to explain the obtained results in two parts:

- Results of Measurement method (BDT).
- Results of Simulation method (DB).

The first section is related to the results based on the measurements method. As it was already explained in Chapter 4, the research was developed using BDT as a measurement method. In particular, the section is focused on finding the infiltration and ventilation effectiveness rate of the building.

The second section presents the results of the research based on the simulation method with DB software. This second section is divided into two subsections, 1- thermal comfort and infiltration analysis, 2- CFD analysis.

At the end of this chapter, conclusions of the analysis of the building will be illustrated. The presented information in this section is useful to find some solutions in order to improve the existing conditions to have more effective ventilation in the buildings.

5.2 Outline of BDT Procedure

In order to assess the building infiltration and air permeability rate by measurement methods, the BDT was selected as a way to measure the building infiltration and exfiltration. Today, standardized test procedures for performing BDT are described in the European Standard EN-13829 [195], which is implemented in most European countries, and will also be used in this research. BDT procedure is associated with the regulations of EN-ISO-13790 [196], EN-ISO-13829 [197], and ISO-9972 [212].

In order to establish the initial setting of measurement procedures the standard of EN 13829:2000 (thermal performance of the buildings- determination of air permeability of buildings- Fan pressurization method) was used.

Pressurization and depressurization tests were done by blowing air into or out of the spaces. Based on the depressurization test, in which the air is pulled out from the house, it was possible to figure out how the air comes inside through the cracks in the building envelope. Before starting the test, all entrance air was sealed off.

Based on EN ISO-13829 [197], BDT consists of the installation of a fan that can insufflate air up to 70pa which can then be reduced gradually at intervals of 5-10pa. Since the BDT method is based on the pressure difference, the maximum pressure difference changes, depending on the volume and shape of the building, are usually 50pa or above and are used as a measurement point [213].

BDT procedures are based on the theory of mass conservation, according to which the flow passing through the fan should be compensated for by an equal amount of flow through the envelope's leakage. Consequently, by measuring the airflow through the Retrotec Model 1000 Blower Door and the building properties, the necessary parameters of airtightness have been calculated.

It is necessary to find the air change rate (ACH) of the building and consequently its air leakage. To determine the ACH_{50} by BDT, at the first step, the amount of airflow in CFM will be determined.

After that, based on the achieved amount of CFM by the calculation process of the selected software, the number of CFM result is multiplied by 60 and then divided by the building volume in order to find the ACH_{50}. The final value is the air change rate of the building in ac/h [214].
As stated in Section 4.3, regarding the procedures of the BDT, the temperature and barometric pressure of inside and outside of the building was previously measured by a thermometer. By inserting this data in the software associated with Blower Door Fan, the program, in two phases of pressurization and depressurization starts. In a second phase, the measured information is inserted in the *Rectorec Fantestic* software and the final results of the measurement regarding the infiltration rate and also related figures are obtained. This will be presented in the next section. Since the research has been done in four different buildings with different characteristics, the results will be explained for each one individually.

5.2.1 First case study

The first apartment tested with BDT was in a multi-family house and located on the third floor. Figure 45 shows the process of BDT in this case study. As it was illustrated in Section 4.5.2, the characteristics of the building remain the original ones. Some modifications were made that only affected the appearance of the building. The apartment has two rooms and the natural ventilation occurs as a double-side/cross ventilation. There are three main openings in the west side of the building (main faced) and two small openings in the east side.

Figure 45: BDT process – Case study 1

The floor area (A_c) of the tested apartment is 45.8 m^2, the envelope area (A_E) is 108.9 m^2 and the volume (V) is 128.1 m^3. Figure 38 presents the plan of the apartment and more information about it is available in Appendix 1.

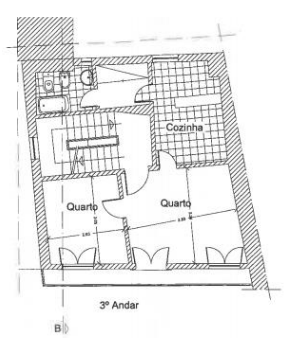


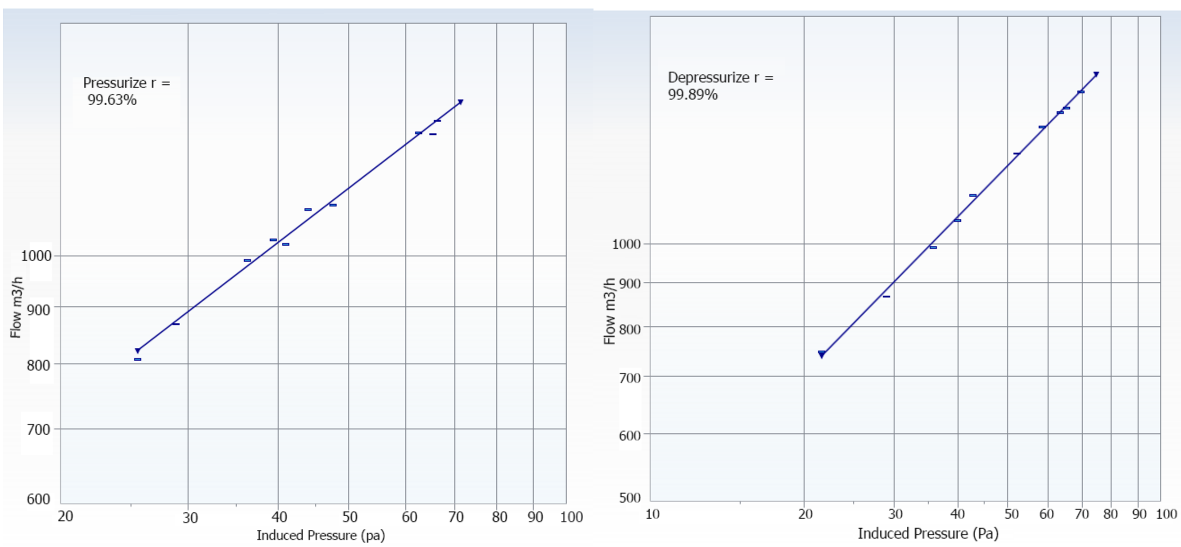
Figure 46: Plan of the tested apartment- Case study 1

The pressurization test was the first to be conducted. These tests used a pressure range between 20-70 pa within 10 points of data collection, which were set in each 5 pa difference pressure. Essential information such as, initial temperature, final temperature, barometric pressure is presented in Table 19.

Table 19: The mandatory data to start the test in both pressurization and depressurization test – Case study 1.

	Barometric Pressure (pa)	**Initial Temperature (°C)**		**Final Temperature (°C)**	
		Interior	**Exterior**	**Interior**	**Exterior**
Pressurization	101.36	24.9	23.1	24.6	23.3
Depressurization	101.36	24.0	24.9	24.3	23.7

The air leakage condition of the building is obtained by inserting the measured data by the fan in the *Rectorec Fantestic* software. The result is presented in Figure 47.



Right-side figure is pressurization and left-side one is depressurization results.

Figure 47: The relation between induced pressure and airflow in the pressurization and depressurization test- Case study 1

Figure 47 shows the relation between the total airflow (V_r) m^3/h and the induced pressure in both pressurization and depressurization. Each presented point represents the measured rate of the airflow for each specific pressure. After that, in order to present the relation between the airflows in different pressures, V_r rate is corrected with a correlation percent which is 99.63% in pressurization case. Therefore, the corrected line with the slope (n) of 0.49 is drawn and show the condition of V_r for the tested building. As the test was done in two phases on pressurization and depressurization, Figure 47 right-side illustrates the relation between induced pressure and airflow during the depressurization phase in the tested building.
According to the above figure, the correlation percent for depressurization test (r) of the apartment is 99.89%, and the corrected line of V_r is drawn with a slope (n) of 0.61. Hence, the presented plots illustrate that the rate of air-flow (V_r) to the induced pressure in the depressurization test is bigger than the pressurization test. Since the depressurization means sending the flow from inside to the outside by the fan and on the other hand the airflow coming inside through the crack of the envelope, these plots show that

the rate of air change in depressurization is higher than pressurization and the cracks of envelopes cause to bring airflow inside.
It is possible to find the properties of building air leakage and infiltration based on the measured data of BDT according to the EN13829:2000. The next tables (Tables 20) demonstrate the related information for both pressurization and depressurization phases.

Table 20: The obtained results of BDT during the pressurization/depressurization test - Case study 1

	Air Flow at 50 pa , V_{50} (m^3/h)	**Air Change at 50 pa, n_{50} (h^{-1})**	**Permeability at 50 pa, q_{50} ($m^3/h.m^2$)**	**Specific leakage at 50 pa, W_{50} ($m^3/h.m^2$)**	**Effective leakage area at 50 pa, ELA $_{50}$ (cm^2)**	**Equivalent leakage area at 50 pa (cm^2)**	**Normalized leakage area at 50 pa, NLA50 (cm^2/m^3)**
Pressurization	1150	8.97	6.073	25.113	350.5	574.0	1.851
Depressurization	1235	9.63	11.334	26.961	376.1	616.5	3.455

As Table 20 shows, the air change rate of the building is 8.97 h^{-1}, which means that the building has approximately 9 renewals per hour. According to the *California* and *Pennsylvania* standards for existing building infiltration and BDT [215], the building with ACH 9 h^{-1} is classified in the group of the moderate to leaky buildings. Subject to the depressurization test, the air change rate of the building is 9.63 h^{-1}, which means that the air volume of the building will be replaced approximately 10 times per hour. Based on California and Pennsylvania standards for existing building infiltration and BDT [215] means the rate of ACH classifies this as a leaky building.
While based on ASHRAE regulation [156] the air change rate of the building at the normal pressure should be maximum 0.35 h^{-1}. Portugal also has a specific rate for ACH based on its own regulation (REH) [216]. In order to consider the leakage condition of the building based on the ASHRAE and Portuguese regulation, it is necessary to adapt the obtained results of BDT on the pressure of 50 pa to the normal pressure. To do so, there is a specific application from LNEC which was developed in 2014 in order to define the ventilation rate for REH and RECS [217]. After inserting the obtained results of BDT on the LNEC application, the ACH rate of the tested building, based on the pressurization condition, is 1.63 h^{-1} at normal pressure. However, this rate based on the Portuguese regulation (REH) [216] should be maximum 0.4 h^{-1} in the winter time and 0.6 h^{-1} in the summer time and due to the ASHRAE regulation it should be 0.35 h^{-1}. The following figure (Figure 48) describes the air change rate of the building, based on LNEC application which is higher than 0.8 h^{-1} in more than 82% of the time.
In conclusion, the tested apartment is classified as a leaky building based on the ASHRAE and REH regulation. Considering Portuguese regulation and LNEC application, the air permeability of the building (q_{50}) of the construction in Portugal should be 2.9 $m^3/h.m^2$ despite in the tested building this value is 6.07 $m^3/h.m^2$ and 11.33 $m^3/h.m^2$ for pressurization and depressurization respectively. Regarding Portuguese regulation, the ACH rate of the building is higher than the standard rate. It means that the building has too many cracks in its envelopes and needs to improve in order to control the air permeability and energy demands of the building.

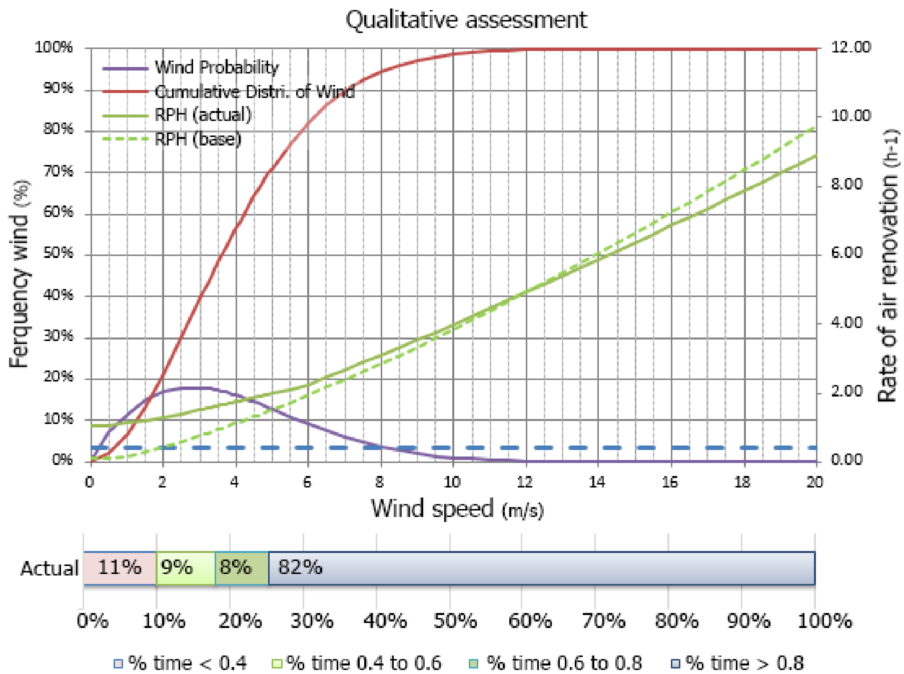


Figure 48: Results of LNEC application - Case study 1

5.2.2 Second case study

The second apartment that was tested with BDT is an apartment on the fourth floor of a multi-family house. As it was illustrated in Section 4.5.2, this apartment is located in the same building as the first case study. It has two-rooms and includes double-side cross ventilation with three openings in the main faced that is oriented to west side and two small openings in the east side. The floor area (A_c) and the envelope area (A_E) of the tested building are 50.5 m^2 and 197.1 m^2 respectively, and the apartment volume (V) is 141.3 m^3. Figure 49 presents the plan of the apartment with more information available in Appendix 1. Table 21 presents the condition of the building.

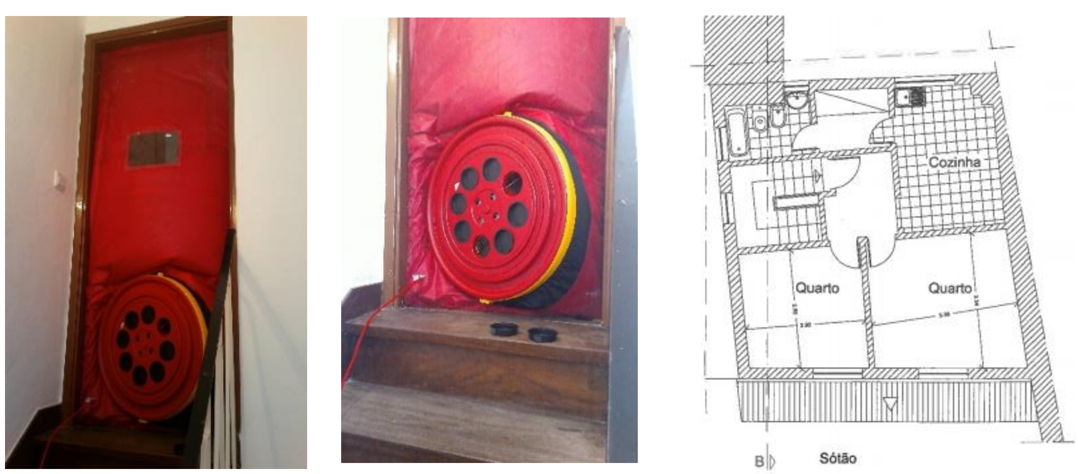


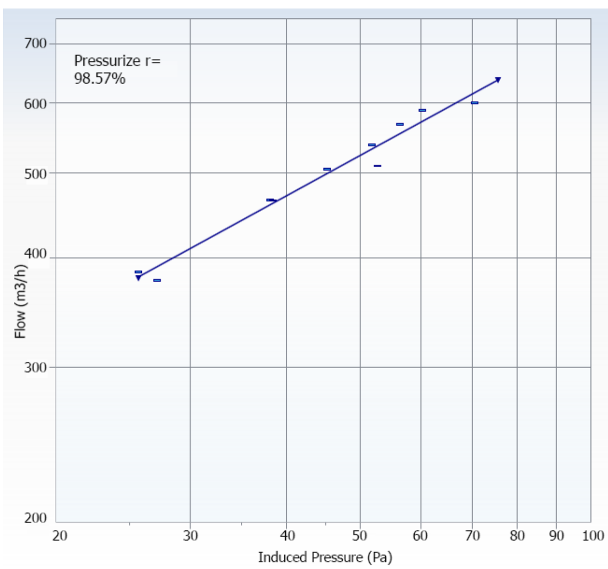
Figure 49: Plan and figure of the tested apartment- Case study 2

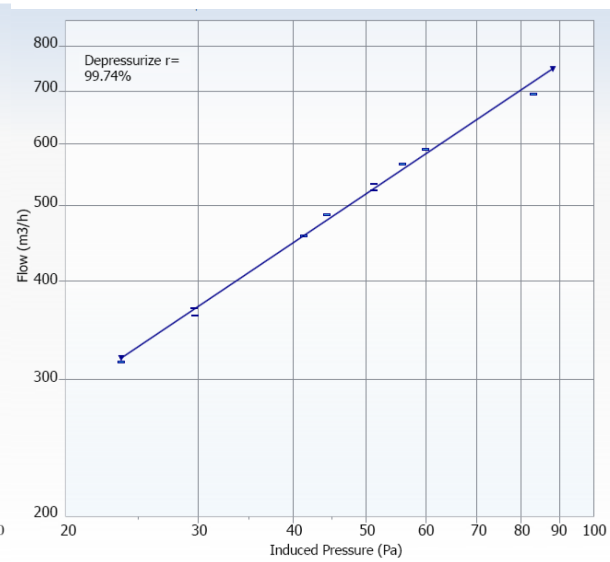
Table 21: The mandatory data to start the test in both pressurization and depressurization test - Case study 2

	Barometric Pressure (pa)	**Initial Temperature (°C)**		**Final Temperature (°C)**	
		Interior	**Exterior**	**Interior**	**Exterior**
Pressurization	101.36	23.8	23.7	23.3	23.2
Depressurization	101.36	23.3	23.7	24.1	23.2

In this test, the pressure varies between 20-70 pa in 10 points. After measuring the data of the apartment in both phases of pressurization and depressurization, the collected data was inserted in the mentioned software. Due to the setting of the software based on the EN-13829:2000 [216], the final results of BDT about the building infiltration was calculated. The obtained results of the building air leakage are presented in Figure 50 and Table 22.

Figure 50 illustrates the relation between the airflow and induced pressure in the pressurization test. The correlation line is plotted by a corrected rate (r) of 98.5%. According to this figure, in the first point, the airflow is 385.7 m^3/h in the pressure of 25 pa and at the last point, the airflow is 600.4 m^3/h in the induced pressure of 70 pa.





Left figure is pressurization test and right one is depressurization test.

Figure 50: The relation between airflow and induced pressure in the pressurization and depressurization test- Case study 2

As previously explained, the second phase of BDT is the depressurization test. Figure 50, right-side, presents the relation between airflow and induced pressure during the depressurization test. The correlation line for this test was drawn by the corrected rate (r) of 99.74%.

These two graphs show a correlation line for depressurization test that has a slope of 0.64 while the slope of this line for pressurization is 0.48. This means that during the depressurization, when the air is blown to the outside by fan, the more airflow comes inside through the cracks in the building envelope in comparison with the pressurization test. However, the apartment infiltration in both is almost the same and close to each other. The final result of BDT in both phases of pressurization and depressurization is obtained *by Rectorec Fantestic* software based on the EN-13829:2000. The following table (Table 22) presents this information.

Table 22: The obtained results of BDT during the pressurization /depressurization test- Case study 2

	Air Flow at 50 pa , V_{50} (m^3/h)	**Air Change at 50 pa, n_{50} (h^{-1})**	**Permeability at 50 pa, q_{50} ($m^3/h.m^2$)**	**Specific leakage at 50 pa, W_{50} ($m^3/h.m^2$)**	**Effective leakage area at 50 pa, ELA $_{50}$ (cm^2)**	**Equivalent leakage area at 50 pa (cm^2)**	**Normalized leakage area at 50 pa, NLA50 (cm^2/m^3)**
Pressurization	910.25	7.1	6.073	19.877	277.4	454.3	1.47
Depressurization	1006	7.85	9.239	21.977	299.2	502.5	2.8

According to the obtained results, the air change rate of the apartment (n_{50}) is 7.1 h^{-1}, meaning that approximately 7 times per hour the indoor air is renewed, so that there is an excess of ventilation. This extra ventilation rate is unnecessary and causes discomfort for the residents. According to the California and Pennsylvania standards for existing building infiltration and BDT [215] this rate of ACH places the building in the moderate class of air leakage. As it was already explained in previous building, in order to compare the building ACH based on the Portuguese regulation (REH) [216] and ASHRAE regulation [156], the LNEC application [217] was used. According to the results of LNEC application, the air change rate of the building based on the pressurization test at normal pressure is 1.10 h^{-1}. Figure 51 presents the condition of the tested building based on the LNEC application. While due to the ASHRAE regulation it should be 0.35 h^{-1} and due to the REH regulation [216], it should be less than 0.4 h^{-1} in the winter time and 0.6 h^{-1} in the summer time.

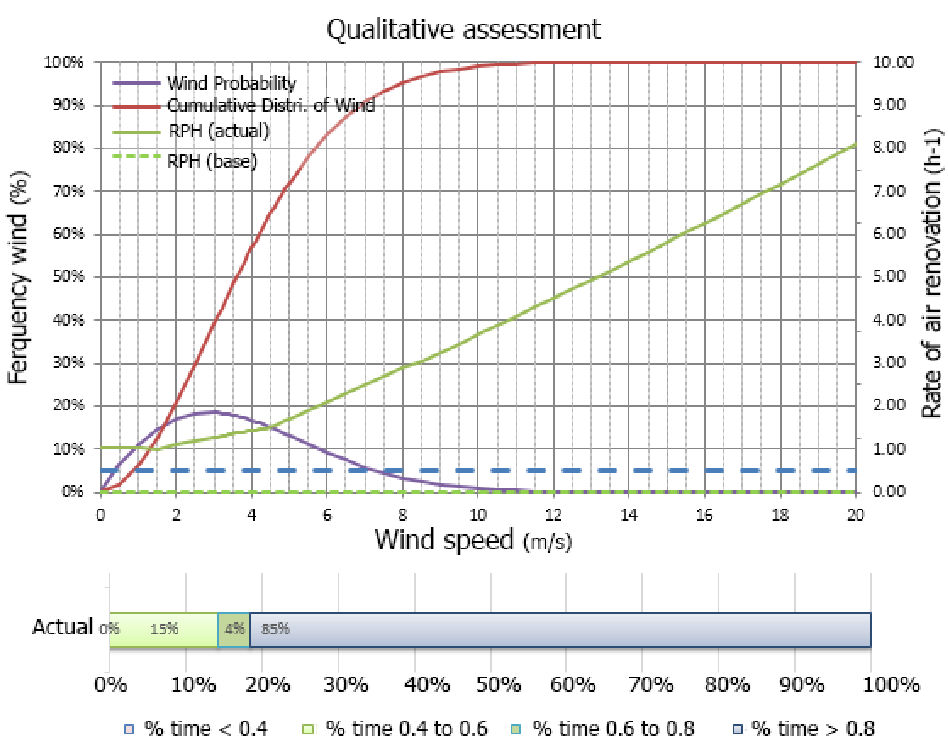


Figure 51: Results of LNEC application – Case study 2

Also, the results of LNEC application show that the building has an air change rate of higher than 0.8 h^{-1} in more than 81% of the time. In conclusion, it has been observed that the apartment is located among the buildings with a moderate rate of leakage based on the *California* and *Pennsylvania* standards for existing building infiltration and BDT [215]. However, based on the LNEC application as well as ASHRAE and REH regulation, it does not have any acceptable conditions and it is a leaky building.

On the other hand, based on LNEC application and Portuguese regulation, the rate of q_{50} should be 2.9 $m^3/h.m^2$ while it is 6.07 $m^3/h.m^2$ in the tested building. It means that this building has an excessive level of air leakage based on Portuguese regulation. Therefore, the building needs more energy for heating based on this excess of air permeability.

5.2.3 Third case study

The third case study is a retrofitted flat with a living area, kitchen, and bathroom. Following on what was mentioned in Section 4.5.2, it is located on the first floor of a multi-family building. The apartment has one facade on the west side of the building. However, there are two small exterior openings which help the apartment's air circulation. More information about this case study can be found in Appendix 1. The apartment works based on the cross ventilation. The floor area (A_c) of the tested apartment is 25.4 m^2, the envelope area (A_E) is 57.2 m^2 and the volume (V) is 71.2 m^3. Figure 52 presents the plan of the apartment and its entrance door with the equipment for BDT test installed.

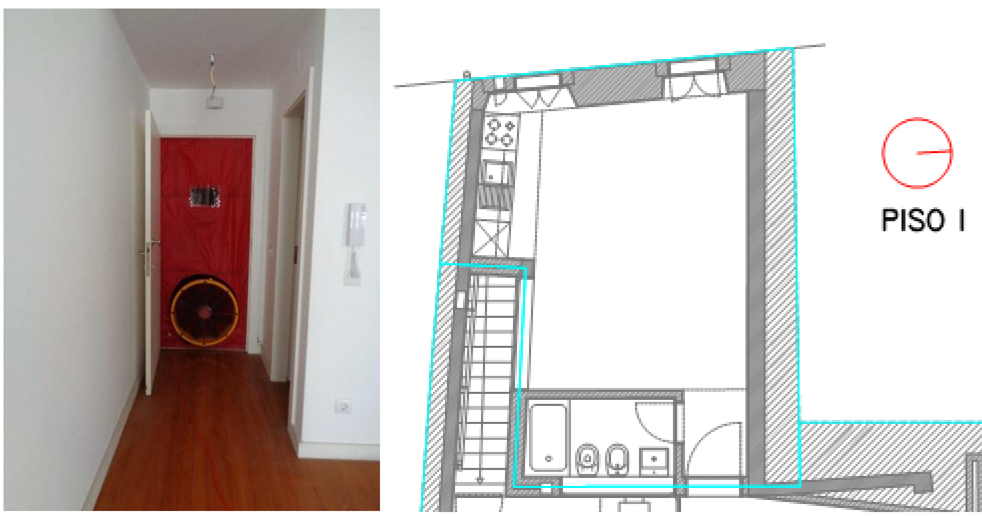


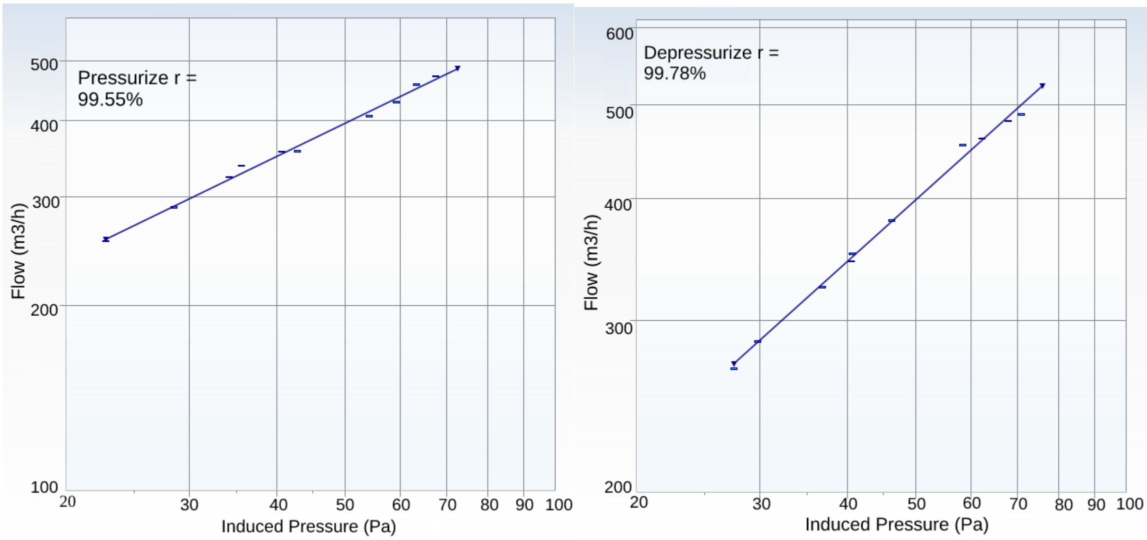
Figure 52: Plan and the figure of the tested apartment at the time of BDT- Case study 3

The properties of the building such as interior and exterior temperatures, and barometric pressure are presented in Table 23.

Table 23: Mandatory data to start the test in both pressurization and depressurization test – Case study 3

	Barometric Pressure (pa)	**Initial Temperature (°C)**		**Final Temperature (°C)**	
		Interior	**Exterior**	**Interior**	**Exterior**
Pressurization	101.3	22.2	23.1	21.6	21.5
Depressurization	101.3	22.4	22.6	21.9	21.8

Due to the variation of the pressure in 10 different points from 20-70 pa in this test, the results of the BDT for pressurization and depressurization were collected and inserted in the mentioned software. At the end, the properties of the apartment infiltration and air leakage has been calculated. The following figure (Figure 53) and also Table 24 present the achieved results.



The left-side figure is pressurization and right-side figure is depressurization results.

Figure 53: The relation between airflow and induced pressure in the pressurization and depressurization test- Case study 3

Based on the presented information in Figure 53, it is understood that the correlation rate (r) of airflow versus induced pressure in the pressurization method is 99.55%. The results of depressurization test, Figure 53 bottom, demonstrate the condition of airflow versus induced pressure during the depressurization test. The correlation line for this test is drawn by the corrected rate (r) of 99.78%. Grounded to the comparison of the obtained results of the apartment, it can be observed that the correlation line for depressurization and pressurization method has almost the same slope of 0.64. On the other hand, the air change rate of the building in a pressure difference of 50 pa (n_{50}) in the pressurization and depressurization are 5.48 h^{-1} and 5.59 h^{-1} respectively. Table 24 presents the characterization of the tested apartment based on EN-13829:2000.

The results show that the apartment has approximately 6 times per hour air change to obtain a qualified IAQ. Based on the *California* and *Pennsylvania* standards for existing building infiltration and BDT [215], this apartment is considered to be in the moderate class of air leakage. However, based on the LNEC application, the air change rate of the building is 0.64 h^{-1} which shows that the apartment is not a moderate building. Because based on the ASHRAE the air change rate should be maximum 0.35 h^{-1} and according to the REH regulation, it should be less than 0.4 h^{-1} in the winter time and 0.6 h^{-1} in the summer time.

Regarding the infiltration and air leakage of the building and also the limitation of REH and ASHRAE regulations, the building does not have any acceptable conditions. However, due to the California and Pennsylvania standards, a classified building with this rate of air change is in the moderate class and its condition is acceptable for the existing building.

As previously explained, the tested building is a refurbished one which has an important effect on the air leakage and infiltration condition of the apartment. Figure 54 presents the condition of the tested building based on the LNEC application.

Table 24: The obtained results of BDT during the pressurization /depressurization test – Case study 3

	Air Flow at 50 pa , V_{50} (m^3/h)	Air Change at 50 pa, n_{50} (h^{-1})	Permeability at 50 pa, q_{50} ($m^3/h.m^2$)	Specific leakage at 50 pa, W_{50} ($m^3/h.m^2$)	Effective leakage area at 50 pa, ELA_{50} (cm^2)	Equivalent leakage area at 50 pa (cm^2)	Normalized leakage area at 50 pa, NLA50 (cm^2/m^3)
Pressurization condition	390.5	5.48	6.824	15.3467	214.1	350.7	1.10
Depressurization condition	395.85	5.59	6.971	15.678	218.3	357.8	2.05

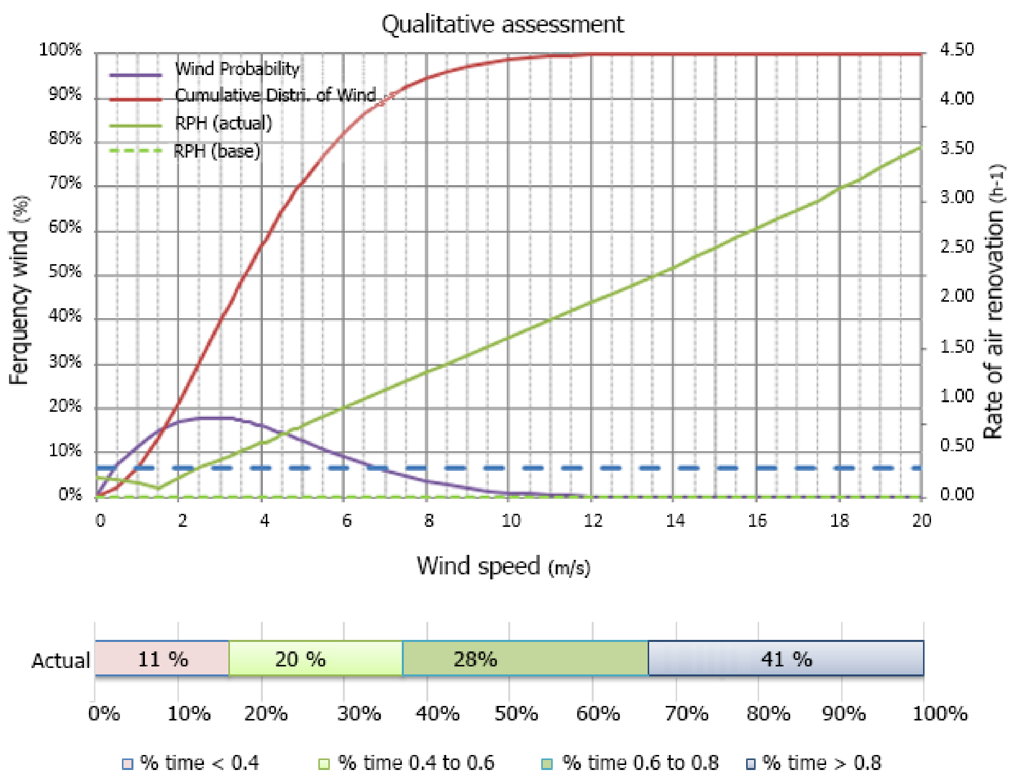


Figure 54: Results of LNEC application – Case study 3

According to the presented figure, the building has an air change rate of 0.6 to 0.8 on 28% of the time and also a rate of higher than 0.8 on 41 % of the time.

The air permeability of the building in the pressure difference of 50 pa (q_{50}) is found by BDT and equal to 6.82 $m^3/h.m^2$ for pressurization, and 6.97 $m^3/h.m^2$ for depressurization test. But based on the obtained results of the LNEC application, this rate should be 2.9 $m^3/h.m^2$ in the pressure difference of 50 pa. Therefore, it can be concluded that the air change rate of this building is also higher than allowed rate in the Portuguese regulation.

5.2.4 Fourth case study

The last case study is a single-family house with four floors. The building uses the stack ventilation system and has one facade oriented to the west side. The floor area (A_c) is 139.1 m^2, the envelope area (A_E) is 338.1

m^2 and the volume (V) is 378.1 m^3. Figure 55 presents the tested building with additional information presented in Appendix 1.

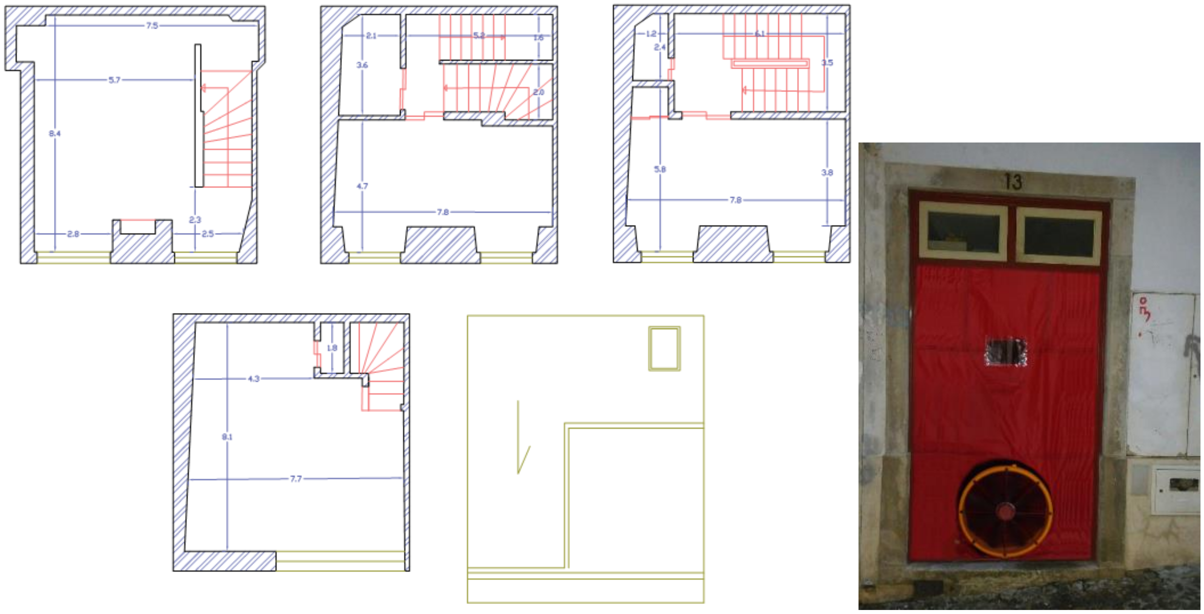


Figure 55: The ground floor plan and figure for the tested building- Case study 4

Based on the procedures of BDT in the research which has been explained, Table 25 presents the measured data for temperature and barometric pressure to proceed the test.

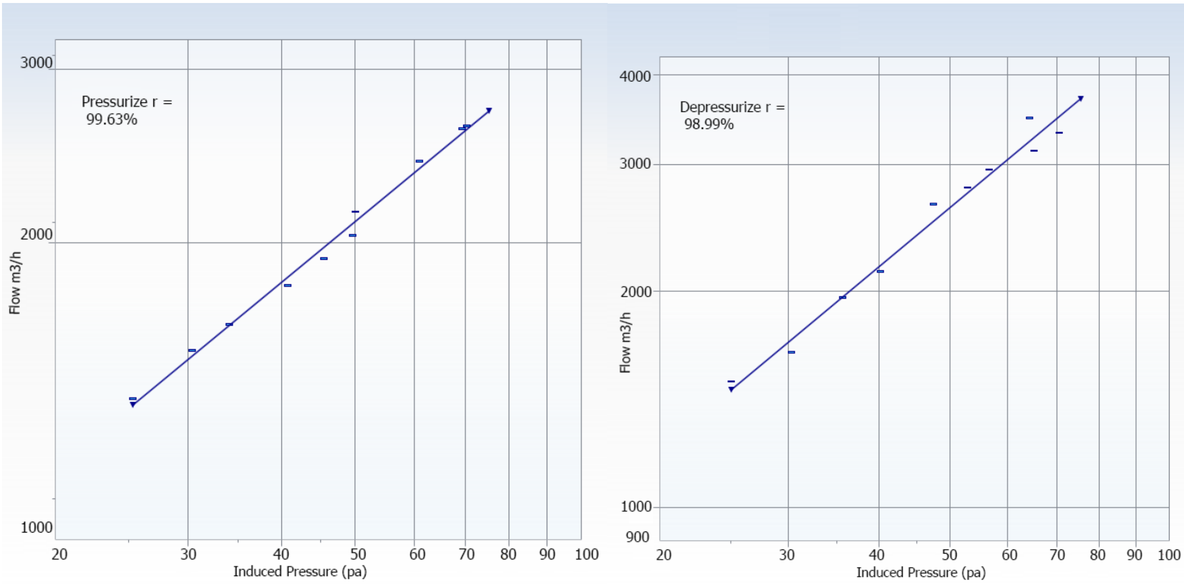
Table 25: Necessary data to start the test in both pressurization and depressurization test- Case study 4

	Barometric Pressure (pa)	**Initial Temperature (°C)**		**Final Temperature (°C)**	
		Interior	**Exterior**	**Interior**	**Exterior**
Pressurization	102.420	20.3	20.1	20.1	19.8
Depressurization	103	20.1	20.0	20.2	19.9

According to the presented information in Figure 56, it is observed that the correlation rate of airflow versus induced pressure in the pressurization method is 99.63%.

Depressurization results of BDT in the tested building presented in figure 56 right-side, show that the correlation line of airflow versus induced pressure is plotted by a corrected rate (r) of 98.99%. Grounded to the comparison of the obtained results of the apartment, it can be observed that the correlation line for pressurization and depressurization method has the slope of 0.63 and 0.61 respectively.

Subjected to the comparison of results, it is observed that the air change rate of the building in a pressure difference of 50 pa (n_{50}) in the pressurization and depressurization is 5.56 h^{-1} and 6.91 h^{-1} respectively. Table 26 presents the characterization of the tested building based on EN-13829:2000.



Left-side figure is pressurization result and right-side figure is depressurization one.

Figure 56: The relation between airflow and induced pressure in the pressurization test- Case study 4.

Table 26: The obtained results of BDT during the pressurization/depressurization test – Case study 4

	Air Flow at 50 pa , V_{50} (m^3/h)	**Air Change at 50 pa, n_{50} (h^{-1})**	**Permeability at 50 pa, q_{50} ($m^3/h.m^2$)**	**Specific leakage at 50 pa, W_{50} ($m^3/h.m^2$)**	**Effective leakage area at 50 pa, ELA_{50} (cm^2)**	**Equivalent leakage area at 50 pa (cm^2)**	**Normalized leakage area at 50 pa, NLA50 (cm^2/m^3)**
Pressurization	2105	5.56	6.221	15.122	640.0	1050	1.896
Depressurization	2615	6.91	7.731	18.793	796.5	1305	2.356

According to the obtained results, the building has approximately 6 times per hour air renewals on the pressurization method and 7 times per hour air renewals in the depressurization method.

Hence, due to the *California* and *Pennsylvania* standards for existing building infiltration and BDT [215], the moderate class is selected as the class of air leakage condition of the building. However, based on the LNEC application, the air change rate of the building is 0.76 h^{-1} which illustrates that the current rate is higher than the permitted rate based on the REH and ASHRAE regulations. This shows that the building does not have acceptable conditions for air change rate and it is classified as a leaky building. Figure 57 presents the condition of the tested building based on the LNEC application.

The air permeability of the building (q_{50}) found by BDT is equal to 6.22 m3/h.m^2 for pressurization and 7.73 $m^3/h.m^2$ for depressurization test. This rate should be 2.9 $m^3/h.m^2$ in the pressure difference of 50 pa based on the obtained results of the LNEC application. It is concluded that the air change rate of this building is also higher than the Portuguese regulation.

The presented results of BDT show that none of the buildings are tight enough and their air leakage rate and infiltration rate are higher than Portuguese regulation recommends. However, the third and fourth case studies have a better condition in comparison with the other cases.

The next section is devoted to the simulation results of the buildings in two fields: i) thermal comfort / infiltration and ii) air circulation and distribution.

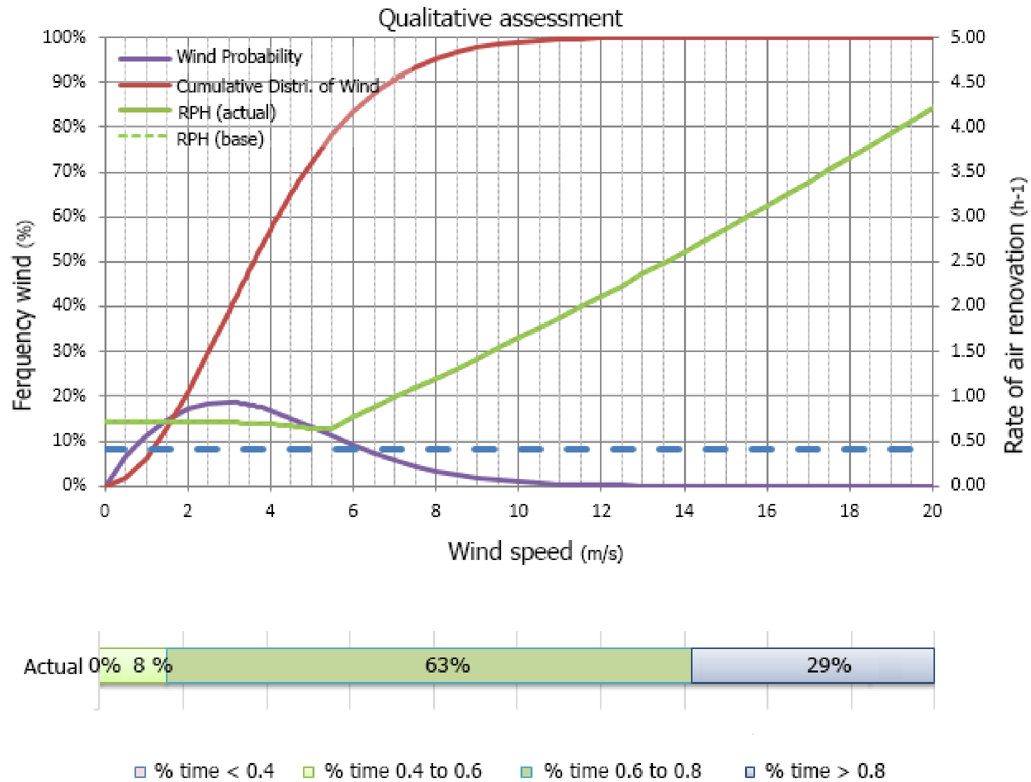


Figure 57: Results of LNEC application – Case study 4

5.3 simulation of the buildings

After analyzing the building air leakage and air infiltration by measurement methods (BDT), the second phase of the research is devoted to the analysis of the building energy performance and airflow distribution. To do so, DB software was selected as the simulation program based on some properties explained in 4. 2. The general functionality of DB and its setting for this research are initially explained in the section 5.3.1. Subsequently the results of the simulations in two categories of energy simulation and CFD are presented.

5.3.1 Functionality of DB tool in the research

DB is a comprehensive interface software associated with Energy Plus. In order to start the work with this software, the location of the building and also the weather information should be selected as initial data. The building geometry can be modeled or imported from Auto CAD as a DXF file. DB needs a variety of information including activity, internal load, construction types, opening, lighting, ventilation and HVAC. The general structure of DB is illustrated in Figure 58.

After providing all these parameters, it is possible to run the energy simulation of the building for different periods such as daily or annually in order to understand its thermal performance. The airflow distribution and ventilation effectiveness of the building can be obtained using the CFD module of DB. Since this research analyzes the effectiveness of natural ventilation in existing buildings, the next sections present the results of the simulation of buildings in two categories of thermal comfort and airflow distribution.

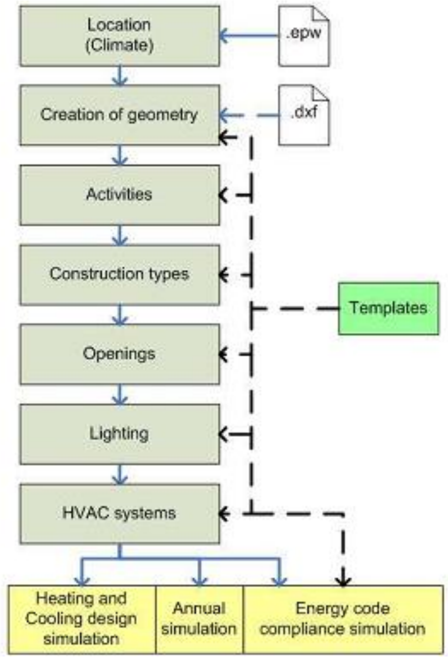


Figure 58: General structure of DB [218]

5.3.2 Specific setting of DB software in the research

DB software 5.0.0.03 which is linked to Energy-plus 8.1 was used in this research. After modelling the case study and inserting fundamental information such as location and weather data, which simulate and analyze the thermal comfort of the buildings, additional information such as building construction, HVAC information, lighting, ventilation, etc. was inserted.

As previously noted, this research is about existing residential buildings in Coimbra. The necessary information of DB about the building construction such as U-value of the wall, floor, roof, and their construction layer were obtained based on the finalized studies and projects in this area like, *Ramos* [210], or project of the *University of Coimbra* for renovation of downtown of *Coimbra* [129]. Table 27 presents the existing U-value of different construction elements based on the mentioned references.

Table 27: Existing U-value of building elements

Element	Existing U-Value
Exterior wall	1.92
Interior wall	2.16
Floor	1.40
Window	3.90
roof	3.80

There are different methods to find the rate of infiltration of the building in which the simulation will be based. In this research, the simulation is set based on the rate of n_{50}. Subsequently the obtained rate is converted to natural airflow rate h^{-1}. Hence, by setting the simulation options based on the real condition of the building and environment, the simulated results of the thermal performance are saved. In order to find the airflow distribution in the building, the CFD module of DB, which is based on the *Navier-Stokes* equation, is used. Based on the obtained result of CFD, designers and researchers have information on probable air velocities, pressures and temperatures that will occur at any point throughout a predefined air volume in and around building spaces, with specific boundary conditions which may include the effects of climate, internal heat gains and HVAC systems.

DB-CFD can be used for both external and internal analyses. External-CFD analyses provide the distribution of air velocity and pressure around the building structures due to the wind effect. These results can be used to assess pedestrian comfort, to determine local pressures, for positioning HVAC intakes/exhausts and to calculate more accurate pressure coefficients for Energy Plus and natural ventilation simulations. Internal analyses provide the distribution of air velocity and pressure throughout the inside of the building spaces. This information can be used to assess the effectiveness of ventilation systems design and to evaluate interior comfort conditions.

The numerical method used in DB-CFD is known as a primitive variable method, which involves the solution of a set of equations that describe the conservation of heat, mass and momentum. The calculations procedures of CFD are steady state. An important concept for CFD analysis is the boundary conditions. The specification of boundary conditions for external analyses is relatively straightforward and requires setting the building exposure, wind velocity and wind direction based on the specific conditions of case studies. However, internal analysis boundary conditions tend to be a bit more difficult and require the addition of zone surface boundaries. This information is imported from the energy simulation of the software.

The calculation settings panel incorporates the Turbulence Model. The turbulence model which is used for this research is k-ε Model and is one of the most widely used and tested amongst turbulence models. It belongs to the so-called RANS (*Reynolds-Averaged Navier-Stokes*) models family. The residuals of the simulation are 10^{-3} and the simulation process has converged on 2500-15000 iterations according to the case study properties. Based on this short explanation about the setting of the CFD for the simulation, the next section presents the results of simulation for each building in two subsections of energy simulation and airflow distribution. Since there are four different apartments used as case studies in this research, Figure 59 presents the location of all selected buildings in the urban area.

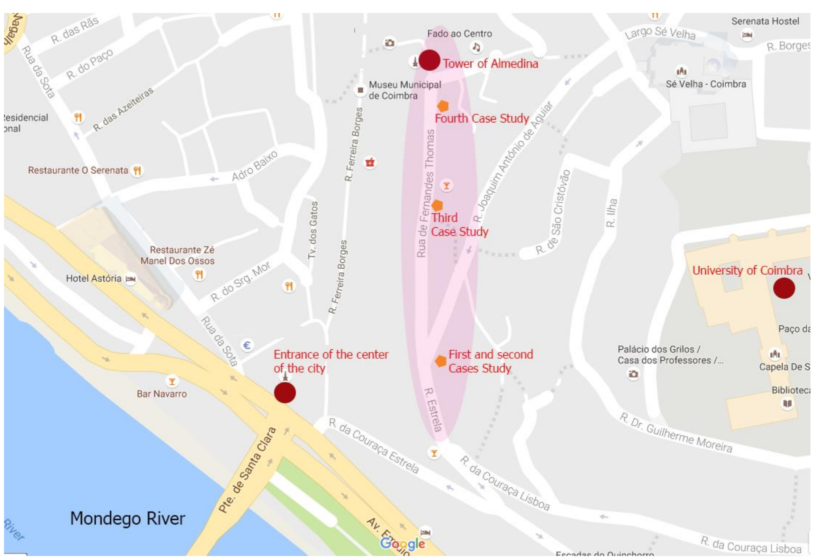


Figure 59: Location of Cases study in the urban area

5.3.3 First Case study

Concerning the presented information about the properties of the first case study and its location, Figure 60 presents the building appearance modeled in the DB.

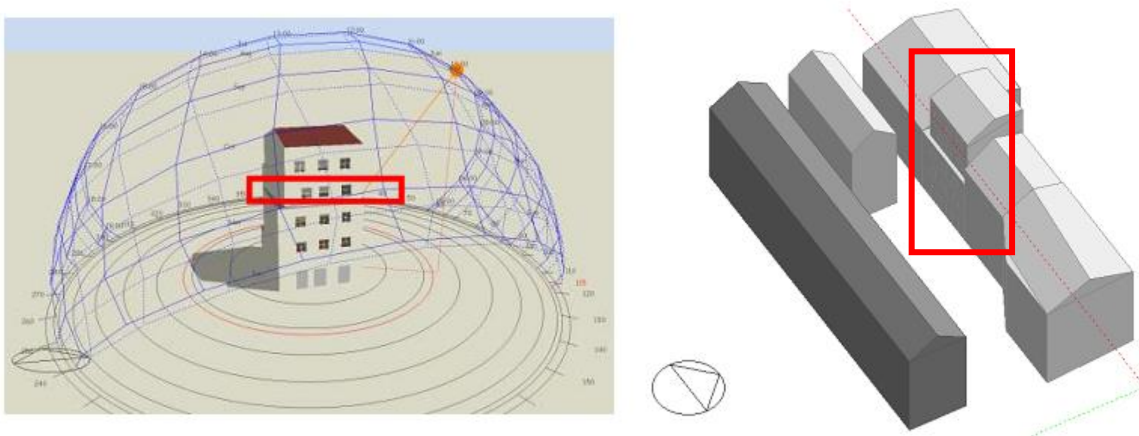


Figure 60: The appearance of the first case study in DB

As the apartments in the third and fourth floors, respectively, are the first and the second case studies, the analysis of thermal performance of this building is divided into two parts one for each case study. The results of energy simulation and the airflow distribution for the first and second case study are presented in sections 5.3.3.1 and 5.3.3.2 respectively.

5.3.3.1 Thermal performance analysis of the first case study

The first part of results for thermal performance is based on the site data properties of the building. Figure 61 presents the input of the properties that affect the results of building performance.

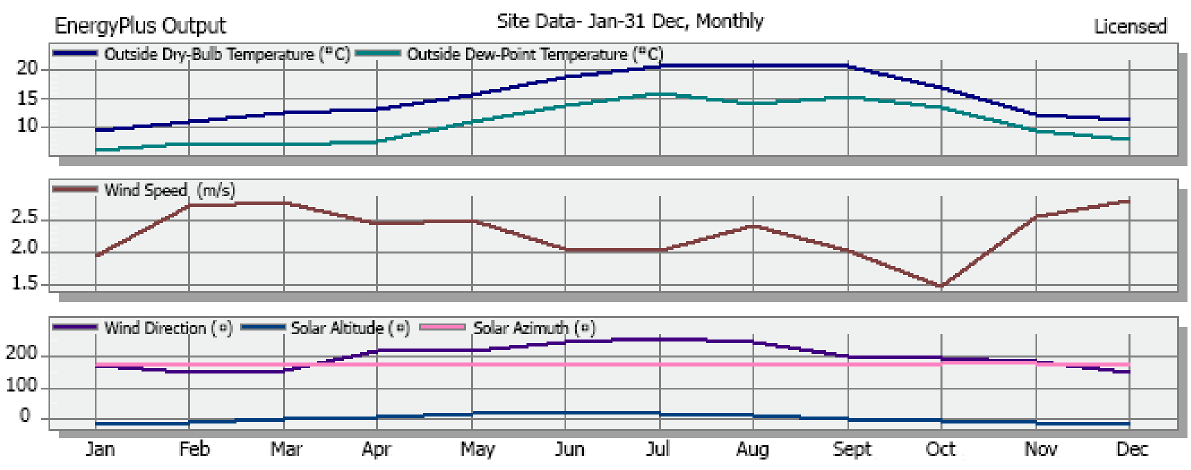


Figure 61: The site data of the simulated apartment- Case study 1

As Figure 61 shows, the maximum and minimum dry-bulb temperatures are in the period of July to September with 20.50 °C and in January with 9.76 °C, respectively. The maximum of dew-point temperature is in July at 15.50 °C while its minimum is 5.18 °C in January. If the dry-bulb temperature is close to the dew-point temperature, which is the air temperature that corresponds to the saturation point, then the relative humidity can be high in the apartment. Therefore, these inputs from the local weather data of this simulated apartment show that the relative humidity of the apartment in the autumn season is high because the measured data of dry-bulb temperature and dew-point temperature in this season are closer than other months, especially in November. On the other hand, there is a high wind speed around the building of 3 m/s in December and 2.85 m/s in February while this parameter is low with a minimum value of 1.5 m/s in October. Based on this presented site data information in Figure 61, in order to find the thermal comfort of the tested apartment, the results of the environmental comfort of the apartment in an annual period presented in Figure 62.

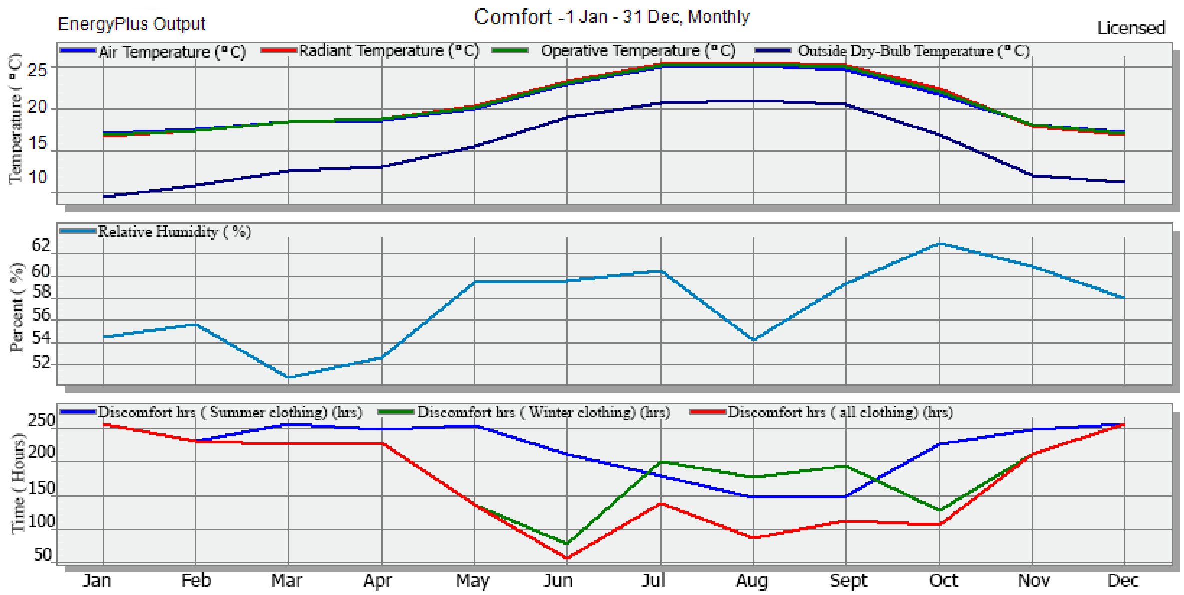


Figure 62: The analysis of the environmental comfort of the simulated apartment – Case study 1

Based on the presented figure and observing the minimum and maximum rates for air temperature, radiant temperature, and operative temperature, outside Dry-bulb temperature, relative humidity, and also discomfort hours. The monthly comparison of this discomfort is illustrated in Figure 63.

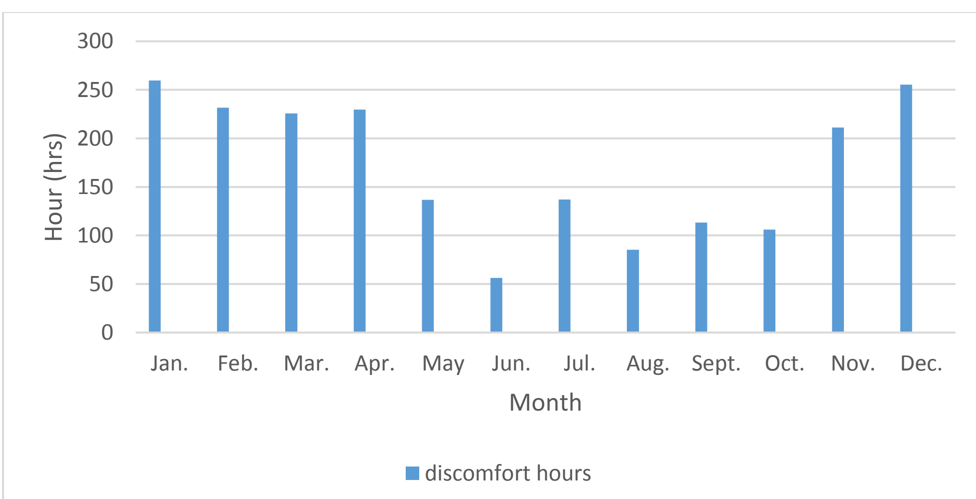


Figure 63: The discomfort hours of the building during the year- Case study 1

Figure 63 shows that the maximum and minimum discomfort hours of the building are in January with 259.66 hours and in June with 56.28 hours, respectively. Comparing the two Figures (62 and 63) it can be seen that the building in June has the lower rate of environmental discomfort while the air temperature is around 26 °C and the relative humidity is around 60%. These conditions result in 56.28 discomfort hours which is less than three days. January is the most uncomfortable month for this apartment when the interior air temperature is 17 °C and the relative humidity is 59%. These factors result in 259.66 discomfort hours, which is around 11 days.

As stated in section 2.8, there are different models to analyze the thermal comfort condition of a building. Some of them are developed based on the heat balance approach. *Fanger* model is the basic model of this approach.

Since the DB thermal comfort analysis is associated with the heat balance approach of thermal comfort, different existing models of this approach were selected and the thermal comfort condition of the simulated building was analyzed based on them. Generally, on the heat balance approach, there are two main parameters: PMV and PPD. PMV has a seven-scale rate from +3 (really hot) to -3 (really cold), with 0 as the neutral and comfort level. If PMV rate is far from 0, the building is far from reaching its thermal comfort condition. The first simulated apartment was analyzed based on four different methods; *Fanger* PMV, *Pierce* PMV ET, *Pierce* PMV SET, and *Kansas Univ*. Thermal Sensation Vote (TSV).

Figure 64 presents the thermal comfort condition of the apartment based on the results obtained by DB. The results of this analysis confirm that the building has better comfort condition in June as its PMV rate is near to 0.

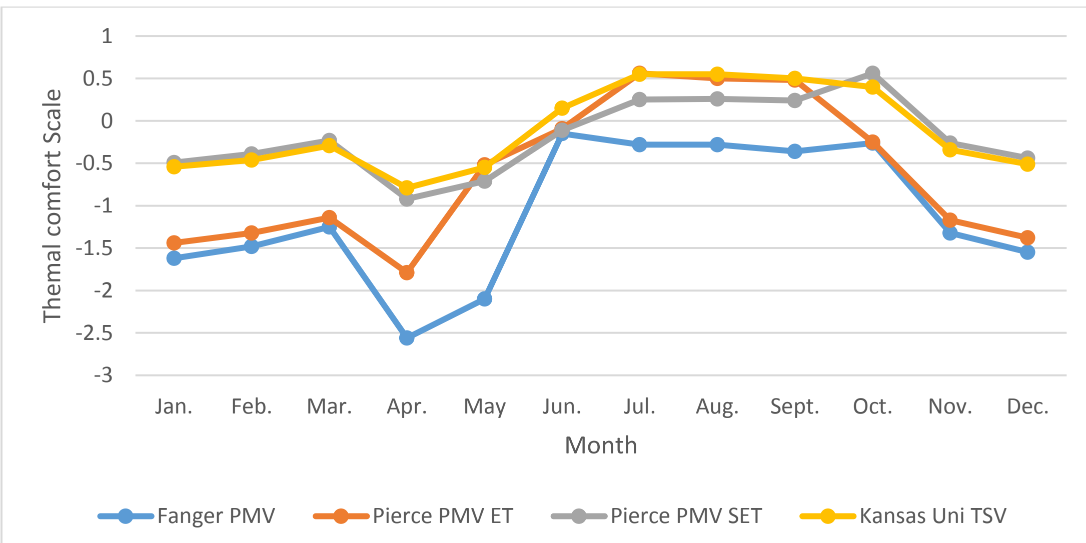


Figure 64: Thermal comfort analysis of the building based on different models – Case study 1

Based on all obtained results of comfort and discomfort levels and discomfort hours of the simulated building, the PPD rate of the building has been calculated and the minimum of the building is 7% in June and the maximum is 36% in January. According to previous information, a PPD of 5% is the best rate for a comfortable condition. The results show that the building is more comfortable in June and gradually losses its comfort conditions by the cold time of the year and the maximum level of discomfort is achieved in January with a PPD of 36%. Therefore, increment of ventilation rate in summer time is one of the influenced parameter which helps to the comfort condition of the building.

The aim of this research is finding the effectiveness of the natural ventilation in existing buildings. To obtain better information about the existing condition of the ventilation systems, heat gain through internal and external natural ventilation and also the building infiltration rate should be considered.

Figure 65 presents the heat gain of the building due to air exchange through the external natural ventilation or internal openings like doors, window, cracks, and holes. It can be seen that the building earns more heat through internal vents and holes in the cold months of the year in comparison with the external one.

On the other hand, the heat loss percentage through the external holes which are connected to the external air in the cold seasons is higher than the warm seasons which it is 31%. However, in the warm seasons (summer and spring) a heat-loss exists through the external natural ventilation which shows that natural ventilation works in this building. The question is how effective is it?

The infiltration rate line also shows that the building needs more air change rate in summer comparing other periods of the year. This rate in August is around 9 times per hour. Since this rate of air change in DB has been found based on n_{50}, the obtained results were inserted in LNEC application. It was discovered that the building has an ACH 1.62 h^{-1} in August while it should be 0.6 h^{-1} in the summer time due to the Portuguese regulation.

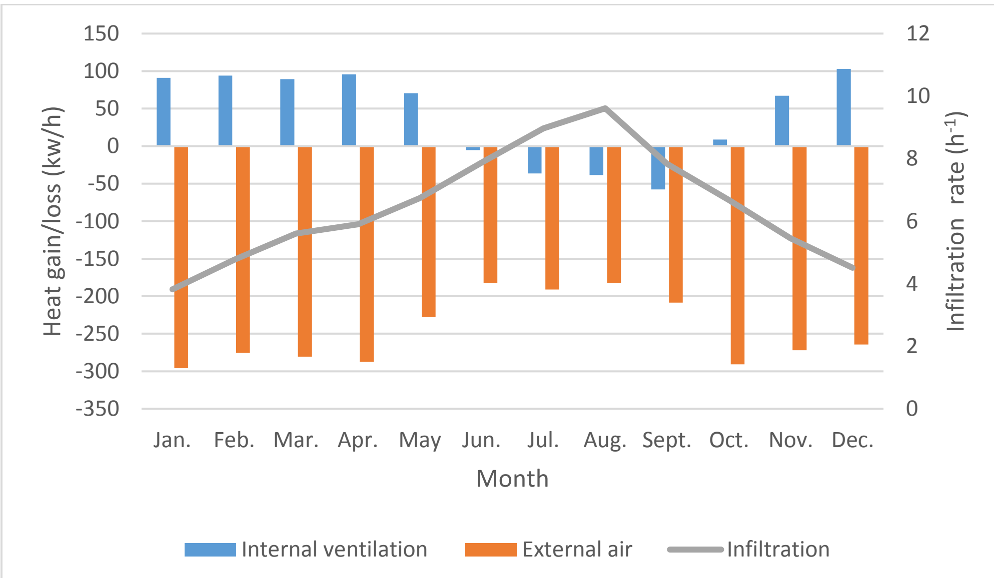


Figure 65: Analysis of internal and external natural ventilation - Case study 1

As all obtained results of BDT are based on the time of BDT test on July 2nd, Figure 66 presents the results of simulation for that specific time. This figure helps us to have the results of ventilation and infiltration of the building in a specific period in both measurement and simulation methods. According to this figure, it is observed that the airflow which enters from the ventilation aperture is less than the airflow which leaves. Also, the infiltration graph shows that the highest infiltration rate was registered for the period of 6 am to 12 pm when BDT was also done at that time. The natural air change rate of the simulated building based on the Portuguese regulation and the LNEC application at that period is 1.43 h^{-1} while it should be 0.6 h^{-1} in the summer time. The presented figure assumes that the air circulation system in the building does not work as perfect as it should, therefore the modeling of airflow distribution in the building was done by CFD module of DB software in order to find the distribution of airflow in the simulated building. The next section presents the results of CFD simulation.

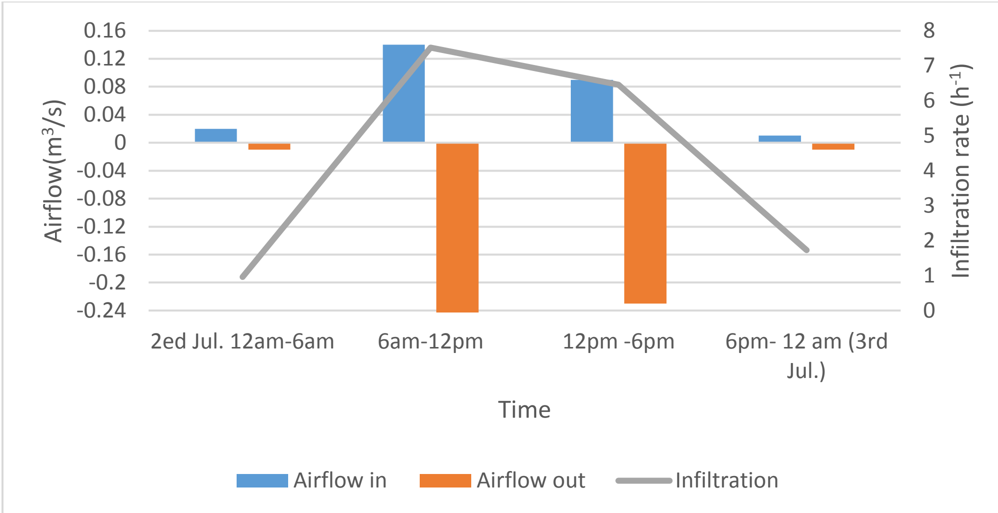


Figure 66: Analysis of the airflow and infiltration on July 2nd – Case study 1

5.3.3.2 CFD analysis of the first case study

The external CFD shows the air velocity and pressure around the building. Figure 67 presents the airflow distribution around the simulated building.

Figure 67-A, shows the air distribution in the urban area in the height of 5 m (middle of window in the second floor) figure 67-B presents the air distribution around the tested building in the height of 7.5 m (above the floor of third floor), figure 67-C is for the height of 10.50 m (middle of the window in the third floor) and finally the figure 67-D shows the height of 14 m (fourth floor). These figures are useful for finding the effect of the building height on the air distribution by both pressure difference and air velocity. Through the comparison of these figures we can observe that the height of the building in an urban area is one of the important factors in pressure and velocity distribution. As it is demonstrated, the air velocity on the lower level is slower than upper floors. On the other hand, there is a negative pressure in the lower floor (ground) over the building envelope and in the urban area, and as the height increases the pressure is going to be on the positive side.

The effect of building height on the air pressure and velocity is visible in Figure 68. According to this figure, the air pressure and velocity increase with the building height (Fig 68-A and 68-C). In other words, the highest floors are more exposed. Based on Figure 68, as an alley exists behind this building, the air circulation behind the simulated building must be a concern (Fig 68-A left Circle, 68-B, and 68-D).

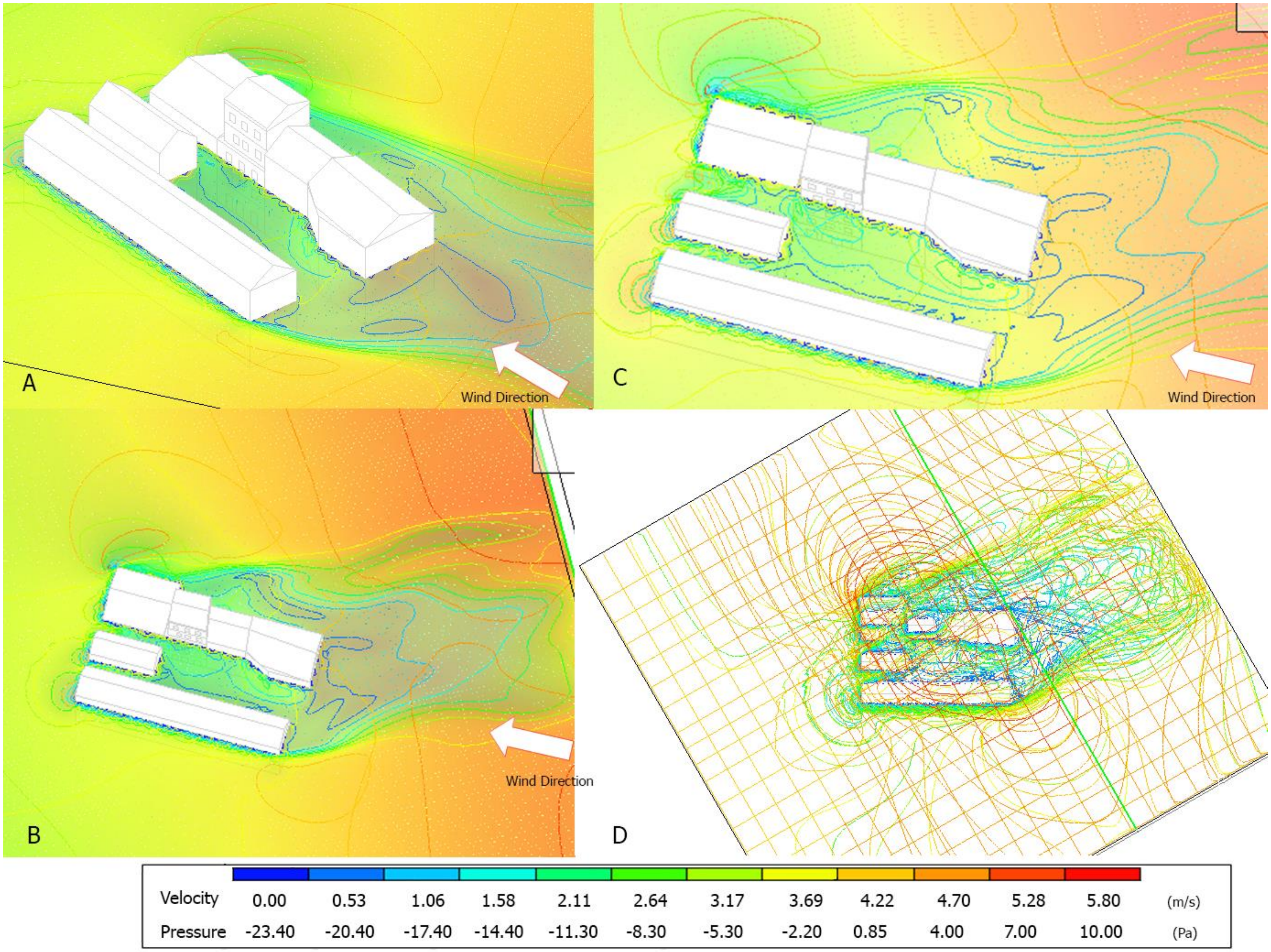


Figure 67: Analysis of the airflow distribution based on the external CFD – Case study 1

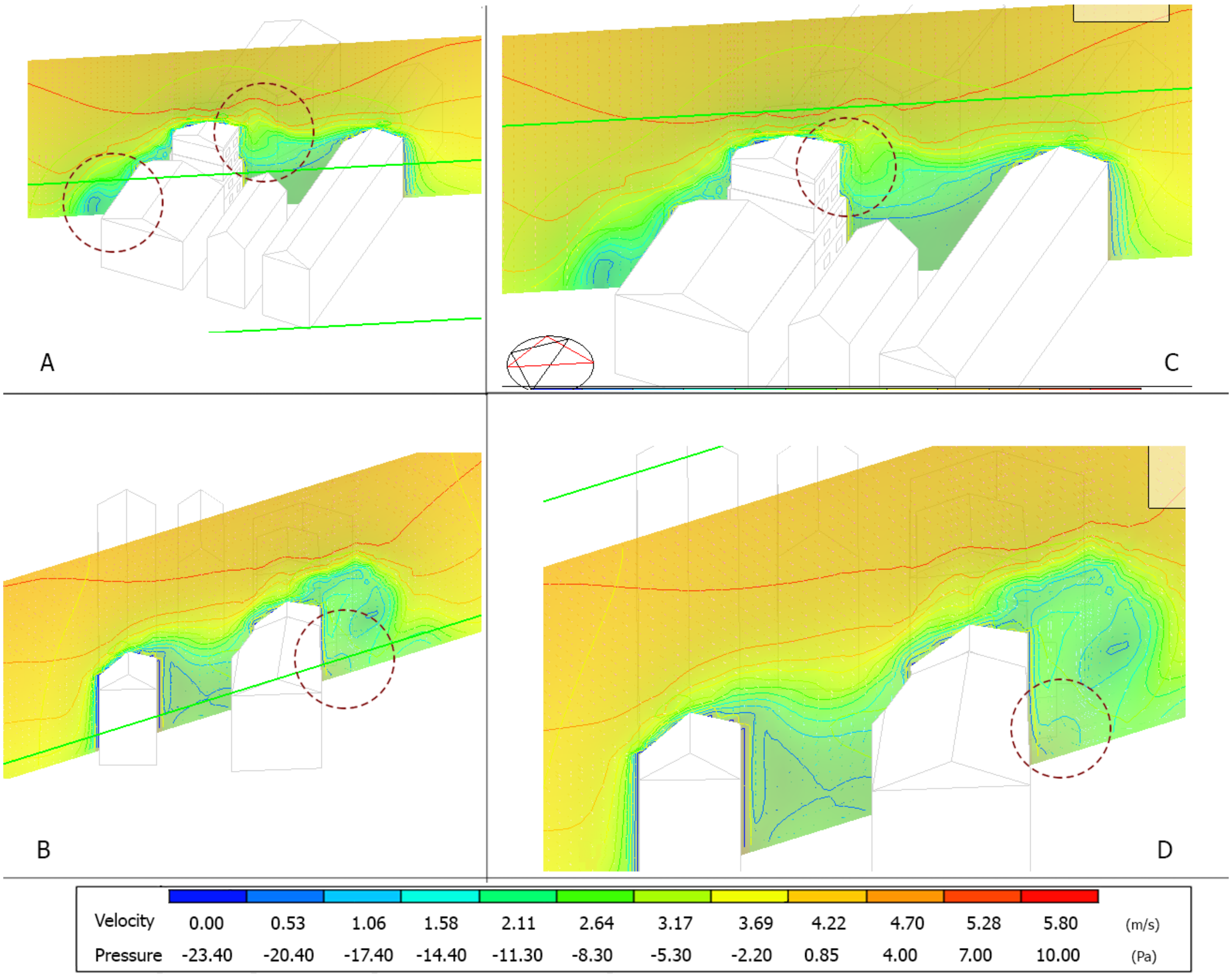
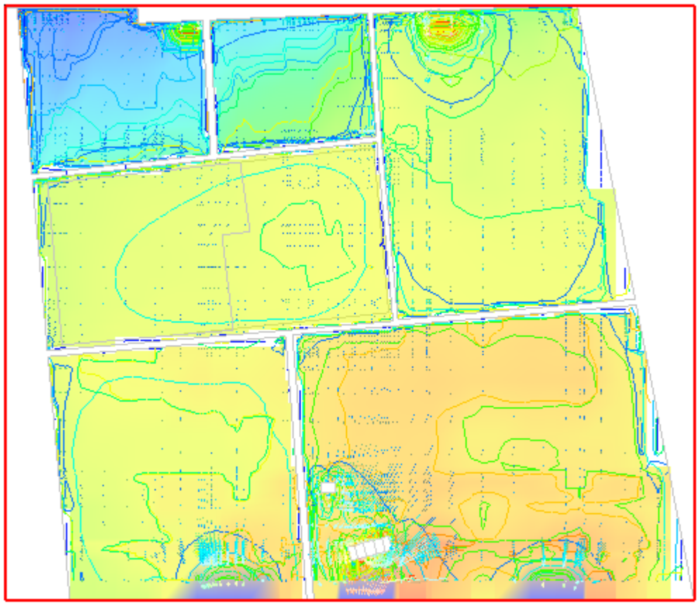


Figure 68: Analysis of the airflow distribution in the urban area – Case study 1

In order to analyze the air distribution in the interior spaces, the internal CFD analysis was also used. Figure 69 shows the results of internal CFD on July 2nd mid-day.



Velocity	0.003	0.006	0.009	0.012	0.019	0.025	0.037	0.05	0.07	0.09	0.1	0.12	(m/s)
Temperature	18.50	19.80	21.20	22.50	23.80	25.10	26.40	27.70	29.00	30.40	31.70	33.00	(C)
Pressure	-2.40	-0.42	0.817	1.871	2.726	3.636	4.457	6.569	7.273	8.198	9.093	10.00	(Pa)

Section has drawn from the middle of the window.

Figure 69: Analysis of the airflow distribution in the interior space – Case study 1

Figure 69 shows that spaces which are located near the main faced have higher air velocity, pressure and temperature when compared with spaces like the bathroom, which is located in the rear of the building and has less connection with the main facade. It is also possible to see that the areas which are supported by windows are really small and the entered air has covered only a small area of the rooms. It also shows the distribution of air in the interior spaces which are linked to the location and orientation of the window. Figure 70 presents more information about the air distribution in the interior spaces through the windows. It shows that when the air enters through the windows which are located in the main facade, most of the entered air leaves through the same opening and the air circulation is limited to the same space. It means that the air does not circulate in the other spaces to find a way to leave and this is because of the lack of openings to exit the air and also because the interior partitions do not allow the circulation of the air.

Figure 71 shows the distribution and velocity of the air in the whole spaces of the building where one can see that the air circulation only covers areas around openings and no circulation exists in the whole building, as it is observed between kitchen and living room. Even the air circulation of the living room covers the front of the openings and the inlet opening acts as the outlet openings in this building (Fig. B). Also, spaces like the WC, which has no window has problems related to air velocity and circulation. This issue provides bigger problems related to condensation and moisture.

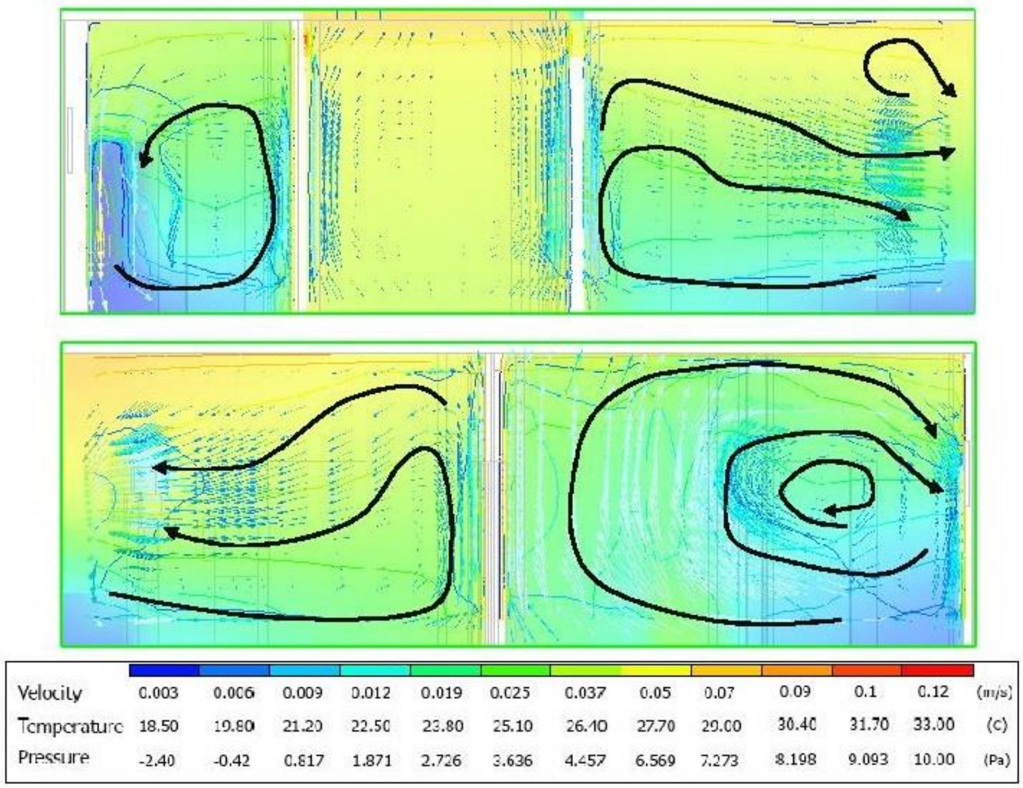


Figure 70: Interior airflow circulation – Case study 1

Figure 71 shows the distribution and velocity of the air in the whole spaces of the building.

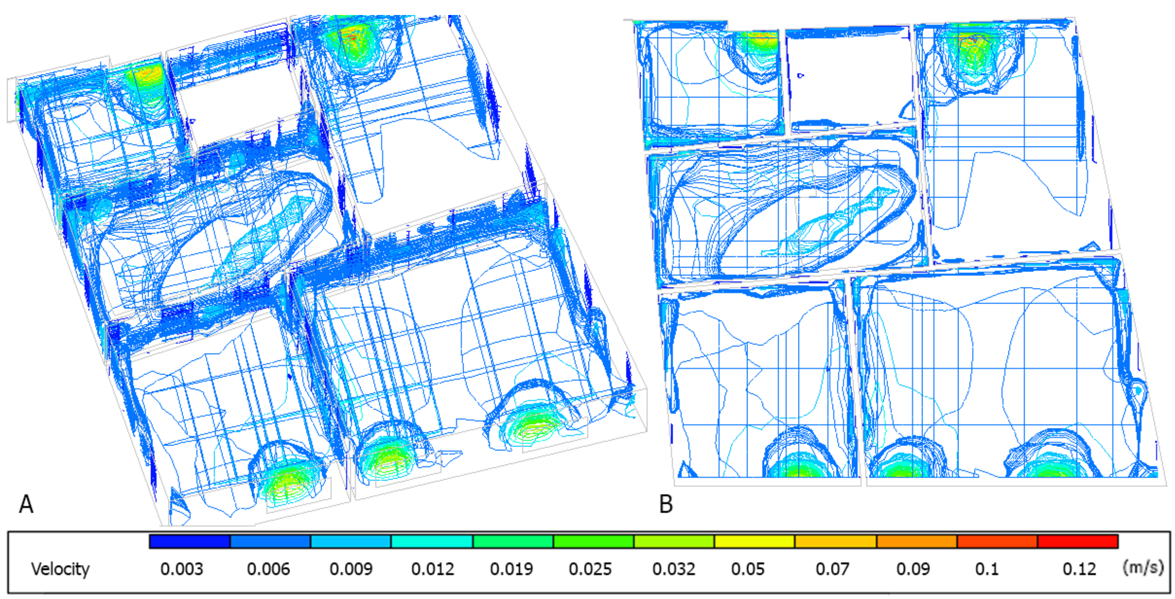


Figure 71: Interior air circulation and distribution in whole apartment – Case study 1

The rate of Air Change Effectiveness (ACE) is another important factor which can be discussed for this simulated building. Based on *Gungur* [219] and ASHRAE [220], ACE is the rate of air distribution which can deliver the ventilated air to the interior spaces. This rate is related also to the ventilation effectiveness. ACE rate varies between 0 and 1 and as higher as the value and closer to 1, the air change of the building and the quality of the ventilation is better. Concerning the CFD simulation of the building, the ACE rate of the simulated building is 0.17 which means that the air circulation and distribution of the building cannot deliver the ventilated air to all parts of the building in order to provide the most effective ventilation system.

5.3.4 Second case study

Concerning the presented information about the properties of the second case study and also its location, Figure 72presents the building appearance modeled by DB.

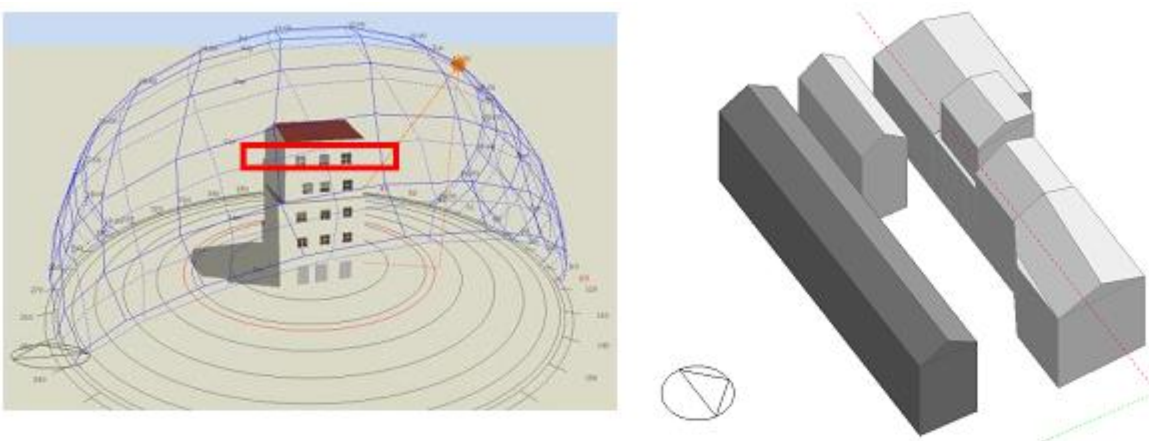


Figure 72: The appearance of modeled apartment by DB – Case study 2

5.3.4.1 Thermal performance analysis of the second case study

The apartment located on the fourth floor is the second case study, therefore in this section, its analysis of the thermal performance is presented. Section 5.3.4.1 presents the results of thermal performance simulation and consequently the airflow distribution results is illustrated in section 5.3.4.2. As the building is the same as the first case study, there is no need to present again the related data and the information about the details of local condition presented in section 5.3.3.1.

The environmental comfort of the apartment in an annual period is presented in Figure 73 to study the thermal comfort of the building.

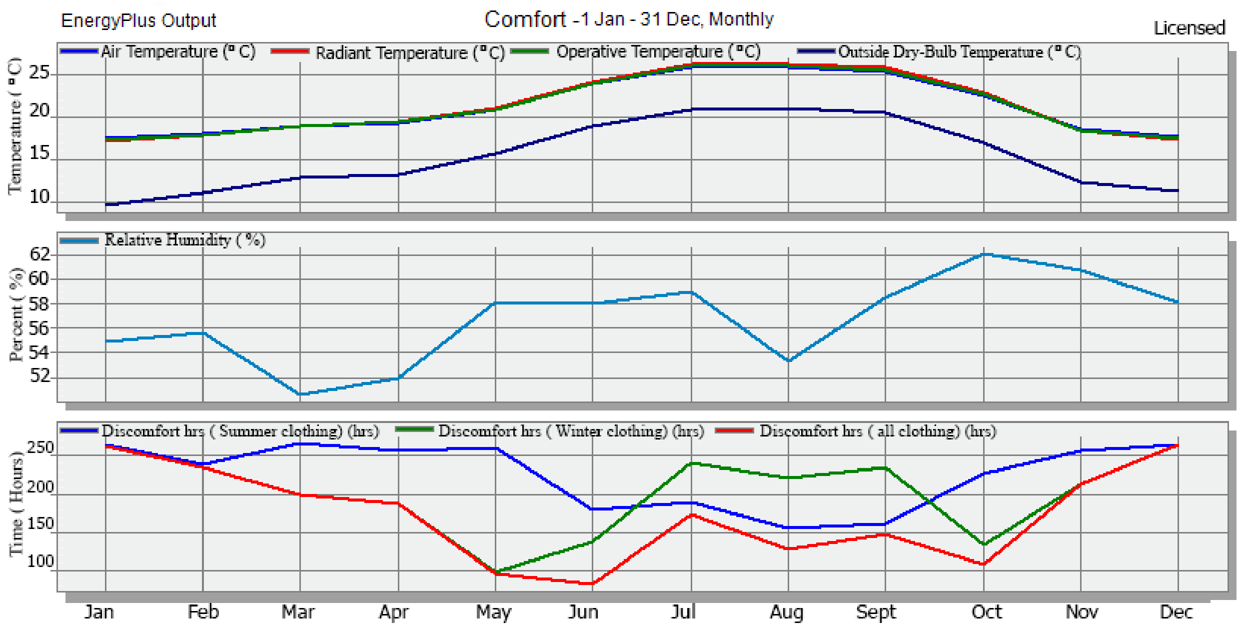


Figure 73: The environmental comfort analysis of the simulated apartment – Case study 2

The figure illustrates some information about the radiant temperature, operative temperature, outside dry-bulb temperature, relative humidity, and also discomfort hours of the building in all months. The feeling of the occupants of the building during the year in this building can be evaluated. In order to find the total discomfort hours of the building, Figure 74 shows the results for each month.

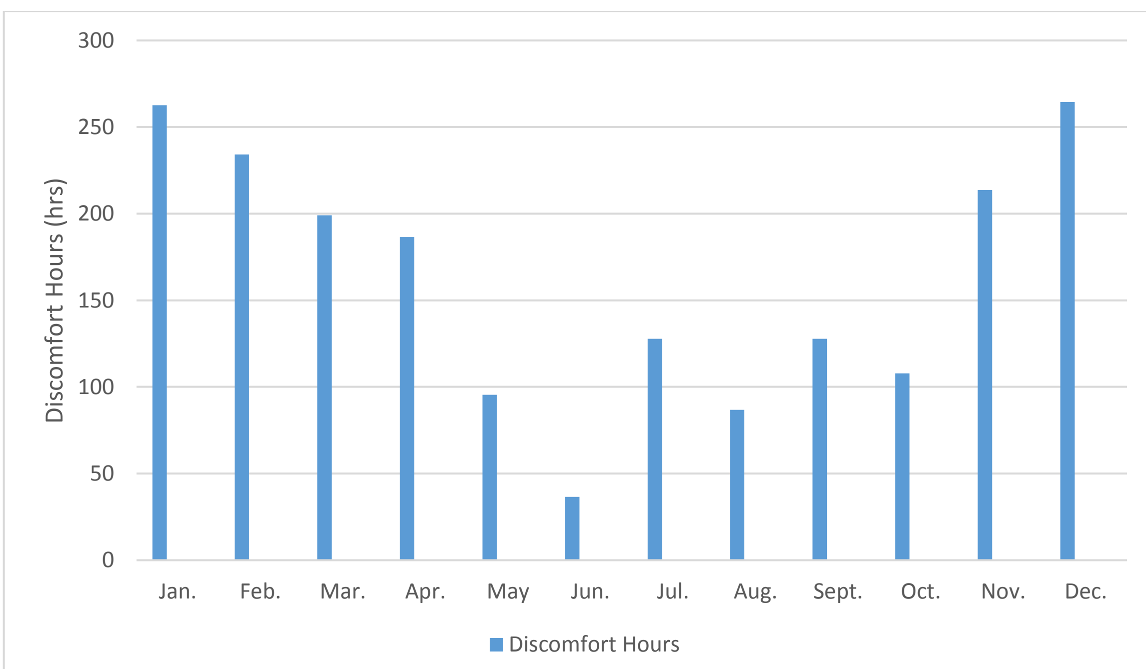


Figure 74: The discomfort hours of the apartment during the year – Case study 2

As Figure 74 shows, the apartment has the highest discomfort conditions in December, during 264.41 hours and the lowest ones in June during 36.57 hours. The comparison between Figures 73 and 74 states that the building has an air temperature of 22 °C, relative humidity of 55% and 36.57 hours of discomfort in June which is the lowest rate of environmental discomfort that lasts for less than two days. On the other hand, December is the most discomfort month of the year with 264.41 hours of discomfort which is around 11 days.

In order to show the thermal comfort condition of the building, Figure 75 presents the obtained results of DB simulation.

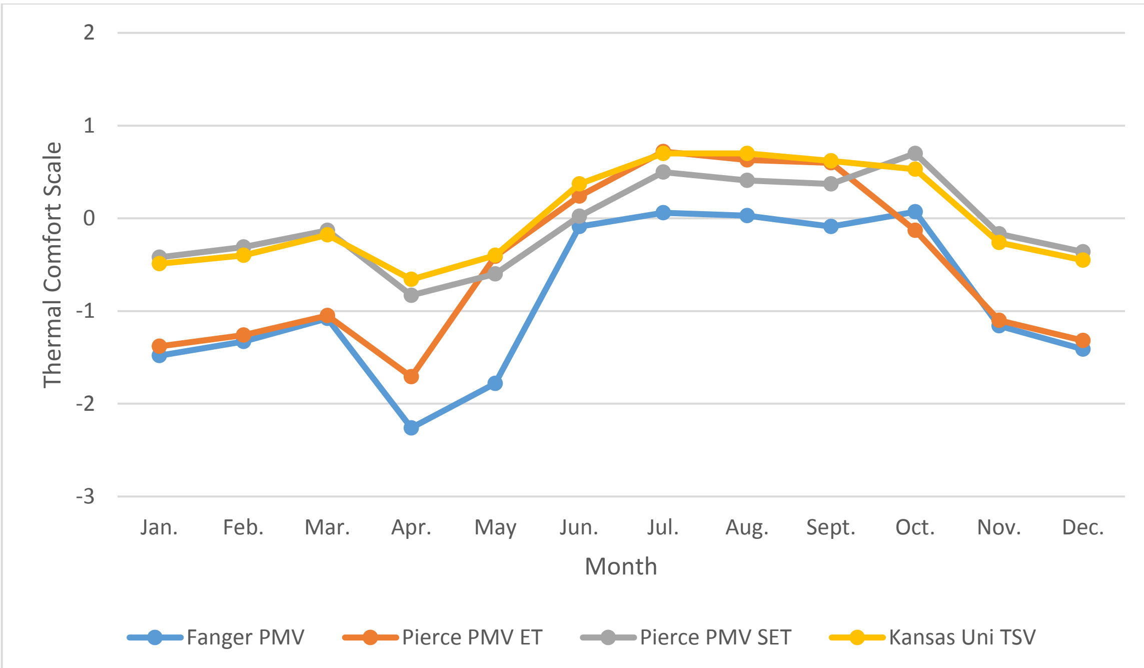


Figure 75: The thermal comfort analysis of the apartment based on different existing models – Case study 2

According to the information in section 2.3.1, there are a variety of models to analyze the thermal comfort condition of a building. Models are divided into two main approaches of heat balance approach and adaptive approach. The thermal comfort models of DB software are based on them and belong to the heat balance approach.

The results of comfort condition of the simulated building are presented in Figure 75 and it can be seen that the minimum and maximum PPD rate of the building is 11.5 % in June and 36.7 % in December respectively. While the PPD of 5% is the best rate for a comfortable condition, the results of the simulated building shows that the apartment is a bit far from the thermal comfort condition even in June and this rate increases by going to the cold time of the year when the building achieves the maximum level of discomfort.

In order to analyze the effectiveness of the natural ventilation in the existing building, the internal solar-gain for internal natural ventilation and external air and also the building infiltration rate have been studied and Figure 76 presents these properties and shows that the building has more heat loss than heat gains through internal or external ventilation. Since the rate of heat losses through external ventilation is more than internal ventilation, there is a flow between inside and outside of the building through the external ventilation, but it should be evaluated how this system would be effective.

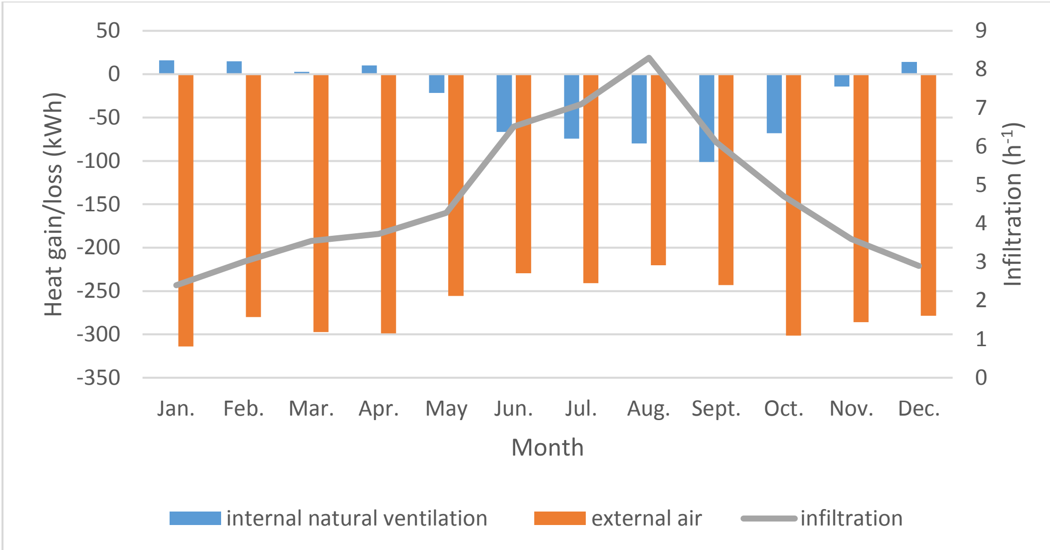


Figure 76: Analysis of internal and external natural ventilations – Case study 2

Based on the infiltration data presented in Figure 76, it is possible to observe that the building has more air change rate in summer time than other periods of the year. This rate in August is more than 8 times per hour and the rate of infiltration based on the LNEC application is 1.12 h^{-1} while it should be 0.6 h^{-1} in the summer time due to Portuguese regulation.

Since the BDT of the apartment has been performed in July, the following figure (Figure 77) illustrates the condition of ventilation in the simulated building for the purposed time. The figure intends to show the results of ventilation and infiltration of the simulated apartment in a specific period of measurement.

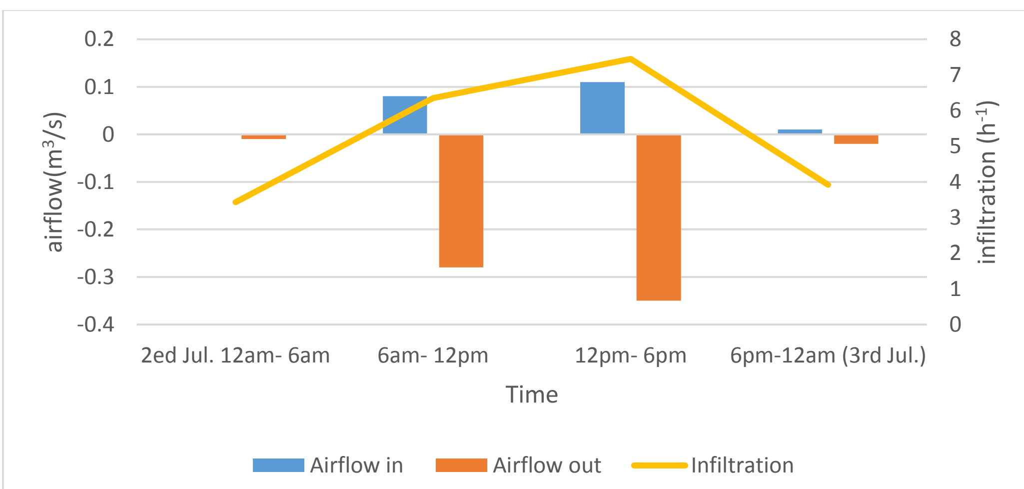


Figure 77: Analysis of the airflow and infiltration on July 2nd – Case study 2

It is observed that the airflow which comes in is less than the amount that goes out. The infiltration graph states that the highest infiltration rate occurs in the afternoon (12 pm-6 pm). The infiltration rate based on the Portuguese regulation and the LNEC application is 1.08 h^{-1} in normal pressure, while it should be 0.6 h^{-1} in the summer time.

According to the achieved results, it can be concluded that the thermal comfort of the apartment is similar to the previous case study. In order to determine the distribution of airflow in the simulated building the CFD module of DB was used and the results are presented in the next section.

5.3.4.2 CFD analysis of the second building

Since the second case study is located in the same building as the first case study, the results of the external CFD analysis of the simulated building are the same and were presented in Figures 67and 68. Therefore the CFD simulation is used to present the air circulation and distribution in the interior spaces. Figure 78 demonstrates the internal CFD of the apartment in 4th floor on July 2nd.

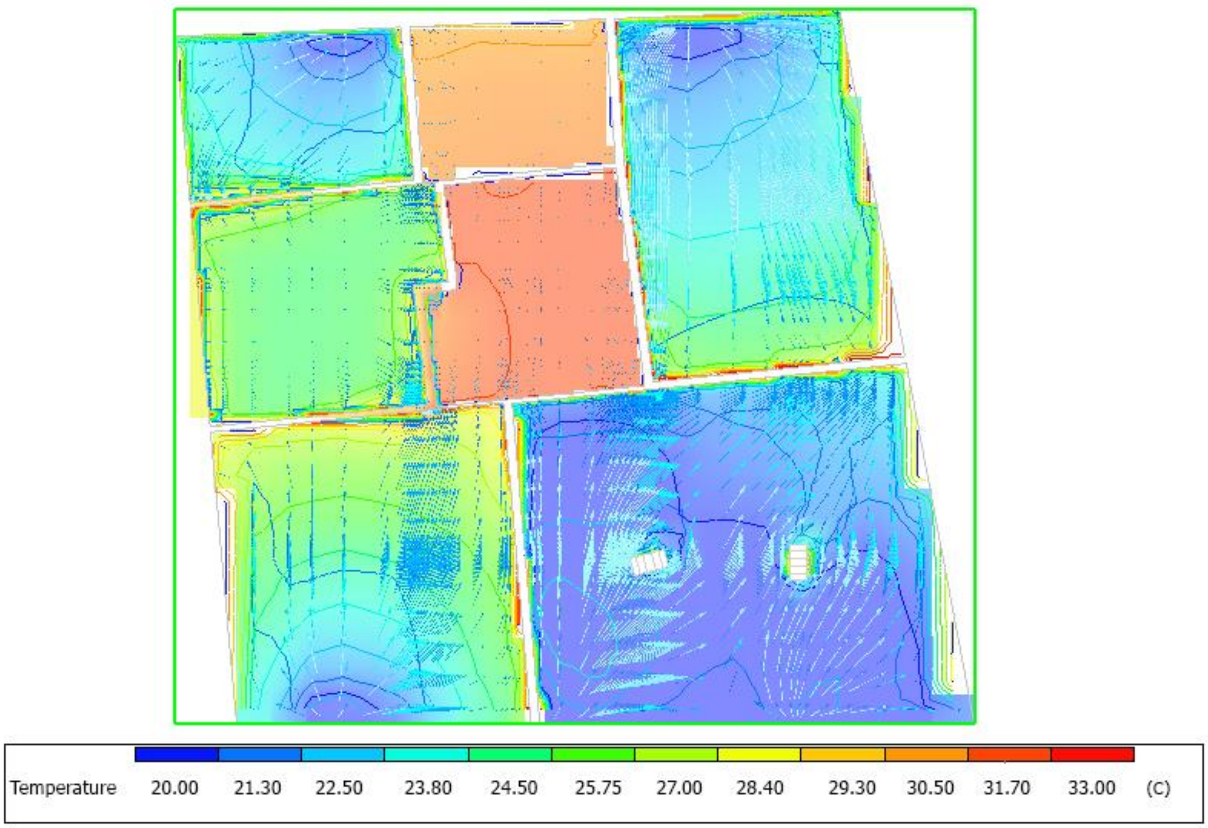


Figure 78: Analysis of the airflow distribution in the interior space – Case study 2

The figure shows the effect of openings in the air distribution of the building. As it is seen, the temperatures in the areas which are closer to the openings connected to the outside are lower than the areas away from them. The biggest issue observed by this simulation is associated with the spaces with a lack of exterior openings. The hierarchy of the temperature in these spaces and the one adjacent to them shows that the airflow does not circulate well. For example, the difference in temperature between two adjacent spaces (bathroom and toilet) at the north side of the building confirms the existence of this problem (Figure 78, and 79).

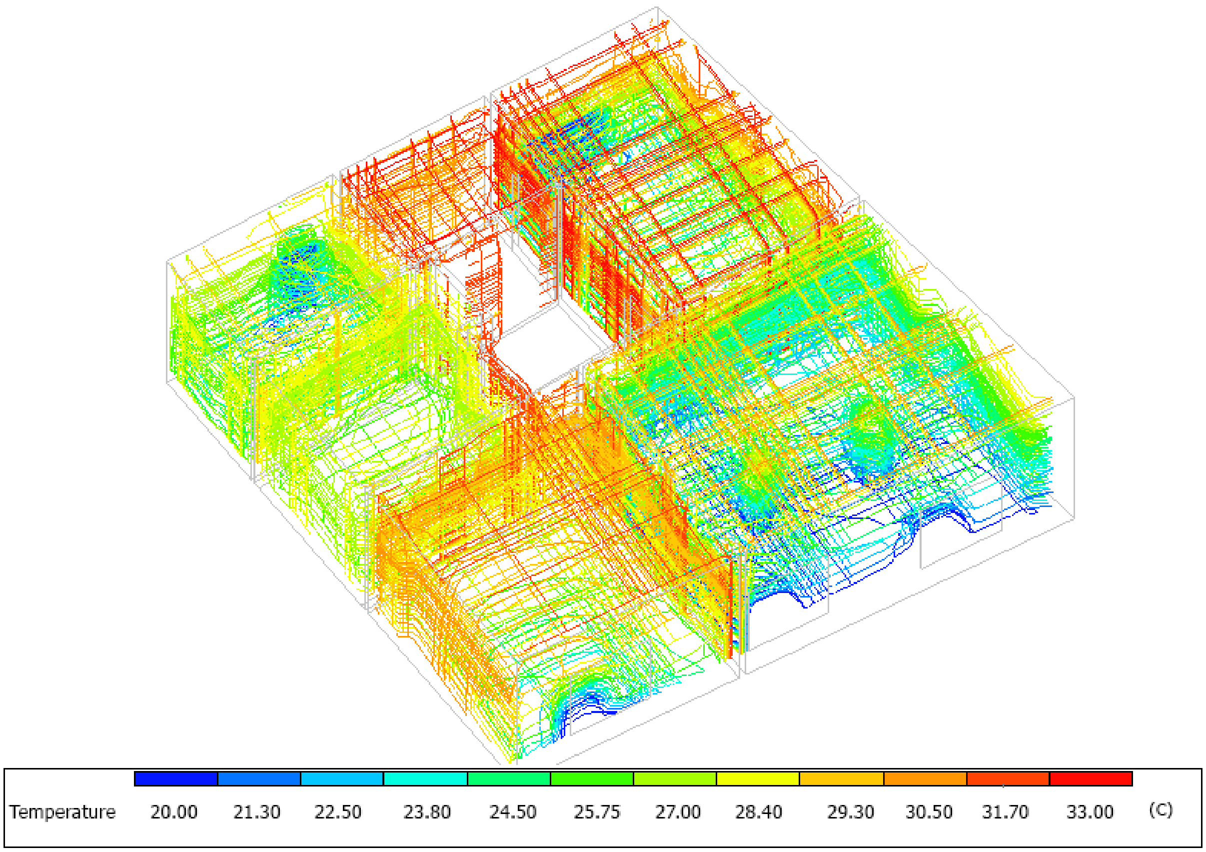


Figure 79: Analysis of the temperature difference in the whole apartment – Case study 2

Since the air velocity is another important factor in the effectiveness of the ventilation, Figure 80 illustrates the air distribution in the interior spaces. In order to show the air circulation and distribution in the apartment, two sections for two different parts of the apartment were selected. These two sections show how the air circulates in the apartment and how the air enters and leaves. It also illustrates the temperature difference of the building in different heights.

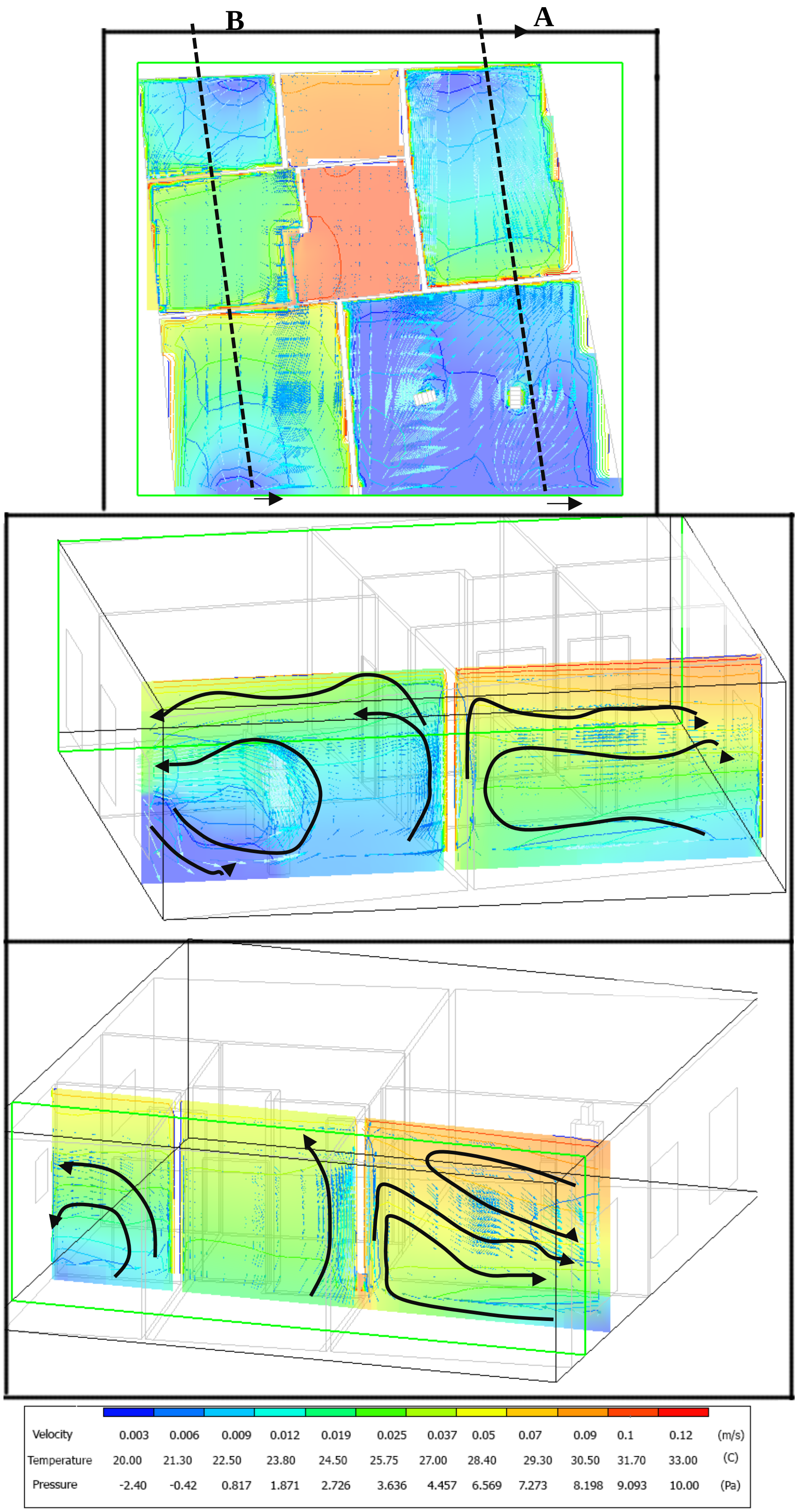


Figure 80: Analysis of the air circulation in the interior spaces – Case study 2

Based on the analysis of Figure 80, it is observed that despite double-side ventilation, the building behaves as a building with single side ventilation system. As the figure shows, when the air enters through the openings which are connected to the outside, most of the entered air leaves through the same openings and the air circulation is also limited to the same space and there is no cross ventilation. To have more analysis about this point, the air velocity distribution in the interior spaces is presented in Figure 81.

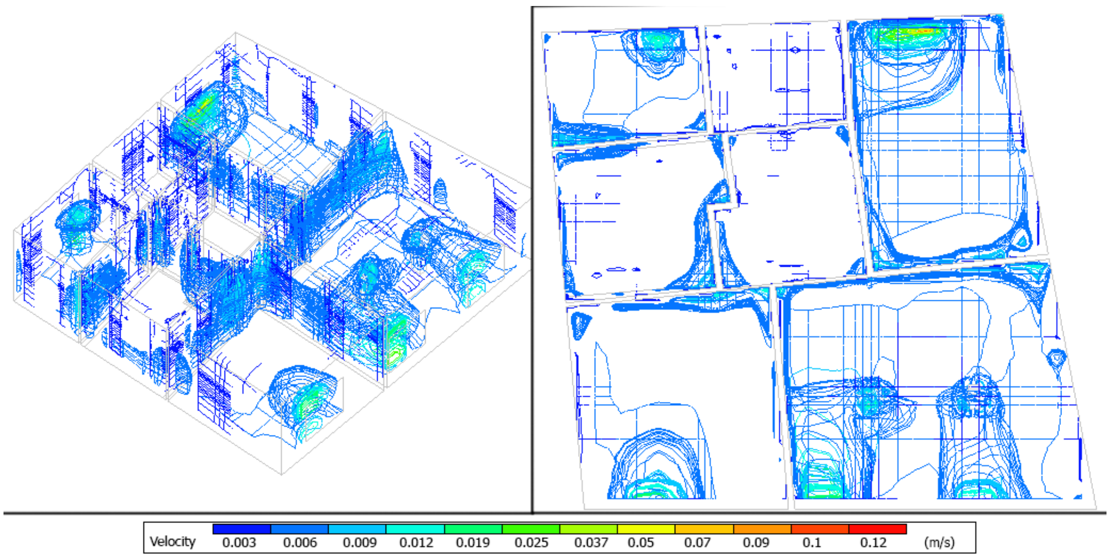


Figure 81: Analysis of the air velocity distribution in the interior spaces – Case study 2

Regarding the presented figure, the air fluctuates around the openings areas. Besides that, there is some air fluctuating in the corners of the rooms. Based on the idea of the ventilation effectiveness, the rate of ACE is another important factor which was analyzed. According to the CFD simulation of the building, the ACE rate of the simulated building is 0.32 which means the air circulation and distribution in the building cannot reach all parts of the building to propose the most effective ventilation system.

5.3.5 Third case study

The third case study is a flat located in the first floor of a multi-family house. Figure 82 shows the modeled building. However, more information about the case study is available in Chapter 4.

The analysis of the ventilation effectiveness of the building is divided into two different fields of thermal comfort and airflow distribution which are presented in sections 5.3.5.1 and 5.3.5.2 respectively.

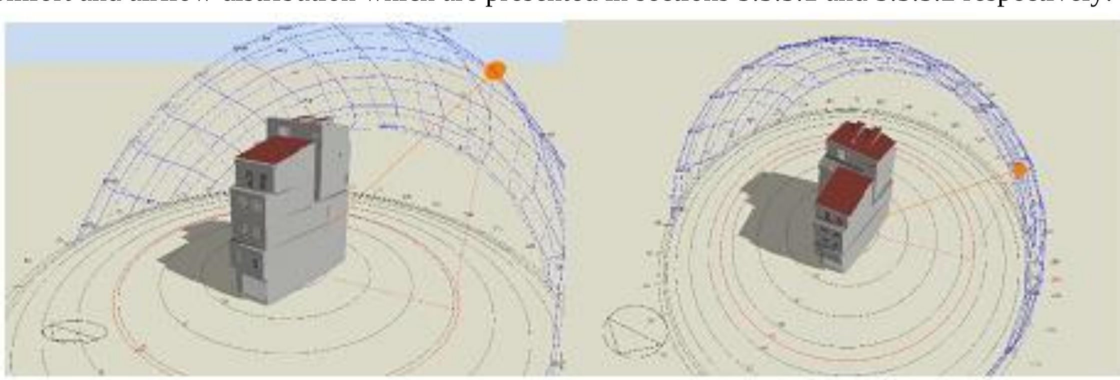


Figure 82: The appearance of the modeled building in DB – Case study 3

5.3.5.1 Thermal performance of the simulated building

As the building is located in the same street as the first and second case studies, the results of site data are the same as those presented in section 5.3.3.1. The results of the environmental comfort in an annual period are demonstrated in Figure 83 where one can see the comfort/discomfort feeling of occupants during the year based on the information of radiant temperature, operative temperature, outside dry-bulb temperature, relative humidity, and discomfort hours.

The building, like the previous one, has a difference between the interior air temperature (the real air temperature) and operative air temperature (the temperature that the occupants feel). This point influences their comfortable feeling. The third chart of Figure 83 illustrates the discomfort condition of the building during the year. To have more information about the discomfort condition, Figure 84 presents the discomfort hours in the building categorized for each month.

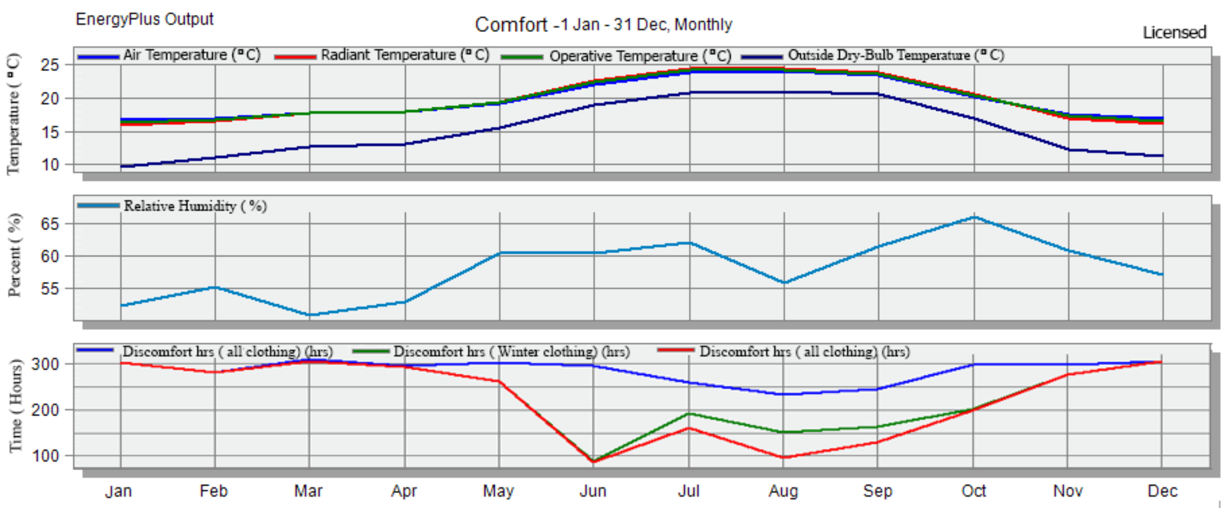


Figure 83: The Environmental comfort analysis of the simulated apartment – Case study 3

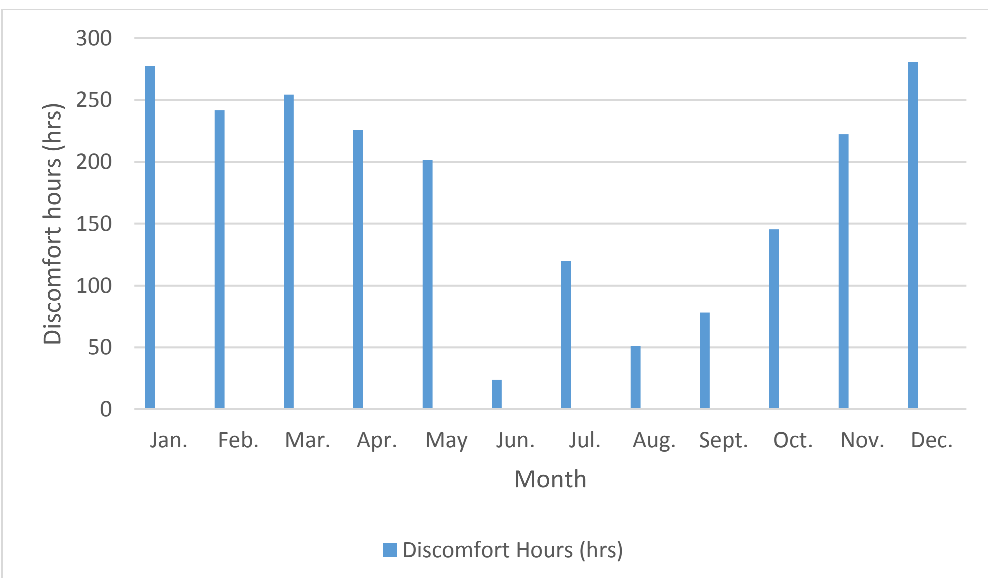


Figure 84: Discomfort hours of the apartment during the year – Case study 3

As it is seen in Figure 84 the maximum and minimum discomfort hours belong to December with 280.86 hours, and June with 23.77 hours respectively. By comparing these two figures, it is observed that the building has better comfort condition in June. In this month the building holds an outside air temperature of around 18 °C, inside air temperature and the operative temperature are almost overlapped and they are 22 °C, the relative humidity is 62% with 23.77 hours discomfort in the whole month which is around 1 day. However, December is the worst month for the simulated building with more discomfort: the outside air temperature is around 11 °C, the operative temperature and inside air temperature is 16 °C, the relative humidity is 57% and it presents 280.86 hours of discomfort which is almost 11 days. The analysis of the thermal comfort condition of the building is shown in Figure 85. As DB works using different heat balance-based models, the following figure illustrates this analysis based on a different existing model in DB.

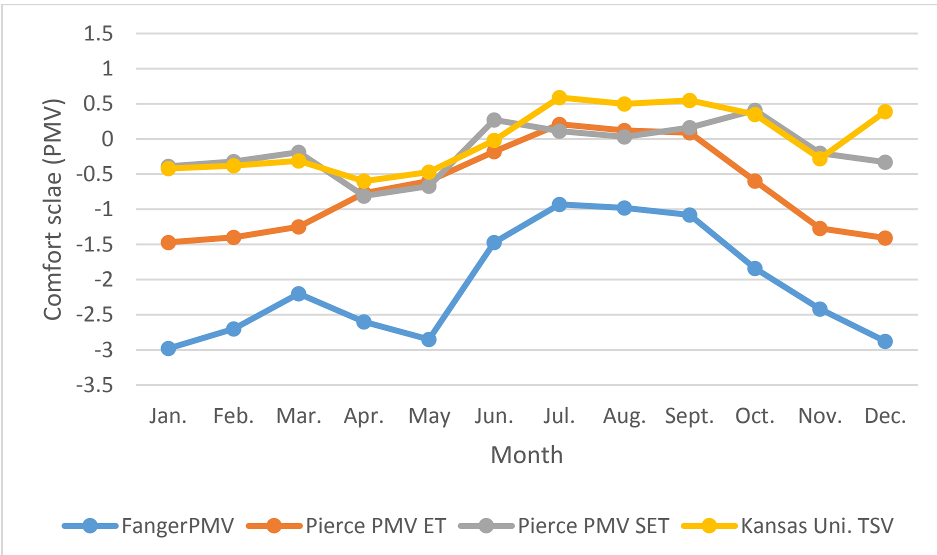


Figure 85: The thermal comfort analysis of the apartment based on different existing models – Case study 3

The building has better thermal comfort condition in July and August based on the *Pierce* ET and *Pierce* SET models, and *Kansas Univ*. model. The PPD level of the building is obtained based on the results of comfort and discomfort hours and shows that the building has 6% PPD in June as is the most comfortable month. In December it has 35% of PPD that means it is the most uncomfortable one. Due to the information in Chapter 2, the best rate of PPD for the comfortable condition is 5% and it is obtained for this building in June.

Figure 86 shows the heat gain/loss of the building through the internal ventilation and external air. As the heat loss by air exchange through the external ventilation is higher than internal ventilation, there is a flow which fluctuates between inside and outside. However, the level of effectiveness of flow fluctuation is an issue that should be considered. Figure shows that the building has air change 6 times per hour at maximum in the summer time. Due to the Portuguese regulation and LNEC application, the air change of the building is 0.67 h^{-1}. However, this rate should be 0.4 h^{-1} in the winter time and 0.6 h^{-1} in the summer time. So the obtained result confirms that the building is not far from the accepted rate of the Portuguese regulation but it does not have any comfortable condition.

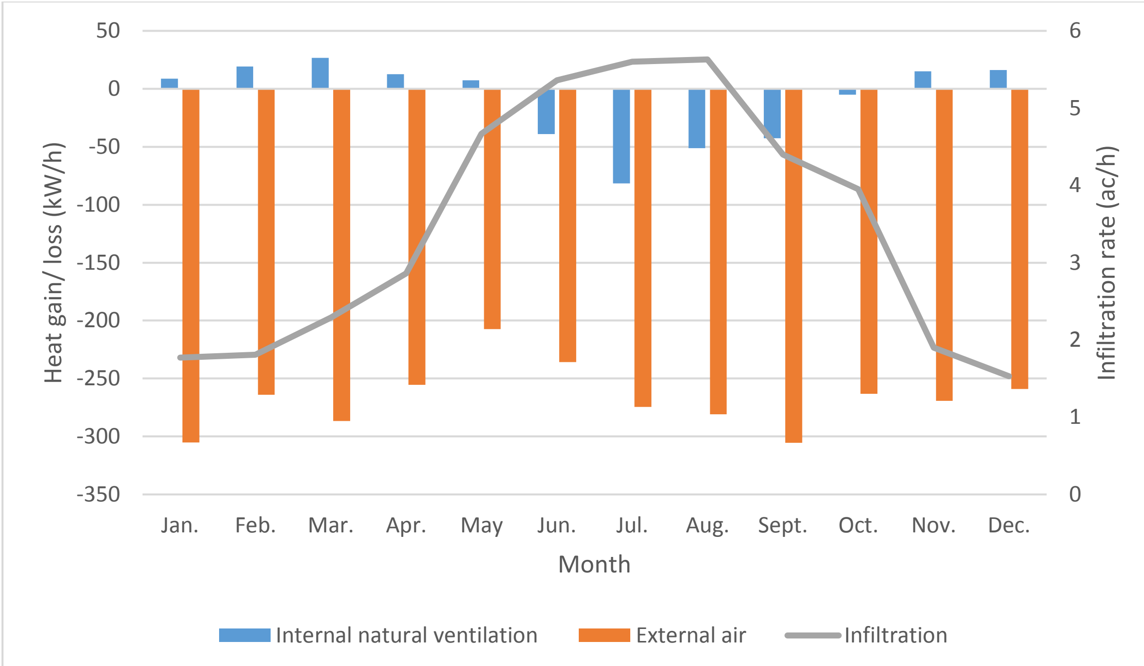


Figure 86: Analysis of the internal and external natural ventilation – Case study 3

Since the BDT of the apartment was completed in May, Figure 87 illustrates the ventilation properties of the simulated building at the same month.

As the figure shows, the highest amount of the infiltration rate occurs in the afternoon (12 pm-6 pm). This rate based on the Portuguese regulation and the LNEC application is 0.61 h^{-1} what it should be 0.6 h^{-1} in the summer time. On the other hand, building tends to have more airflow coming in than exhausting it.

According to the obtained results, it is concluded that the infiltration rate of the building has a good level based on the national and international regulations. In order to have more information about the air circulation of the building, the CFD simulation was used to determine the distribution of airflow.

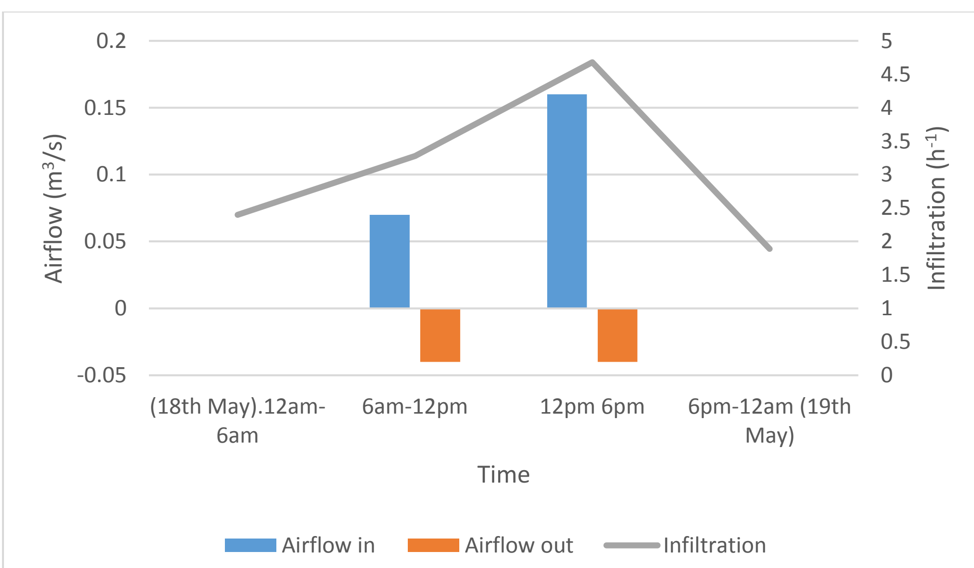


Figure 87: Analysis of the airflow and infiltration on 19th May – Case study 3

5.3.5.2 CFD analysis of the third building

Air circulation of the building is associated with the interior and exterior conditions. Hence the CFD simulation is organized in two parts of external and internal CFD analysis. Figure 88 shows the air distribution around the building in the urban area.

Figure 88 confirms that, the height of the building in an urban area is an important factor in the pressure and velocity distributions. As it is demonstrated in Figure 88- A and 88-B, the air velocity at the bottom of the building is lower than at the upper part. Also, there is a negative pressure over the building envelope in the bottom of the building while it is positive in the upper floors. Even the velocity and pressure are lower in the corners of the building where there are some breakings of the building like the position of the circle in Figure 88-C and 88-D.

It can be seen that in the higher positions of the building the air pressure and velocity increases (comparison of Figure A, B, and C). However, the form of the building has an effect in this process. For example, Figure 88-A shows that the changes on the air velocity and air pressure are obvious when the wind faces with the corners and holes of the exterior appearance (form) of the building. These changes also happen in the direction of the wind as presented in Figure 89.

In order to find the effect of exterior pressure on the interior air distribution, the interior CFD presents the condition of air circulation and distribution in the interior spaces. Figure 90 demonstrates the results of internal CFD for the simulated apartment. The presented figure shows four different floor plans which A belongs to the height of 1.5 m, B the height of 2.2 m, C 2.5 m and finally D the height of 2.7 m.

As Figure 90 shows, the air distribution of the simulated building is related to two different factors: openings and height of the building.

As all figures show, in higher positions, the air temperature, velocity, and pressure increases. On the other hand, the location of the openings and its effect on the intake air to the interior spaces change the air distribution and circulation.

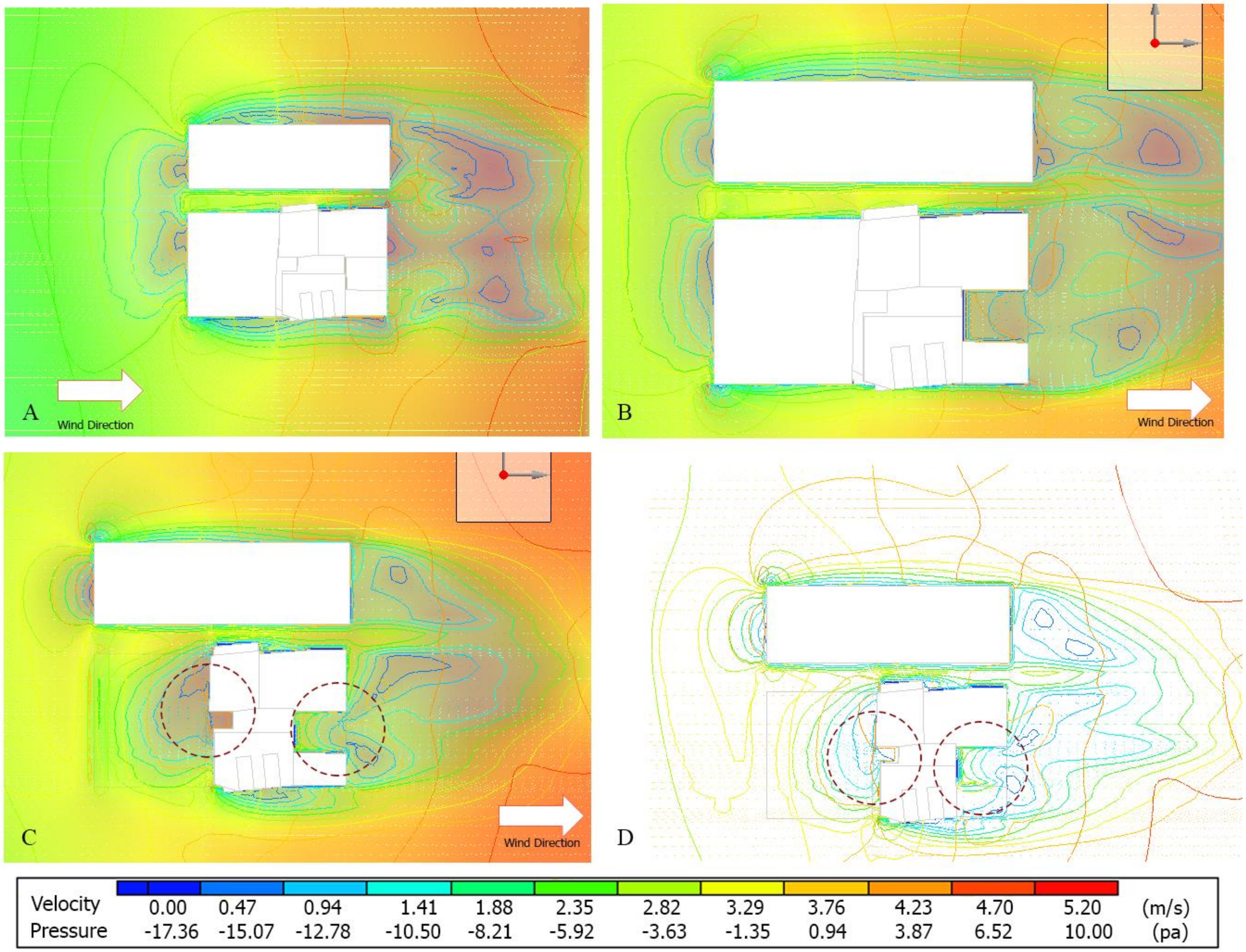


Figure 88: Analysis of the airflow distribution in the urban area – Case study 3

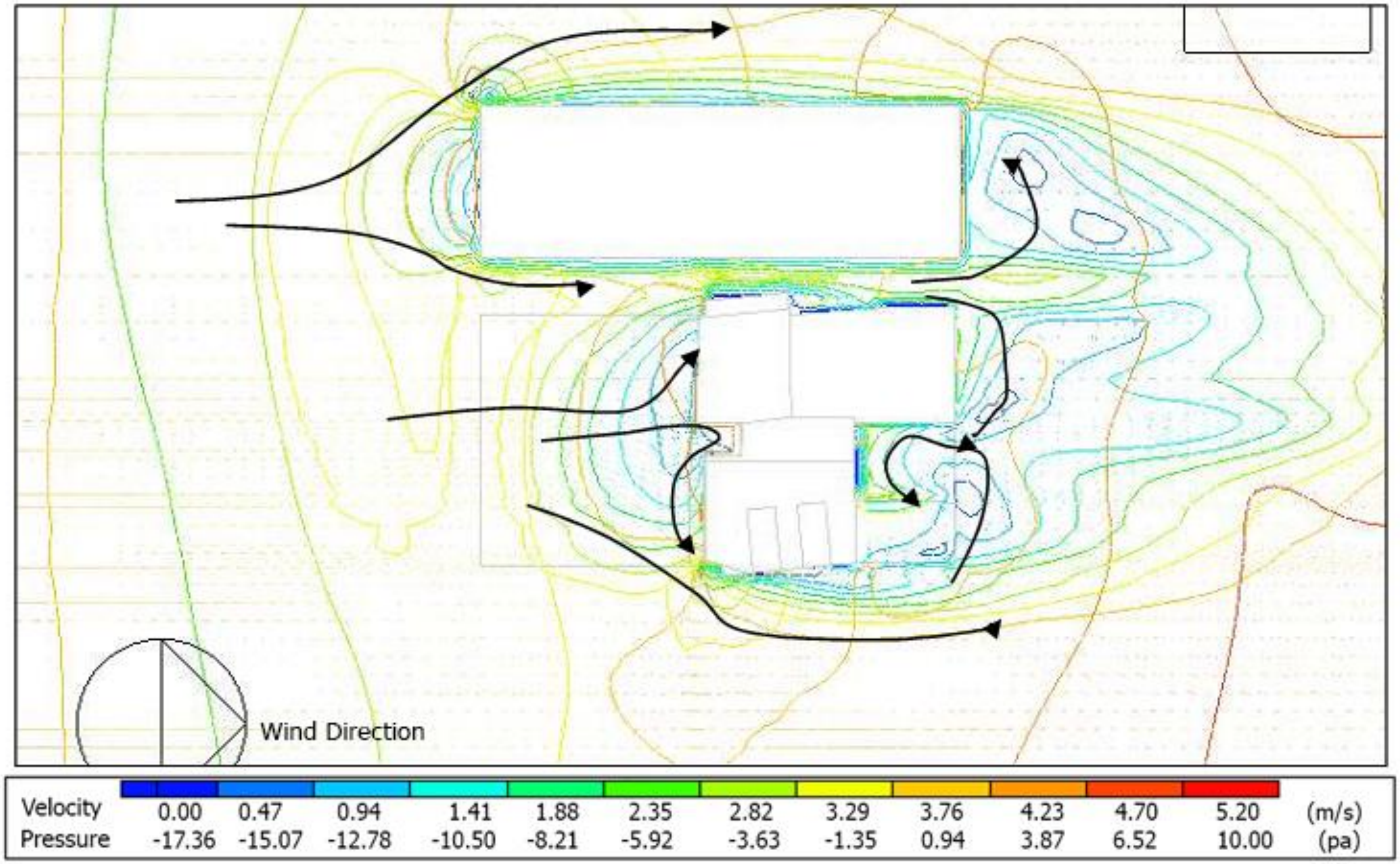


Figure 89: Analysis of the airflow circulation around the building – Case study 3

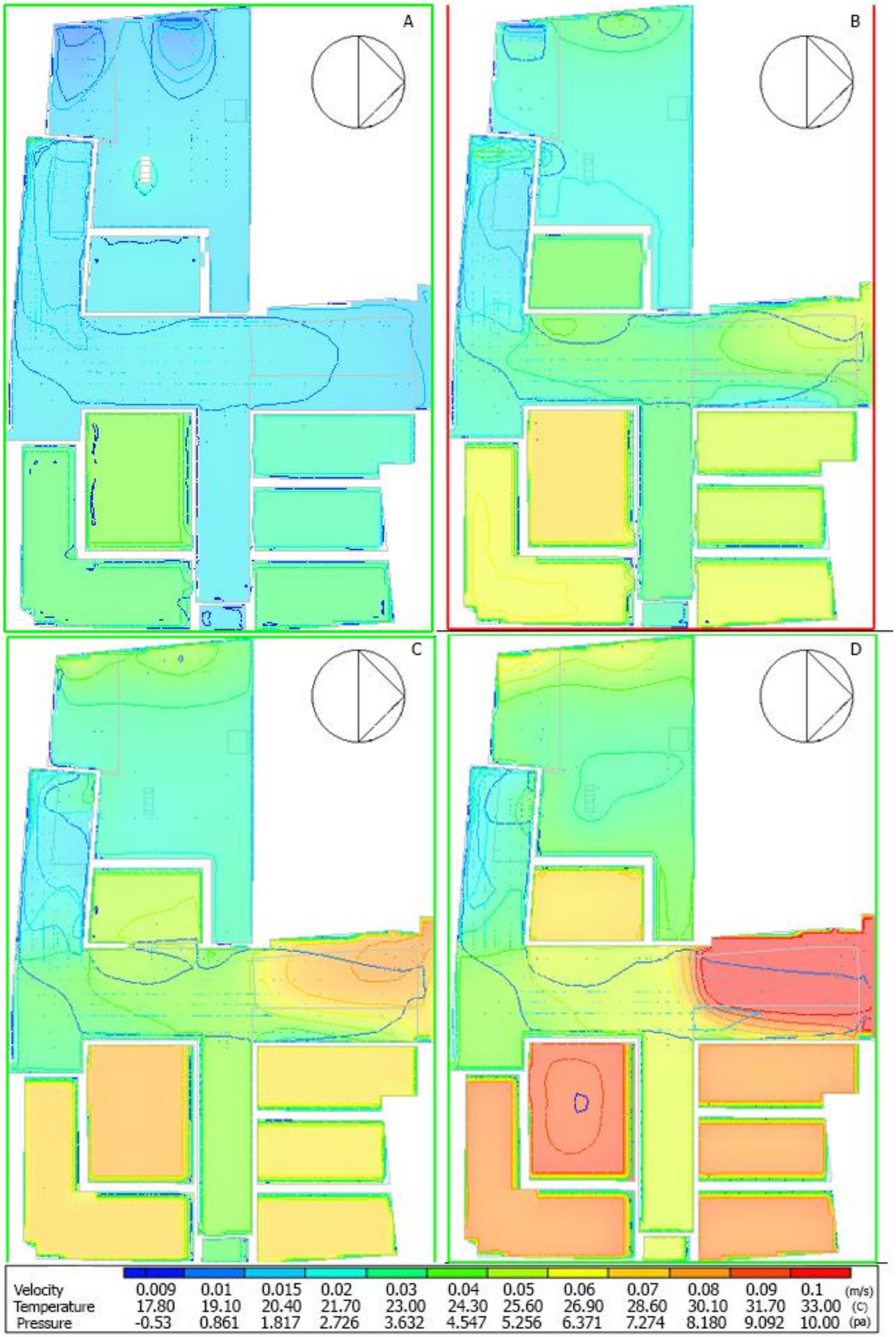


Figure 90: Internal CFD analysis of the simulated apartment – Case study 3

In order to find the air distribution behind the opening, Figure 91 presents the airflow spreading after coming through it.

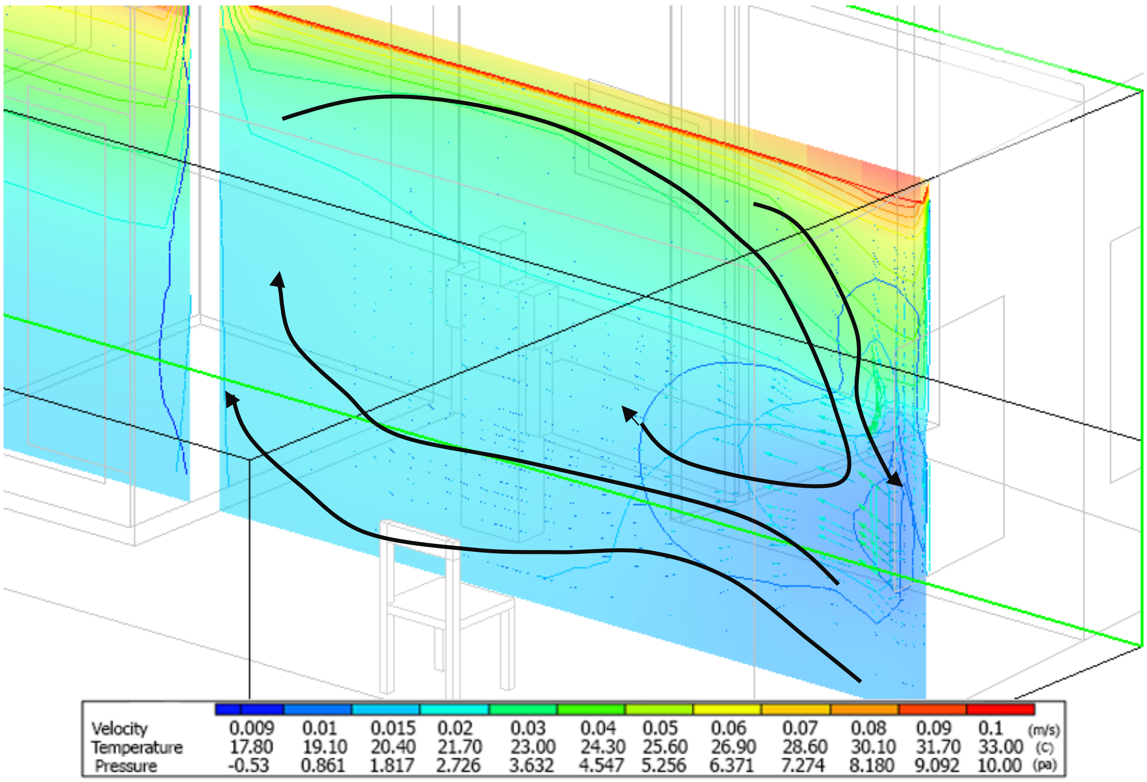


Figure 91: Air circulation behind the openings – Case study 3

The figure shows that the airflow moves to the down-side of the room after crossing the opening and then turns to the upper parts. But the important point of this air circulation is that the air exhaust from the upper part of the same opening (inlet). However, this case study works based on the cross ventilation system, and there is another opening which plays the role of outlet for the interior natural ventilation.

Air velocity is another important factor in the effectiveness of a ventilation system. Figure 92 illustrates the difference and distribution of the air velocity in the interior spaces of the building according to its speed.

As it has presented in Figure 92, the opening which is located in the corridors works as an inlet for this apartment. However, it should be the outlet of the cross-ventilation in this apartment.

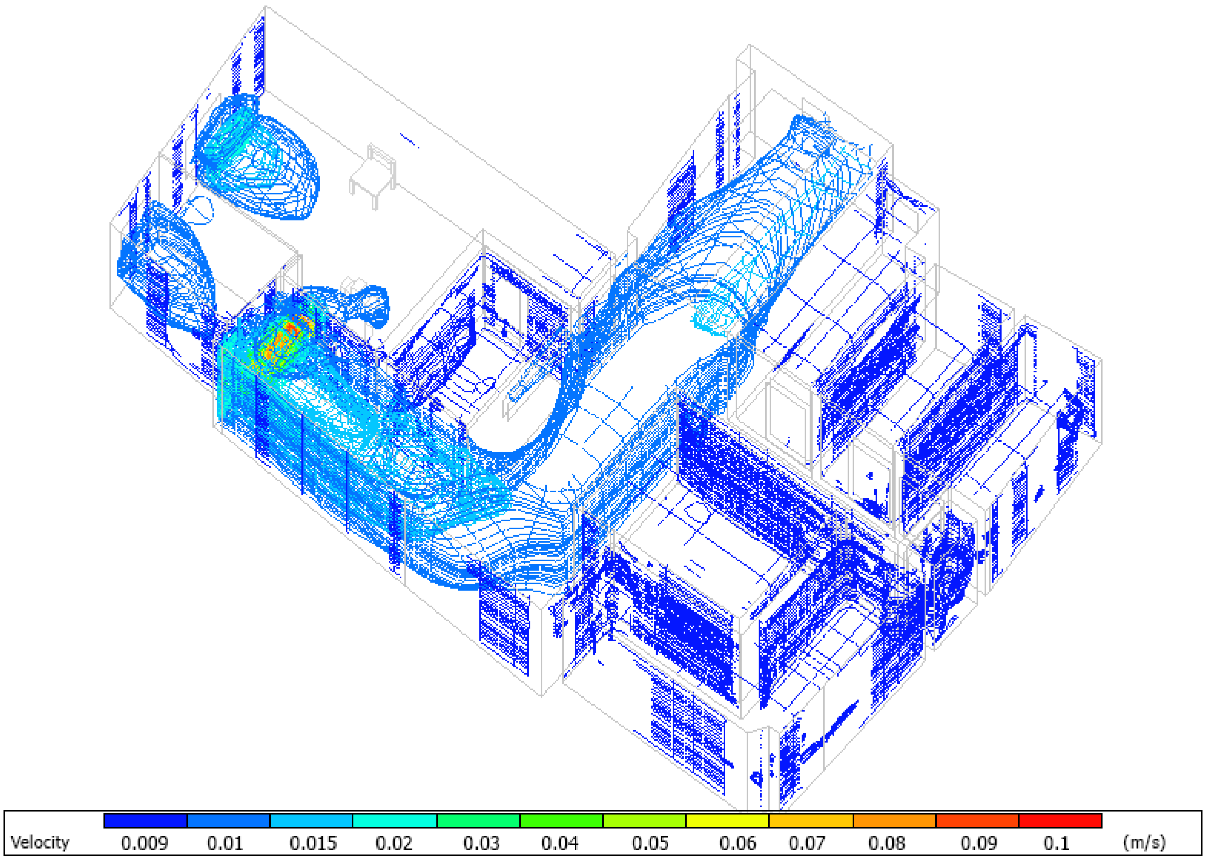


Figure 92: Analysis of the air velocity fluctuating in the interior spaces – Case study 3

Based on the analysis of Figure 92 it is observed that the airflow comes into the interior spaces. After that, some air goes out from the window on the other side of the flat (bathroom) and some goes out from the same windows of air entering, which is located in the main facade of the building.

This amount of air enters from the lowest parts of the window and leaves from the upper parts. Also, the percentage of opening for in-take air is bigger than the one for exhaust. Therefore, the room has to use same of the openings for exhaust air despite the existence of the cross ventilation system in the building. On the other hand, the corridor is well ventilated because the exhaust openings are bigger than intake opening, so the air that enters to the corridor through the entrance stair-case and flat (our case study) leaves through the opening located at the end of the corridor. Subjected to the effect of ACE in the ventilation effectiveness, the rate of ACE in the simulated building is 0.54, it means that the air circulation and distribution of the building is not as effective as it should be. However, it is better than other cases.

5.3.6 Fourth case study

The fourth case study is a single-family house which is organized in four floors. Figure 93 presents the modeled building. As in the previous cases, more information about the building is available in Chapter 4.

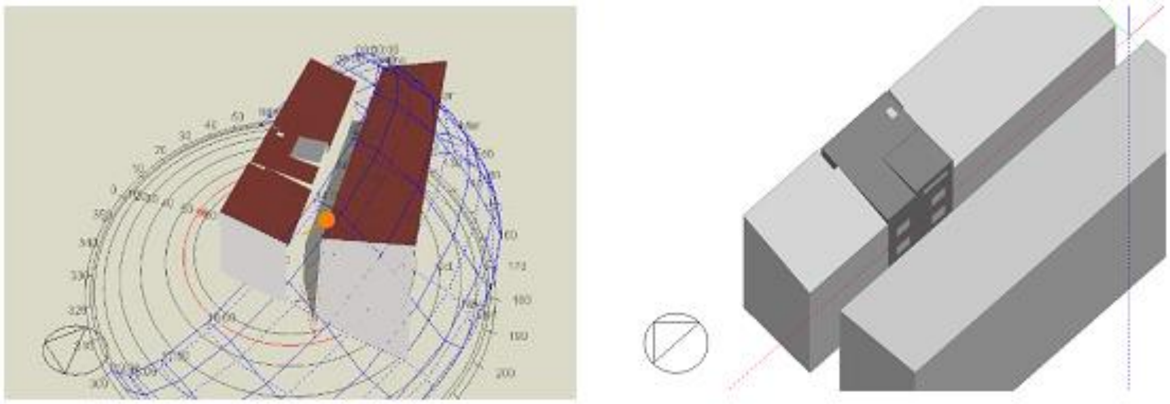


Figure 93: The appearance of the modeled building in DB – Case study 4

The analysis of the effectiveness of the ventilation is divided into two different parts: thermal performance (section 5.3.6.1) and airflow distribution and air circulation (section 5.3.6.2).

5.3.6.1 Thermal performance analysis of the fourth case study

The analysis of the thermal performance of the fourth building starts with the study of the environmental comfort in an annual period, which is presented in Figure 94.

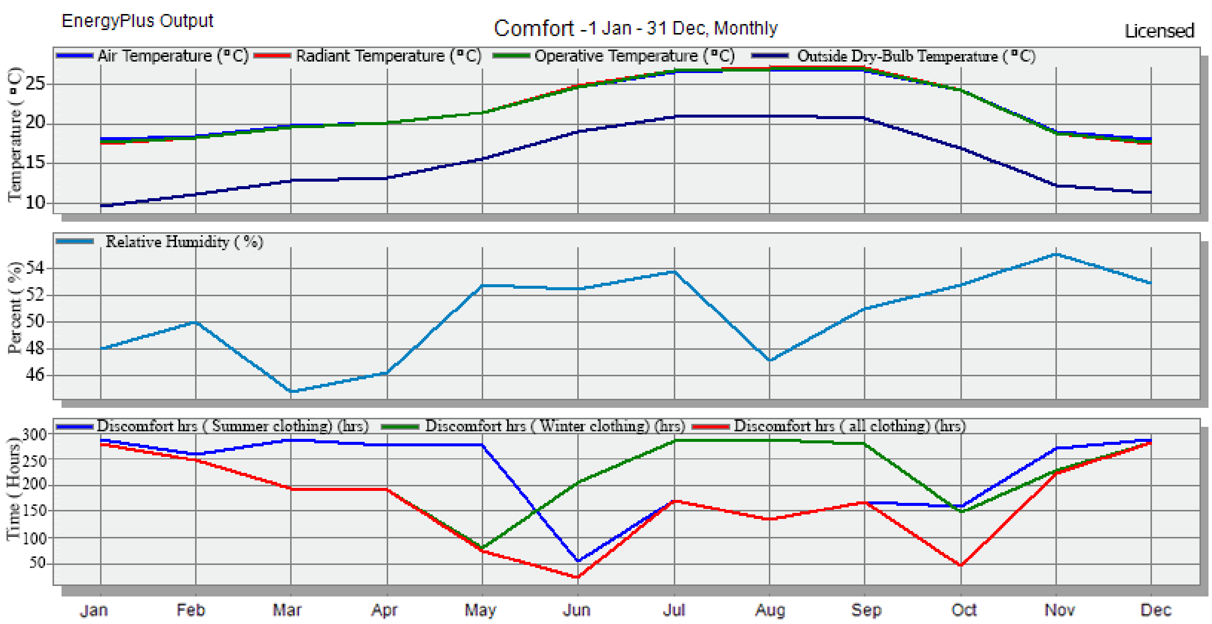


Figure 94: The environmental comfort analysis of the simulated building – Case study 4

Based on the information available in this figure about the radiant temperature, operative temperature, outside dry-bulb temperature, relative humidity, and also discomfort hours of the building, the comfort/discomfort feeling of the occupant of the building during the year was studied. Despite the existence of a difference between air temperature and operative temperature in the first part of this figure, the relative humidity of the building varies between 45-55 % in the whole year. Based on the effect of this two first graphs, the third one shows the amount of comfort/discomfort hours of the building. According to this graph, the occupants feel less discomfort in June and October. On the other hand, the most discomfort feeling is observed in December.

Figure 95 presents the discomfort hours of the building. It shows that the maximum and minimum discomfort hours are observed, respectively, in December with 260.62 hours (around 11 days), and in June with 32.77 hours (less than 2 day). Therefore, the PPD level of the building in June is around 7% and in December is 39.7%.

To develop the analysis of thermal comfort, the building condition has been simulated based on different existing models of thermal comfort which are based on heat balance approach. Figure 96 shows the building thermal comfort condition based on different models of DB.

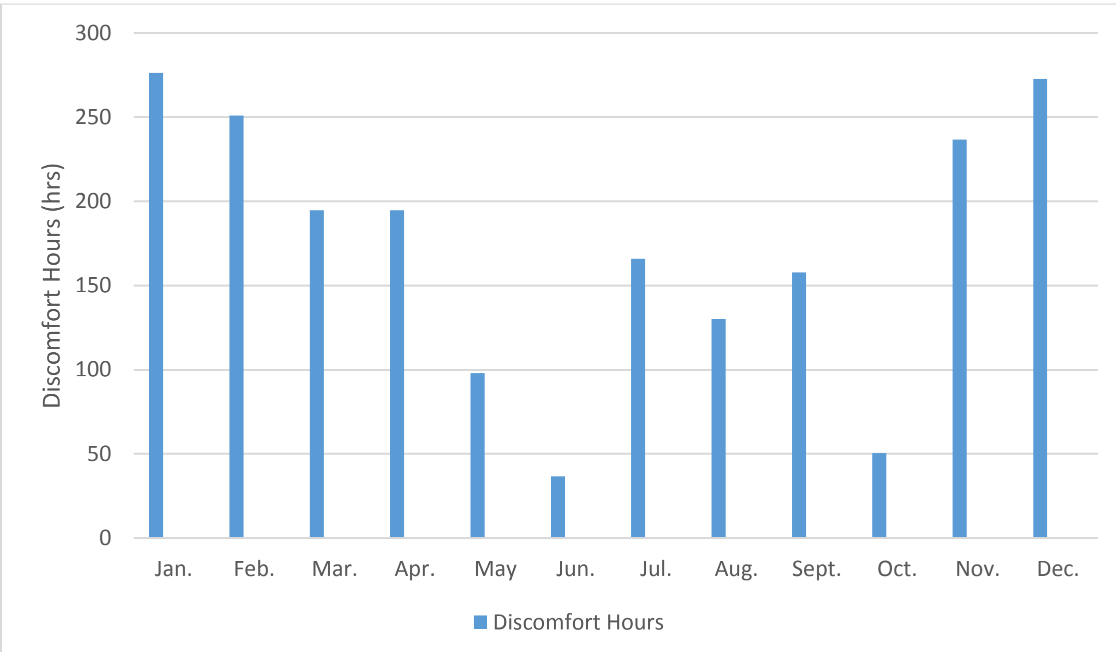


Figure 95: Discomfort hours of the building during the year – Case study 4

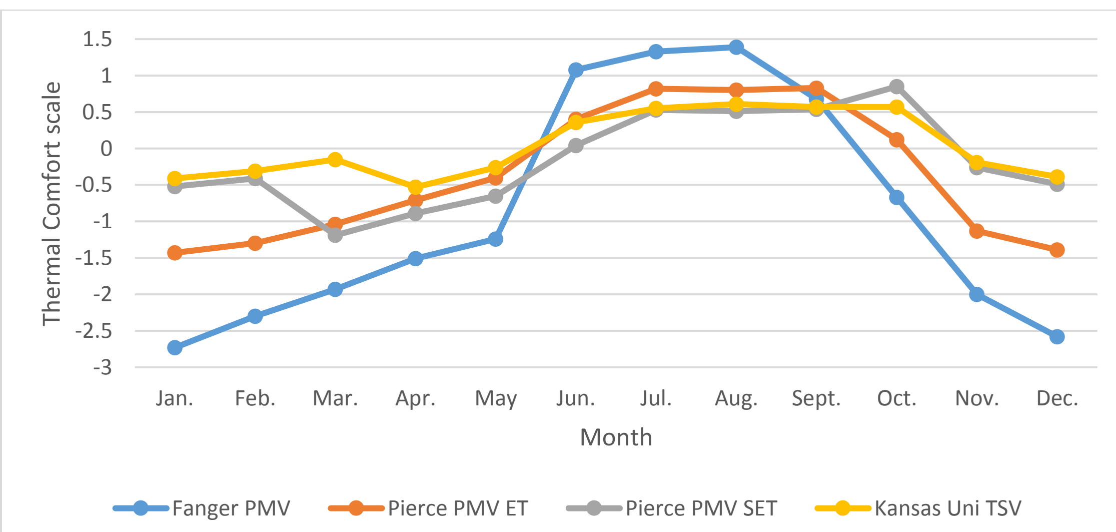


Figure 96: The thermal comfort analysis of the building based on different existing models – Case study 4

Based on information presented in Chapter 2 about the PMV and PPD parameters, this figure states that the building has better thermal comfort conditions in July, August and September based on the *Fanger´s* model. Due to the effect of some factors like internal solar gains and building infiltration rate on the effectiveness of ventilation in the building, Figure 97 presents the analysis of the ventilation effectiveness for this building.

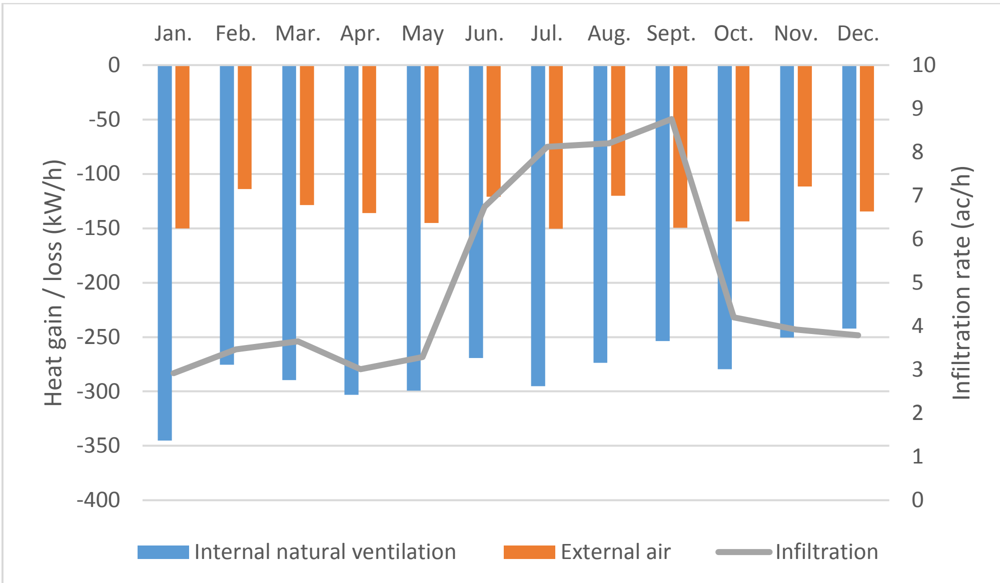


Figure 97: Analysis of the internal and external natural ventilation – Case study 4

Figure 97 presents the heat gain/loss of the building through the internal ventilation and external air. The building has heat loss by ventilation system (internal and external) during the year and this rate is higher for external than for internal ventilation, which means there is a flow which fluctuates between inside and outside. However, the percentage of effectiveness of airflow is a questionable point. Grounded to the presented figure, the building has the maximum of 6 times per hour changing the air in the summer time. Due to the Portuguese regulation and LNEC application, the air change of the building is 0.91 h^{-1}. However, this rate should be 0.4 h^{-1} in the winter period and 0.6 h^{-1} in the summer period. Since the BDT of the apartment was performed in October, the following figure (Figure 98) illustrates the ventilation properties of the simulated building for the mentioned time.

The biggest value for infiltration rate, based on the presented figure, happens in afternoon (12 pm-6 pm). The infiltration rate based on the LNEC application in the simulated building at 6pm is 0.77 h^{-1} while it should be 0.4 h^{-1} in the winter time. On the other hand, the building tends to exhaust more airflow to outside than intake.

In order to have more information about the air circulation of the building, the airflow distribution has been performed by CFD module of DB software. The next section is devoted to the results of the CFD simulation.

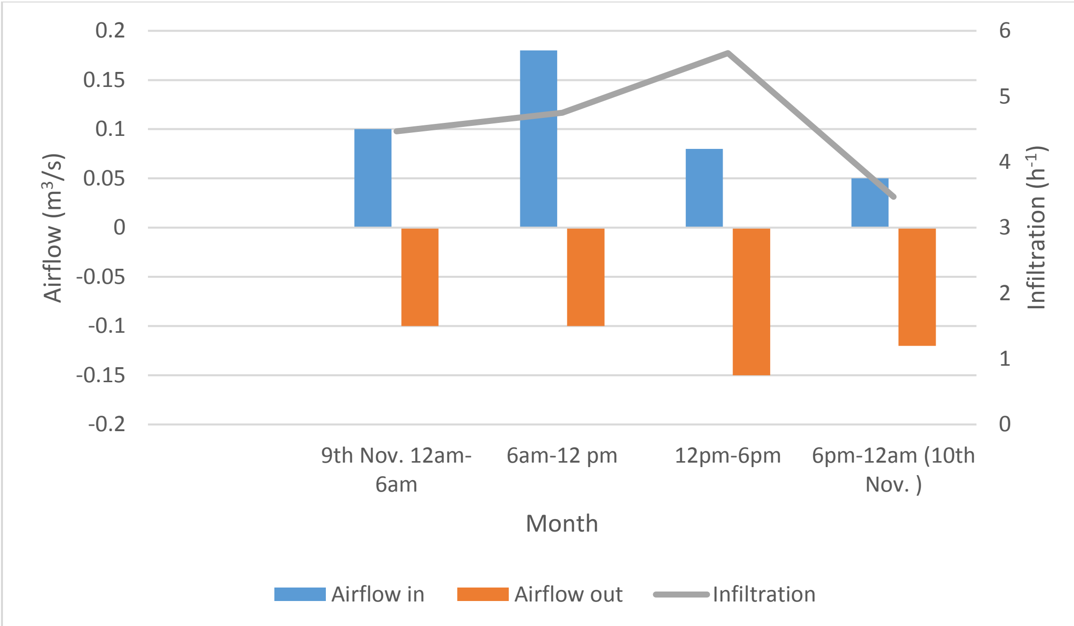


Figure 98: Analysis of the airflow and infiltration of the building on 9th Nov. – Case study 4

5.3.6.2 CFD analysis of the fourth case study

CFD simulation shows the airflow circulation and distribution in the interior and exterior areas. Since the air distribution around the exterior shell of the building and around the facades has an effect on the interior condition, Figure 99 illustrates the results of external CFD analysis for the simulated building, where one can see the airflow distribution over the exterior shell of the building. Generally, the air flows in this street come from the riverside as is shown in the figure, but as the building is located at the end of street with a narrowest width, and the building is little affected by the wind flowing from the riverside. On the other hand, the building is connected to another street on the opposite side that is really wide. So, the effect of the wind fluctuating from this side on the building envelope is more than from the riverside. There is also a narrow alley behind the building which has effect on the air distribution over the envelope.

It is observed in Figure 99-C, that height is an important factor in exterior air distribution. When the height of the building increases, velocity and pressure also increase over the envelope. We can also see a disturbance in front of building, and in the street, due to interfering two airflows from the opposite sides (Figure 99-D). The difference in velocity and pressure based on the height influences the air circulation between interior and exterior areas. At first, the air circulation in the interior area was considered and after that, the relation between these two areas was studied. Besides the decrement of the interior pressure by an increment of the height, there are other factors such as air velocity and temperature difference in the whole building that shall be considered. Figure 100 shows the status of air velocity and temperature in different floors of the building.

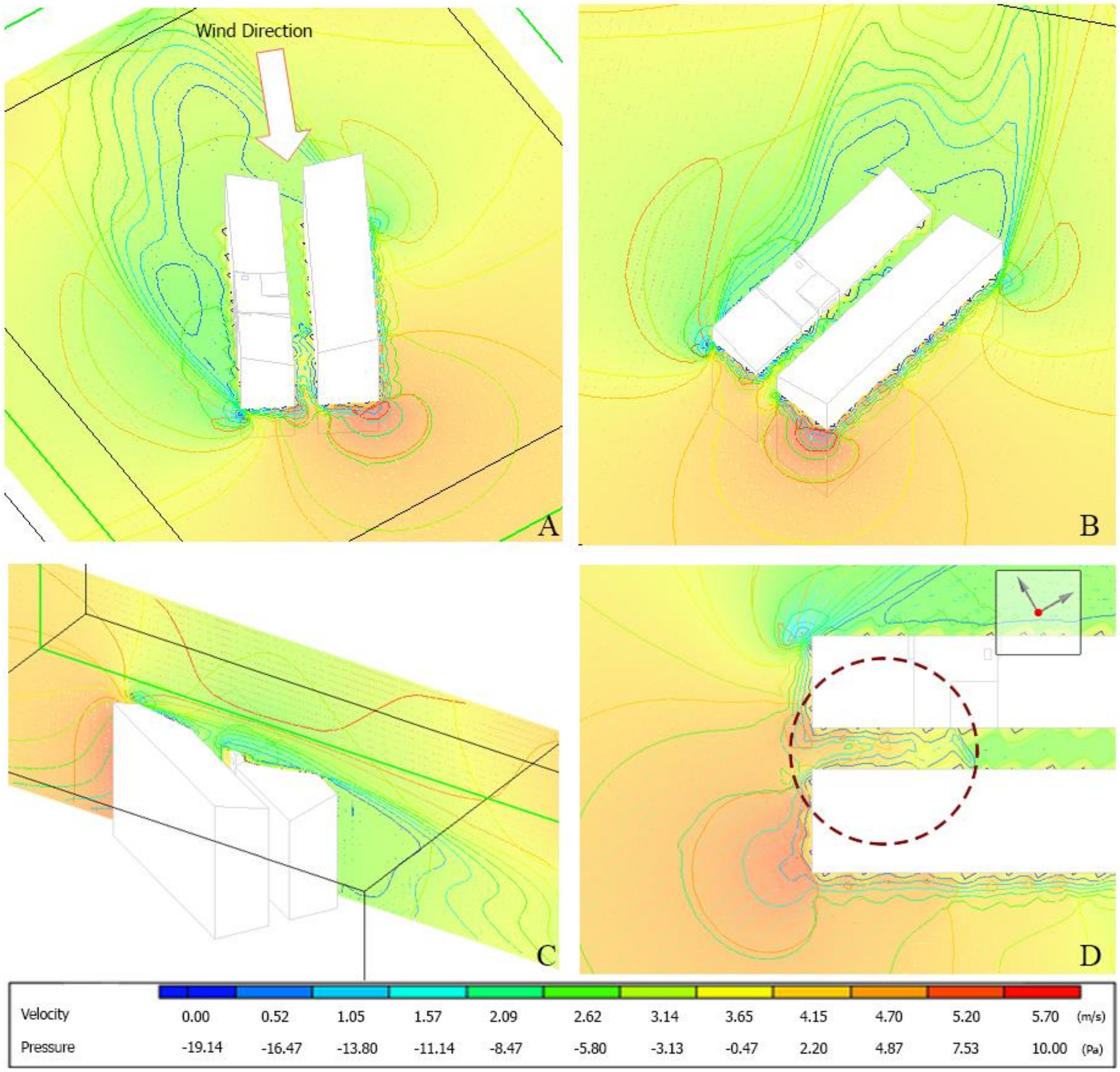


Figure 99: Analysis of the airflow distribution in the urban area. – Case study 4

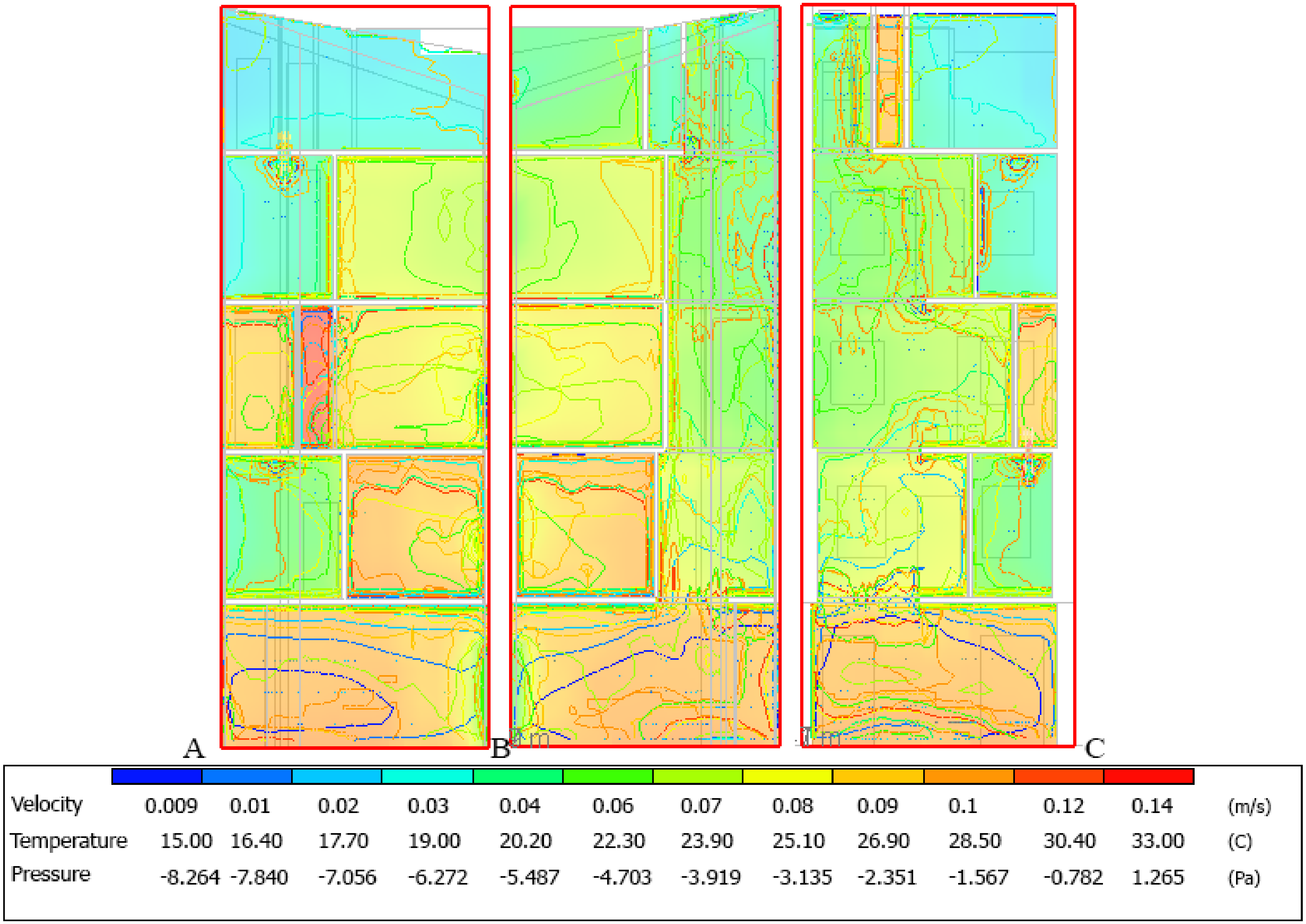


Figure 100: Analysis of the air temperature distribution in the interior spaces (sections) – Case study 4

As it is observed from the figure, the interior temperature decreased in the upper floors. Based on the Figure 100-A, the air enters from windows on the envelope and after passing the interior openings goes down and then circulates in the building. On the other hand, the staircase of the building acts as a duct of ventilation and the opening located on the top pulls the air up, while some airflow also enters from that part. Therefore, the role of this opening in the ventilation of the building is not as strong as it could be.
Figure 101 shows the plan of the building in different floors which A belongs to the ground floor, B the second floor, C the last floor, and D is the direction of air velocity in the last floor. Based on the presented results, the staircase, and upper floors are ventilated very well because of the stack effect which is influenced by the staircase. However, the opening of the staircase should be bigger than the intake air located in the envelope in order to send more air to the outside through it and provide the lower floor with better ventilation.
Figure 102 shows the distribution of air velocity in the simulated building. Based on this figure, the air velocity is fluctuated in different floors. These changes are due to the position of openings in the interior spaces and also exterior openings.
The rate of ACE in the simulated building is 0.58 for the whole building, while it is respectively 0.35 and 0.93 in the first and third floors. Thus, it is concluded that the building needs a more effective solution for ventilation, in order to have an acceptable amount of airflow circulating in the whole building.

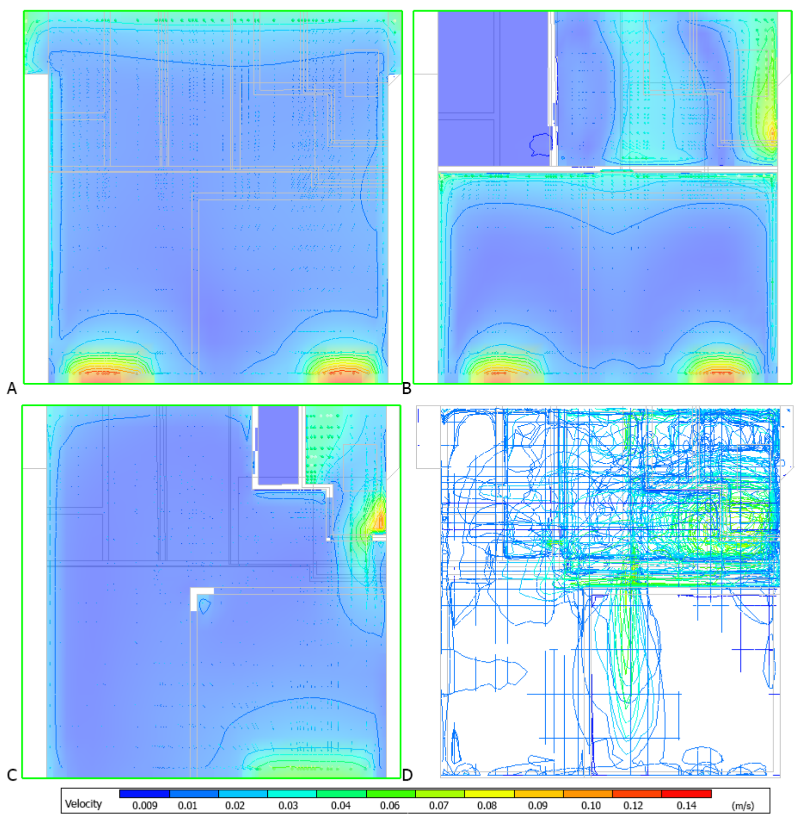


Figure 101: The air circulation behind the openings- Case study 4

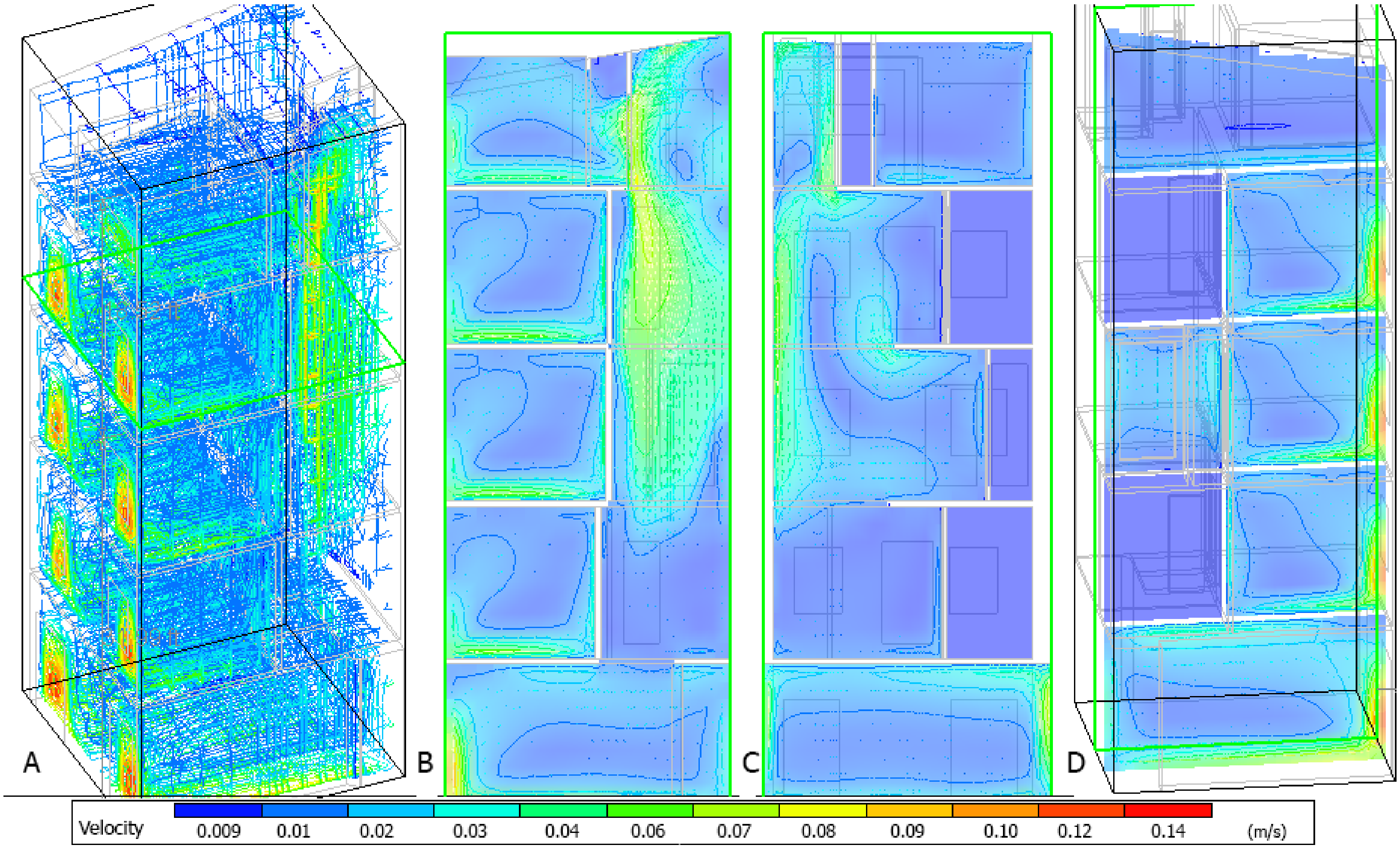


Figure 102: The distribution of the air velocity in the simulated building – Case study 4

5.4 Conclusion

After studying all case studies by different models including measurement (BDT) and simulation (DB), the following figures illustrate the characterization of all them together, in order to compare their conditions and problems. Figure 103 compares the results of the measurement for pressurization and depressurization of all case studies with the results obtained by simulations.

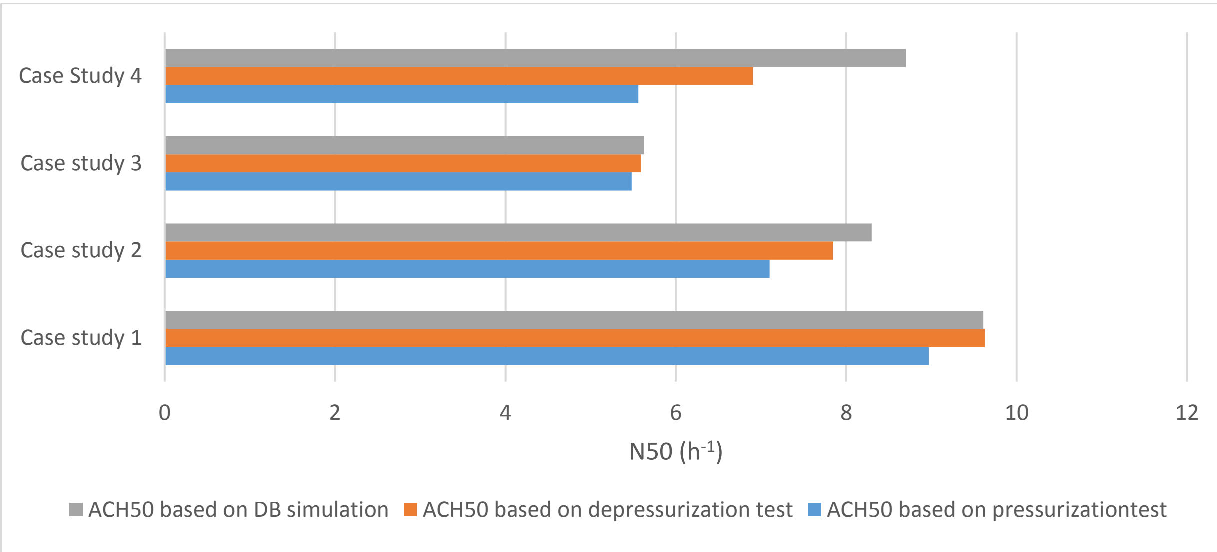


Figure 103: Comparison of the results of measurement and simulation methods

Figure 103 shows that the two first case studies located in the same building are leaker than the others. A difference of 1-7 % among the results of simulations and measurements was verified. On the other hand, there are some national and international regulations which mention specific rates for the air change rate and infiltration. Figure 104 illustrates the status of cases studies based on these regulations.

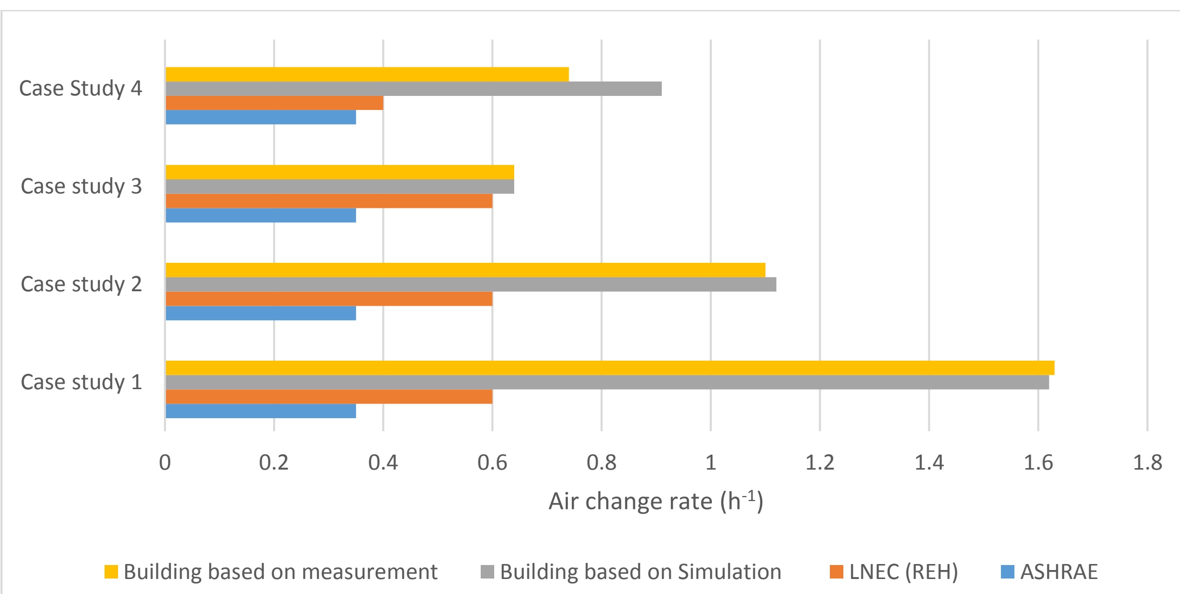


Figure 104: Comparison of the air change rate based on different regulations

Comparison of the results of all studied building with different national and international regulations states a big difference among the existing rates of air change per hour in the buildings and the regulation, especially in the first and second case studies. The third case study which was recently rehabilitated has a better rate.

All studied buildings have two types of natural ventilation systems (wind and stack effect) and all of them have infiltrations that also contributes to its natural ventilation. These relationships between obtained infiltration rate of the building and temperature variation and also between infiltration rate and wind speed by DB software are considered in Figure 105 and Figure 106.

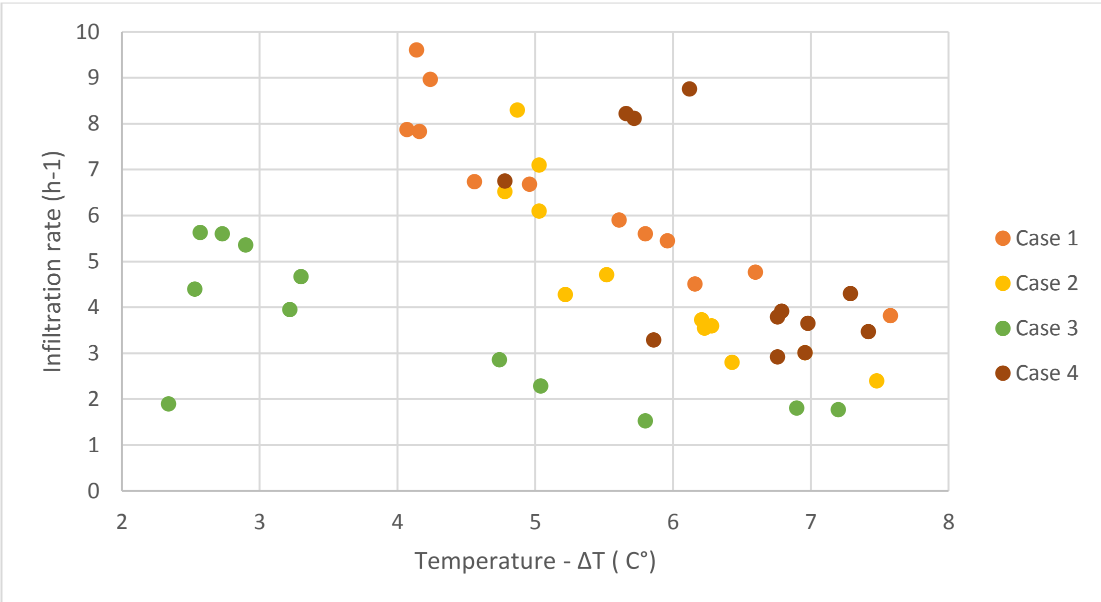


Figure 105: Correlation of the infiltration rate of the buildings with the temperature difference

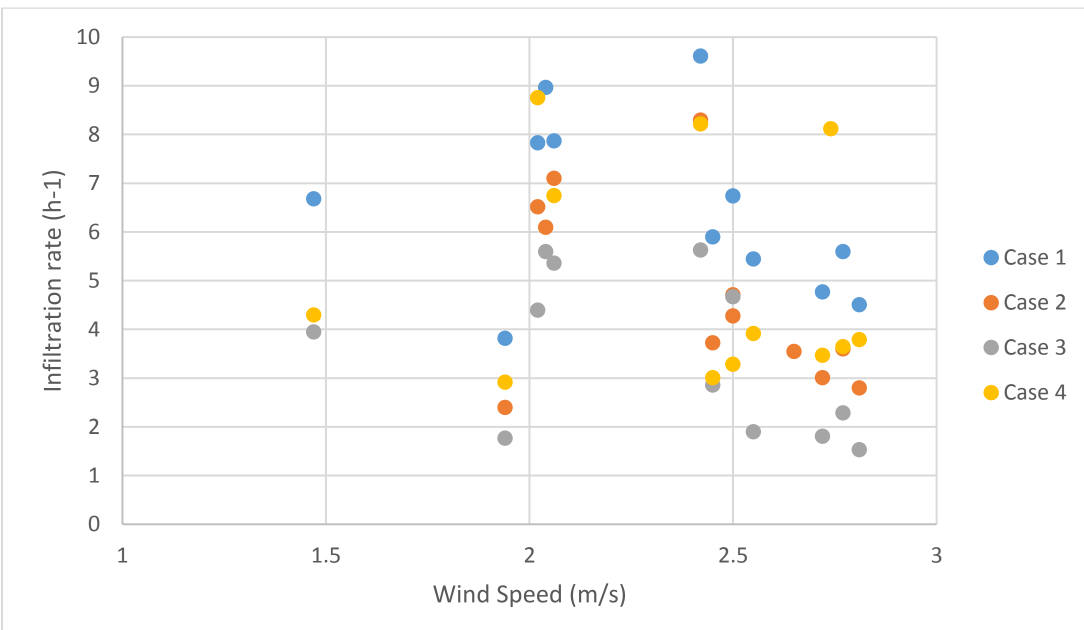


Figure 106: Correlation of the infiltration rate with the wind speed around the building

Figure 105 indicates that when temperature difference increases, infiltration of the building decreases. On the other hand, in order to consider the effects of the wind in the natural ventilation, it has been observed that those buildings which are faced with the wind speed of more than 1.8 m/s (it called light breeze based on the EN-13829:2000) in most times of the year, have the highest infiltration rate. It means that the most of the infiltration has happened in the wind speed more than 1.8 – 2.2 m/s.
In order to have a more precise analysis on the natural ventilation and its relation with the wind effect, next figure (Figure 107) shows the correlation of airflow in/out (the airflow which intakes or exhausts the building based on the wind) and the average of infiltration rate in an annual period.

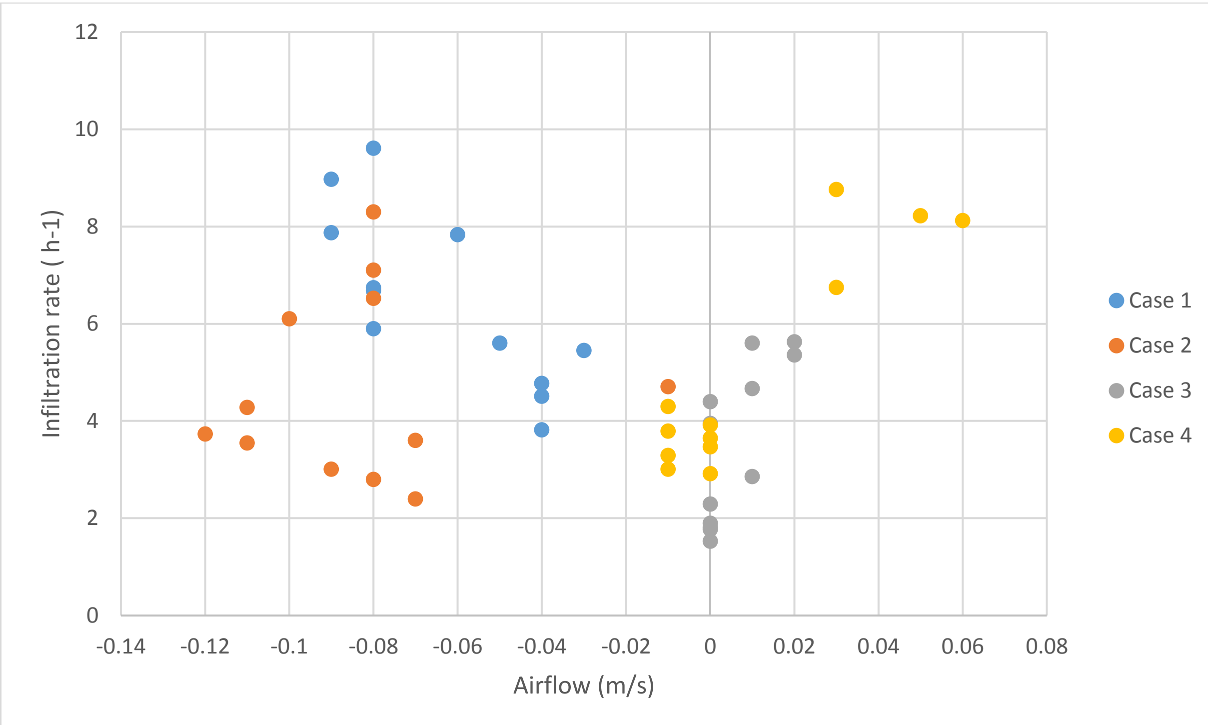


Figure 107: Correlation of the airflow and infiltration rate in an annual period

The figure shows that the first and second case studies have more outflow than inflow. This means that the building faces higher pressure over the main faced because of the location of the building and the sources of the intake air. However, there are some openings in another facade of the building (in the opposite facade).
On the other hand, the third case study has low airflow between the interior and exterior in most time of the year and it needs to increase the air intake in the building in order to increase the exhaust potential. The results of the last case study show that the building has more outflow during the year through the main facade of the building in comparison with the intake air.
As this chapter concludes, the buildings need some solutions to improve the intake air from the main facade as well as their effective exhaust in order to have efficient natural ventilation. To do so, the Chapter 6 is devoted to analyze some selected solutions.

Chapter 6:

Improving building's natural ventilation performance

Index of chapter 6

"Ventilation is the profound secret of existence".

Peter Sloterdijk

6-1 Introduction

Concerning the BDT measurement and simulation results of the analyzed buildings which were presented previously, the current chapter will describe some proposals to improve its actual conditions in term of ventilation effectiveness. Since the tested buildings have double–side, cross, and stack ventilation strategies and based on the mentioned problems in chapter 5, the recommended solutions to improve the efficiency of their ventilation have been divided into two phases:

- General recommendations.
- Specific recommendations.

This is because the case studies are located in an old built environmental zone and it is crucial to have specific considerations for these kind of buildings/ urban areas.

Section 6.1 is an introduction and then in the following section, 6.2, a general overview strategy on the ventilation idea is presented. Consequently, section 6.3 comes with a brief explanation about the recommendations to improve the ventilation in all type of the residential buildings.

Then, recommended solutions for the existing residential buildings based on the previously mentioned problems will be illustrated in Section 6.4.

Finally and due to the importance of the case studies and its limitation for rehabilitation and preservation, some specific solutions (as the best solutions) which are organized based on the preservation of historical area roles, are demonstrated in Section 6.5 as discussion and conclusion of the chapter.

6.2 A review of the functionality and strategy of ventilation

According to what was already discussed in previous chapters, openings have a strong effect on ventilation. Different types of opening configurations are useful for different purposes. In order to have a well-design natural ventilation, the permanently open-vents are used to provide background of ventilation and controllable openings are necessary to meet transient demand. The size and number of openings depend on the ventilation needs and local driving forces.

Based on the influence of the properties of wind and buoyancy effect (temperature difference, pressure difference) on the ventilation, direction of the airflow from the openings is associated with the pressure and temperature differences (negative pressure in the interior space and positive pressure in the exterior area).

Generally speaking, the airflow direction according to *Starube* [221] shows that, if the floor is leakier than the wall, the inlet air occurs (from positive to negative) up to NPL which is located in the middle of the building's height. Consequently, the parts of building which are located upper than NPL, the direction is reversed and air leaves the interior space with a negative pressure and goes outside with a positive pressure. On the other hand, if the top of the building is leakier than the bottom, the NPL is located at higher level while the directions of the airflows are the same and the air enters from the lower part and exhaust from the upper part.

The interior pressure of the building is associated with the location and number of openings. The change of interior pressure in different heights is due to the pressure coefficient based on Bernoulli equation. Ventilation based on temperature difference causes the change in airflow direction based on the temperature. If the interior air temperature is higher than the exterior one, the air enters from the lower openings and leaves from the upper ones. If the interior air temperature is lower than the exterior one, the direction of the airflow is reversed. On the other hand, incrememt of the airflow rate when the temperature of exterior air is low enough to push the heat from the building, increases passive ventilation.

6.3 Recommendation to improve effectiveness of ventilation in buildings

There are some general recommendations to improve ventilation according to the available regulation and researches such as *SF1* [222], *Thomas et.al* [223], *Irving* et.al. [224], *Kleiven* [225], Awbi [97] and etc. which are presented below:

1- The ratio between of room´s depth (W) and height (H), must be W <5H for cross ventilation strategy if the height of the building is 2.7 m. The room´s depth may also be extended to 15 m if the room height was more than 2.7 m. This ratio should be W<2H in the single-side ventilation if the room´s height was 2.7 m. However, the room´s depth can extend up to 6 meters for living spaces. The ratio of W<2.5 H is used in single-side ventilation with stack effect.

2- Interior plan of the building: In order to have an effective ventilation, the floor depth should not be more than 15 meters.

3- Size and orientation of the windows: the location of the building and its openings are important factors and all naturally ventilated buildings need openings on windward and leeward sides. However, it is better if the openings in the leeward side (outlet) are bigger than the windward side (inlet opening). Because in natural ventilation, when the outlet is bigger than the inlet, the air will stack with more power. Consequently, the velocity of the air will increase and therefore the ventilation would work better.

4- Window operable area: in order to have a fresh airflow in the interior spaces, the window should have an operable area. The effectiveness of the operable area depends on the window configuration. In other words, some kinds of window configurations can effect on the wind direction and some of them cannot effect on the wind direction. For instance, a side-hung window is unaffected on the direction of the flow while the awning windows can increase or decrease the intake airflow based on the wind direction. Hence, the properties of the opening configurations are one of the most important factors which should be taken into account

5- Sealing of the building: a building faces the subject of ventilation and infiltration in two different ways. If the building is leaky, it is not efficient in the energy sector. On the other hand, if the building is too tight, it is not efficient about the natural ventilation. Hence, in order to have an efficient building for ventilation and energy performance, it is necessary to have a balance of its leakage rate. It means that the leaks of the building should be sealed as much as the building ventilation can work well.

6- Configuration of the window: the shape of the window is another important factor which impacts the ventilation effectiveness. For example, if the window is a casement one, it influences the direction and control of ventilation, while the roof window (skylight) is useful to enhance the ventilation.

Generally, the outlet openings should be larger than the inlet ones due to the indoor air velocity. Otherwise, bigger inlet opening causes the reduction in indoor air velocity, as well as the reduction in ventilation effectiveness. If the inlet and outlet openings have the same size, the window to wall ratio (WWR) would be increased in order to extend the air velocity in the interior area. Also, the maximum comfort air velocity in the interior area is 2 m/s. However, more than 2 m/s could be also comfortable but it depends on the air temperature.

7- Overhangs and fins: overhangs and fins are elements that are located around windows as vertical or horizontal surfaces. These surfaces can help airflow circulation and the air distribution in interior spaces. This affects the air pressure and velocity, besides protecting the interior area from the solar radiation.

Considering our discussion about effective factors, it should be noted that some of these factors are not effective for existing buildings. For example, aspects 1, 2, 3, and 4 are useful for new buildings or existing buildings that have no limitations such as our case-studies. However, aspects 5-6 are applicable in existing areas with limitations of intervention. Therefore, based on the aim of this research and the existing limitations, analysis of the opening configuration is the most applicable solution and will be explained in the following section.

6.4 Ventilation effectiveness in old residential building in the center of the city of Coimbra

Due to the importance of our case study as well as to the international regulations regarding preservation and conservation of the old built environments, like the UNESCO world heritage regulations [226] (some of the old residential buildings in the city center of Coimbra are part of UNESCO world heritage), the process of improving ventilation effectiveness in these constructions is different from the general solutions that can be used in other type of buildings. Hence, in order to present some solutions, this section is divided into two sub-sections: 6.4.1 where theories of recommended solutions are presented and 6.4.2 in which the recommendations are simulated in order to find the rate of their effectiveness.

6.4.1 Recommended solutions

The analysis of ventilation effectiveness of residential buildings with specific consideration to the old built environment focuses on some internal factors such as opening configurations, window types, trickle vent (inlet and outlet in the opening), and skylight (roof window). Some descriptive details on each one of these components and their effects on the effectiveness of the ventilation in these buildings are presented in the following.

6.4.1.1 Opening configuration

Opening configuration is an important factor in naturally ventilated buildings. There is some literature concerning the relation of the ventilation performance and opening configuration. As stated by *El-Agouz* [227] ventilation performance in the single-side ventilation strategy with two openings works better if there is a longer horizontal distance between them. *Evolaet*. et al. [228] also studied the wind driven ventilation with different opening configurations. They found that, if only one opening exists in the building for ventilation purposes, it is better if it is located on the windward side of the building to get a better ventilation rate due to the importance of the wind on the wind-driven ventilation.

The type of window opening is another factor which influences performance of building ventilation. *Heiselberg* [229] studied the characteristics of different window types. Considering the outcome of mentioned research, it is concluded that awning window has better performance on the interior air circulation in winter because it is possible to change the opening angel in this type of window. However, side-hung window is preferred for summer time because it directs the air to the occupied zone and therefore both the amount and velocity of the air increases.

Due to the existing gap in the literature in what concerns to the quantitative evaluation of the influence of the window configuration on the ventilation performance, this research thesis intends to contribute to this issue. Hence, the types of window configurations concerning the position of the opening (side-hung, top-hung, bottom-hung…) will be analyzed to find the best one for our case studies.

Based on current conditions of the building, it was noticed that, four different opening configurations are presented in the area of the research (old part of Coimbra city). Figure 108 shows these four opening configurations.

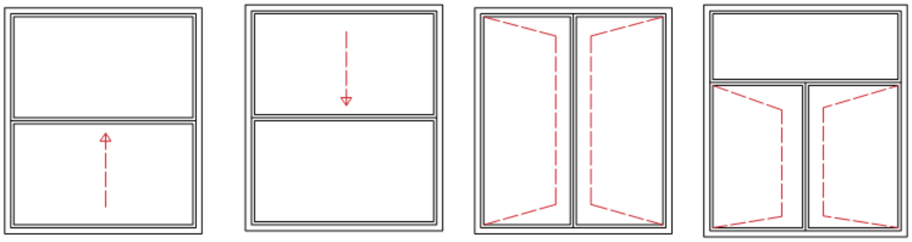


Figure 108: Different opening configurations available in the old town of Coimbra

6.4.1.2 Trickle vent (air-vent)

Trickle vent is a narrow opening located in the building facade elements like doors or windows to control and distribute airflow in the interior spaces. It forces the extraction of polluted air to the exterior area and its location is related to the condition of the ventilation system in the building. However, its best location is on the exterior facade of the building. It helps/regulates the ventilation of the building when the ventilation elements (door and window) are closed.

Due to the idea of using air-vent to improve ventilation effectiveness in residential buildings, it can be installed in the frame of the window, over the frame, or glazing. It is possible also to fit it in any type of material. Nowadays there is a new generation of windows in which the air-vent has been inserted in its frame in order to regulate the ventilation requirements. Generally, a window is one element of natural ventilation and it is used in the summer time to supply and extract air (or to exchange airflow). It may cause over-ventilation problems and increasing energy consumption in the winter time. However, it is not possible to close windows permanently due to the risk of appearance of condensation and air pollution in the interior spaces. Air-vent affects the energy efficiency of the building and also IAQ by reducing condensations, avoiding over-ventilation in the building and consequently minimizing energy consumption. The following figure (Figure 109) shows a kind of the trickle vent (air-vent) in the frame fitting position. More information about how this trickle vent can be applied in these case studies and how effective is it, is illustrated in Section 6.4.2.

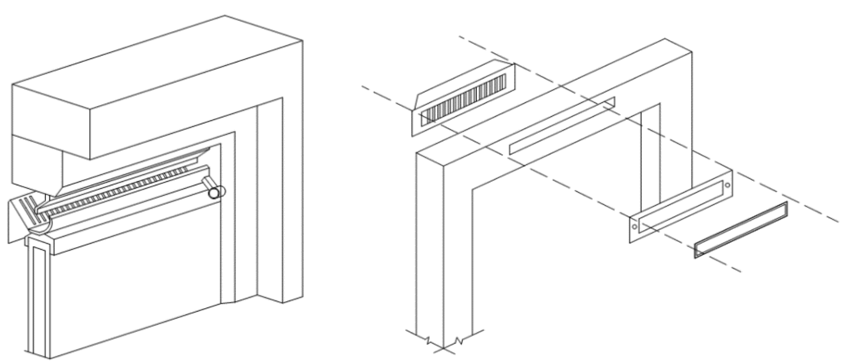
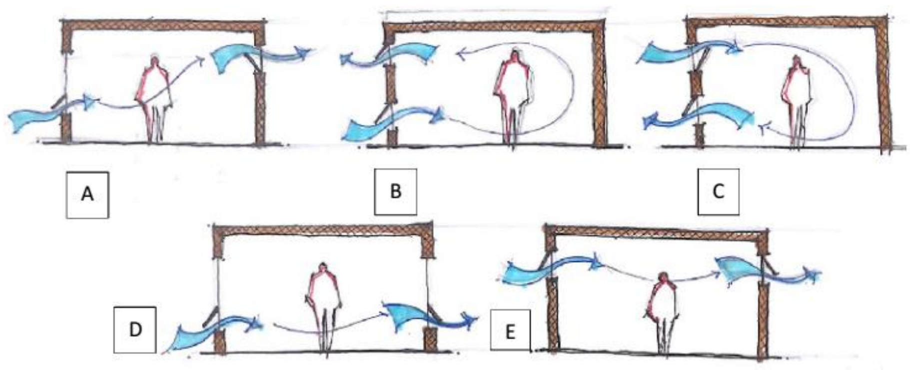


Figure 109: Position of air-vent in the frame of the window

Figure 110 shows different possible locations of air-vent in the building. Location and direction of the air-vent are related to the principles of ventilation. If ventilation is based on the temperature difference with $T_{int} > T_{out}$ the air enters from the lower part and extracts from the upper part (Figure 110-b). On the other hand, if $T_{int} < T_{out}$ the air enters from the upper part and leaves from the lower part (Figure 110-c). This theory is useful for single-side and cross ventilations.



(A: when air supplies from the lower part and extracts from the upper part in a cross or double-side ventilations. B: when air supplies from the lower part and leaves from the upper part in single-side ventilation. C: when air supplies from the upper part and extracts/leaves from the lower part in single-side ventilation. E: when air supplies and extracts form the upper part in a cross or double-side ventilations).

Figure 110: Direction of the air supply and extraction from the building based on temperature difference

This air-vent is not only applicable for the top or bottom of the window but is also usable for its sides. It can be joined to the structure and frame of the window or located separately on the wall. However, the second method is not allowed in our area of study. Next Figure (Figure 111) illustrates air-vent joined to the side of the frame of the window.

Figure 111: Combination of air-vent with the window structure [230]

6.4.1.3 Skylight (Roof-window)

As stated before there are two types of natural ventilation: wind-driven and stack ventilation. In order to take advantage of stack ventilation in residential buildings, inlet should supply air from the bottom of the room and outlet should be located at the top level of the room to extract the air. The stack ventilation works better if the distance between the inlet and outlet is larger. Since stack ventilation does not work by the wind, on hot days with no wind the natural stack ventilation can cause the building become colder with a stable airflow. The effect of wind is insignificant in this ventilation method. It also influences the location of the inlet opening. The following figure (Figure 112) shows the stack effect on natural ventilated building. Thus, the skylight is a way to improve natural ventilation of the building, but it is necessary to study its properties and configurations. The size and position of the openings in the skylight are really important and have a significant effect on the ventilation performance. They also influence the amount of gained solar radiation load as well as heating and cooling loads of the building. One way that skylight and stack can use in the residential building is through the staircase. This means that normally the skylight is located at the top of the staircase and the stack ventilation works due to the chimney effect, which is a Roof-window can be used to ventilate the roof space over the last floor by creating the chimney effect. Therefore, air is supplied from the lower level of the building and will be extracted from the highest level or leeward side of the chimney in order to have proper ventilation. More detailed information about the skylight (Roof-window) and stack ventilation, their changes and effects on the ventilation performance of the case study will be presented in Section 6.4.2.

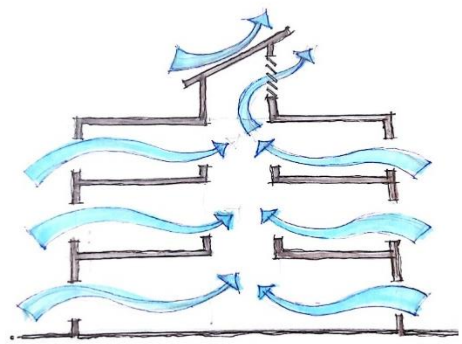
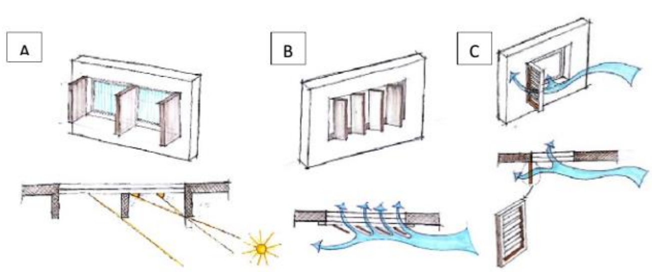


Figure 112: Stack effect through an atrium.

6.4.1.4 Shading devices (louvers, overhangs, and side-fin)

Shading devices are another important passive technique. Besides of the importance of controlling the solar radiation and the limitation of heat gains which compromise the thermal comfort, they are useful to control airflow from surrounding to interior spaces. As stated by *El. Sherif* [231] there are some factors such as the position of the sun orientation and physical properties of the shading devices which have an impact on its behavior. Shading devices are divided into two main categories: fixed and movable ones. Fixed shadings are categorized in horizontal shading (overhangs) and vertical shading (side-fins). Movable shadings are also divided into different types such as retractable louvers as roller shading, venetian blinds, curtains, movable light shelves and movable sun catchers. Movable shadings can be mechanical and electrical ones, but based on the strategies of this research, the electrical type is not considered.

Due to building orientation and climate properties (altitude and latitude), the geometry of the shading devices can be different. Angle, width, and height of shading are three important factors that should be considered based on the building orientation properties to protect the interior spaces from over-receiving solar radiation. According to the location of the case studies and the properties of the urban area such as the width of the street and height of the building (urban canyon), there is no problem concerning over receiving the solar radiation and heat gains of the buildings through the windows which needs to protect the interior spaces from them. Hence, the application of shading devices is not to control the solar radiation, but to supply more airflow in the interior spaces. Therefore, concerning the increasing of air intake by shading devices, it is better to select vertical shading (side-fins). Figure 113 presents different side-fins and their effects on the interior air distribution.



A- Fixed side-fin with a vertical orientation. B- Fixed side-fin with slant orientation. C- Movable side-fin with a vertical orientation.

Figure 113: Different side-fins and their effects on the interior air distribution

Due to the properties of the case study, the movable side-fin is better because it is used to increase the airflow supply whenever it is needed (see Figure 113, 114). More information on the properties of this shading (configuration, and location) will be presented in Section 6.4.2.

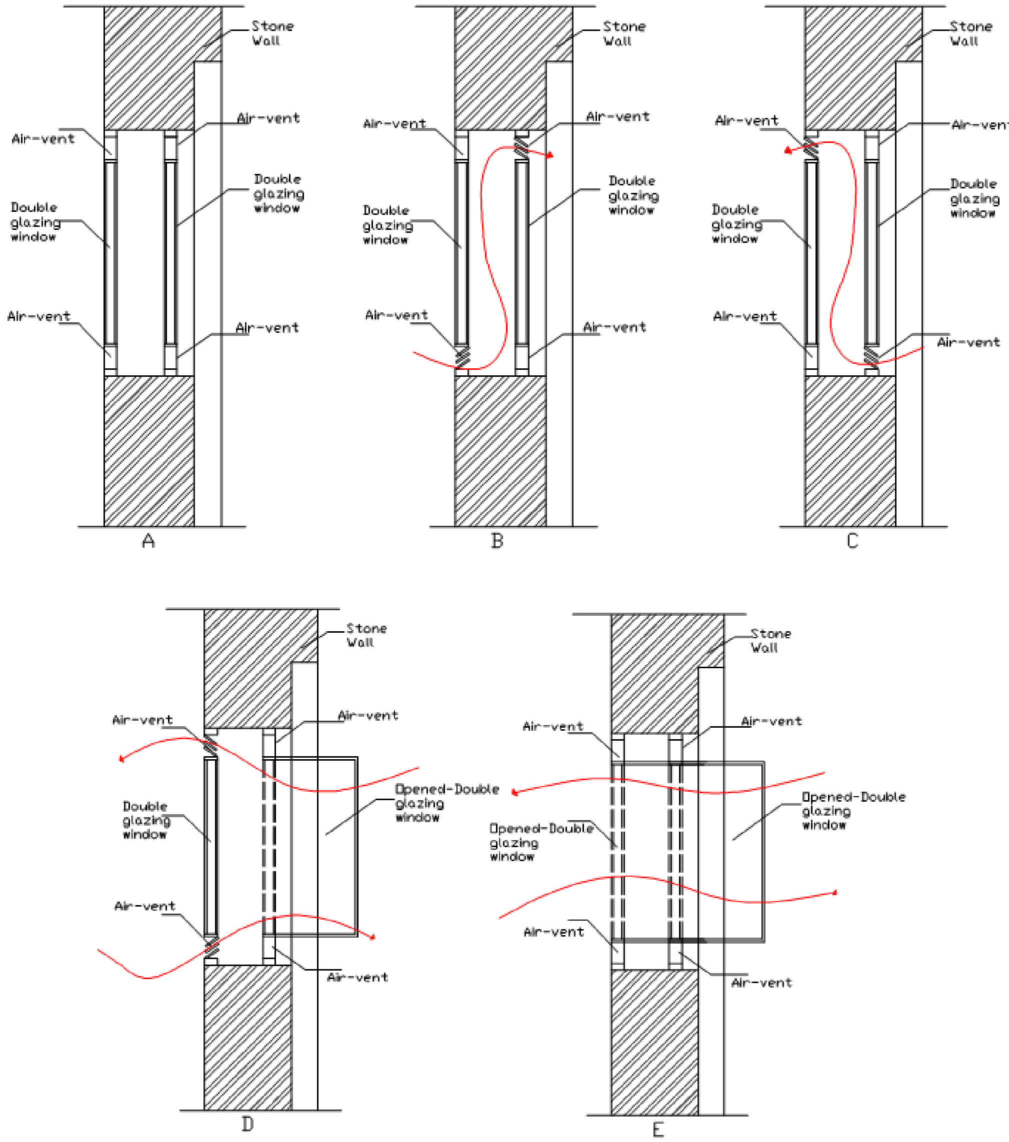
Figure 114: Window-vent surface in front of the window

6.4.1.5 Double windows

The use of double windows is an idea to increase the effectiveness of naturally ventilated buildings. It works based on a cavity (open to the outside) to extract the polluted air from the building while it extracts also the heat of solar radiation from the building when needed. The idea of ventilated double windows has been extracted from the existing condition in the case studies. Because there are a window and a wooden protector door on the interior side of the window in some of the selected case studies (Figure 115), and this construction could be an appropriate solution, to develop the idea of a double window. Figure 115 shows the window configuration in the Portuguese construction in Coimbra which have been used for developing the idea of a double window.

Figure 115: The properties of existing windows in Portuguese construction in Coimbra

The window is develops based on the air-layer which exists in the existing condition. Two windows are located with an air layer between them (the second window is located before the wooden door) and both windows have trickle-vent (air-vent) at the top and bottom as an inlet vent and outlet vent. After that, the wooden door has located on the interior side of the second window. In the other words, on summer time, when the window is open the interior airflow is supplied by free flow and the air-vent does not affect the airflow. But during winter time, when a high rate of ventilation is not necessary and the window is used just to bring fresh air, the air-vents will be used. The extraction of the airflow through this window works by the chimney effect. Figure 116 shows the configuration of this idea. The effect of this new concept has been simulated by DB in some of the case studies, when was possible and its effectiveness will be presented in Section 6.4.2.

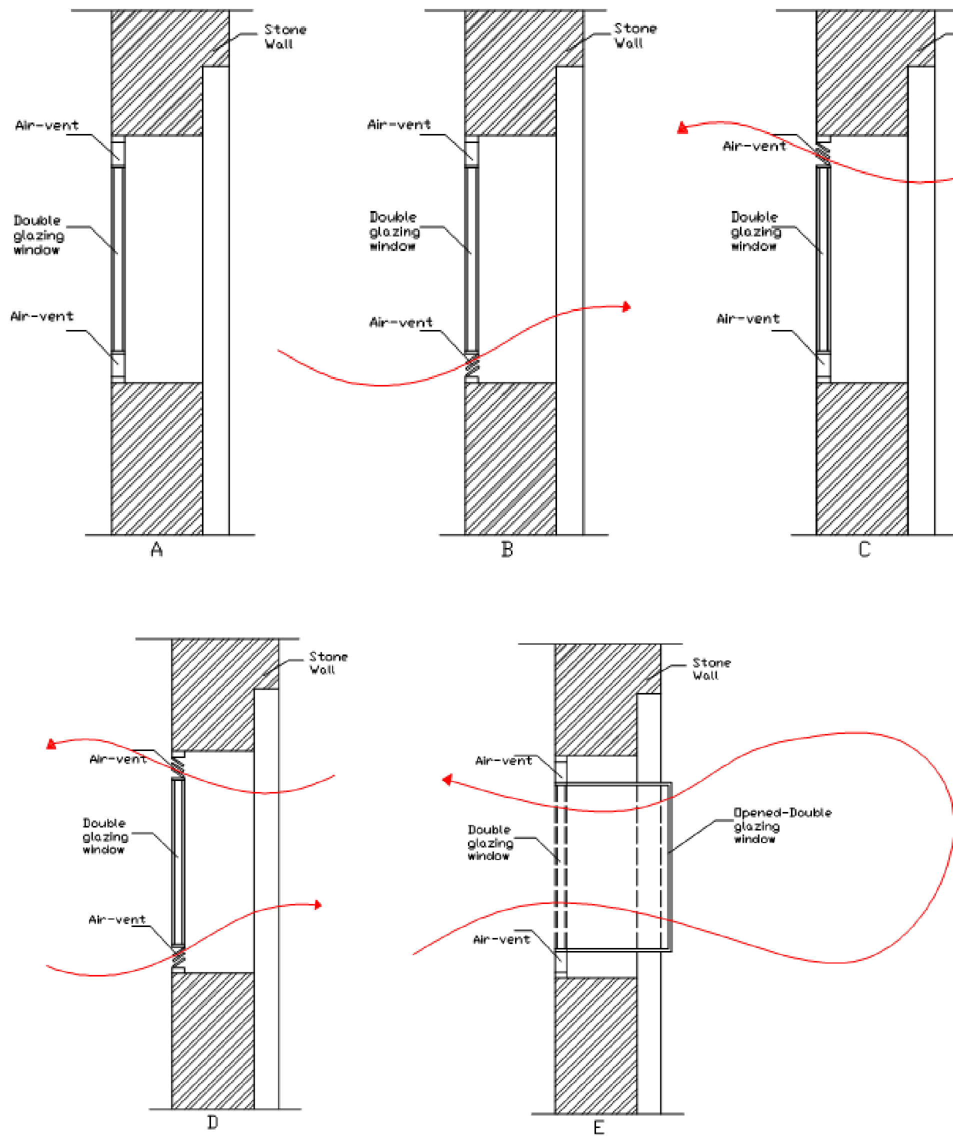


A: General idea of the double window when both the windows are close. B: Using bottom air-vent of the exterior window and top air-vent of the interior window in order to enter more fresh air to the interior space in the winter time. C: Using top air-vent of the exterior window and bottom air-vent of the interior window in order to extract the polluted air from the interior area in the winter time. D: Using both air-vents of the exterior window and opening the interior window in order to ventilate the room. E: Using the whole operable area of both windows to ventilate the room in the summer time.

Figure 116: Sketch of the idea of double window

6.4.1.6 Ventilated Single window

Another idea which can be used is a ventilated single window. It means that there is only a double glazing window with two controllable air-vent at its top and bottom. Based on this idea, the window will be open for ventilation in the summer time and it works as a normal window. However, in order to avoid over-ventilation (hyperventilation) and increment of energy consumption in the winter period, the air-vent will be used to change the interior air. The important point about this window is the installation of the air-vent at the frame of the window as a part of it. This solution (ventilated single window) is applicable in some of the case studies, but not all of them. Figure 117 shows a general sketch of this window.



A: General idea of ventilated single window when the window is close. B: Using bottom air-vent of the window in order to enter more fresh air to the interior space in the winter time. C: Using top air-vent of the window in order to extract the polluted air from the interior area in the winter time. D: Using both air-vents of the window in order to ventilate the room. E: Using the whole operable area of the window to ventilate the room in the summer time.

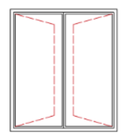
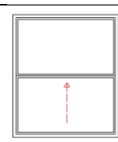
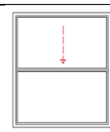
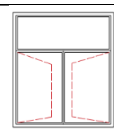
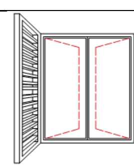
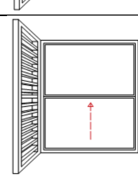
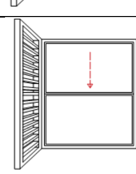
Figure 117: Sketch of idea of ventilated single window

Since the idea of the double windows or ventilated single window are not applicable at the same time in a case study and based on the existing properties of the case study just one of them will be used as a recommendation. Therefore, from now they will be called the new configuration as a new idea of recommendation in the simulation results and in each section will mention which one of these two ideas is used as the new configuration.

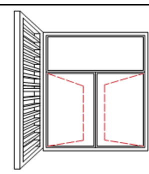
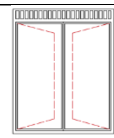
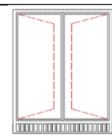
6.4.2 Analysis of effectiveness of recommended solutions

All presented recommendations are applicable in our case studies since they have been selected due to the construction properties of the buildings and the limitations of rehabilitation in the old urban areas of Coimbra. In order to know the answer to the question: how much each one of these solutions is effective? Firstly, the recommended solutions have been added to the modeled building by DB software. After that, the obtained results of comfort, air infiltration and air distribution for each one of the different recommendations have been compared to find the best solutions in each case study and then it is possible to answer the above-mentioned question. The following table (Table 28) shows all the recommended solutions proposed and their identification.

Table 28: List of recommended solutions for improving natural ventilation effectiveness

Recommendation		**Detail**	**Description**	**Identifying Code**
Opening configuration	Side-hung		The original configuration was kept and the glass has been changed from single glazing to double glazing.	O-S
	Bottom-hung		Double glazing window with bottom-hung configuration.	O-B
	Top-hung		Double glazing window with top-hung configuration.	O-T
	New-configuration		New design window which was already explained in section 6.4.1.5 and 6.4.1.6.	O-N
Shading (Side-fin)	Side-hung with side-fin		The original configuration has been kept and besides changing the window glazing from single to double, a side fins has been added.	S-S
	Bottom-hung with side-fin		Double glazing window with bottom-hung configuration and side-fins.	S-B
	Top-hung with side-fin		Double glazing window with top-hung configuration and side-fins.	S-T

Continued *Table 28: List of recommended solutions for improving natural ventilation effectiveness*

Recommendation		**Detail**	**Description**	**Identifying Code**
Shading (Side-fin)	New - configuration with side-fin		New design window which has been already explained with a side-fins.	S-N
Air-vent opening around the windows	Top of the window		Double glazing window with an air-vent at the top of the window. The configuration of the window is the original one.	AV-T
	Bottom of the window		Double glazing window with an air-vent at the bottom of the window. The configuration of the window is the original one.	AV-B
Skylight (roof window)	Bigger skylight (roof window)		Increase of the size of the roof-window to have more extraction air.	RW
Outlet size	Bigger Outlet		The size of the outlet has increased in order to extract the air better and thus leads to more air velocity in the interior space.	B-O

However, due to the existing characteristics of the case studies, some of these recommendations are only applicable in some cases. For example, the new opening configurations (O-N, S-N) are based on two different ideas: double windows with/without side-fin or ventilated single window with/ without side-fins which have been illustrated in sections 6.4.1.5 and 6.4.1.6. The building characteristics determine which one of the two solutions should be used: double window or single window.

The main topic proposed in this section is changing the windows of the buildings. The original windows are single glazed windows with wooden frames with a U-value of 5.1 W/(m^2. ◦C) and the proposal is the use two different types of windows. The first one is a normal double glazed window with a wooden frame that has a U-value of 3.3 W/(m^2. ◦C) and the second one is a double window with a wooden frame that has a U-value of 1.8 W/(m^2. ◦C).

The skylight and the change of outlet are also solutions which are possible to use only in two of the case studies. It can be concluded that the proposed solutions will not be the same for all the case studies. According to the characteristics of each building, the proposal of rehabilitation solutions will be differed. In the following, for each one of the case studies, firstly a detailed explanation will be added, showing exactly the solutions proposed and then the obtained results of the simulations of the buildings by DB will be presented.

6.4.2.1 Comparison of effectiveness of solutions in the first and second case studies

First and second case studies are two apartments located at the same building (in the third and fourth floors) benefiting from double-side natural ventilation. The results of the proposed changes, based on the applied recommendations, are divided into two parts. The first part is the result of recommendations in one apartment (apartment in the third floor) regarding comfort and infiltration changes because they have the near condition and results, then second part refers to the results of changes in the whole building concerning the air circulation and CFD simulation.

- Analysis of changes in comfort condition and infiltration of building after applying recommendations:

Due to the double-side natural ventilation in this building and in order to improve its ventilation system concerning the circulation, air distribution, infiltration, as well as air permeability, some recommended solutions from Section 6.4.1 have been selected:

1- Opening configuration:

Based on current conditions of the building such as air circulation and airflow in/out (inflow and outflow), as well as limitations of this urban area, different existing opening configurations with the same size and orientation was studied and were presented in Figure 108. In order to find the effect of these opening configurations on the ventilation effectiveness, the four configurations that were already presented in Table 28, were simulated in the modeled building by DB and their effects on the ventilation were analyzed.

2- Shading devices (Side-fins):

As it has already been mentioned, side-fin are used to increase airflow supplying to the interior spaces in the summer time. Since these fins are only needed in the summer time, they can be used as movable fins in summer, it would be possible to disassemble them during winter time.

3- Ventilated single window:

Another idea which could be applicable in these two case studies is a ventilated single window. It means that there is just a double glazing window with two controllable air-vent at its top and bottom (this recommendation has called in the figures and analysis of this case study as the new configuration). Based on this idea, the window will be opened for ventilation in the summer time and it works as a normal window, but in order to avoid over-ventilation (hyperventilation) and increment of energy consumption in the winter period, the air-vents will be used to change the interior air. This recommendation (ventilated single window) is applicable in these two case studies. Figure 117 showed a general sketch of this window.
Figure 118 shows the original windows of this building which are at the origin of the choice of a ventilated single window (there is no space between the window and the wooden door to install another window).

4- Air-vent at top or bottom of the window:

According to the presented information about the air-vent (section 6.4.1.2) and also based on the theories of ventilation, the next recommendation is to analyze the effect of air-vent on the ventilation of this building. Hence, the existing configuration of the window has been kept while the simple glazing was replaced by a double glazing and an air-vent at the top or bottom of the window was inserted. The location of these air-vents depends on the location of the window, if the window works as an inlet, the air-vent would be located at the bottom of the window and if the window works as an outlet, it would be located at the top of window. This placement of air- vent was done based on the presented information on chapter 2 and 3.

Figure 118: Window properties in the case studies of 1 and 2

Therefore, all these selected recommendations have been introduced in the modeled building by DB and then it has been re-simulated to find the effects of these changes on the comfort and infiltration of the building. It should be mentioned that all the recommendations are intervention solutions in the building ventilation and without using a proper solution the building would be too tight, which it would be a weak point for the building. The following table (Table 29) shows the list of selected solutions (recommendations) for these two case studies based on the properties of the building.

Table 29: List of selected recommendations in order to use in the first and second case studies

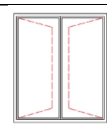
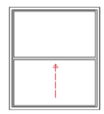
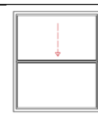
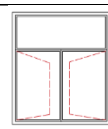
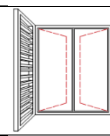
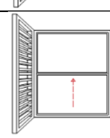
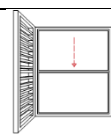
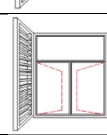
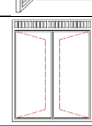
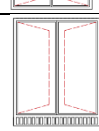
Recommendation		**Detail**	**Description**	**Identifying Code**
Opening configuration	Side-hung		The original configuration was kept and the glass has been changed from single glazing to double glazing.	O-S
	Bottom-hung		Double glazing window with bottom-hung configuration.	O-B
	Top-hung		Double glazing window with top-hung configuration.	O-T
	New-configuration		New designed window based on the idea of ventilated single window which has already explained in section 6.4.1.6.	O-N
Shading (Side-fin)	Side-hung with side-fin		The original configuration has been kept and besides changing the window glazing from single to double, a side fins has been added.	S-S
	Bottom-hung with side-fin		Double glazing window with bottom-hung configuration and side-fins.	S-B
	Top-hung with side-fin		Double glazing window with top-hung configuration and side-fins.	S-T
	New -configuration with side-fin		New design window which has been already explained with a side-fins.	S-N
Air-vent opening around the windows	Top of the window		Double glazing window with an air-vent at the top of the window. The configuration of the window is the original one.	AV-T
	Bottom of the window		Double glazing window with an air-vent at the bottom of the window. The configuration of the window is the original one.	AV-B

Figure 119 shows the comfort conditions of the apartment on the third floor based on the Fanger PMV model and it can be seen that by changing the configuration of the opening and/or using side-fins, the comfort conditions of the building changes. It should be noticed that, in order to have a precise analysis, the first step should be comparing the existing condition and the (O-S) recommendation with each other, since the difference among these two is related to the U-value and solar factor effect, as the opening configuration is the same. Then it is possible to compare other recommendations with (O-S) recommendation in order to find the effect of changing the configuration on this improvement.

As it is shown in Figure 119, the comfort condition of the building in a whole year, especially from June to September has been changed. Comparison of the existing condition and (O-S) recommendation shows 68% improvement[6]. Comparison of other recommendations with (O-S) shows that the new configuration concerning the idea of ventilated single window with side fins (S-N) has an improvement of 12% comparing with (O-S), followed by the new configuration without side-fin (O-N) with 10% improvement and then side-hung configuration with side-fins (S-S) with the 9% improvement. It means that by adding the side fin to the (O-S) condition, it is possible to improve the building comfort condition based on Fanger PMV up to 9%.

The top-hung with/without side-fins (S-T and O-T) are not proper configurations for this building because their improvement rate comparing with (O-S) recommendation is negative (-27%). However, this negative effect of top hung configuration is related to the location of the apartment on the third floor. In the fourth floor, the worst change belongs to the bottom-hung windows with a negative rate of (-23%) as is presented in Figure 120. The reason about why top-hung in the third floor and bottom-hung in the fourth floor are the worst configurations is based on the theories of ventilation which have been explained in chapter 2 and 3 which means that based on the temperature and pressure difference how airflow supply and extracted from the openings.

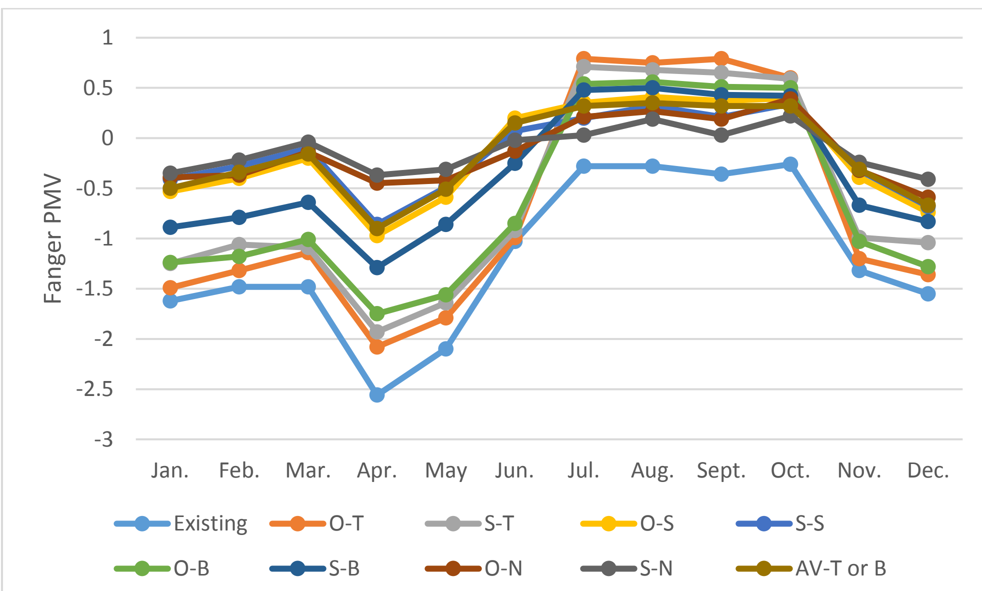


Figure 119: Comfort conditions of the apartment based on the Fanger PMV model - Case study 1

[6] In order to calculate the improvement, the average of Fanger PMV in both cases, (existing and the casa study), was determined based on the whole year. Then the improvement in percent has calculated as follows:

$$Improvment = \left|\frac{Average\ of\ first\ parameter - Average\ of\ second\ parameter}{Average\ of\ first\ parameter}\right| \times 100$$

This methodology was used for all analysis.

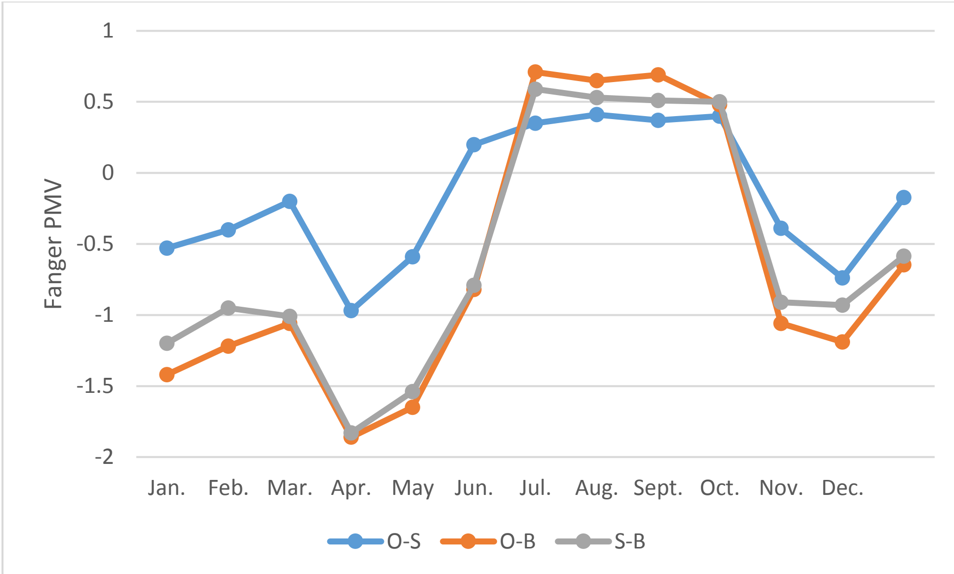


Figure 120: Comparison of O-S configuration with O-B configuration in the fourth floor- Case study 2

Since ventilation effectiveness of the building is related to the infiltration rate, next figure (Figure 121) presents the results of apartment air infiltration. The figure illustrates that, by changing the configuration and adding double glazing windows instead of single glazing windows, the rate of infiltration decreases tremendously which can also affect the energy consumption. Figure 121 shows that (O-S) recommendation has improved the infiltration rate with 82% decrement [7] comparing to the existing condition. Comparison of other recommendations with (O-S) shows that the new configuration based on the ventilated single window without side fins (O-N) has better infiltration rate with 34% improvement comparing to (O-S) and the suggested rate of infiltration due to the Portuguese regulation (REH) can be obtained. The worst case belongs to the top-hung configuration (S-T) with side-fins because it has higher infiltration rate comparing to (O-S).

[7] In order to calculate the improvement, the annual infiltration rate in both cases, (existing and the casa study), was determined. Then the improvement in percent has calculated as follows:

$$Improvment = \left|\frac{Average\ of\ first\ parameter - Average\ of\ second\ parameter}{Average\ of\ first\ parameter}\right| \times 100$$

This methodology was used for all analysis

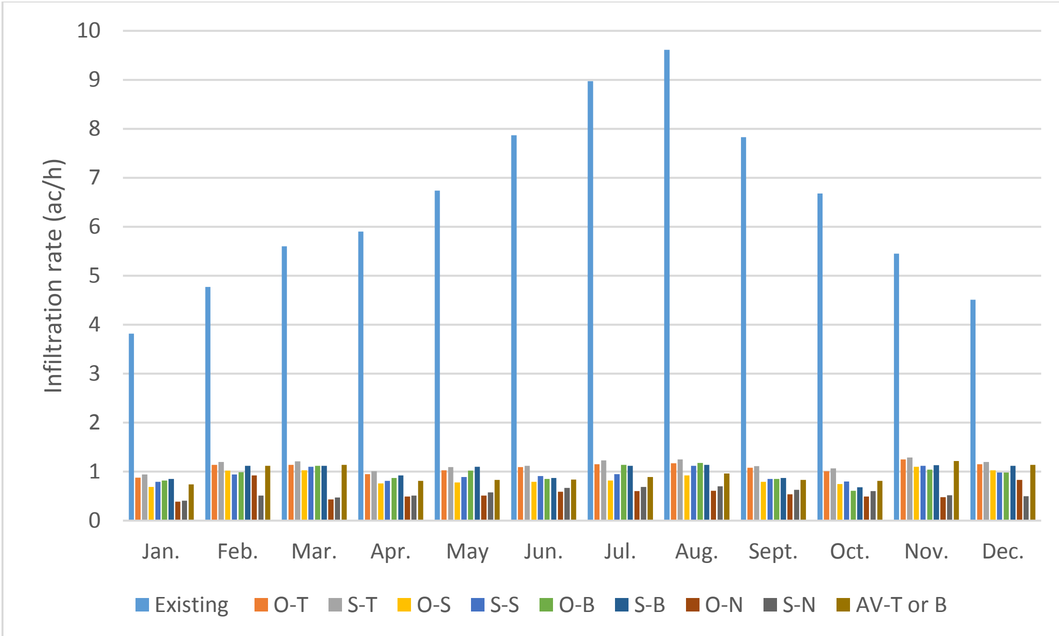


Figure 121: Analysis of the air infiltration rate based on different conditions of opening configurations - Case study 1

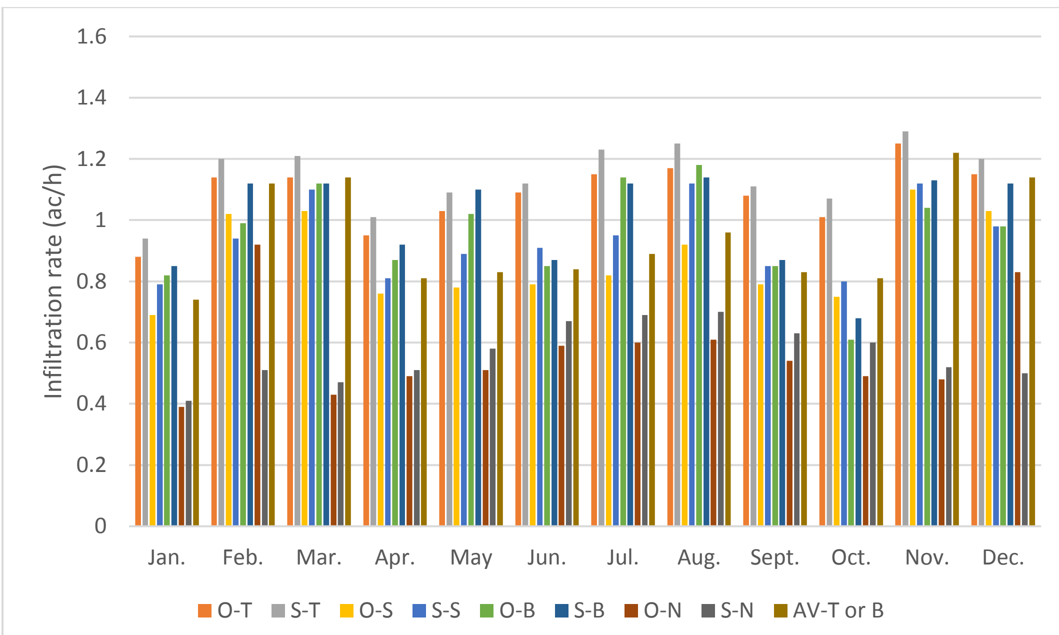


Figure 122: Analysis of the air infiltration rate based on different conditions of opening configurations (with-out existing condition) - Case study 1

Discomfort hours of the building is another factor which is related to the ventilation effectiveness of the building. Figure 123 shows the discomfort hours of the apartment of the different simulated recommendations. The comparison among the existing condition and (O-S) recommendation shows 24% improvement[8].

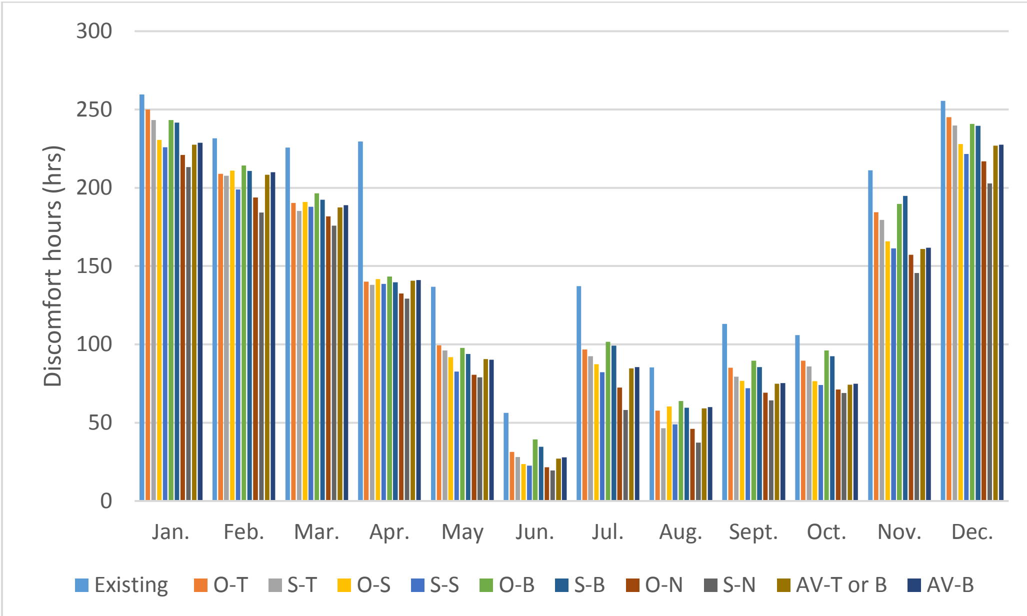


Figure 123: Analysis of discomfort hours in different simulated recommendation - Case study 1

Comparison of (O-S) recommendation with others shows that the new window configuration (S-N) has better effect on decrement of discomfort hours with 27% and it is followed by the new window configuration without side-fins (O-N) with 18% improvement and then the window with side-fins and side-hung configuration (S-S) with 14% decrement. While the top-hung configuration with side-fin (S-T) has not any proper effect on the improvement of condition. Based on these two presented figures (121, 123) the following figure (Figure 124) presents the comparison between the apartment discomfort hours and infiltration rate of the different presented recommendations in whole year.

[8] In order to calculate the improvement, the average of discomfort hours of the building in both cases, (existing and the casa study), was determined based on the whole year. Then the improvement in percent has calculated as follows:

$$Improvment = \left|\frac{Average\ of\ first\ parameter - Average\ of\ second\ parameter}{Average\ of\ first\ parameter}\right| \times 100$$

This methodology was used for all analysis

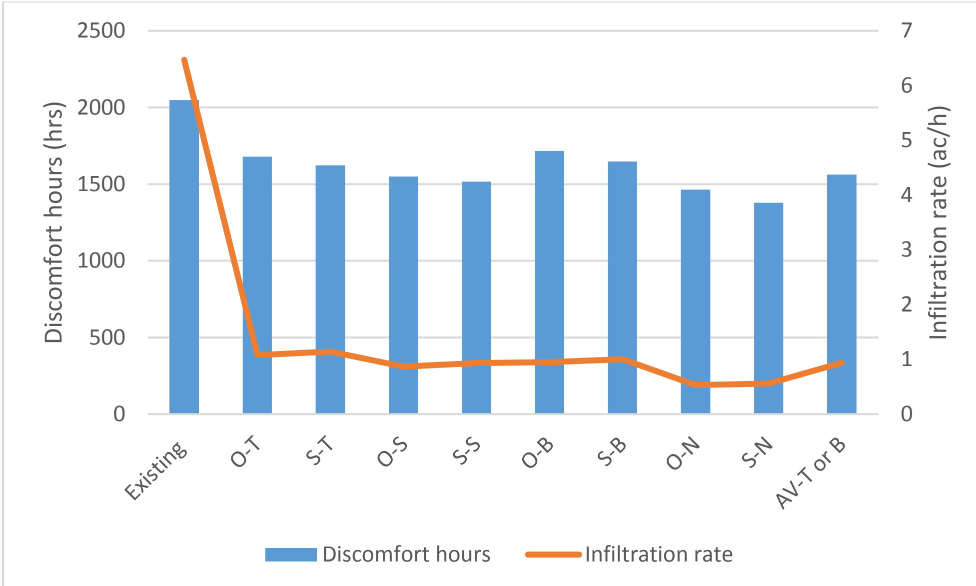
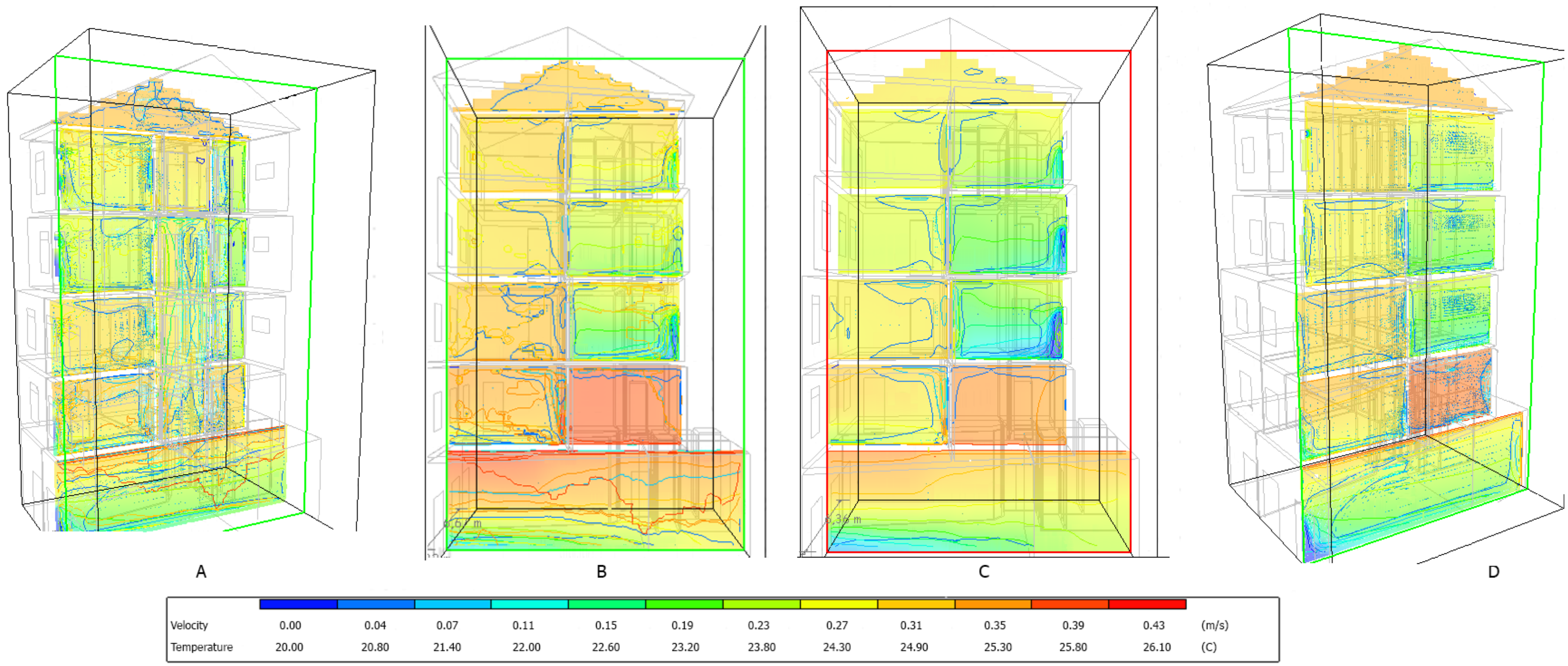


Figure 124: Comparison of discomfort hours and infiltration rate in different simulated recommendations - Case study 1

- Analysis of changes in air circulation and air distribution of the building after applying recommendations:

Other factors that need to be considered are air distribution and air circulation in the building. As presented in Chapter 5 the building intakes the air from outside but due to the problem of airflow in the interior spaces as well as the temperature and pressure difference, air cannot circulate in the interior area and tends to leave from the same opening without properly circulating in the interior area. Therefore, it was intended to improve the ventilation and air circulation in the interior area by changing the opening configurations and using the side-fin, air-vent and etc. Figure 125 shows the results of CFD simulation of the building in different conditions. Based on the changing opening configuration and also having side-fin, a difference between conditions of the air circulation is observed.

Generally, all the recommendations have been simulated by CFD module of DB and the results of air circulation have been found. But as it has been observed that the difference between the cases with the same configuration but with side-fins is very close/not very considerable. For example, the results of the side-hung configuration with/ without side-fins (O-S and S-S) are quite similar. However, it should be noticed that the window's configuration with side-fins has better air movement (airflow and distribution in the interior spaces). Hence, in order to illustrate the air circulation changes based on the suggested recommendations, the next figure (Figure 125) shows the airflow circulation in the interior space of the building in each configuration with side-fins.



From left to right: A. ventilated single window/side-fin (S-N), B. bottom aperture position of the openings/side-fin (S-B), C. side-aperture openings/side-fin (S-S) D. aperture position of the opening at top of the window/side-fin (S-T)

Figure 125: Analysis of the CFD simulation of different recommendations in the selected building – Case study 1 and 2

According to the figure, there is a difference among the air circulation in the interior area in each one of the opening configurations. The new opening configuration (S-N, Figure 125-A) has better air circulation and interior condition in comparison with others. As it has been illustrated, the interior temperature distribution in most of the spaces in (S-N) configuration (Figure 125-A) are between 23.20 to 24.90 ˚C. Since the CFD simulation has been run for a day on July at noon time, it shows that an interior temperature of the maximum 24.90 is not hot and uncomfortable at that time.
The main problem of air circulation in the existing condition was that the air does not circulate at all parts of the room and just circulate at the front of the opening and then it has exhausted from the same opening. After simulating the suggested recommendations in building, it has observed that, the air tends to leave from the same opening, despite of the improvement of interior air distribution and circulation. (Figure 126). In order to improve the above-mentioned problem about air distribution, the ventilated single window as the new configuration (S-N) (Figure 125-A) is better than other configurations. Because in addition using opening of the window to supply airflow, the air-vent at the top and/or bottom could be used to improve air circulation by opening them whenever it is needed. So it takes advantages from air-vent at the top and bottom of the window. However, the air circulation is not effective when the air enters from the top and bottom of opening as it shown in figure 125-B and 125-D. This means that when the window configuration is top-hung or bottom-hung, the air circulation encounters a problem. Next Figure (Figure 126) shows the interior air distribution in this configuration in third and fourth floor.

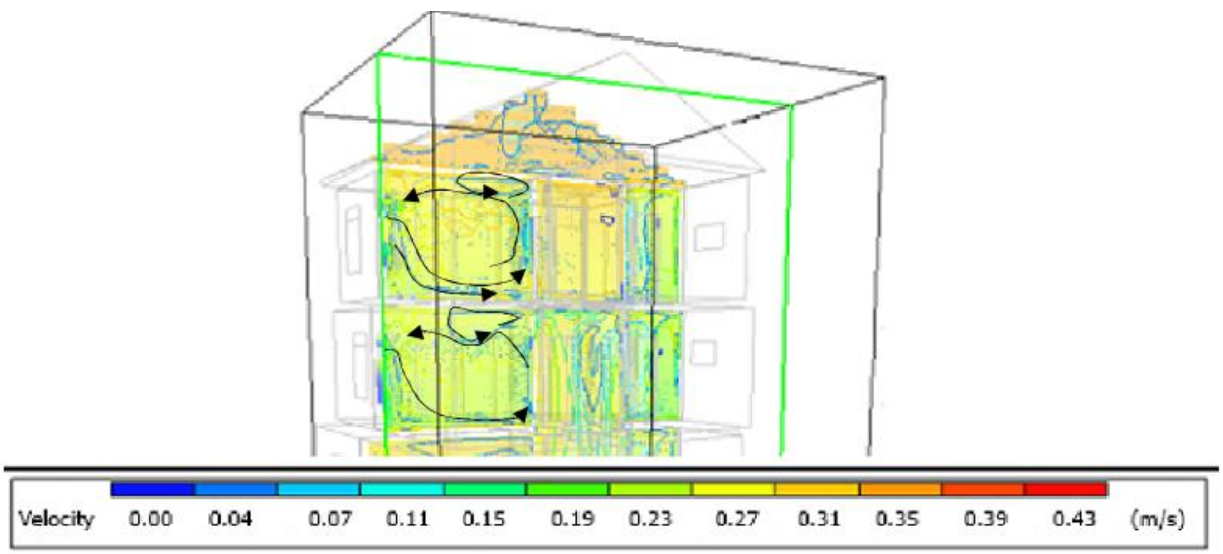


Figure 126: Interior air distribution in the new configuration with side-fins (S-N) - Case study 1 and 2

6.4.2.2 Comparison of effectiveness of solutions in the third case study

The third case study of the research is a residential apartment in a multi-family residential building with a natural ventilation system and which benefits from double side-cross ventilation. Some of the suggested solutions presented in Section 6.4.1 were considered sufficient for this case. Therefore the models of the apartment have been developed based on the selected recommendations for this case study. Then the simulation has been done in order to find the rate of effectiveness of each one of the solutions. In the following, the results of the simulation are presented in two sections of comfort/ infiltration and air circulation/distribution by DB software.

- Analysis of changes in comfort condition and infiltration of the apartment after applying recommendations:

Based on the double side-cross ventilation and properties of the construction of the building, some of the presented solutions in section 6.4.1 are appropriate for this case and are explained:

1- Opening configuration:

As already explained in section 6.4.1.1, due to the existing condition of the building, existing configuration in the selected area (old part of Coimbra city) which has been presented in Figure 108, and also the limitations of the urban area, different presented configurations of the window in Table 28 has been selected as the recommendations to improve ventilation effectiveness. But the question is, how much are they effective in this case study? In order to answer this question, the simulation of each one of the configuration should be done by DB software.

2- Shading devices (Side-fins):

More information about the aim of side-fin was already explained in section 6.4.1.4 and 6.4.2.1.

3- Double windows:

Based on the existing building properties and also the existence of the wooden protector door behind of the window, the idea of double windows which has been already presented in section 6.4.1.5 and Figure 116, will be used to improve the ventilation effectiveness of this apartment. The original condition of the windows of the apartment is presented in Figure 127. According to this figure, the main concept of this new window was developed based on the air layer between the window and wooden protector door. In order to preserve the building characteristics, the wooden door has been kept and just installed after the second window in the interior side.

Figure 127: Properties of the original window- Case study 3

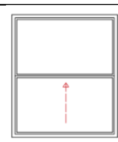
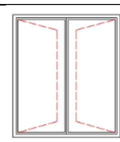
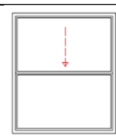
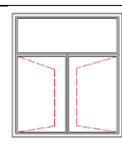
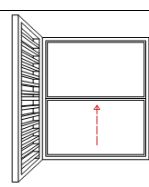
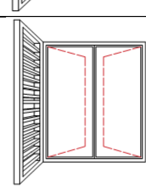
4- Air-vent at top or bottom of the window:

Based on the presented information about the air-vent in section 6.4.1.2, another recommendation to analyze the effect of air-vent on the ventilation of this apartment is to utilize the air-vent at the top or bottom of the window. Hence, the existing configuration of the window has been kept while the window is a double glazing with an air-vent at the top or bottom of the window. The location of this air-vent depends on the location of the window. If the window works as the inlet, the air-vent was located at the bottom of the window and for outlet opening, it is located at the top of the window.

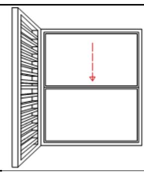
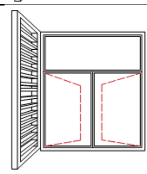
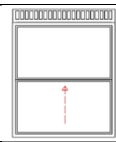
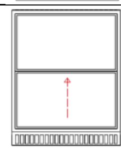
5- Size of the outlet:

Based on the theories of ventilation which were presented in Chapter 2, in order to have more efficient double side / cross ventilation, the outlet should be bigger than the inlet. Hence, the next change which is done in this apartment is about the size of the outlet. Since the outlet opening of the building is located in the interior area of the corridor and because this corridor is connected to the exterior area, it is possible to change the outlet and use a bigger one. There are not any limitation for changing the size because it does not effect on the building appearance. More information about the method of calculation of the size to make it bigger is presented in Appendix 2.
In conclusion, the mentioned recommendations have been inserted in the modeled building in DB and after that, the models were re-simulated to find their effects on the energy and IAQ results. The following table (Table 30) shows the list of selected solution as the recommendation for this case.

Table 30: List of selected recommendations in order to use in the third case study

Recommendation		**Detail**	**Description**	**Identifying Code**
Opening configuration	Bottom-hung		The original configuration was kept and the glass has been changed from single glazing to double glazing.	O-B
	Side-hung		Double glazing window with side-hung configuration.	O-S
	Top-hung		Double glazing window with top-hung configuration.	O-T
	New-configuration		This is a new window configuration based on the idea of double window. (More information in 6.4.1.5).	O-N
Shading (Side-fin)	Bottom-hung with side-fin		The original configuration has been kept and besides changing the window glazing from single to double, a side fins has been added.	S-B
	Side-hung with side-fin		Double glazing window with side -hung configuration and side-fins.	S-S

***Continued** Table 30: List of selected recommendations in order to use in the third case study*

Recommendation		**Detail**	**Description**	**Identifying Code**
Shading (Side-fin)	Side-hung with side-fin		Double glazing window with top-hung configuration and side-fins.	S-T
	New - configuration with side-fin		New design window which has been already explained with a side-fins.	S-N
Air-vent opening around the windows	Top of the window		Double glazing window with an air-vent at the top of the window. The configuration of the window is the original one.	AV-T
	Bottom of the window		Double glazing window with an air-vent at the bottom of the window. The configuration of the window is the original one.	AV-B
Size of the outlet	Bigger outlet	The size of the outlet has increased in order to extract the air better and thus leads to more air velocity in the interior space.		B-O

As previously explained, in order to have a better analysis, initially the existing condition of the building should be compared with the (O-B) recommendation which has the original configuration and only the window changed from single glazing to double glazing. The amount of changes in this first comparison will be neglected while it is related to the U-value and other factors which are not about the aim of this research. After that, other recommendations can be compared with (O-B) in order to find the effect of an opening configuration in the interior condition of the building.

Figure 128 shows the comfort conditions of the building based on the Fanger PMV rate. As it is seen in the mentioned figure, the (O-B) recommendation improved the Fanger comfort rate up to 56% in comparison with the existing condition.

Comparison of other recommendations with (O-B) shows that the building has more comfortable situations/conditions based on the side-hung configuration with side-fins (S-S) with 66% improvement compare to the (O-B) recommendation. And it follows with the new configuration of the window with side-fins which is based on the idea of the double window (S-N) with 53% improvement. However, in some specific periods like July to September, window with (AV-T or B) configuration also have an improvement of 18% compare to (O-B) configuration.

The changes among different solutions show that the worst case belongs to the bigger outlet (B-O) with a negative effect because it has the same inlet as existing condition and just the outlet has been changed. The results also show that the existing configuration is not proper for ventilation and air circulation in this apartment. Therefore, keeping the inlet configuration and changing the size of the outlet, will not be an effective solution.

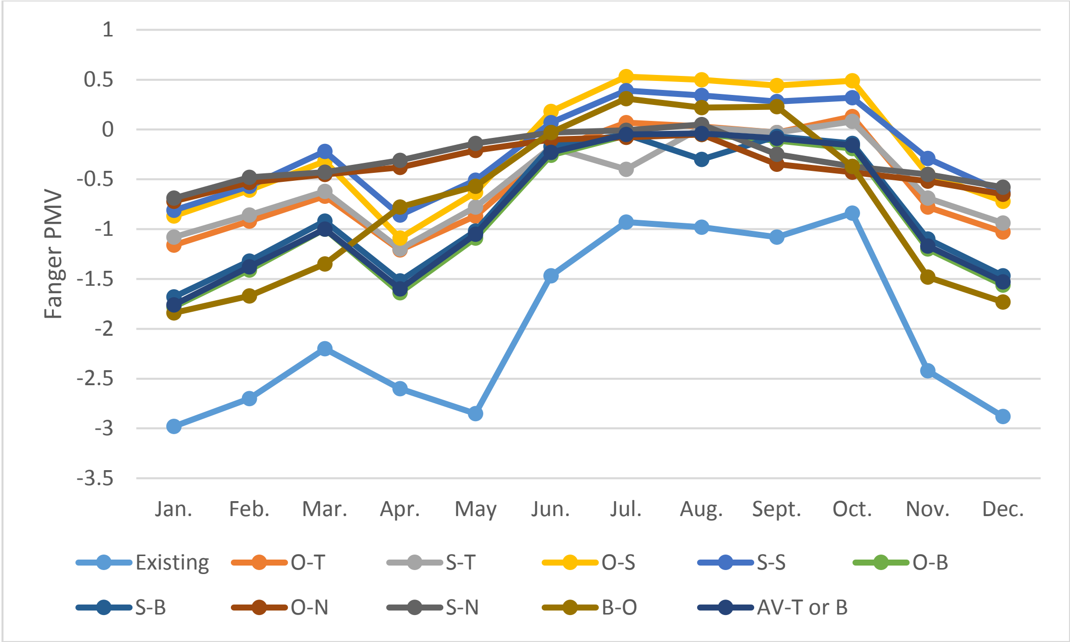


Figure 128: Analysis of comfort conditions of the building based on Fanger PMV model for different recommended solutions - Case study 3

The air change rate of the building is analyzed in Figure 129 which shows that the bottom-hung configuration (O-B) has improved the infiltration rate of the apartment up to 35 % in comparison with the existing condition. After that, in order to compare the effect of the other recommendations, their results were compared with (O-B). This comparison shows that the building with side-hung configuration with side-fins (S-S) has better permeability and infiltration rate while it has decreased the infiltration rate up to 60% in compare with (O-B) recommendation. It follows with the new configuration of the window with side-fins (double window (S-N)) with 54% improvement. However, sometimes the window by top-hung configuration (O-T) has a negative effect on the improvement process.

Another important factor which should be considered in this case study is the hours of discomfort during the year. It helps to know how much the solutions for the natural ventilation system are effective. Figure 130 shows this factor and its change in different recommended solutions. According to the presented figure, the (O-B) configuration decreased the discomfort hours up to 84% in comparison with the existing condition. However, this change is also related to changing the U-value of the window. In order to consider the effect of opening configuration and the selected recommendations on the improvement of discomfort hours, the next step is to compare (O-B) recommendation results with others. To do so, the comparison shows that the new window configuration with side-fins (S-N) with 40% improvement is working better than O-B. New configuration without side-fins (O-N) with 37% and then side-hung configuration with side-fins (S-S) with 35% improvement are also better than (O-B) recommendation.

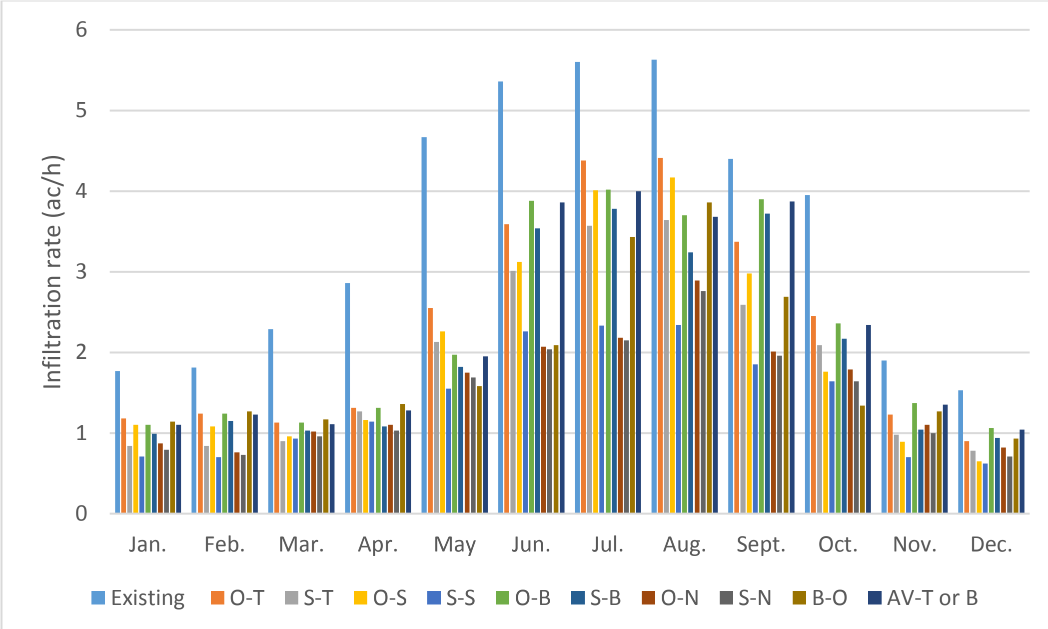


Figure 129: Analysis of air infiltration- Case study 3

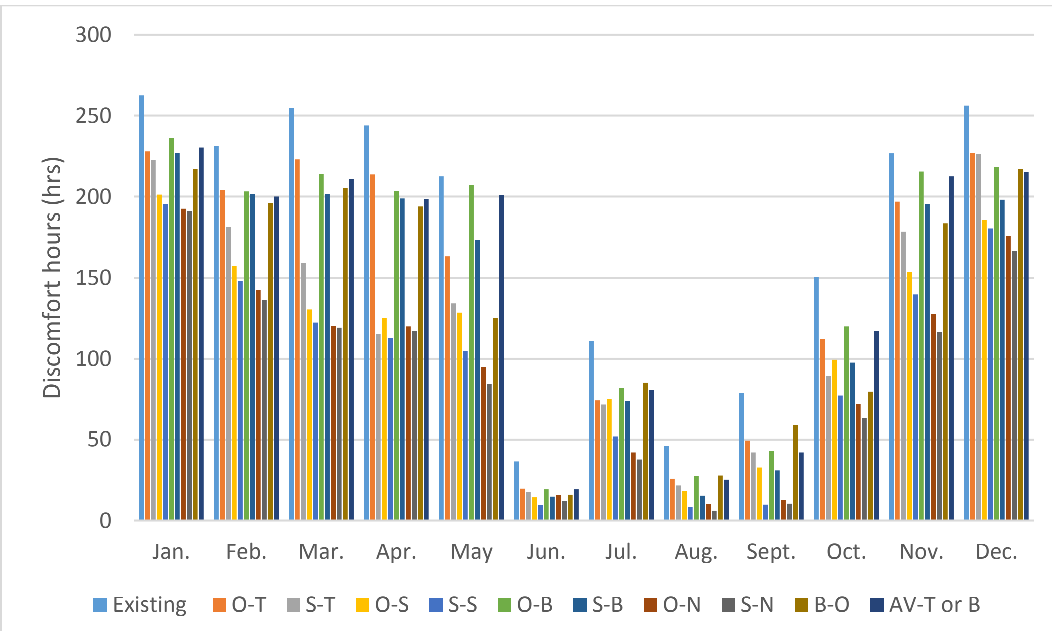


Figure 130: Analysis of the discomfort hours of different recommended solutions- Case study 3

According to the presented information in Figures (129, and 130), it is possible to find a relation among the discomfort hours of the apartment and infiltration rate. To do so, the rate of discomfort hours as well as infiltration rate in a yearly simulation of DB, has been found. After that, the correlation between these two factors is presented in Figure 131.

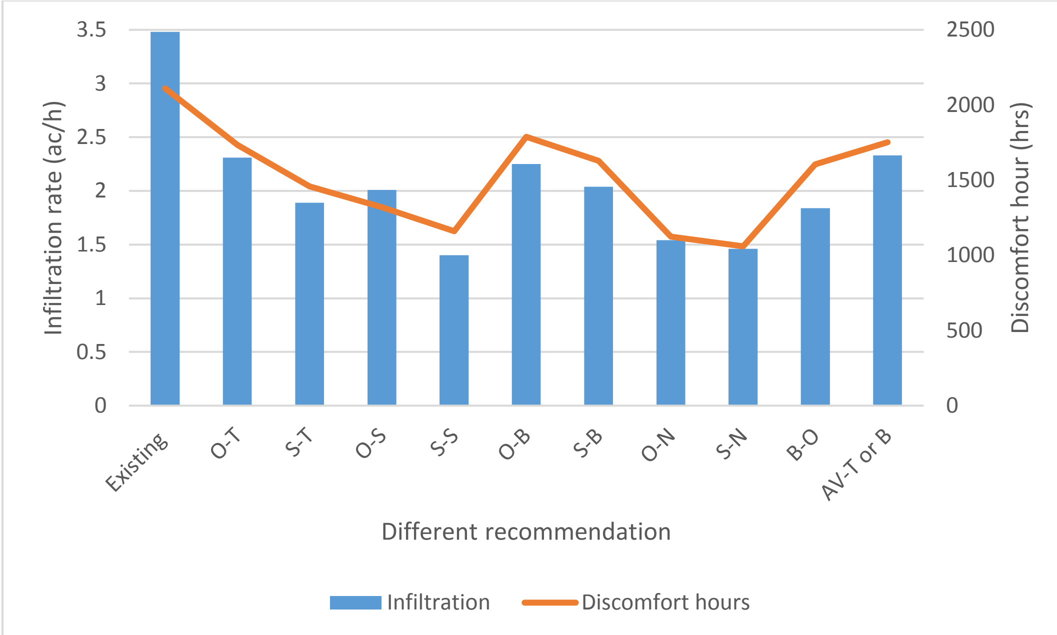
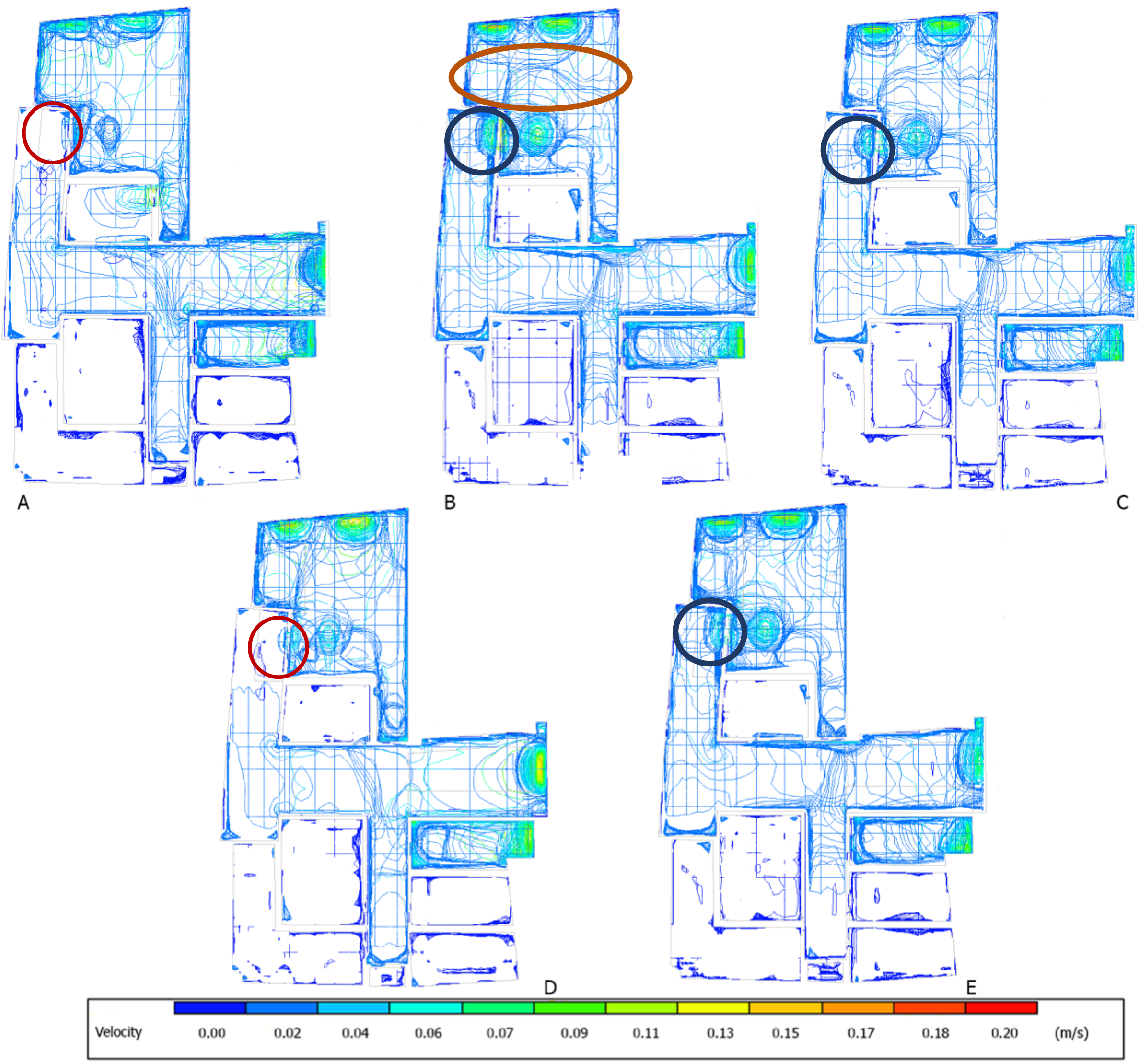


Figure 131: Cross analysis of infiltration rate and discomfort hours in all recommended solutions- Case study 3

According to the presented figure, there is a direct correlation between infiltration rate and discomfort hours of the building. It means that by an increment of infiltration rate, discomfort hours of the building also increases.

- The analysis of building´s changes in air circulation and air distribution after applying recommendations:

Subject to the idea of ventilation and air circulation analysis, CFD simulation of the suggested recommendations has been done by using DB software. The existing condition of the apartment presented in Chapter 5 shows that the apartment encounters an air distribution problem where air tends to go out from the inlet opening despite the cross ventilation system of the apartment. Based on the recommended solutions, they will be analyzed to determine how the selected solutions are effective and how the air is distributed in each one of them. Comparison of different configurations in Figure 132 shows that the problem of exhausting the air by outlet has remained (Figure 132-A and 132-D). The presented red circle shows the location of outlet in this apartment and the air should be exhaust from this opening based on the double side-cross ventilation strategy. However, it has not happened in these two configurations (Figure 132-A and 132-D). On the other hand, other configurations illustrate that the outlet opening is working for exhaust the air. Because it is showed some air distribution behind of the outlet opening in the corridor (dark blue circle in figures 132-B, 132-C, and 132-E).



A: bottom-hung with side-fin (S-B), B: top- hung with side-fin (S-T), C: side-hung with side-fin (S-S), D: bigger outlet (B-O), and E: new window configuration with side fin (S-N).

Figure 132: Analysis of the air distribution in the interior spaces due to different suggested solutions- Case study 3

Among the three remained configurations of (132-B, 134-C, 132-E), the Figure 132-B shows that the air distribution of top-hung configuration with side-fins has another problem; there is a disturbance in the air circulation in front of the window and middle of the room. As it has highlighted with a brawn circle. However, by using the side-hung aperture with side-fin (S-S) (Figure 132-C) and new configuration of the window with the side-fins (S-N) (Figure 132-E), the air extracts from the outlet opening and the ventilation system works better. In order to find the process of air distribution and circulation in the new configuration (S-N), next figure (Figure 133) shows it behind of the inlet and outlet openings.

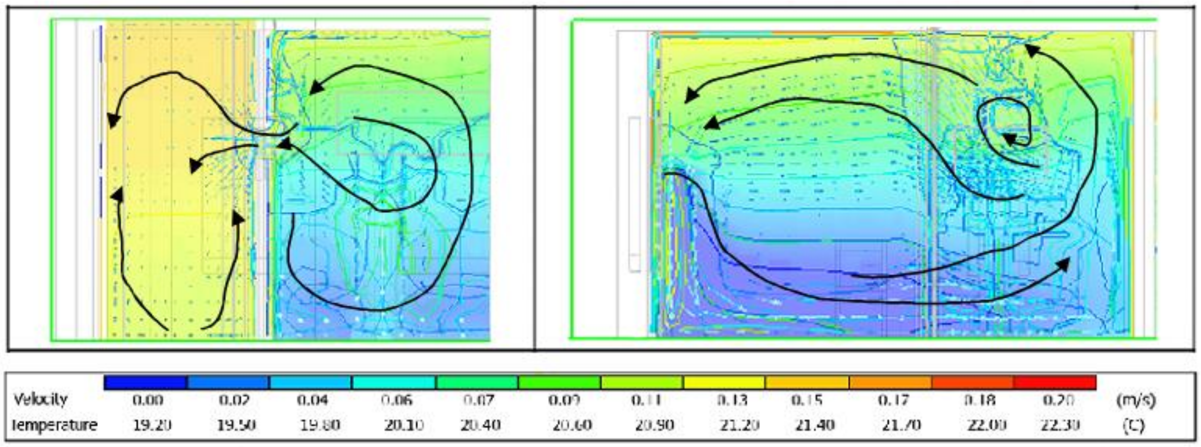


Figure 133: Air circulation in the interior space based on (S-N) configuration- Case study 3

6.4.2.3 Comparison of effectiveness of solutions in the fourth case study

The fourth case study is a single-family residential building with natural ventilation system based on stack ventilation (chimney effect). The building's model was developed based on some of the recommended solutions which presented in Section 6.4.1 in DB software. In order to observe the effectiveness of each one of the recommendations, the obtained results of the DB simulation are presented in two sections of comfort / infiltration, and air circulation by CFD.

- Analysis of changes in comfort condition and air infiltration in the building after applying recommendations:

Based on construction properties of the building, some of the presented recommendations in Section 6.4.1 are selected to improve its ventilation effectiveness. The applied recommendations are:

1- Opening configuration:

The necessary information about this solution has been presented in previous sections. The only important subject is about the original configuration of windows in this building. At the moment the building benefits from the side-hung configuration.

2- Shading devices (Side-fins):

Moveable shading side-fins have also been selected for this case study. The only difference between this building and other buildings is the location of the side-fins. In other buildings, based on the wind direction on the street from the river-side, the side-fins are located at the right-side of the window to catch more airflows and send more airflow to the interior space. In this building, the side-fins are located at the left-side of the opening because the building is located at the end of the street. According to the results of exterior CFD simulation on chapter 5 for this building, the velocity of the air from the river side near to this building is too low. However, there is higher air velocity from opposite side of the street and the building receives more airflows from this side. Therefore the side-fins are located at the left-side of the opening to catch the airflow from another side of the street.

3- Double windows:

More information about this solution was also presented in section 6.4.1.5 and Figure 116.

4- Air vent at the top or bottom of the window:

To implement this recommendation, the original opening configuration (side-hung) has been kept and just the window was changed from single glazing to double glazing. Also based on the presented information in chapter 2 about the airflow direction in the interior spaces, the air-vents are located at the bottom of the windows in the inlet openings and at the top of the windows for outlet openings.

5- Skylight (roof- win):

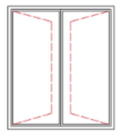
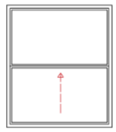
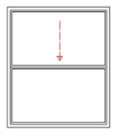
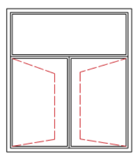
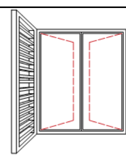
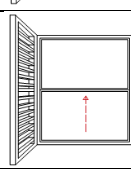
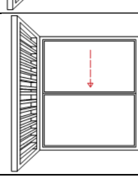
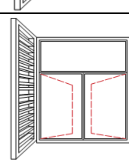
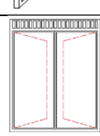
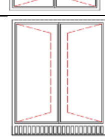
One of the recommended solutions to improve the ventilation of this building is the use of stack effect strategy with a skylight (Roof window). As it has been explained in Section 6.4.1.3, the size and position of the opening influence the air circulation and distribution in the building. The stack ventilation (chimney effect) connects the building through the roof or upper spaces to the outside, which it can be done in two different ways: 1) the first one is using the roof window at the top of an atria or staircase in a single-family house. 2) The second one is using stack ventilation in multi-family houses by using some equipment (Figure 134).

Since the selected case study is a single-family house with a staircase which works as an atrium, it is possible to work on the configuration of the skylight to improve the building ventilation. It is allowed to change the size of the outlet as it does not affect the building appearance. However, if the building is a multi-family house with no atrium space for stack ventilation, there is another way to use the stack- effect. In cases where the use of skylight (Roof window) is not possible, there is a new technology called "SOLATUBE" which is a passive device to be installed in the building to deliver the sunlight through the roof to the interior spaces when the building lacks exterior window. On the other hand, it has the possibility to promote ventilation in the building by stack ventilation solution because there is an air vent joint which connects the interior spaces to the outside by chimney effect (see Figure 134). Since the staircase in this case study benefits from an atrium for the stack ventilation, it is not necessary to install this device to improve the ventilation.

Figure 134: SOLATUBE device [232]

The effectiveness of the ventilation is improved by working on the size and the configuration of the skylight. The changes of the opening size were developed based on the WWR, and more information about it is presented in Appendix 3. Despite changing the opening size, the configuration of the opening should also be changed. Based on the presented information on chapter 2, the outlet opening should be located on the leeward side of the roof in order to help the ventilation system and also to extract the airflow. Hence, based on the illustrated CFD simulation results in chapter 5 for this building and also the condition of pressure distribution over the roof of the building, a skylight (Roof window) has been selected with the top-hung pivot window. Table 31 presents the list of selected recommendations in the fourth case study.

Table 31: List of selected recommendations in order to use in the fourth case study

Recommendation		**Detail**	**Description**	**Identifying Code**
Opening configuration	Side-hung		In this case, the original configuration has kept and just the window has been changed from single glazing to double glazing.	O-S
	Bottom-hung		The Window is a double glazing with Side-hung configuration.	O-B
	Top-hung		The Window is a double glazing with top-hung configuration.	O-T
	New-configuration		This is a new designed window based on the idea of ventilated double layer window which has been explained in section 6.4.1.5.	O-N
Shading (Side-fin)	Side-hung with side-fin		In this case, the original configuration has been kept and besides changing the window glazing from single one to double one, a side fins also is added.	S-S
	Bottom-hung with side-fin		The Window is a double glazing with Side-hung configuration and side-fins.	S-B
	Top-hung with side-fin		The Window is a double glazing with top-hung configuration and side-fins.	S-T
	New-configuration with side-fin		This is a new designed window based on the idea of ventilated double layer window with a side-fins.	S-N
Air-vent opening around the windows	Top of the window		In this case the window is double glazing with an air-vent at top of the window, but the configuration of the window is the original one.	AV-T
	Bottom of the window		In this case the window is double glazing with an air-vent at bottom of the window, but the configuration of the window is the original one.	AV-B
Skylight (window-roof)	Bigger opening	The size of the outlet has been increased in order to have better extraction of the air and more air velocity in the interior space, while its aperture has also been changed.		B-SK

According to the results presented in Figure 135, comfort condition of the building has been changed by different opening configurations. In order to show the effect of recommendations, as was done in other previous buildings, first of all, the exiting condition and side-hung configuration (O-S) recommendation have been compared with each other and then other presented recommendations have been compared with the (O-S) one.

The comparison shows that the comfort condition of the building in the (O-S) configuration in the whole year and especially in the cold months (December to February) and hot Months (June to August) has been changed. The maximum improvement belongs to February with 52% improvement and the minimum improvement belongs to May with 36% improvement while the yearly improvement of (O-S) configuration is 45% in comparison with the original condition. Since the difference between these two conditions is just about changing the window glazing from the single glazing to double glazing, the improvement is related to the changing of U-value and the solar factor of the window.

After that, other recommendations have been compared with (O-S) configuration and the results show that the average improvement of the building is 39% in the new configuration (S-N) while the maximum change in this configuration belongs to August with 50% and the minimum change has happened in January with 21%.

After the (S-N) configuration, the most improvement was verified in the new configuration without side-fins (O-N) with (24%) and then in the side-hung with side-fins (S-S) with 14%. However, the (AV-T or B) configuration has a condition the same as (O-S) configuration in a whole year.

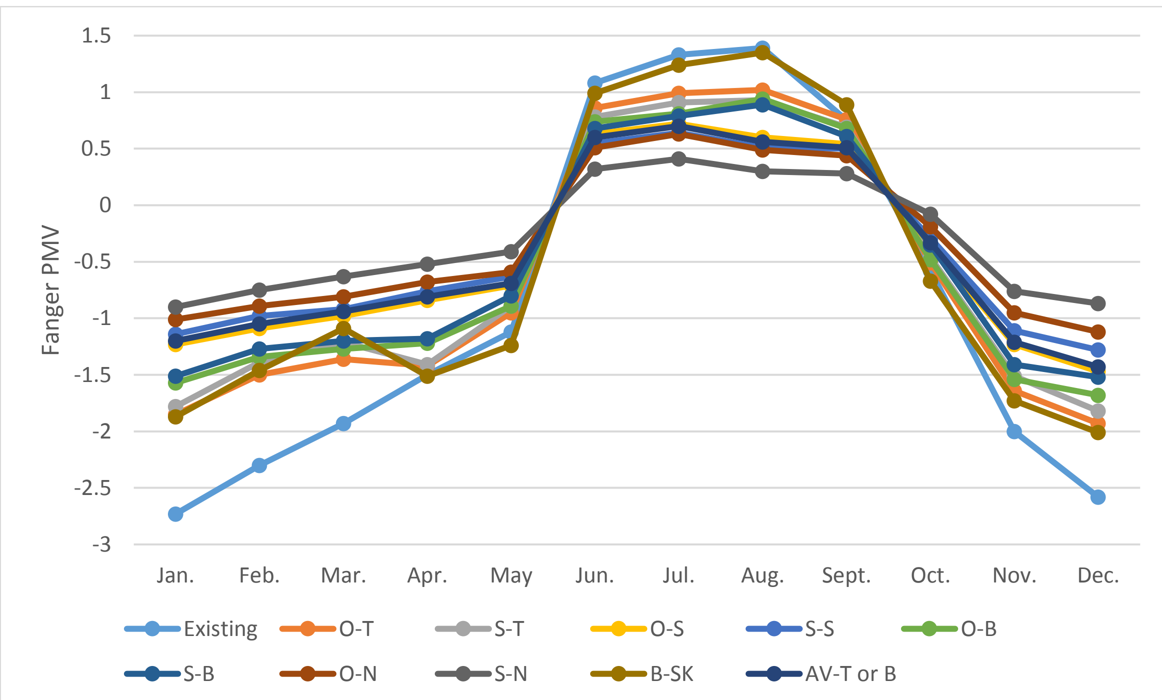


Figure 135: Comparison of Fanger PMV rate based on different recommendations- Case study 4

One of the ideas of this research was to improve the ventilation effectiveness of the building so that resident could feel more comfortable. Therefore, analysis of the discomfort hours of the building and comparison of different conditions are extremely important. Figure 136 shows that by changing the opening configuration and using the ventilated window and/or air-vent, the air circulation of the building has been changed and discomfort hours of the building have also decreased. The figure illustrates that the improvement in (O-S) configuration is 43 % compared with the original condition. This change is related to changing the U-value of the windows. After that, in order to find the effect of opening configuration and other recommendations on the building condition, other simulated recommendations have been compared with the (O-S) configuration.

In terms of discomfort hours, the comparison shows that the improvement in the new configuration with side-fins (S-N) is 21 % in which the maximum rate is 46% in July and the minimum belongs to November with 6.5 %. This improvement is followed by the new configuration without side-fins (O-N) with 13% and then the side-hung configuration with side-fins (S-S) with 6% improvement and finally, openings with air-vent at the top or bottom of the window (AV-T or B) with 4% improvement.

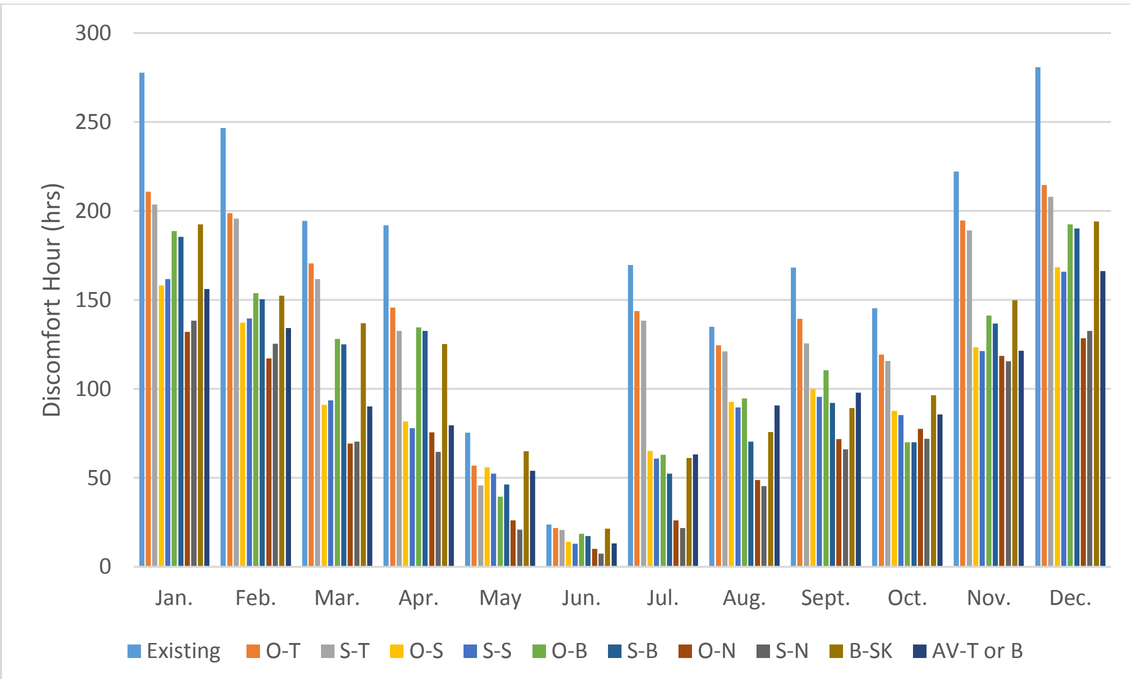


Figure 136: Analysis of discomfort hours of the building based on different recommendations - Case study 4

The improvement of ventilation can be obtained by changing the opening configuration and other recommendations, while the infiltration did not increase. It means that the ventilation, air distribution and circulation not only have been improved, but also a decrement of air change rate has been verified as it is shown in Figure 137.

As the previous analysis, the first comparison has been done on the existing condition and (O-S) recommendation which shows 76% improvement in the infiltration rate in which the maximum improvement has happened in July and August with 83% and the minimum belongs to March with 45%. Then the comparison of others recommendations with (O-S) shows that the best improvement corresponds to 48% in (S-N) recommendation and then with 23% improvement in (O-N) recommendation. Subsequently, 18% improvement has happened in (S-S) recommendation. This reduction in infiltration rate has been obtained with the improvement of air circulation and distribution by changing the opening configuration and using the side-fins.

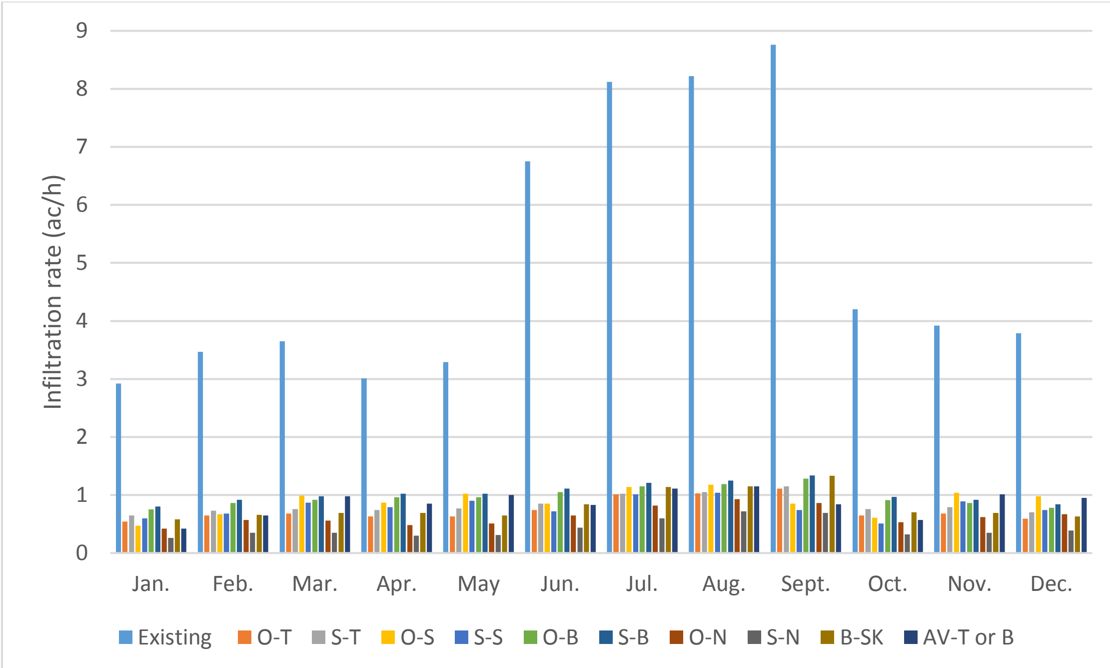


Figure 137: Analysis of the air infiltration of the building based on different simulated recommendations - Case study 4

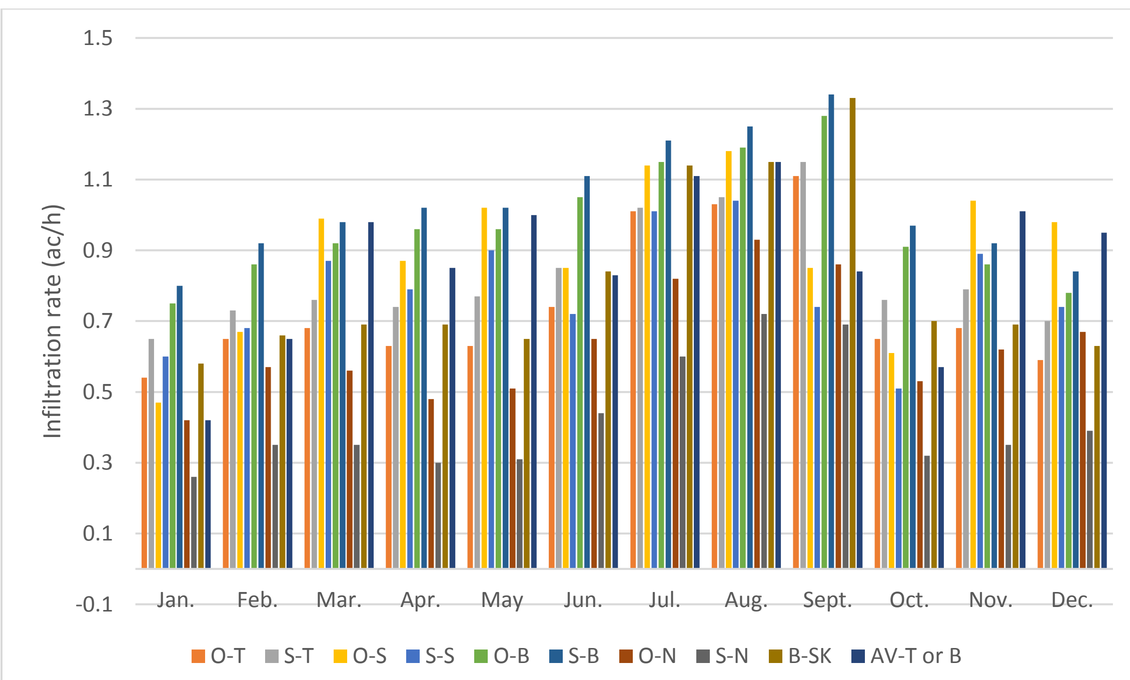


Figure 138: Analysis of the air infiltration of the building based on different simulated recommendations (Without existing condition) - Case study 4

In order to analyze the improvement of the air circulation condition of the building, the airflow in and out (inflow and outflow) of the building has been considered in Figure 139 and Figure 140 to know how much air enters/leaves to and from the building and how much effective were these changes.

The figures show that in all recommendations with side-fins we have better air circulation in the interior spaces regarding the inflow and outflow. As it has been observed, the inflow in the (S-N) configuration has acted better and it is followed by the (O-N), (S-T) configurations. In what concerns to outflow, the (S-N) configuration followed by (B-SK) and (O-N) acts better than other configurations in this building.

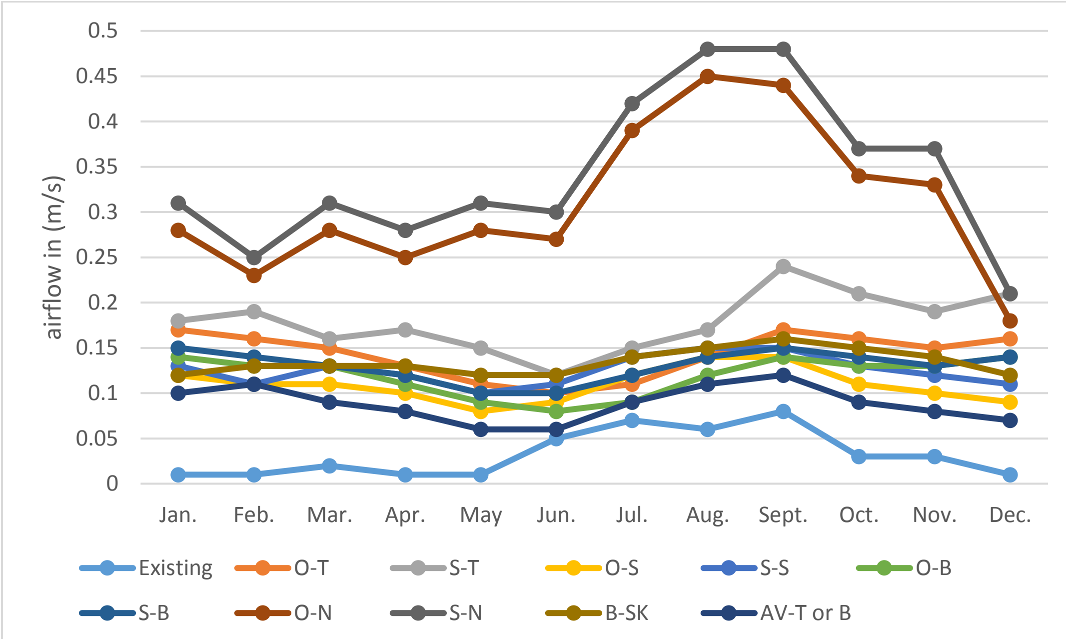


Figure 139: Analysis of inflow through the openings by different configurations - Case study 4

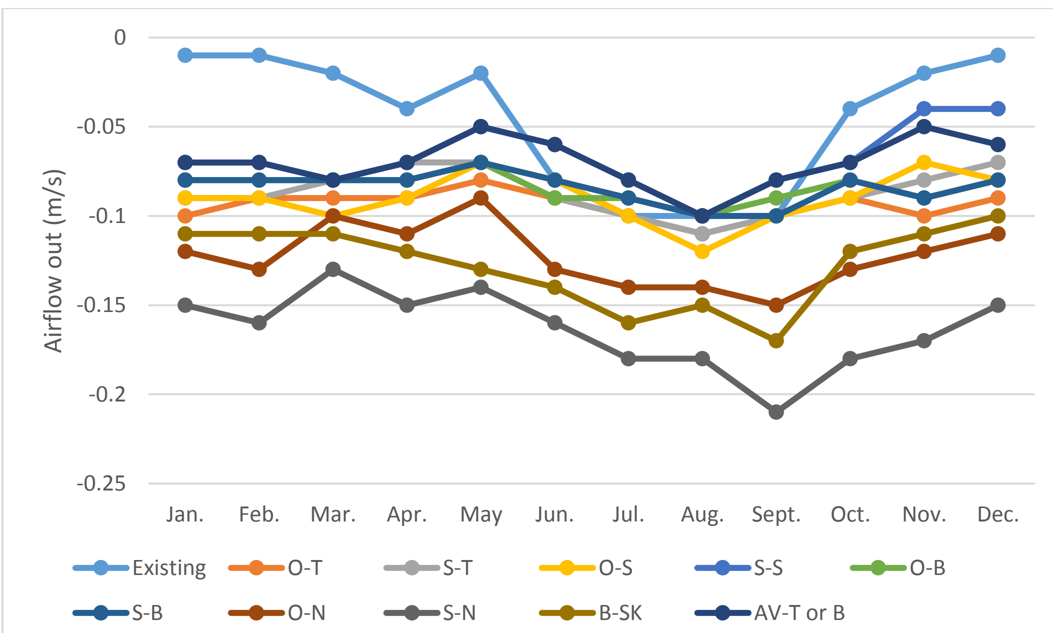


Figure 140: Analysis of outflow through the openings by different configurations - Case study 4

Therefore, it has been observed that by using these recommendations, there are more inflow and outflow in the interior spaces in comparison with the existing condition. But it is necessary to know how does this airflow circulate and distribute in the interior area. Hence, the next section will present the air circulation and distribution of the interior spaces in all suggested recommendations, by using DB simulation.

- Analysis of changes in the air circulation and distribution in the building after applying recommendations:

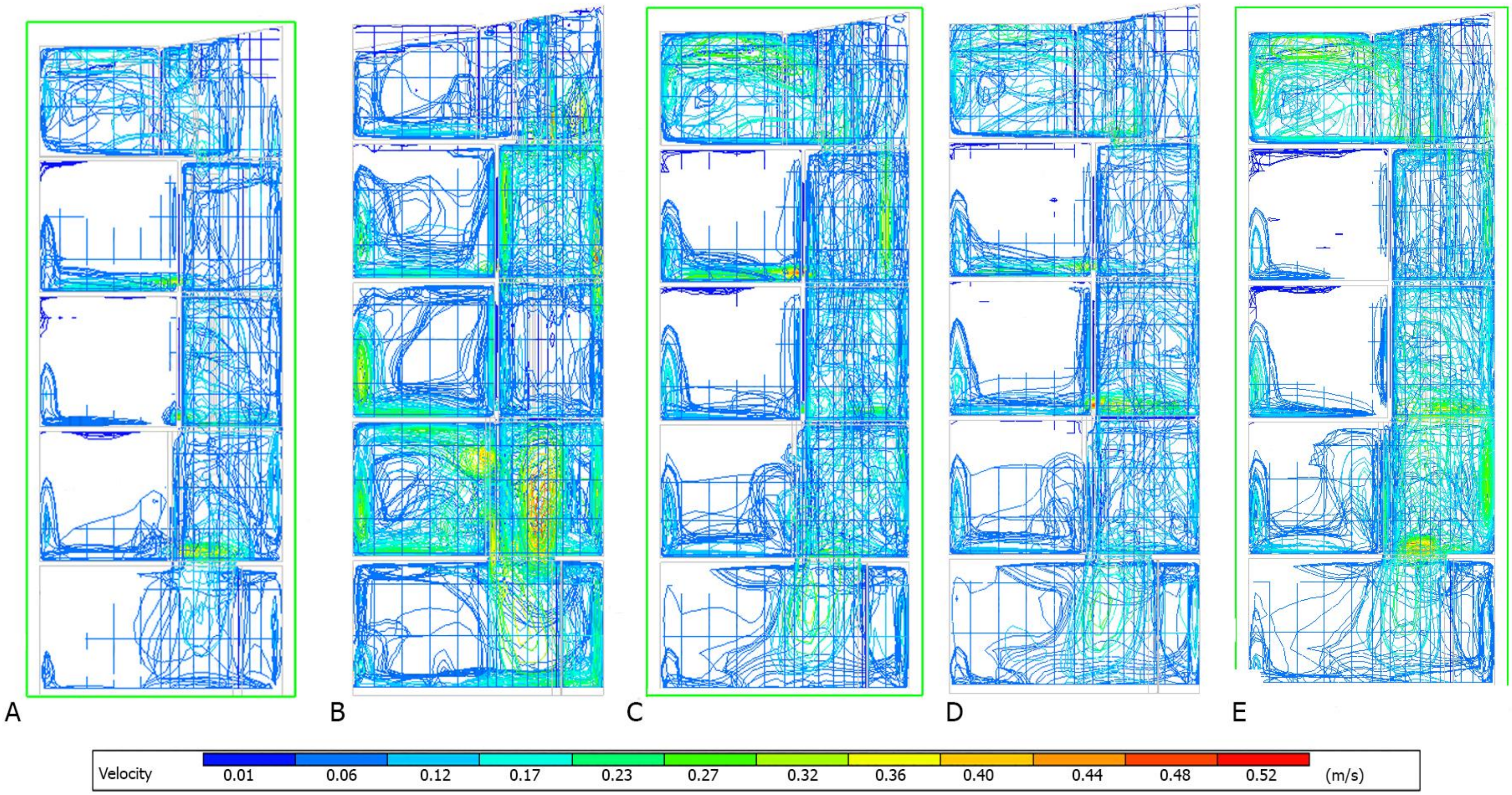
According to the condition of this building, described in chapter 5, the improvement should be considered on the increase of inflow and also on the condition of the outlet, as there exists a problem in the air circulation because air tends to leave through the inlet openings. This is the opposite of stack and cross ventilation in which the air leaves through the outlet openings. Therefore, the aim of this study is to find a solution to improve this condition besides of improvement in the inflow.

To do so, the recommended solutions were simulated in CFD module of DB software to find the air circulation of the building in each one of the recommendations but based on the small difference between the configurations with/without side-fins, the following figure (Figure 141) shows the results of configuration with the side-fins which has more changes and difference.

Figure 141 shows that by changing the opening configuration and using side-fins the air velocity distribution also changes. The higher air velocity in the interior spaces was observed when the top-hung configuration with side-fins (S-T) is used which could be a disturbance. This configuration makes also a perturbation in the air distribution of the room. Because of the entered air from the top of the room, especially in the lower floors, interferes with the interior air as it is presented in the Figure (141-B).

On the other hand, the bigger skylight opening pushes/stacks the airflow from rooms to the staircase (like an atrium) and pushes it from the skylight to the outside (Figure 141-E). Since the last floor does not have a door to separate the room from the staircase, the stacked air on the top of the staircase also goes to the room in the last floor and is extracted by openings in the room besides of the skylight.

The bottom-hung configuration with side-fins (S-B) brings the air in a low height of the building and send it to the outside (staircase) to extract (Figure 141-A). This distribution is not worth because occupants cannot feel comfortable with this low air circulation when they stand up or sit on a chair. However, in the new window configuration with side-fins (S-N) and side-hung configuration with side-fins (S-S) the air has a uniform distribution, namely in higher heights that make a comfortable condition in the entire space at different levels (Figure 141-C, and 141-D).



A: bottom- hung configuration with side-fins (S-B); B: top- hung with side-fins (S-T); C: side- hung configuration with side-fins (S-S); D:New Window Configuration with side-fins (S-N); E: bigger skylight with side-fins besides vertical openings (B-SK).

Figure 141: Analysis of air velocity in the simulated building based on different recommendations- Case study 4

6.5 Discussion, conclusion, and analysis of the best-recommended solutions

All four case studies have been simulated by DB software with different recommendations in order to improve the ventilation effectiveness of the buildings according to the natural ventilation strategies.

Since some of the recommendations were applicable in each building and the results of their effects in the buildings have been presented in Section 6.4, this section is devoted to present and discuss the final simulations of the buildings with the most appropriate recommendations to show the most effective ventilation conditions.

6.5.1 First and second case studies

As the first and second case studies of the research benefit from double-side cross ventilation, the most appropriate recommendations which are selected to realize the most effective condition of the building are:

1- Based on the obtained results, the most appropriate configuration for these case studies is the new window configuration with side-fins (S-N) which is a ventilated single window and it follows by the new window configuration without side-fins (O-N) and then the side-hung configuration with side-fins (S-S). Hence the final suggested model of the building has been modeled with the new window configuration with side-fins (S-N).

2- According to the presented results on Figure 125, the top-hung configuration is better than other configurations for an outlet. However, in order to extract more air, it is recommended to use the air-vent at the top of the outlet. The reason for this position at the top of the outlet opening is because when the air-vent is located at the top height, it stacks the air from the lower height of the building to the higher height and therefore the air crosses more zones of the building in this process.

3- On the other hand, the air-vent at the bottom of the inlet in the first, second, and third floors should be used, while the located air-vent at the top of inlet in these floors could be used if necessary (because there are two air-vents at top and bottom of the ventilated single window). The process for the last floor is reversed. It means that the top air-vent will be used for ventilation and the bottom air-vent is used just in case of necessity. The reason why the first to the third floors use air-vent at the bottom and the last floor uses the air-vent at the top of the window depends on the location of NPL in the building.

Figure 142 shows the process of the building air circulation due to the weather condition and also building properties. This figure shows that when the building air circulation works based on temperature and/or pressure difference, and the internal air temperature is higher than external air temperature ($T_{int} > T_{out}$), the NPL is located at the middle of the building and the process of intake and extract is the one presented in the figure while the ventilation system of the building is a double-side (it is because of temperature difference between lower and upper height of the building or pressure difference between the lower and upper height).

Wind is one of the main factors which helps to provide a better ventilation. Therefore, due to the existing condition of the building and the effect of the wind for optimizing the ventilation, by a combination of these two conditions (existing condition and wind flow), the process of the air supply and extract is similar to Figure 143.

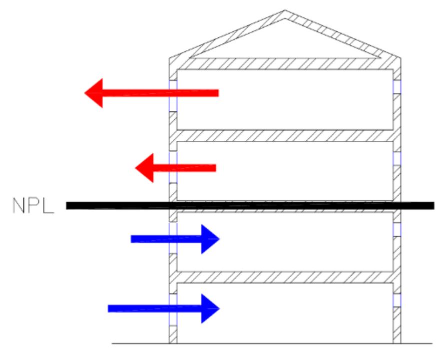


Figure 142: The process of the air supply / extract in the building and position of the NPL - Case study 1 and 2

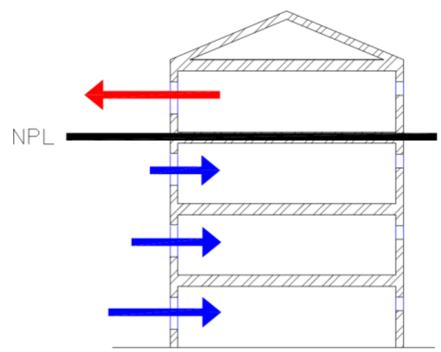


Figure 143: Condition of the air supply / extract by combination of the wind and temperature - Case study 1 and 2

Hence the new window configuration, which has two air-vents at its top and bottom, uses the bottom air-vent in the first three floors to supply the air and the top air-vent in the fourth floor. The second air-vent of the window is used for some especial time as well as heating season in which the process of the air supply and extract reverses and these air-vents are controllable by occupants. Based on all presented information till now, Figure 144 presents a general scheme of opening and air-vent condition in this building.

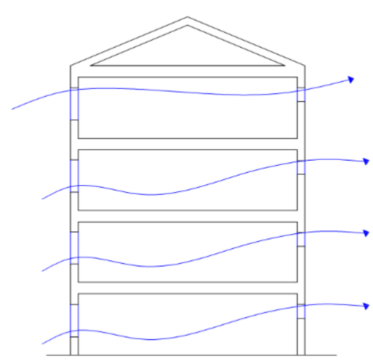


Figure 144: Analysis of the effect of opening and air-vent location on the airflow circulation- Case study 1 and 2

4- Movable side-fin is another selected solution which can be added to the building as it was used in the analysis of recommendations in section 6.4.2.1. It is controlled by occupants during the year. So this side-fin is used to lead more airflow to the interior spaces in the cooling season, while it would be disassembled in the heating season. Figure 145 shows the schematic condition of the final model.

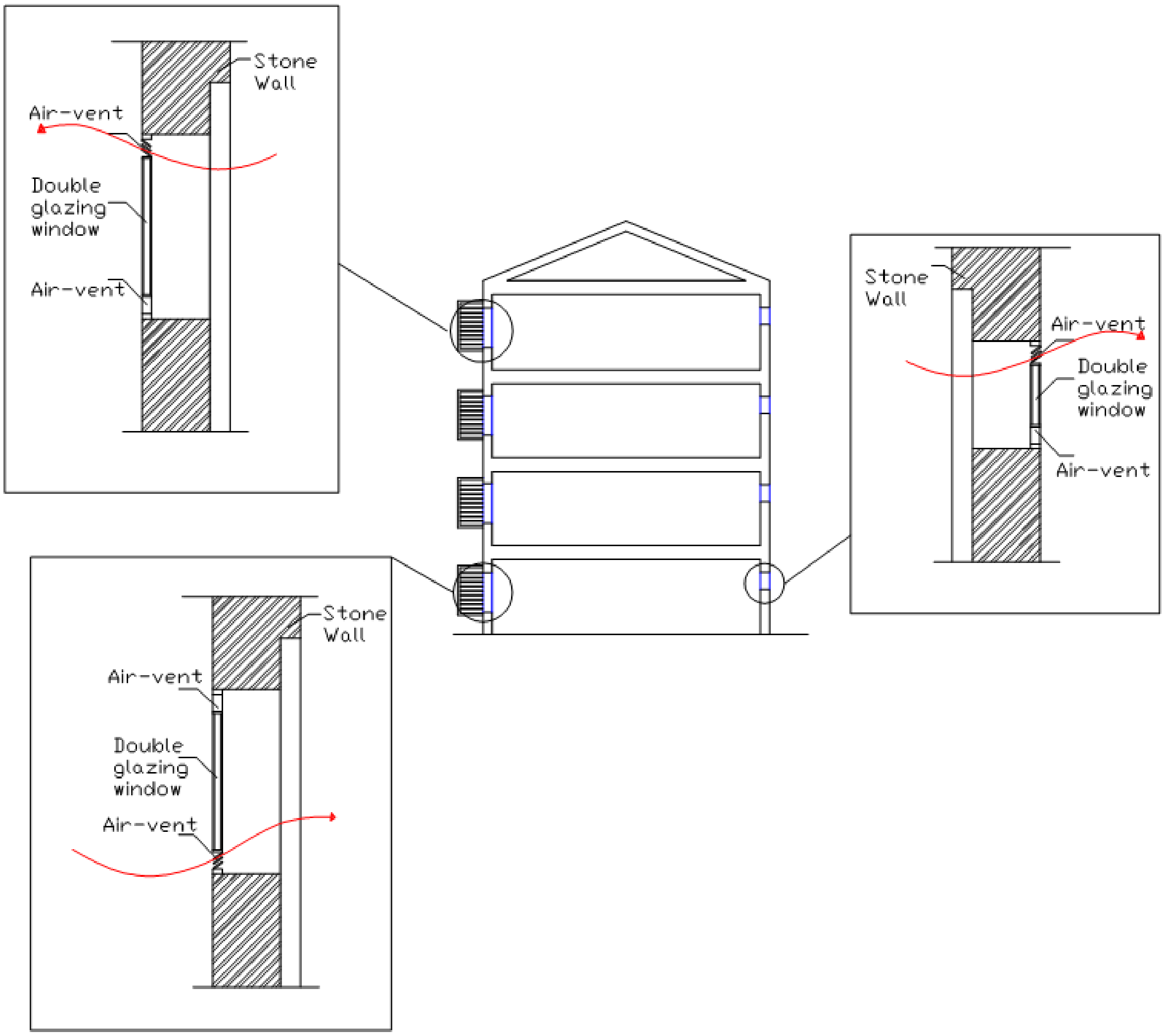


Figure 145: General scheme of final model for the case study of 1and 2

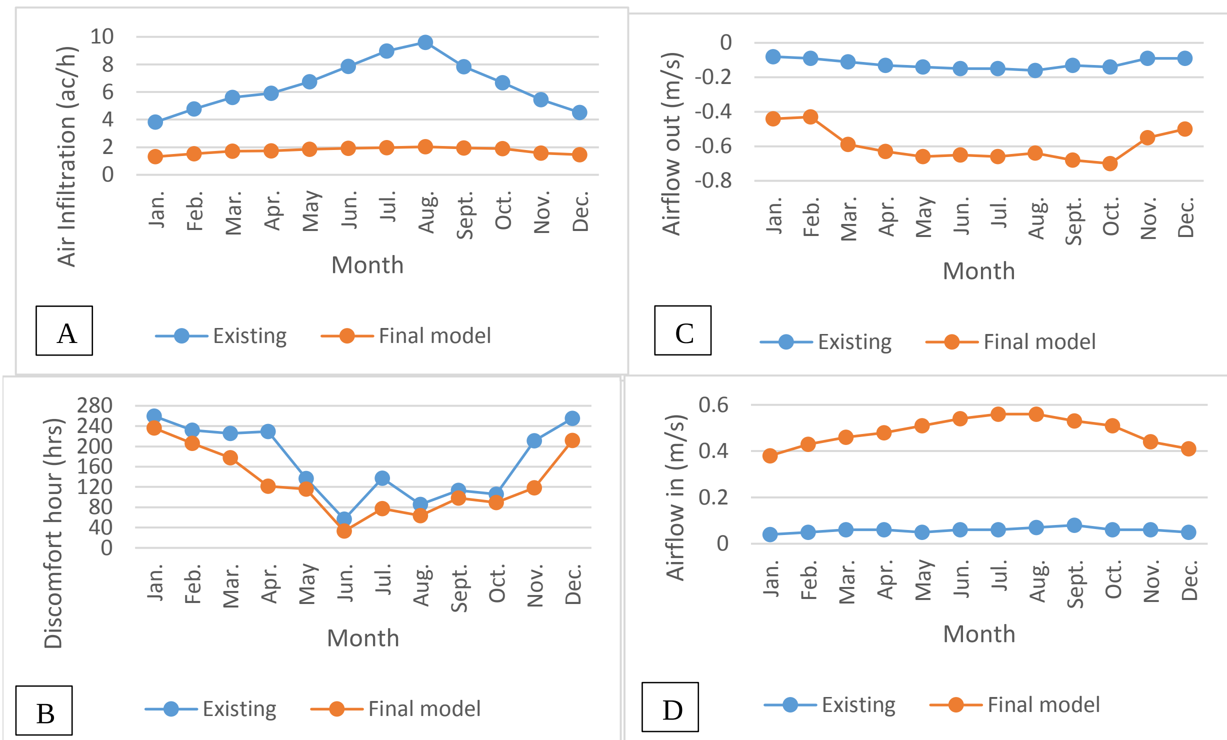
Based on all these information, the suggested model has been developed and re-simulated with DB. The comparison of the suggested and existing model for IAQ, ventilation and comfort is presented in the following. Figure 146 presents the improvement of the existing conditions with suggested models for the first and second case studies.

The analysis of air infiltration is presented in Figure (146-A). It presents that the infiltration rate of the building in the suggested model has improved up to 58% in the winter time and 78% in the summer time in compared with the existing condition.

Discomfort hours is another factor that has been improved in the suggested model. The graph of discomfort hours (figure 146-B) shows that the building model has 27% fewer discomfort hours in the suggested model comparing with the existing building. While the maximum improvement belongs to July with 43% and the minimum improvement was in January with 8%.

Figures (146-C and 146-D) show the comparison of the airflow in/out. It is illustrated that the intake (airflow in) and extracted air (airflow out) in the suggested model of the building have increased about 8 times and 5 times respectively. It means that the air moves/circulates better in the interior spaces and we have more air in the interior area as well as more extracted air. The most increment has happened in July and the less increment belongs to the January. However, the airflow in/out of the building in the existing condition was too low and the occupant felt no air circulation in the interior area which had a negative impact on the natural ventilation condition.

As a conclusion, the ventilation effectiveness of the building has been measured by DB software. It shows that the ACE of the building in the suggested model is 0.81 in the third floor and 0.85 in the furth floor. However, it was 0.17 in the existing condition on the third floor and 0.32 for the fourth floor. Due to the presented information in section 5.3.3.2 about ACE, as much as it closes to 1, the ventilation effectiveness is better. Therefore this increment of ACE in the suggested model justify that by decreasing air infiltration, discomfort hours and increasing of air velocity in the interior area, the building would have a more comfortable condition based on the double-side ventilation system and finally, the improvement of ventilation in the building will happen.



A: Air infiltration, B: Discomfort Hours, C: Airflow out, D: Airflow in

Figure 146: Comparison of existing model with the suggested models - Case study 1 and 2

6.5.2 Third case study

As the third case study of the research takes advantage of double side-cross ventilation, the most effective suggestions for this building according to the presented results in section 6.4.2.2 are:

1- The most proper opening configuration for this building is the new window configuration based on the idea of double window with side-fins (S-N), which has two air-vent at top and bottom of the window and these two air-vents are controllable by occupants (Figure 116). This air-vent is controllable and occupants can open/close it whenever is needed.

2- Based on the (S-N) configuration, the building has side-hung configuration with side-fins for inlets which the side-fins are located on the right side of the opening and are movable based on the interior condition of the building. The reason for using the fins is to conduct more airflow to the interior space based on the problem of lower air velocity in the existing condition.

3- The size of outlets should also be bigger and the configuration for the one which is located in the kitchen is side-hung while it has a top-hung configuration in the bathroom. These configuration has been selected based on the CFD results which is presented in Figure 132.

Figure 147 illustrates a general scheme of the suggested condition in this case study which was designed based on above-mentioned solutions.

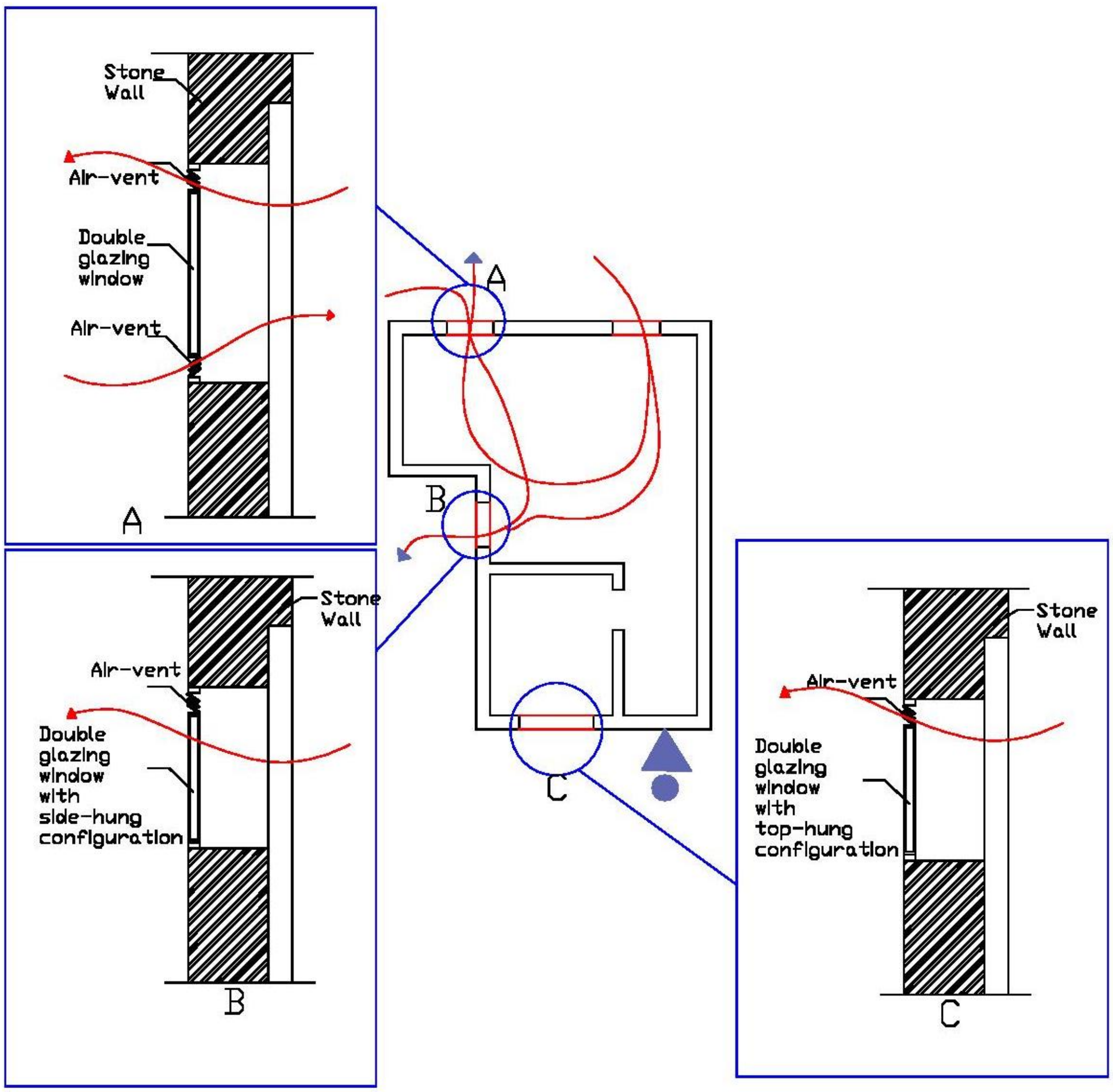
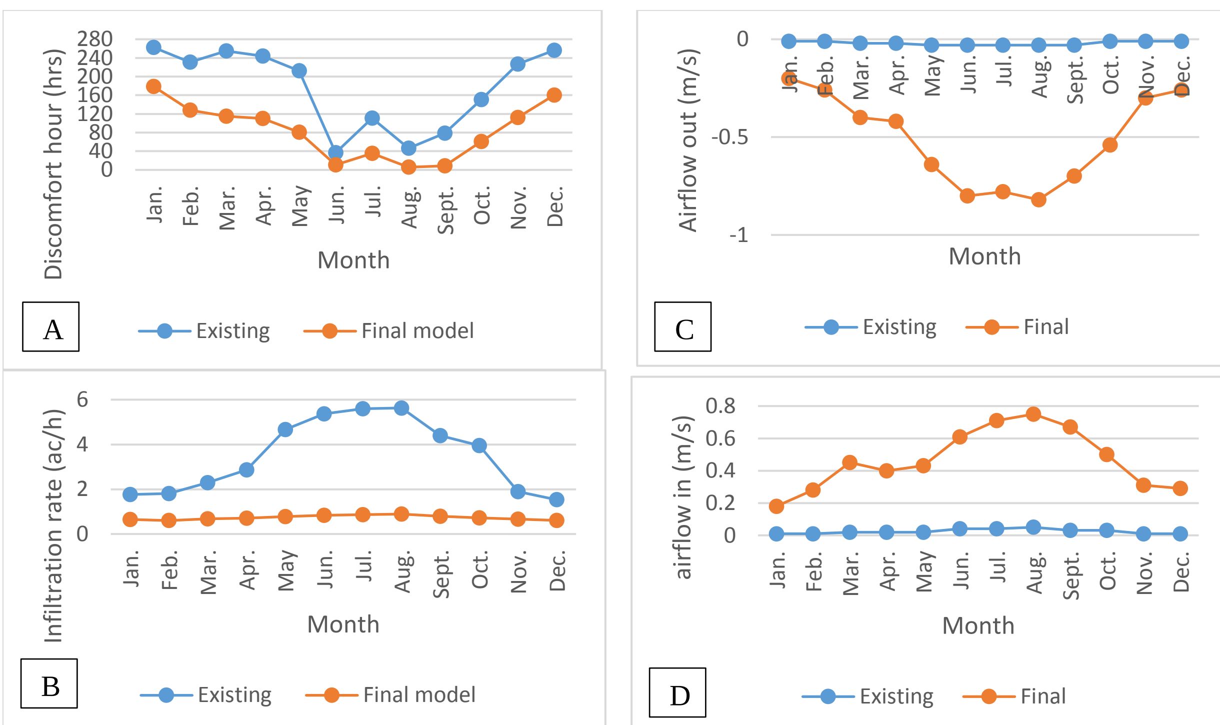


Figure 147: General scheme of the suggested condition - Case study 3

According to the presented information, the suggested model of the building was re-simulated in DB software and the comparison of suggested and existing model his presented in Figure 148. The figure shows improvements in most of the conditions of infiltration, discomfort hours and air circulation comparing with the existing model.

In order to analyze the difference between the suggested models of the building with the existing condition, Figure 148-A shows the discomfort hours of the building. According to this figure, the suggested model of

the building is more comfortable with 52% improvement on the discomfort hours comparing with the existing model in a yearly average base of improvement. The maximum improvement corresponds to August with 85% improvement and the minimum improvement belongs to January with 31%.
Another factor that has been considered is the infiltration rate (Figure 148-B). The figure shows that the yearly average of improvement in the suggested model comparing with the existing model is 72%, and the maximum improvement belongs to August with 82% and the minimum in December with 61%.
Figures (148-C and 148-D) show that the distribution of the air in the interior spaces has been increased up to 9 times for in-taking and 5 times for extracting the air to and from the interior spaces. This improvement in the air circulation happened because of the improvement in the infiltration rate and also changing the configurations. So it can be concluded that this suggested condition for the building can be useful to improve its ventilation condition.
To conclude the ventilation effectiveness of the building, the ACE of the suggested model has been measured with DB software. The suggested model has an ACE of 0.87 while it was 0.61 in the existing model. Based on the presented information on Chapter 5, this improvement in ACE shows that the building with the suggested solutions would have more effective ventilation and air change condition. Hence the occupants will be more comfortable in this building compared to the existing condition.



A: Discomfort Hours, B: Infiltration rate, C: Airflow in, D: airflow out.

Figure 148: Comparison of existing conditions and suggested model - Case study 3

6.5.3 Fourth case study

As the fourth case study takes advantage of stack ventilation (chimney effect), the most appropriate recommendations which are selected to realize the most effective condition of the building due to the results of section 6.4.2.3 are:

1- The new window configuration (S-N) based on the idea of a double window, is the most proper configuration for this building.
2- In order to conduct more airflow to the interior space based on the problem of lower air velocity in the existing condition, the side-fins of the selected window configuration will be useful.
3- However, the new window configuration has the air-vent at the top and bottom of the window but the air-vent at the bottom of the window will be used on the lower floors and the air-vent at the top of the windows in the fourth floor due to the NPL position. The second air-vent will be used if it is needed in some specific times.
4- Having a bigger skylight with a proper configuration and operable direction to improve the air extract process.

Based on the results of simulation in section 6.4.2.3, the intake and extracted air to and from the building shows that the building works based on the temperature difference and NPL is located at the middle of the building, while the building benefits from chimney effect. Hence, by adding the air-vent at the bottom of the window on the lower floor and on top in the last floor as well as working on the configuration and size of the skylight, the air stacks more to the upper level and extracts from the last floor and roof. Therefore the NPL level goes up as it was presented in Figures 142 and 143. The position and direction of the air-vent are the same as Figure 149 presents. Due to the shape of building's roof and position of the negative pressure over the roof, the best configuration is a skylight with a top configuration to the leeward side. It helps to extract the air from the building to the leeward side. Because if the opening direction was to the windward side, it will cause to intake the air instead of its extraction. Figure 149 shows the schematic condition of the building based on this idea.

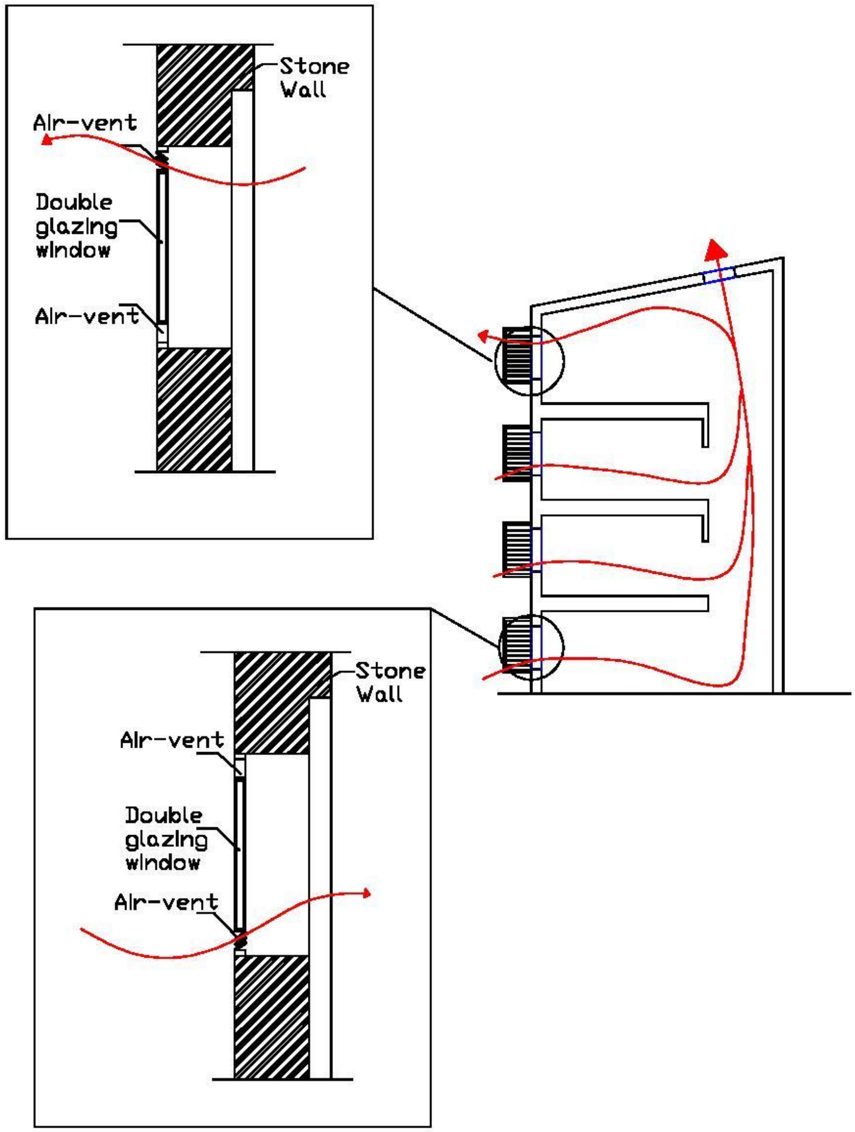


Figure 149: Configuration of opening and apertures in different floors of the fourth case study

Figure 150 illustrates the difference between the existing conditions with the suggested model for the fourth case study. This figure shows the analysis of different conditions of discomfort hours, infiltration rate and air circulation in both models. The Figure (150-A) presents the difference of the discomfort hours between the suggested model and the existing condition. It shows that the relative difference [9] of the existing building with the suggested model is 0.32 in the winter time and 0.65 in the summer time. It means that the suggested (optimized) model has better conditions in comparison with the existing model in such a way that the number of discomfort hours has been decreased up to 63%. However, the maximum improvement corresponds to July with 83% and minimum one belongs to February with 51%.

[9] Relative difference is a mathematical description which helps to find the amount of change between two values. It makes the amount of the change as a non-dimensional value.

It is found by the following equation: $Relative\ difference = \left|\frac{First\ Parameter - Second\ Parameter}{First\ Parameter}\right|$

A: Discomfort hours, B: Airflow out, C: infiltration rate, D: airflow in.

Figure 150: Comparison of existing model with the recommended models - Case study 4

The Figure 150-C shows the comparison of infiltration rate between the two models. The figure demonstrates a yearly average improvement of 76% in the suggested model in comparison with the existing building while the biggest improvement was verified in September with 89%. It means that the building with the suggested condition has a better condition about the infiltration rate.

According to Figures 150-B and 150-D, the suggested model offers more air circulation in the interior spaces while the intake air has been increased from 3 to 18 times during the year, as well as the extraction of the air through the outlets has been increased up to 10 times. It means that the air circulates between the inlet and outlet with more speed and distributes better in the interior area while the velocity of the air in the existing conditions was too low and the air could not circulate appropriately.

As a conclusion, the ACE of the suggested model has been measured with DB software and it shows that the suggested model has an ACE value of 0.88, while it was 0.58 in the existing condition. This improvement of ACE shows that the building would have better conditions in the sense of ventilation and comfort for living.

6.5.4 Conclusion

Based on the presented information at the beginning of this chapter, there are different possible recommendations which can be used in buildings of the old city to improve its ventilation. However, the properties of the buildings are another important factor which makes a border in this process and it is not possible to apply all kinds of the recommendations in this area. As it was shown in section 6.4.2, it is necessary to know the properties of the building to select the proper recommendations for its improvement. Hence, the selected recommendations for each one of the case studies have been chosen according to building properties. The simulation results provide the possibility of comparing the effect of different recommendations and knowing which recommendations provide a better quality of the ventilation and air circulation in the interior spaces. By analyzing the case studies it has been concluded that in the first and the second case study the side-hung aperture is the most proper option to improve the ventilation and air circulation. So that, this side-hung aperture could be in the form of the new configuration recommendation with side-fins or the side-hung configuration recommendation with side-fins but the new window configuration recommendation has a better effect. However, this configuration (Side-hung) appears also in the existing condition. It shows that the existing configuration is good and it is necessary only to find a way to increase the amount of intake air to the interior space, despite the existing problem about extracting the air from the correct outlet based on the principle of ventilation.

The third case study also has better ventilation and air circulation behavior with the side-hung configuration in the framework of new window configuration with side-fins or side-hung configuration with side-fins. However, the original configuration of the building is bottom-hung and the simulation results show that the bottom-hung configuration is the worst one for this building and its ventilation system. Hence, it is necessary to change the configuration of the windows to improve the ventilation condition of the building.

The last case study of the research is also working with the side-hung configuration. According to the results of the simulation, this configuration is the best one for this building based on the existing ventilation strategy. It does not matter that it is a configuration in the form of new window configuration with side-fins or side-hung with side-fins. All of them make an acceptable improvement in the ventilation of the building. However, the percent of improvement in the new window configuration with side-fins is more than the side-hung configuration with side-fins.

Therefore, this building does not have any problem about its configuration but the reason of weakness in the ventilation and air circulation is related to the outlet of the building and also the amount of intake air. Therefore the main changes in this building should be done in the changing the outlet openings (skylight) and also have more intake air in the interior space by using side-fins and air-vents.

Based on all obtained results in section 6.4.2 and also suggested model in section 6.5 for each one of the buildings, it is possible to improve the ventilation and comfort of these buildings by changing the window configuration, adding side-fins, and working on the outlets. The suggested models are based on the most appropriate recommendations for improvement of the building's condition. The comparison of these new models with the existing models show how much these suggested conditions are effective and how much the interior condition and air circulation in these buildings have improved in comparison with the existing buildings.

However, there is some difference about the U-value and other properties but it has been neglected in this comparison and analysis of the results while the research just considers the ventilation, comfort, air circulation/distribution and does not work with the energy consumption and its performance in the buildings.

Chapter 7:

Conclusions

Index of chapter 7

"Sickness seizes the body from bad ventilation".

Ovid

7.1 Summary

In the past, natural ventilation was the main way of ventilating residential buildings. So that infiltrations and air permeability were the ways of ventilating buildings. Subjected to the problem of the energy consumption in the worldwide, natural ventilation is one of the best ways to decrease the amount of energy consumption in the construction sector. Therefore, with increased attention to the energy efficiency and sustainability measures, natural ventilation has become again more popular in residential buildings. Natural ventilation as a passive strategy that have some benefits for building comfort and performance like decreasing operation and construction costs, decreasing environmental impact, improving the occupant comfort and IAQ.

Ventilation effectiveness of the building is related to two kinds of different parameters of climate and construction. Climate parameters are temperature difference, air pressure, air velocity, and also humidity. Construction parameters are divided into interior factors such as building design, placement and sizing of the openings and exteriors factors such as placement of the building in the urban area, building orientation, urban topography and etc.

Measurement and simulation were the selected methodologies for predicting the thermal comfort and airflow pattern in a building with natural ventilation. Among different measurement methods, which were presented in chapter 3, BDT was selected as the main method for measuring the building airtightness and air leakage. Simulation is another method for predicting building airflow and ventilation condition and CFD is one of the improved simulation methods in this field. Validation of the simulation results was also necessary to evaluate the improved models. In this research, the validation of simulation results was done by measurement results. Based on this general overview of the research, the following section is devoted to the conclusions of the research.

7.2 General conclusions

The framework of the research was made based on the presented questions in the first chapter. Hence, in order to conclude the research, the answer to the mentioned questions based on the previous chapters is illustrated in following:

- What are the ventilation requirements to grant an interior healthy environment?

Generally, natural ventilation works based on pressure difference and also humidity difference. Pressure difference is provided by the wind or buoyancy-drove (temperature difference) so, in order to have a natural ventilation, it is necessary to have wind (pressure difference) or temperature difference. Since natural ventilation is a circuit of airflow between supply and exhaust with equal importance, the existence of openings as a technique to complete ventilation circuit is necessary.

The amount of airflow through the openings is related to different factors such as: Wind speed, pressure speed, buoyancy pressure, characteristics of openings, and effective area of the opening.

However, in the process of natural ventilation, it is necessary to pay attention to the airflow direction and also its distribution in the interior area in order to have an effective ventilation.

- How much is the minimum/maximum air change rate to keep the good air quality and to avoid pathologies based on the regulation in the tested building?

The minimum and maximum ventilation rate depend on the applicable regulation. Some countries use the minimum rate and the other use the maximum rate. Also, some of the countries have ventilation rate for different rooms while there is just a ventilation rate for a whole house in other countries like Portugal. Hence it is necessary to clarify which one of the existing regulation has been used in the development of the research. This research has been developed based on the Portuguese regulation of REH. Based on this regulation the maximum rate of ventilation in the winter time is 0.4 ac/h while it is 0.6 ac/h in the summer time.

- Is there any relationship between house characteristics and the need for of ventilation?

As it was demonstrated in the presented results in chapter 5, the building characteristics have an effect on the ventilation condition. The building age, construction condition, numbers of the floors, location of the apartment in the building, building orientation and even the interior design of the building are effective factors in the ventilation of the building.

As it was presented the apartment in the upper floors have better ventilation in compare to the apartment on the lower floor. Also, it is necessary to have more airflow and air velocity on the lower floor to improve the air distribution and circulation in the interior spaces and consequently ventilation conditions.

On the other hand, as much as the building is older, the infiltration rate of the building is bigger and interior condition of the building is more uncomfortable. Hence, it is necessary to decrease the infiltration rate. However, using insulation to decrease the ventilation is not the best way because it makes the building too tight and consequently, the ventilation of the building goes out of functionality. So it should be analyzed and find a balance between the insulation of the building and ventilation rate in order to have a comfortable condition in the interior spaces.

The typology of the building (multi-family of the single-family) is another factor which has an effect on the ventilation needs of the building. As it was illustrated in the presented figures, improvements of ventilation and supply the best ventilation condition in a single-family house is better than a multi-family house. Because in the single-family typology, the whole building is working as one system and there is just one circuit of air distribution and ventilation in the whole building, while in the multifamily house, there are different apartments and it is necessary to make a good connection between them to have an appropriate air circulation and distribution and consequently effective ventilation, as the apartments are working as different circuits.

- What practical intervention actions must be changed to solve the IAQ of the building?

Actually, one of the most popular intervention to improve energy performance of a building is using insulation layers. However, based on the observed problems after interventions in some of the rehabilitated buildings, adding insulation layers make the building too tight and decrease the building ventilation. Since infiltration is a part of natural ventilation in the old existing buildings, having too tight buildings make the ventilation system of the building out of functionality.

Therefore, it is necessary to make a balance between the energy performance and ventilation conditions of the building. To do so, the analysis, simulation and measurement of the building, before intervention, is necessary to find the best solutions for a good intervention and avoiding the mentioned problems.

- Do the buildings receive adequate ventilation (based on regulation) for the health and comfort of the occupants in the existing condition and also after recommendations?

Based on the presented results of the existing conditions of the buildings, it was demonstrated that buildings in the existing condition do not have sufficient conditions about thermal comfort and ventilation. For example, the ACE rate of the building in the first selected case study is 0.17 while it should be 1 in the best condition. So this difference between the existing and best rate of ACE clarify this problem.
After selecting the solutions based on the limitations of the buildings, the suggested models based on these recommendations show that the thermal comfort and ventilation effectiveness of the building has improved. For example, the first selected case based on the suggested recommendations has the ACE of 0.81.
This 79% improvement of ACE from the existing condition to the suggested condition, shows that by changing the properties of the openings as the main effective factor on ventilation, the building will have better ventilation and thermal comfort.

- How large is the possibility of the variation in supply-exhaust ventilation between different buildings?

The results of airflow in and out as the supply and exhaust ventilation between different buildings in the suggested conditions show that by adding the recommended solutions in the selected case studies the supply and exhaust ventilation have improved in all cases. But the improvement of supply and exhaust ventilation vary between different buildings. The results show that the single –family house has more improvements in compare to the multi-family houses, because the whole building is working as a circuit of ventilation and this property helps the ventilation system of the building. The supply air from an opening in the lowest floor can circulate in the whole building and exhaust from the upper part. While it is not possible to have this circuit in multi-family houses due to the existence of different apartments in a building and also different ventilation circuits.
For example, the fourth selected case study of the research is a single-family house. It has a variation of 8 times between supply and exhaust ventilation, while this variation is 4 times in third case study of the research as a multi-family house.

7.3 Specific conclusions

Based on the structure of this research that have a conclusion section at the end of each chapter and a complete and detailed conclusion in Chapter 6, this section is devoted to a specific conclusion.

- The research was developed using two methods of measurements and simulation, where the measurement method was used to validate the simulation results. According to the validation analysis, there is 1-7% difference among simulation and measurements results.
- Based on the achieved results of BDT, buildings have slightly bigger infiltration rate based on depressurization test in comparison with pressurization one. Since both methods show the rate of building leakage based on the power law equation, we observe that as much as the building is leaker this rate is also higher.
- The selected case studies are not tight buildings because there is a big difference between the obtained results of BDT and DB simulation with the accepted rate of infiltration by national and international regulations. These results confirm that buildings need improvements in their conditions in order to have a comfortable and efficient environment.

- According to literature about the effects of wind and temperature difference in ventilation, the obtained results from the case studies show that by the increment of temperature difference, infiltration rate also increases and the biggest infiltration happens in a temperature difference from 4 to 8 °C. On the other hand, the effect of the wind on natural ventilation has been considered in two phases of flow in and flow out. It shows that building is more leaker in the time flow out, which is also observed in BDT results.
- According to the literature review, higher pressure over the main facades makes out-flow bigger than in-flow. Hence, it is necessary to increase the amount of in-flow in the interior spaces. It means that buildings need to intake more air from outside to the interior area. Consequently, the intake system of the building should also work better which it can be in related to the size, position, and direction of outlets. To do so the following solutions have been selected in order to improve the ventilation of the building:

    1- Double windows or ventilated single window solutions for the main façade of the building;

    2- Air-vent at the top and/or bottom of the windows based on their position and locations.

    3- Movable side-fin beside of the windows in order to increase the air velocity in the interior spaces.

    4- Changes in the size of outlets.

    5- Changes in the configuration of the windows.

    6- Double glazing windows for windows which works as the outlet, in order to decrease the infiltration in the winter time.

    7- The best configuration for outlet window is a top-hung configuration with an air-vent at the top of the window. This air-vent should be selected from the controllable type in order to allow occupants to use it whenever they want.

    8- In order to have better air circulation in the building, the location of air-vent associated with the building condition should be considered. If the building is located in a multi-family apartment, the air-vent as intake should be at the bottom of the opening, at the low height of the building and the air-vent for exhaust should be at the top of the building. This position of the air-vent helps air circulation in the whole parts of the building and consequently air distribution acts well.

    9- Due to the effect of opening configuration, the best configuration of the opening is related to the type of the building. If the building is an apartment in a multi-family building, the windows in main facade have a better perform if they have side-hung and outlet have top apertures. On the other hand, if the building is a single-family house like the fourth case study, the opening in lower floors are better to have side-hung and floor upper than NPL level uses the bottom-hung configuration. While the out-let openings which are located in other facades should have top-hung configuration.

    10- According to the idea of a double window, a second air-vent will be used just in case to increase the air change and circulation. This air-vent is also controllable by occupants.
- Besides of the presented solutions, change of position and geometry of windows is another beneficial solution. However, it is not possible to use it for this research based on architectural limitations of the area of the research.
- Application of the presented solutions in the buildings and their results shows a notable decrement in discomfort hours as one of the important options in consideration of ventilation effectiveness. Most of this decrement was verified in the summer time. However, discomfort hours also decreased in the winter time but not as much as in the summer time. This change is related to the energy performance of the building. It is necessary also to consider the energy performance of the building because of some of its conditions, such as age and construction properties.

- Analyzing the heat gain and loss of the building before and after recommendations, there is a relative difference of 42% for the winter time, while this rate in the summer time is 79%. Therefore, consideration of building condition for energy performance in the winter time is an important topic which should be considered but it is out of the topic of this research. However, it is also controlled through the change of the window configuration, control of the ventilation and air infiltration, but with slight improvements in the results.
- In order to control the problem of over-ventilation, the presented solutions caused a decrement of 82% in the summer time and 65% for the winter time in infiltration and air permeability of the building in order to control the over-ventilation situation. These decrement in the heating load, discomfort hours and also increment in the amount of interior air circulation (in-flow) contribute to a better interior condition in the buildings.
- Generally, by using these recommendations the building energy consumption and discomfort condition was improved by 46% and decreased in 63% respectively. The ventilation system of the building is also more effective and there is a relative difference of 0.84 in comparison with the existing condition.
- Besides of the limitation of the area, in some special cases like third and fourth case studies, it is possible to change the size of the openings which works as the outlet in order to improve the ventilation system of the building.
- According to literature, in order to have an effective ventilation by a chimney effect, the NPL of the building should be located at upper parts of the building. While based on the obtained results, the NPL in the fourth building which works by a chimney effect has been located in the middle of the height. Therefore by adding the air-vent at the bottom of the windows on the lower floors and at the top of the windows on the last floor, changing of opening configuration, and also changing the skylight properties (size and configuration), the NPL of the building has been moved to the higher part and it causes a more effective ventilation. The most important point of the skylight is related to its opening configuration (direction of aperture area), which should be located on the leeward side to be able to exhaust the air otherwise it would be worked as an inlet opening, a situation that is verified in some moments.

After these conclusions, it is necessary to point out some of the limitations of the research and the possibility of its improvement:

Firstly, the building location has a strong effect on the quality and effectiveness of its ventilation system. For example, a building will have different ventilation quality and IAQ if it is located in the center of the city with a deep urban canyon or in a suburban or urban area but not in the center of the city with high concentration of the buildings. For instance, the effectiveness of the recommended solutions in these case studies are related to their location and they will have different effects on other areas.

Secondly, the geometry and position of the openings is another factor which has a big effect on the quality of ventilation. However, it was not possible to study about them in this research because of the architectural limitations. But as it has been pointed out before, by changing the location of the building it is possible to check also the effect of these two options.

Thirdly, nowadays science and technologies are developing absolutely fast. Hence, there are a lot of new technologies for ventilation as mechanical or hybrid. But due to the increased attention to the ZEB in the world, EU, and also based on the importance of research area, this research has only been developed based on the passive solutions and recommendations. The recommendations were selected in order to avoid any main intervention which has an effect on the building or urban area characteristics. In the same way, based on the limitations of the area, it was not possible to consider all kinds of the passive solutions mentioned before.

Fourthly, according to all mentioned limitations and potentials, expressed recommendation is able to improve the ventilation of the building and this effectiveness varies from 72 to 85%. However, the biggest part of this improvement happens in the summer time, although the problem of over-ventilation, which is always important, does not exist in these buildings with the suggested recommendation.

7.4 Future works

Besides of the wide domain of existing research concerning passive ventilation, there is also different topics in this field which should be studied. One of the areas is about the condition of airflow in the interior spaces to predict the building performance. In this section, some ideas in order to develop this research are presented.

- Based on all the things which have been done till now, it should be a good idea to use the monitoring method in a specific period or even one year in order to validate the results. It means that it could be interesting to use the monitoring of the site to validate the results. It would be important if the air velocity in the interior area also monitored.
- Since there is a combined approach concerning the IAQ ventilation and energy consumption in this research, should be interesting to perform also the analysis of life cycle cost.
- The challenge of determining an effective window area (geometry and position) to find the volume and rate of airflow through it in a naturally ventilated building is another idea which researcher would like to study about it as well.
- Consideration of building energy performance in the winter time in this area (for these fourth case studies) in order to control their energy consumption and make them closer to the idea of ZEB.

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Appendix 1: Documents of selected buildings as the case studies

In the following, more detail information about the properties of each one of the case studies of the research has been presented.

1- **First case study: a residential apartment on the second floor of a multi-family building.**

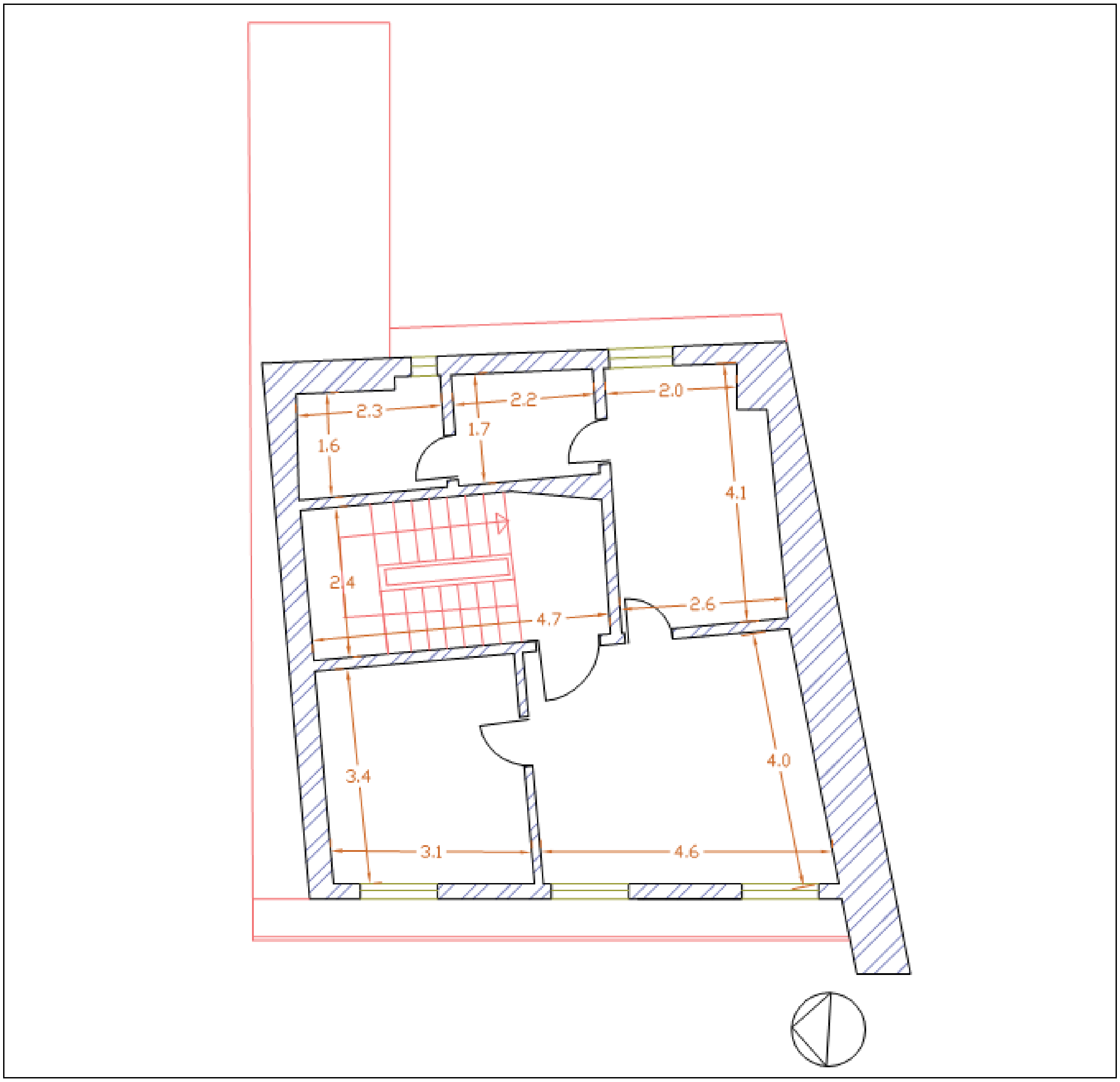


Figure 151: Plan of the apartment sellected as the first case study.

Figure 152: Interior and exterior properties of first case study

Figure 153: Procedures of BDT in the first case study.

2- Second case study: a residential apartment on the third floor of a multi-family building

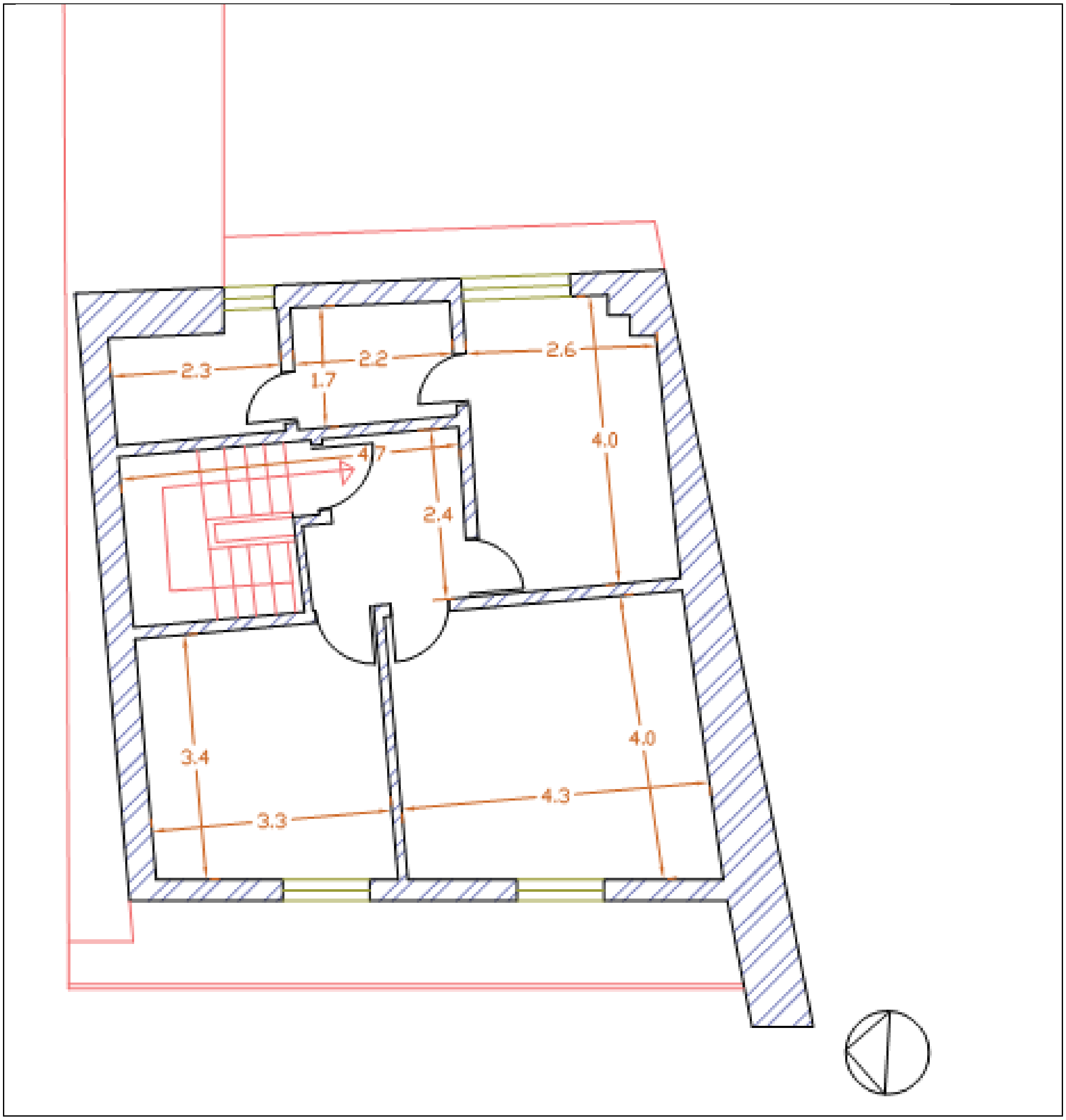


Figure 154: Plan of the apartment selected as the second case study

Figure 155: Interior and exterior properties of second case study

Figure 156: Procedures of BDT in the second case study

3- Third case study: a residential flat on the first floor of a multi-family building

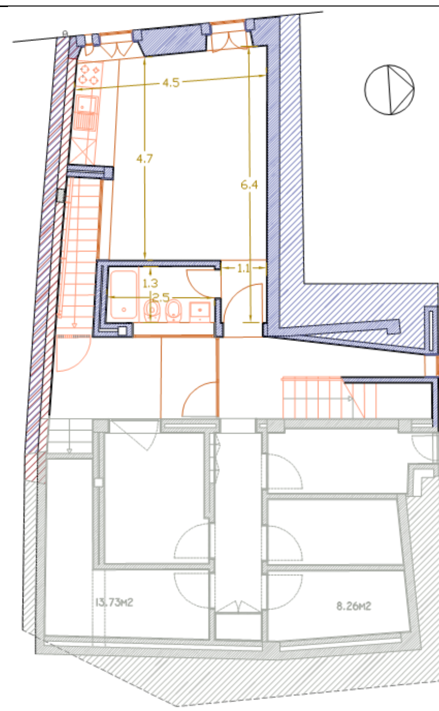


Figure 157: Plan of the apartment sellected as the third case study

Figure 158: Interior and exterior properties of windows of the apartment. Also the procedures of BDT in the third case study

4- Fourth case study: a residential apartment on a single-family building

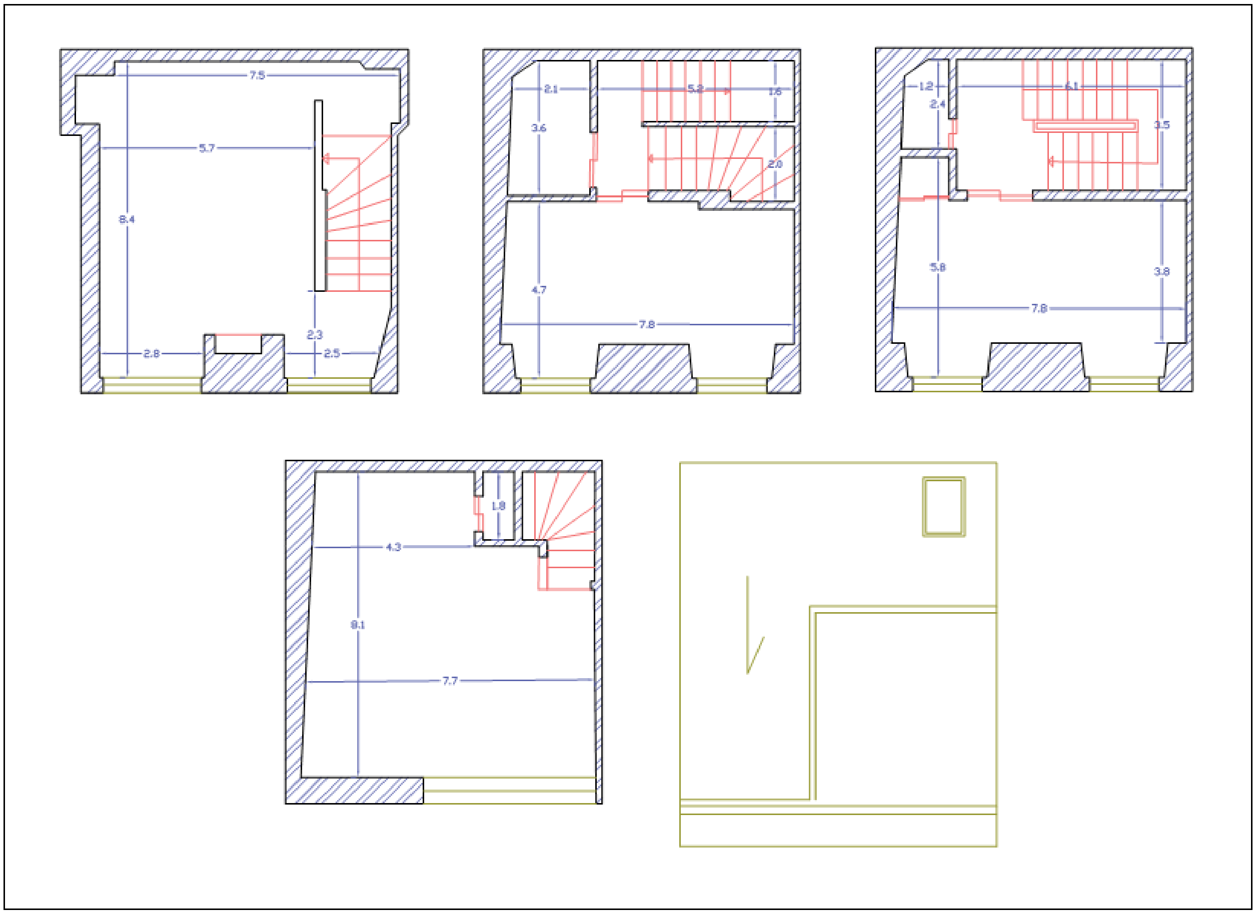


Figure 159: Plan of the apartment sellected as the third case study

Figure 160: Interior and exterior properties of windows of the apartment. Also the procedures of BDT in the fourth case study

Appendix 2: the changes of the opening size based on the WWR in the third case study

WWR is one of the ways to analyze the effectiveness of natural ventilation and improve it in residential the building. Generally, there are different WWRs in the building whose best rate depends on the climate condition and location of the building.

In order to find the typology rate of WWR in Coimbra, thirty residential buildings in the city center of Coimbra have been analyzed to find the dimensional building typology of the Portuguese construction in Coimbra. The obtained values are the average of the analyses of 30 buildings which they were defined and analyzed according to national Portuguese code (ITE 50)[233]. Based on the existing national code, the definition of the exterior envelope (EL1), envelope in contact with soil (EL2), and interior envelope (EL3) have been illustrated in Figure 161.

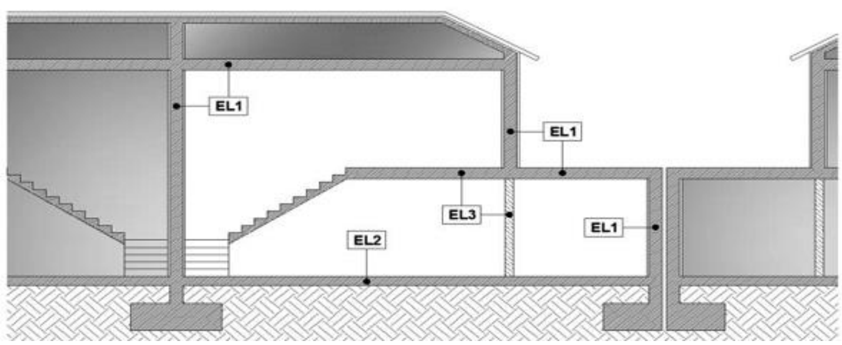


Figure 161: Definition of interior envelope, exterior envelope, and envelope in contact with soil based on Portuguese regulation [233]

Dimensional typology is a way to show the properties of building construction and (its) envelope (opening and constructions). The following table (Table 32) presents the results of dimensional typology in the selected area.

Table 32: Dimensional building typology of Portuguese construction in Coimbra

		Area (m^2)
Number of floors		4
Useful area		202.33
Building height (per floor)		2.47
Exterior envelope	**Opening area**	23.72
	Wall area	64.52
	roof	22.84
	floor	1.93
Interior envelope	**Opening area**	13.70
	Wall area	177.16
	roof	31.51
	floor	8.35
Envelope in contact with soil	**wall**	2.72
	floor	4.89
Building volume		480.95
Building form factor		0.24
Exposed surface area		113.01

Since the WWR factor is used to improve the building ventilation effectiveness, the obtained results of dimensional typology have been used to find the WWR of Portuguese construction in Coimbra old city center. On the other hand, our four case studies have been analyzed in order to find their WWR to compare it with WWR of the mentioned tested buildings (30 buildings) with the real typology to determine that how effective is its natural ventilation. Table 33 compares the results of WWR of Coimbra's typology with our case studies and illustrates that the WWR of Portuguese traditional constructions is 12%. Considering the window as an exterior opening, the rate should be 36.76%. Based on the mentioned information in Table 33 for our case studies, none of the WWR of the latter is the same as sample model.

Table 33: Comparison of WWR in Portuguese construction with the case studies

WWR		**External windows to exterior wall**	**Window to wall**	**Window to Floor**
WWR based on the Portuguese Typology		36.76%	12%	18%
Case 1	**Whole building**	23%	10%	15.89%
	First apartment (third floor)	16%	9.5%	11%
	Second apartment (fourth floor)	13.38%	7.03%	14.94%
Case 2	**Third apartment**	11.39%	6.95%	14.28%
Case 3	**Fourth apartment**	13.55%	6.47%	13.32%

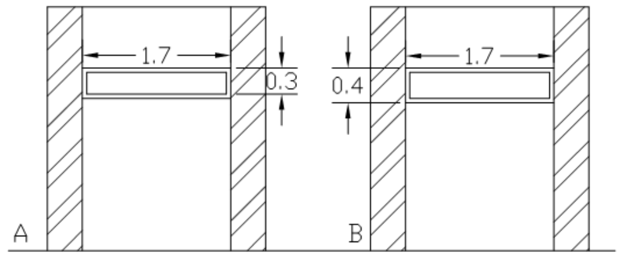
Since the outlet opening of third case study need to be bigger than existing condition in order to have better air circulation and exhaust the air, the following table (Table 34) shows the WWR of third case study and numerical typology of constructions in Coimbra.

Table 34: Comparison of WWR in Portuguese construction with the case studies

WWR		**External windows to exterior wall**	**Window to wall**	**Window to Floor**
WWR based on the Portuguese Typology		36.76%	12%	18%
Case 2	**Third apartment**	11.39%	6.95%	14.28%

In order to increase the size of the outlet, the researcher has been tried to increase the size of the outlet based on WWR. Because the existing area of the outlet is 0.47 m^2. While based on the obtained WWR it should be 0.68 m^2.

To do so, the existing condition of the opening has been checked. There is not possible to increase the width of the opening because it is fitted to the width of the wall. Therefore, the only possibility is related to increase the height of the wall. The following figure (Figure 162) shows the existing and suggested opening size.



A: the existing size of the opening. B: the suggested size of the opening based on WWR.

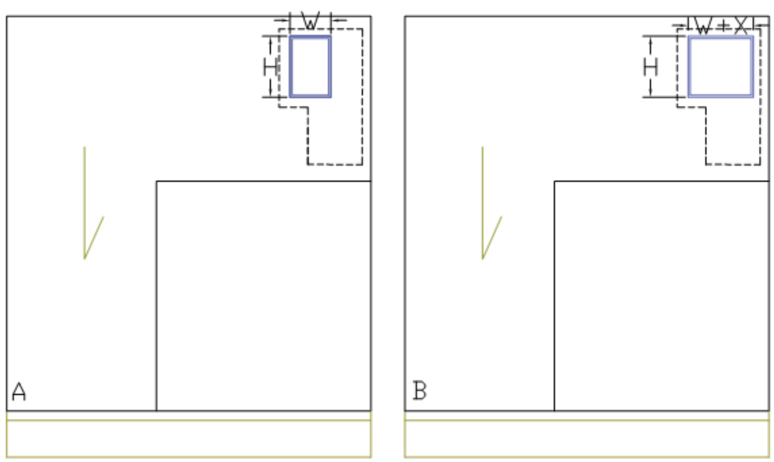
Figure 162: Comparison of outlet size in the existing condition with the suggested situation

Appendix 3: the changes of the skylight size in the fourth case study

One of the suggested recommendation to improve the natural ventilation in the last case study is to change the properties of the skylight (Roof window). The existing skylight outlet is a side-hung opening which opens to the windward side. However, based on the existing researcher, it should be an opening to the leeward side of the roof to work as an outlet. Otherwise, it would be work like an inlet which it is at the moment.

Based on the presented simulation and also existing researches, the top-hung configuration is more proper for this outlet. The last factor which should be considered in order to change the skylight properties is about its size. Due to the existing literature, the efficient size of the skylight is 5-7% of the floor area. While it is 2.1% of the floor area in the existing condition.

To increase the size of the outlet, it is not possible to work on the height of the opening because of the limitation of the existing free area on the roof of the building. So changing the width of the opening is the only possibility of to change the outlet size. The following figure (Figure 163) shows the existing and suggested size of the skylight.



A: the existing size of the opening. B: the suggested size of the opening.

Figure 163: Comparison of skylight size in the existing condition with the suggested situation