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Investigation of single-sided natural ventilation air flow penetration depth in an open plan office space

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Abstract

Nowadays, a lot is being discussed by politicians from all countries to define the energetic goals that will mitigate the negative environmental impact on the planet. On the specific case of office buildings, caused by their larger electrical energy bills regarding climatization when compared to residential ones, there is a necessity of studying and developing different ventilation strategies integration like natural ventilation (NV). Since most non-residential buildings display all the windows in a single-sided (SS) way (all the windows on one façade), this work revolves around the viability of the current imposed limits on the air flow depth (ventilation effectiveness) of SS NV strategies, regarding thermal comfort and good levels of indoor air quality in office spaces. The limits addressed here are given by California’s Title 24 20 ft rule, which specifies a limitation of 20 ft (roughly 6.1 m) between the ventilated façade and the opposed one, and the CIBSE recommendations for the maximum room depth of up to 2.5 room floor to ceiling heights (2.5H). In Portugal, according to RECS, the distances considered for SS NV applications in offices have to be larger than 7.5 m from the façade or 2H. With experimental setup conditions of around 1.5-3 hours of test duration, 7-12 m^2 per occupant and internal gains of 25-28 W/m^2, tested on three distinct rooms with different internal dimensions and namely 3.5-5.7 floor to ceiling heights, values of temperature and CO_2 were measured on several points of the rooms. The results obtained are somehow conclusive for pointing out that the limits are strictly defined, since it was verified that for at least 4H there is still a good ventilation effectiveness when compared to the limits of the rules addressed. Further model validations were also made for each of the three rooms recurring to EnergyPlus simulation tool.

Keywords: Natural ventilation; single-sided ventilation; air flow penetration depth; EnergyPlus.

Resumo

Um dos principais objetivos de uma empresa é maximizar os lucros e minimizar as despesas. É por isso emergente a necessidade de implementar as mais indicadas soluções de redução de custos disponíveis em mercado que visam melhorar significativamente a eficiência (energética e económica) da empresa. Mais concretamente, a ventilação natural (VN) é uma eventual solução possível de ser aplicada que permite grandes reduções nos custos de aquecimento, ventilação e ar condicionado (AVAC), em virtude de ser um processo influenciado por diferenças de pressão e temperatura entre o interior e o exterior de um edifício, ou seja, sem custos de consumo associados. Este é um tópico bastante fulcral na motivação de estudos aprofundados sobre este tema, uma vez que em edifícios de escritórios o consumo de energia em AVAC representa 50%-60% do consumo energético total do edifício.

Historicamente verificou-se que, com o evoluir das tecnologias e da industrialização dos países, e com o aparecimento das unidades de ventilação mecânica controlada, deixou de ser tão prejudicial a quantidade de envidraçados nos edifícios, em termos de conforto térmico no interior em relação à época em que não existia ventilação mecânica controlada. Este facto explica-se devido à procura da maximização de iluminação natural em edifícios de escritórios que faz com que, aumentando a área de envidraçados, existam elevados ganhos solares e, consequentemente, se necessite de efetuar arrefecimento forçado mais frequentemente. Resultantes deste facto advêm alguns casos de falta de estudos em termos da viabilidade de VN em certos edifícios de escritórios, nos quais há capacidade de aplicar medidas otimizadas de VN. Concretamente, nalguns edifícios mais atuais, verifica-se que existe a capacidade de garantir estratégias de VN nos meses em que as condições meteorológicas não são muito extremas.

Uma das soluções arquitetónicas bastante recorrente para edifícios de escritórios, são espaços com janelas apenas numa das fachadas. Assim, e devido à falta de investigação em casos mais específicos, a empresa é obrigada a instalar unidades de ar condicionado sem haver estudo caso a caso. Exemplos destas regras limitam o uso da VN em escritórios com uma só fachada que tenham um comprimento no máximo de 2.5H (2.5 vezes o pé direito do edifício - CIBSE), ou que tenham mais do que 6 metros desde a fachada com as janelas até ao fundo da sala (Regra dos 20 pés presente no California’s Title 24). Em Portugal, segundo consta no RECS, considera-se ineficaz aplicar VN SS em escritórios com profundidades maiores que 7.5 m ou que ultrapassem 2H. O que se pretende concluir com esta tese é precisamente sobre a aplicabilidade de métodos de VN em situações não permitidas por regras instauradas pelos governos, devido à inexistência de um estudo mais específico a cada situação.

Considerando os fatores enumerados anteriormente, e tendo em vista o melhoramento da informação disponível sobre este tema, verifica-se de facto a existência de interesse na investigação do mesmo. Concretamente nesta tese, foi abordado o estudo da ventilação natural com janelas apenas numa fachada de um edifício de escritórios, no qual foram feitos estudos com as aberturas à mesma altura (Single-sided ventilation).

Em termos da estrutura da tese, no primeiro capítulo encontra-se a Introdução. No capítulo seguinte é feita uma análise aos fundamentos teóricos. Já no capítulo 3, outras publicações relevantes para o tema desta tese são analisadas resumidamente. No capítulo 4 é onde se encontra a descrição de todo o processo experimental. Estão descritas as características dos 3 casos de estudo (escritórios Large, Medium e Long), bem como a metodologia ligada quer às medições práticas como às simulações em EnergyPlus. No capítulo 5 são mostrados os resultados na forma de gráficos e tabelas, e subsequentemente analisados. O capítulo 6 resume as conclusões retiradas deste trabalho e, por fim, o capítulo 7 expõe as referências bibliográficas consultadas durante a elaboração desta dissertação.

Antes do início da componente experimental deste trabalho, e após algum estudo introdutório do tema, foram selecionadas 3 perguntas “objetivo”. Perguntas relevantes às quais se procuraria encontrar respostas após o término desta dissertação, sendo essas:

- Qual é a profundidade típica de ar novo em escritórios VN SS?
- Estarão os limites em vigor (da CIBSE e regra dos 20 pés) bem definidos, ou deve continuar-se a estudar este tema e, possivelmente, reformulá-los?
- Qual é a precisão que um Engenheiro que efetue simulação térmica de escritórios com sistemas VN SS espera obter?

Assim, foi dado início à componente experimental onde, neste trabalho, foram realizadas medições em três casos de estudo. Estes são representativos de escritórios com janelas em apenas uma fachada, e mediram-se variáveis como temperatura e níveis de CO_2 em vários pontos das salas, de modo a poder concluir-se sobre a penetração de ar novo em cada uma delas. Daí, concluiu-se também sobre a capacidade ou não de se efeituar ventilação natural monofachada de uma forma que eficazmente cumpra os limites de conforto térmico e de qualidade do ar.

Os três escritórios estão localizados no campus da FCUL (Latitude 38.76 N; Longitude 9.16 W) e tinham dimensões variadas entre si. Um escritório mais largo: Large Office, com dimensões de 12.6 m por 12.6 m e altura de 3.5 m; um escritório médio: Medium Office, com cerca de 9.1 m por 5.7 m e com pé direito de 2.6 m; e um escritório mais estreito e alongado: Long Office, com 14.7 m por 2.8 m e 2.6 m de altura. As condições experimentais variaram a sua duração entre 1.5-3 horas, com 7-12 m^2 por ocupante e ganhos internos de 25-28 W/m^2, sendo as dimensões de profundidade das três salas representadas nomeadamente por 3.5-5.7H.

Respondendo então às questões iniciais, foi verificado a partir dos resultados obtidos que para os escritórios Large e Medium a ventilação foi eficaz até (pelo menos) 3H relativo à posição do último sensor a contar da fachada, enquanto que para o escritório Long essa distância foi de 4H (penúltimo sensor). Este último resultado mostrou que existe uma zona de estagnação ou acumulação principalmente ao nível do CO_2, mas demonstrou também que nos últimos 2.6 m do escritório a temperatura sofreu um aumento abrupto de 0.25 °C.

Quanto à segunda questão, os resultados foram de certa forma conclusivos por demonstrarem que os limites em causa são demasiado restritos, ao ter-se verificado que pelo menos até 4H ainda se garante uma boa eficácia de ventilação quando comparada com os limites, seja a nível de temperatura como também a nível de CO_2.

Durante as medições verificou-se também que os níveis de CO_2 estiveram sempre de acordo com o limite estabelecido na EN 15251 para ventilação natural de 1625 ppm, bem como os níveis de renovações de ar se encontraram quase sempre (exceto em 2.8% do tempo de experiência relativa ao Large Office) dentro dos limites, reforçando assim as capacidades da SS VN.

Os modelos das três salas foram subsequentemente simulados e validados recorrendo-se a simulações em EnergyPlus. Sendo que os resultados daí obtidos também foram positivos. O software demonstrou capacidade em simular a distribuição de temperatura com erros médios de 0.7% e os níveis de CO_2 com 11.4%. Apesar deste último valor não ser muito reduzido, este erro apresentou-se inferior a 10% para os escritórios Medium e Long.

Para o futuro resta lembrar a importância que este assunto tem e reforçar a necessidade de continuar com este tipo de estudos, sendo que um passo bastante importante seria efetuar medições com

procedimentos semelhantes aos escolhidos nesta tese, mas em casos reais de escritórios, pois só assim será permitido concluir absolutamente sobre a viabilidade dos limites e normas em vigor.

Palavras-chave: Ventilação natural; ventilação monofachada; penetração de ar novo; *EnergyPlus*.

Contents

Nomenclature

Abbreviations

ACH – Air Changes per Hour;

BLAST – Building Loads Analysis and System Thermodynamics;

CFD – Computer Fluid Dynamics;

CIBSE – Chartered Institution of Building Services Engineers;

CMV – Controlled mechanical ventilation;

CR – Corner (ventilation);

CV – Cross (ventilation);

DOE-2 – Department of Energy (USA) Building Energy Use and Cost Analysis Software;

DV – Displacement ventilation;

HVAC (AVAC) – Heating, ventilation, and air conditioning (Aquecimento, ventilação e ar condicionado);

NV (VN) – Natural ventilation (Ventilação natural);

SS – Single-sided.

Symbols, Variables and Units

ε	Blackbody relative emissivity
ρ	Air density [kg/m^3]
σ	Stefan-Boltzmann constant
ΔT	Temperature difference [K]
A	Cross section area [m^2]/Body surface area [m^2]
A_s	Surface area [m^2]
A_{op}	Opening area [m^2]
ACH	Air changes per hour [h^{-1}]
Ar	Archimedes Number
$C_{P_{air}}$	Air specific heat
C_p	Pressure coefficient
C_w	Opening effectiveness
C_D	Discharge coefficient
D_H	Height difference [m]
g	Gravitational acceleration [m/s^2]
G_C	Sensible climatization load [W]
G_i	Internal gains [W]
G_S	Solar gains [W]
G_V	Ventilation gains [W]
h	Convective heat transfer coefficient [W.m^{-2}.K^{-1}]
H	Opening height [m]
H	Floor-to-ceiling height [m]
k	Thermal conductivity [W.m^{-1}.K^{-1}]
L	Medium width [m]
$Meas_i$	Measured value for a given instant $t = i$
P	Pressure [Pa]
q_{rad}	Radiative heat flux [W]
q_s	Convective heat flux [W]
q_x	Conductive directional heat flux [W]
Q	Volumetric air flow rate [m^3/s]
Sim_i	Simulated value for a given instant $t = i$

t	Time [s]
T_i	Internal temperature [K]
$T_{outside}$	Outside dry bulb temperature [K]
T_s	Surface temperature [K]
T_{sur}	Temperature of the surroundings [K]
T_{zone}	Zone temperature [K]
T_∞	Temperature of the fluid outside the boundary layer [K]
U	Heat transfer coefficient [W.m^{-2}.K^{-1}]
V_{room}	Room volume [m^3]
W_s	Wind speed [m/s]

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1 Introduction

Nowadays, the energetic sector represents a major driving force of any economic market. For this reason, it matters to contextualize how that sector is divided by type of final energy and how the consumption by each of these divisions are distributed. Regarding the year of 2015, Eurostat presented this data with the subsectors being transport, households, industry, services, agriculture and forestry, and other [1]. For this study, and since offices are part of the services sector, the focus should be this sector, represented on Figure 1.1 with a value of 13.6%. This acts as a motivator for studies that allow the reduction of this sector's energetic consumptions.

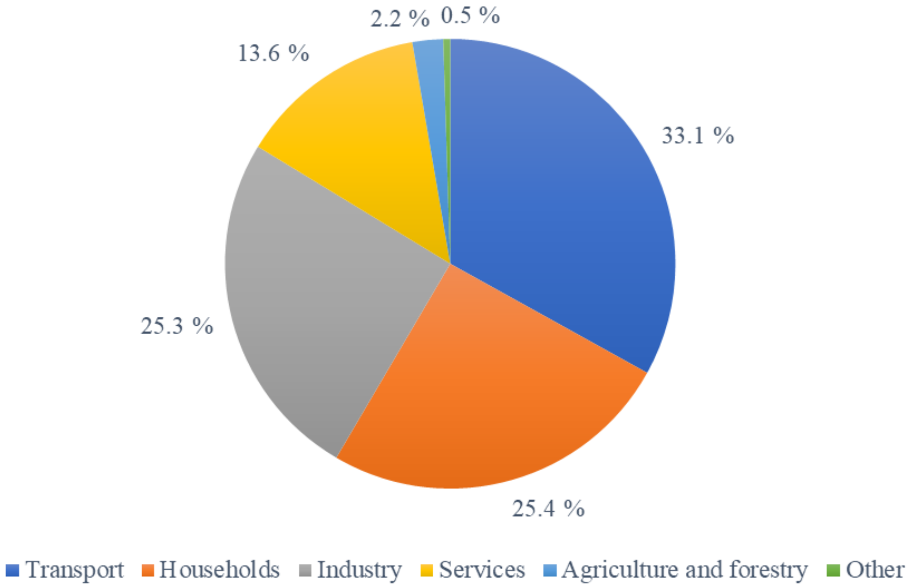


Figure 1.1 Final energy consumption, EU-28, 2015 (% of total, based on tons of oil equivalent) [1].

To add to the previously shown data, one of the biggest goals for most service companies is to maximize its profits and mitigate expenses. Thus, the improvement of new viable economic and energetic strategies is a fundamental necessity for any of these companies to achieve better results and make the companies more effective. A possibly beneficial strategy is the implementation of natural ventilation (NV), which will provide in many cases a significant improvement on the mitigation of HVAC (Heating, Ventilation and Air Conditioning) expenses by increasing the number of hours where the mechanical ventilation system can be turned off, while maintaining good levels of thermal comfort and indoor air quality inside the offices. This happens because NV processes are fully driven by pressure and temperature differences between the interior and the exterior air conditions, which gives no costs associated when the strategy is used in favorable interior-exterior conditions. This is an important topic when addressing the main motivations for this thesis, since nowadays there is a big fraction of energy consumptions in service buildings related to HVAC systems of around 50%-60% [2,3].

Historically, with all the technological developments bringing the industrialization of many nations and many new technologies, the typical setup of offices changed. Namely, the large capacity of air cooling and ventilation of air conditioning equipments and controlled mechanical ventilation (CMV) systems, created an allowance for increasing the internal gains inside offices, while still being able to mitigate the associated heating load of the personal computers and all the fluorescent lighting on office buildings, as well as the negative impact of fully glazed façades on thermal comfort [4]. This last topic is a solution globally spread despite leading to bigger energy bills when compared to the times where mechanical ventilation systems were not commonly used. The justification for the existence of largely glazed façades is the increasing demand of natural light inside the new setup open plan office buildings, giving people nice outside views and better work environments, despite the fact of making it unable for people to manually control the windows. Although being a positive measure for improving work environment, it is something to consider bad when looking at it from an energetic balance perspective. Larger glazed areas increase solar gains, and office buildings are already typically demanding much higher cooling loads than heating loads throughout the year. For that reason, adding high solar gains to the internal gains (already causing impactful interior heat sources), the final balance adds up to increase even more the cooling loads of the buildings and, for consequence, its energetic costs while using air conditioning to compensate that load increase. A lot of companies still tend to prefer the aesthetics of that type of façade (glazed) and ignore the possibility of elaborating beforehand studies on the applicability of SS NV strategies for their soon-to-be offices, by believing that the strategies are not impactful enough. This causes a lack of studies on the viability for this ventilative strategy, even though it could sometimes provide a large positive impact on the financial area with an adequate NV system, and such is lost when not giving it the time to consider and study it. Nonetheless, there are already some conclusions about the general viability of this strategy when applied to more recent buildings, resulting that NV is viable in many cases unless the outside meteorological conditions are too extreme [5,6].

To better perceive the concept of single-sided NV (fundamental to this thesis) one needs to comprehend the definition of a single-sided space beforehand. Any room with all its openings (e.g. windows or grilles) located strictly on one façade is called a single-sided room. This kind of display is very common in small offices, a lot of times part of tall buildings full of floors with these offices. Maximizing the number of offices per square meter, these are built next to each other with only a ventilated façade as border to the outside. Because of this common constructive option, it is important to look at the solutions applicable to them, one impactful solution being single-sided natural ventilation. SS NV is the capability to naturally ventilate a single-sided space. Meaning that the airflow enters from the façade with the openings (when there are more than one), ventilates the space (driven by buoyancy and wind forces) and then leaves the room through the same façade.

Focusing on the SS NV small offices, there are some impositions to always install high capacity HVAC systems without previous case specific studies on NV applicability. One important example of these impositions is California's Title 24 20 ft rule, which states that NV is not effective when there is a bigger distance than 20 ft (roughly 6.1 m) from the exterior façade to the opposite wall of a small SS office room [7]. The other relevant example is related to the CIBSE recommendations on natural ventilation for non-residential buildings, pointing that SS NV strategies are not effective when the depth of the room is larger than 2.5 times the height from floor to ceiling (2.5H) [8] (see Figure 1.2). In Portugal, the limits are 7.5 m depth and/or 2H [9]. It is the objective for this thesis to reevaluate the strictness of these government impositions and to check if there are suitable applications of NV out of these limits or not, in situations where might exist some lack of investigative knowledge.

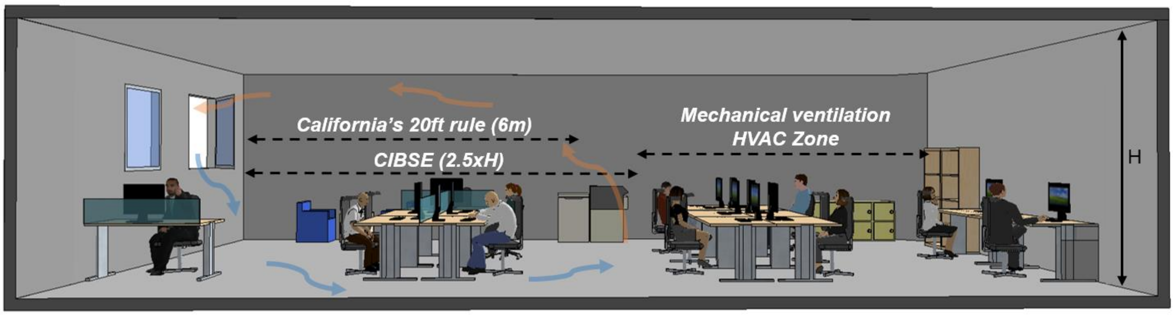


Figure 1.2 Simplified illustration of the CIBSE and California's Title 24 limitations in a single sided small office room.

Considering all the previously mentioned topics and aiming to improve the quality of information available for this area of investigation, one can confirm the relevance of achieving more conclusions about it. For that, on this thesis, a study of three dimensionally different open space rooms was made while setting these rooms as typical offices. These rooms only had one exterior façade and all the windows on that façade: were studied while being single-sided naturally ventilated. Since there was the possibility to do so and to improve the relevance of this thesis, the three rooms were then modeled and simulated on the open-source software EnergyPlus.

1.1. Thesis Structure

Concerning this thesis structure, it starts with the Introduction (Chapter 1). In Chapter 2 there is an analysis to the theoretical background followed by a review of the existing work related largely to single-sided natural ventilation processes in Chapter 3. Chapter 4 holds the main core of the experimental work. There is the full description of the case-studies, the methodology, the experimental setup and the simulations completed on EnergyPlus. Chapter 5 is where the results and its analysis are exposed, regarding both measurements and simulation results and some discussions about those. Finally, in Chapter 6 all the conclusions are exposed and further developments are suggested, where Chapter 7 lists all the references made during the document to where given information was acquired.

1.2. Research Questions

To allow a better perceiving of the fundamental topics and motivations for this thesis, one can ask several questions that justify and prove the necessity of developing this study. These questions aim to open a thinking process parallel to that which occurred during the development of this thesis. Like when addressing the experimental phase of the thesis, here the objective of the questions is to allow significant conclusions on the topic of SS NV, for this reason the answers to the following questions are exposed and debated on Chapter 6 (Conclusions and Further Developments).

- What is the typical penetration depth of SS NV offices?

- Are the current limitations (from CIBSE and the 20 ft rule) well defined, or do those need further studying and a possible reformulation?

- What is the typical precision that a trained thermal simulation engineer can expect to obtain for the simulation of a SS NV Office?

2 Theoretical Background

In this Chapter there is a brief description of the physical phenomena behind heat transfer and NV. There is also an introduction to the simulation tool used (EnergyPlus) and the characterization of the way it works around energy transfer simulation. and some relevant examples of publications where NV processes were studied. The goal of these subchapters is to allow a more holistic perspective of the theoretical principles required on this thesis, as well as to provide the basis behind this area of study. It also familiarizes the reader with an effective description of the software used on the model validation section.

2.1. Heat Transfer in Buildings

Before entering in the specific subject of heat transfer through natural ventilation, one needs to understand the physical reasons behind that, hence the need to describe the variables which affect heat transfer in buildings and the several heat transfer types, these being conduction, convection and radiation. Given that, in the following paragraphs there is a simplified characterization of these three heat transfer mechanisms.

Conductive heat transfer happens in the existence of a thermal gradient in a medium, which causes random collisions between atoms while, transferring energy (in the form of heat) from the higher temperature ones to the lower temperatures ones. The one-directional conduction heat flux q_x (W) is predicted recurring to temperature differences ΔT (K), medium width L (m) and cross section area A (m^2), and thermal conductivity k (W.m^{-1}.K^{-1}), as follows [10].

$$q_x = -kA\frac{\Delta T}{L} \tag{2.1}$$

To describe heat transferred between a surface and a moving fluid (convective heat transfer), the variables to consider are similar to the ones considered for conduction heat transfer. Temperature difference $(T_S - T_\infty)$ (K) is still a key factor since it drives the direction of the heat flux and consists in the difference between surface temperature and the temperature of the fluid outside the boundary layer. A_S (m^2) is the area of the surface in contact with the moving fluid, and h (W.m^{-2}.K^{-1}) refers to the convective heat transfer coefficient (which is considered many times as constant within the surface, for simplification) [10].

$$q_s = hA_S(T_S - T_\infty) \tag{2.2}$$

Finally, the third form of heat transfer is radiation. While both conduction and convection need a presence of a medium in order to occur, radiation does not need one and is, in fact, more efficient in a vacuum. Despite that fact, any body at a nonzero temperature (K) has a radiation emissive power limited by the Stefan-Boltzmann law, where the Stefan-Boltzmann constant, σ ($= 5.67 \times 10^{-8}$ W.m^{-2}.K^{-4}) is present on the radiation predictive expression. Also, in that expression there is the blackbody relative emissivity of the emitting body ε (ranges between 0 and 1, 1 being an ideal radiator, known has black-body), the dependency on the body surface area A (m^2) and, finally, the fourth power temperature difference between the surface and the surroundings $(T_S^4 - T_{sur}^4)$ (K^4). The final expression is as follows [10].

$$q_{rad} = \varepsilon\sigma A(T_S^4 - T_{sur}^4) \tag{2.3}$$

Equations (2.1), (2.2) and (2.3) represent the generic simplified heat transfer mechanisms, but there are other ways of analyzing a heat transfer system. Like any system, heat transfer in buildings respects the energy conservation law. Simplifying, this means that the heat exiting a room is equal to the heat entering that room plus the internal generated heat. Sensible heat conservation in a room can be predicted by the following expression (in Watt) [10].

$$G_i + G_S + G_V + G_C = \rho C_{P_{air}} V_{room} \frac{\partial T_i}{\partial_t} + \sum_{n=1}^{k} A_n U_n (T_i - T_{S_n}) \tag{2.4}$$

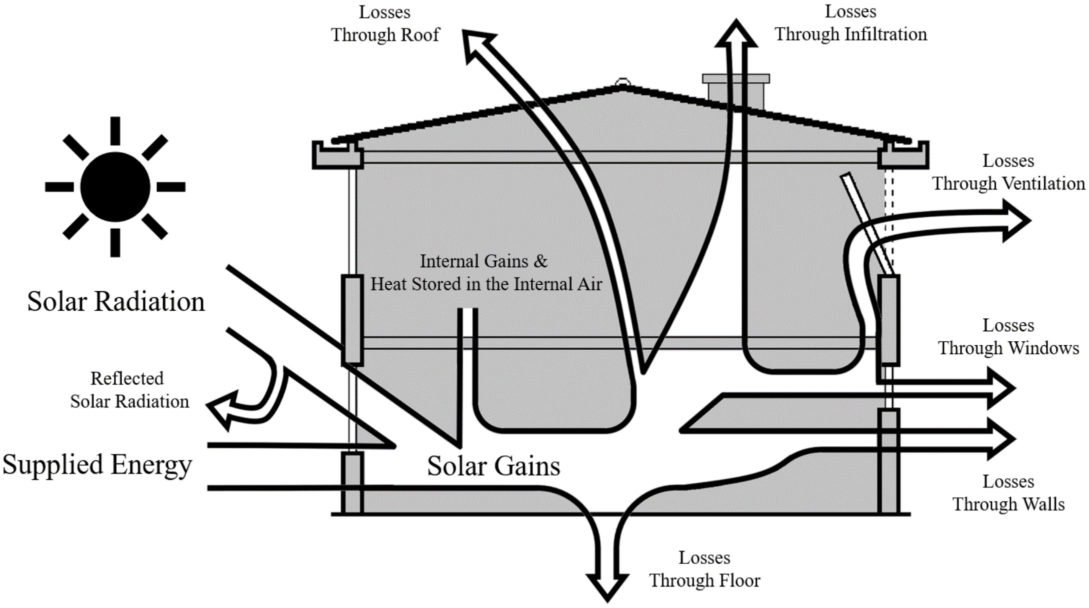


Figure 2.1 Heat balance in a building with Natural Ventilation (Adapted from [11]).

In Equation (2.4) and Figure 2.1, G_i is related to the internal gains, G_S is related to the solar gains, G_V is related to the ventilation gains (including infiltration) and G_C is related to the sensible climatization load (represented as “Supplied Energy” in the figure). The next component, $\rho C_{P_{air}} V_{room} \frac{T_i}{\partial_t}$, is related to the energy stored in the air inside the room. Here, ρ is the air density value (kg/m^3), $C_{P_{air}}$ is the air specific heat ($J.kg^{-1}.K^{-1}$), V_{room} is the room volume (m^3) and $\frac{\partial T_i}{\partial_t}$ represents the time variation of the internal temperature (K). Lastly, to represent the heat conduction through the boundaries of the system there is the expression $\sum_{n=1}^{k} A_n U_n (T_i - T_{S_n})$. A_n being the area of a given "n" surface (m^2), U_n being the heat transfer coefficient of a given "n" surface (W.m^{-2}.K^{-1}), and $(T_i - T_{S_n})$ representing the temperature difference between the interior air and the surface "n" temperature (K). Applying the summation to all the boundary surfaces of a room, one gets the heat transferred through conduction between the interior and the exterior of the system.

At all times, the application of the expression previously defined should give a net value of 0 W, which proves the heat conservation on the system (room/building) [10].

2.2. Natural Ventilation

Natural ventilation processes are driven by two distinct parts. There is the contribution caused by the wind effects and characteristics, and the contribution from the effect of temperature/buoyancy differences (stack-driven ventilation).

For the wind-driven part, there is the necessity of a pressure difference, caused by the wind, between the ventilated zone and the outside. These pressure differences are mainly caused by the wind speed and direction and have a fundamental effect on NV processes. The magnitude of the contribution given by this factor is strongly related to the wind intensity on the ventilated façade(s).

Stack-driven ventilation is affected by the temperature difference between inside and outside of a space, or the difference between connected spaces. Opposed to the wind-driven, the stack-driven ventilation happens when differences of temperature among the air occur (and thus differences of its density) inside a space. The last effect of these differences is the stratification of the air caused by different buoyancy forces applied to each layer of air. This stratification can lead to several different arrangements for air flow paths, depending on whether air mixing devices exist or not, and on the significance of the wind-driven component. When the ventilation is fully driven by temperature differences and there are no devices to promote air mixing in the room, because of the lower density of hot air it will rise and get accumulated near the ceiling of the ventilated space [12].

To calculate the contributions of both ventilation driving forces, Equations (2.5), (2.6) and (2.7) are applied. (2.5) calculates the values of the pressure coefficient, which represents the ratio between the local wind-driven static pressure (applied by the wind on the façade) and the incoming wind pressure. This coefficient in addition to the reference wind speed and air density, is relevant for the calculation of the wind-driven component in terms of pressure difference caused, Equation (2.6). As with buoyancy-driven ventilation, air density, gravitational acceleration, the difference of heights between the outlet and the inlet air, and the temperature difference between outside air and the outlet air divided by the outlet air (in Kelvin), allow to quantify its contribution to the system, Equation (2.7). To obtain the total contribution of both pressure differences, one needs to apply Equation (2.8) [13].

$$C_p = \frac{P_{local}}{\frac{1}{2}\rho W_s^2} \tag{2.5}$$

$$\Delta P_{wind} = \frac{1}{2}\Delta C_p \rho W_s^2 \tag{2.6}$$

$$\Delta P_{buoyancy} = \rho g (H_{outlet} - H_{inlet})\left(\frac{T_{outside\ air} - T_{outlet\ air}}{T_{outlet\ air}}\right) \tag{2.7}$$

$$\Delta P_{total} = \sqrt{\Delta P_{wind}^2 + \Delta P_{buoyancy}^2} \tag{2.8}$$

Where:

C_p – Pressure coefficient [adimensional];

P – Pressure [Pa];

ρ – Air density [kg/m^3];

W_s – Wind speed [m/s];

g – Gravitational acceleration [m/s^2];

H – Opening height [m];

T – Temperature [K].

Typical natural ventilation strategies require one or more openings. Considering the simple case where there are only two openings, it might result in one of four forms of natural ventilation: single-sided, cross, corner, or displacement. In Figure 2.2 there are the schematics of these strategies, followed by the explanation of its differences [14].

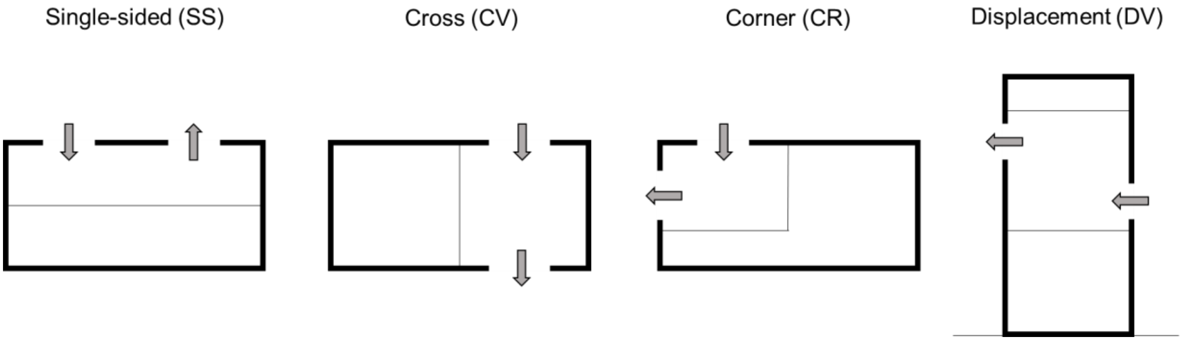


Figure 2.2 Different strategies of natural ventilation. Note: The view angle is from the top of the room, except on the DV example where it is a side view (adapted from [14]).

Regarding single-sided ventilation (SS), the situation can have different behaviours. If there is only one opening for the ventilated room, and since the air flow can only enter and exit the space from that opening, the wind effect is somewhat weaker than the buoyancy one. The stacking of the air in this situation causes the cooler air to enter the space through the lower part of the opening and the hot air to leave it through the upper part of the opening. This situation can also occur when there are more than one opening situated at the same height on the façade.

Cross ventilation (CV) is considered one of the most effective forms of NV, given the larger air flows provided by this method. This happens because the air path crosses the entire room, meaning that it enters through one façade and exits through the opposite one. Although being barely affected by the buoyancy effect, this strategy strongly depends on the wind velocity and direction, which can be somewhat uncomfortable when the ventilated room is situated on an area with regular high wind speeds which cause a lot of strong drafts.

Behaving similarly to CV, Corner ventilation (CR) can also provide large air flows, although not being able to provide the same air penetration depth to the ventilated room. This situation happens when the room is built in such a way that the openings are situated on perpendicular façades.

When the openings are at different heights on any façade, it is called displacement ventilation (DV), but this thesis focuses on single-sided NV with all the openings (when there are more than one) at the same height [14].

2.3. Thermal Simulation - EnergyPlus

EnergyPlus is a simulation program that performs modeling of buildings and all the associated heating, ventilating, and air conditioning equipment. It works in a standard form of “garbage in, garbage out”, meaning that the user inputs are not proof-checked as plausible or not for the problem being solved, and the outputs are a direct result of the inputs which are not adjusted by the program. This results in the fact that there is always the need of an engineer (or someone certified) to operate the simulations and the necessity of avoiding the usage of the program in substitution of a technician. With the energy crisis of the 1970s and the acknowledgement of the influence of buildings on the energetic sector, energy and load simulation tools like BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 (Developed for the U.S. Department of Energy) started to appear. EnergyPlus is based on the two previous cases and its function is to perform energetic analysis and thermal load simulation. With the inputs given by the user (e.g. building geometry, occupancy, electrical equipment, schedules and surrounding weather conditions), the simulation program will calculate the heating and cooling thermal loads (in comparison with the temperature setpoints given as input) on a user-defined timestep. Since the intended audience are design engineers or architects that wish to size HVAC systems, not only can the software solve simple cases of thermal loads, but also more specific characteristics (among a lot more) like HVAC related coil loads or air handling units sizing. Despite the HVAC applicability, solutions like NV can also be modelled in this program and can sometimes be compared with HVAC alternatives and proven better. More recently EnergyPlus upgraded some of its objects to improve ways of working not only with mechanical ventilation, but also with natural ventilation. These objects allow the operator to model the building without artificial ventilation and to define the openings, making it possible to develop studies for a given building comparing these two strategies (or even a mix of the two: hybrid ventilation systems) [15].

In a simplified way of putting it, the user gives the software building inputs and weather file inputs for the days of study, and the program's integrated solution generator solves the heat transfer processes occurring while using code-based algorithms like internal air balance generator or surfaces heat balance generator. Finally, after the processing of the inputs and the application of the models needed for a given problem, the outputs chosen by the user, from a wide list presented on the interface, are presented to download. Figure 2.3 shows an example of the processes taken for solving a problem.

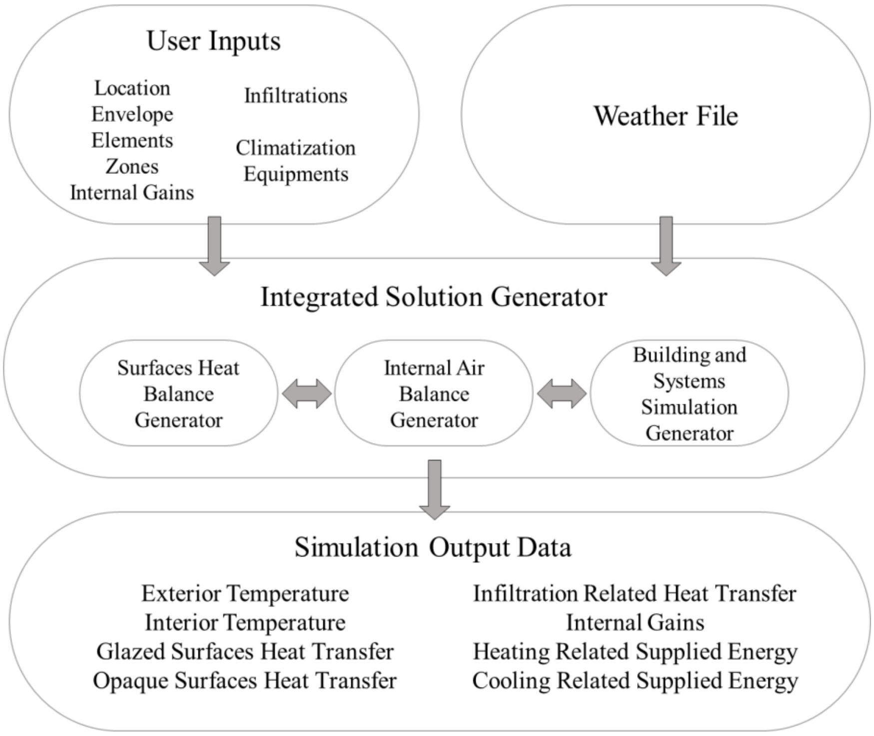


Figure 2.3 EnergyPlus operation process schematics. (Adapted from [11])

This is just a brief explanation of what the software is intended to do but there are a lot more capabilities. Adding to the previously presented ones, some early features of EnergyPlus are "Heat balance based solution", "Transient heat conduction", "Combined heat and mass transfer", "Thermal comfort models", "Daylighting controls", "Atmospherical pollution calculations", etc. [15].

3 Review of Existing Work

This section mentions several other studies related to SS NV systems. While explaining its main objectives and comparing them with the work that originated this thesis, it is possible not only to notice some similarities and core ideas, but also differences in both the approach taken and the final objective of the work despite the common subject. All the mentions to these studies are followed by brief explanations of the selected approaches and the main conclusions obtained. A summary of the methodology is exposed in Table 3.1.

Table 3.1 Some examples of previous publications related to the subject of this thesis. Note: W stands for wind and B for buoyancy (or stack).

Reference	Building type	Driving mechanisms	Experimental Approach
R. R. Walker *et al.* [16]	Office	W&B	Field Measurements
M. White *et al.* [17]	Office	W&B	Field Measurements
T. S. Larsen *et al.* [18]	Test Cell	W&B	Wind Tunnel
M. F. Detaranto [19]	Test Cell	W&B	CFD
N. C. Daish *et al.* [14]	Story blocks	W	Wind Tunnel
X. Ma *et al.* [20]	Test Cell	W&B	CFD
K. Huang *et al.* [21]	Room	W&B	Field Measurements
J. Park *et al.* [22]	Test Cell	W&B	CFD

Following a chronological order, around 1992 in R. R. Walker *et al.* [16] an office room was selected as case-study to conclude about the depth of SS NV. Using tracer gas, the authors were allowed to conclude about the movements of the air inside the office caused by the incoming air. The studied office had 10 meters depth and the experiments showed that along the whole depth the fresh air was generally well distributed. They also concluded that with additional measures like window blinds (interior and exterior), one could significantly reduce solar gains and its undesirable effects on the thermal comfort for the office (solar gains are one of the main causes of overheating). In comparison to the CIBSE limitations, which limited a SS office to 6 m depth and a SS office building to have 15 m limit for the width (considering 2 offices separated by a 3 m corridor), the results obtained in this work suggest that it is possible to have this kind of buildings with a width larger than the imposed 15 m. Generally, the main conclusion is that SS NV might be a viable strategy to apply on deep open-plan offices. In comparison to the work studied on this thesis, both the approach and the desired conclusions are comparable: office case-study measurements with the aim to conclude on the over strict limitations mentioned.

After the previously mentioned study, Walker joined White in M. White *et al.* [17] (1996) to continue investigations in the SS NV area (also including CV). The experimental approach was to measure the air flow paths inside offices to further conclude about the effectiveness of both SS and CV strategies. Since this thesis focus is SS, this analysis will not consider CV conclusions obtained. The first conclusion regards to the applicability of the rule of thumb already mentioned (6 m depth limitation), where the authors found out that this only applies to air speed and situations where the air currents are unmixed, meaning that only until 6 m from the façade air speed notes some variations. This situation changes when there are some artificial mixing devices like ceiling fans that enables larger depths with guaranteed air mixing and thus proper ventilations rates and thermal comfort. These conclusions are also somehow related to the previous work done by the authors mentioned and by this thesis.

In T. S. Larsen *et al.* [18] (2007) the authors aimed to define a new design expression including both wind and temperature components of SS NV. They found out that wind direction is also an important factor to consider given that it has shown to have an impact on the air change rate. During the experiments the authors concluded that the dominating force (wind pressure or temperature difference) changes in function of the wind direction and as a function of the ratio between them. With the help of wind tunnel measurements, the new expression was defined. It allows to predict the SS NV air flow in function of different wind directions, and it contains three different cases of wind direction: windward, leeward, and parallel flow. When compared to outdoor measurements, the new expression was found to have an uncertainty of 14%.

Later (around 2014), M. F. Detaranto [19] presented some CFD studies on a 2.5H (H stands for floor to ceiling distance) test cell to develop the analysis of air flow patterns and heat transfer in several structures. On passive cooling, two studies were established in the SS 2.5H test cell. The aim of this testing was to check the impact of positioning the windows on different places on the façade; the first case had both windows close to each other vertically on the center of the wall, and the second case had them farther apart (one on top of the façade and one on the bottom part of it). Both cases presented a presumably well-ventilated room, and the air flow patterns did not show stagnant air regions. The room with the top and bottom windows presented to be the one with higher ACH (air changes per hour), due to the larger pressure difference between openings, causing it to be the best studied window disposition for SS NV.

In N. C. Daish *et al.* [14] (2016), recurring to wind tunnel experiments, investigations on the impact of horizontal aperture separation (instead of vertical variations like the previous mentioned study) were developed, concluding that the flow rate is dependent of the wind velocity, its angle with the façade, and on the aperture separation. About this last factor, the authors found out that when the separation is low (distance between the two openings is around 10% of the façade’s width) the benefits of increasing its separation are strong. Until the separation distance represents 50% of the façade’s width the benefits keep increasing at a high rate, although from that value on the advantages are starting to get less noticeable. Summarily, the conclusion was that larger air flows occur when the separation distance is higher than 50% of the façade’s width. This study also registered the occurrence of a new flow driving mechanism called vortex shedding, which happens when the openings are on the leeward side of a SS ventilated building and the wind direction is almost perpendicular to the opposite façade, causing the wind to be pumped inside the building.

In 2017, X. Ma *et al.* [20] studied, on a Test Cell recurring to CFD, the effects of the window placements for three NV strategies: SS leeward, SS windward, and CV. Focusing on SS for the purpose of this thesis, the conclusion relevant to mention is that because of the recirculation bubble (vortex shedding) occurring on leeward SS NV, this strategy has shown to promote larger air flows when compared to the studied windward SS NV. Despite this result, the authors pointed out that this is not so conclusive since many other publications have shown the opposite result. Given that, they ended with an encouragement to the necessity of investigating more about this inconclusive situation.

Also, during 2017, K. Huang *et al.* [21] includes some field measurements in a real room to investigate the error of 3 empirical models for SS NV, in the situation of great indoor-outdoor temperature differences. Looking only into the initial conditions of the room, the three methods have shown a discrepancy of 11.8%, 12.8% and 7.3%, when compared to the field measurements. From these three, the best model to calculate air change rates under large temperature differences is Warren’s with 7.3% deviations only. The crucial characteristics of this model are as described in the publication: “the hot press formula is based on the analytical solution, assuming that the neutral surface is at the middle of the opening, the temperature inside and outside the opening is constant and the pressure is linearly distributed.”. Despite not following that much this thesis' subject, it helps situating SS NV studies and the state of the art related to predictive models.

More recently, J. Park *et al.* [22] (2017) applied some CFD modeling to study the effect of wind and buoyancy interaction on SS NV in a building (represented by a test cell). They introduced the Archimedes number (Ar) as an evaluator of the interaction between buoyancy and wind effects and concluded that under a positive temperature difference between the inside and outside of the building, the interaction between the two forces is destructive, resulting in the combined effect to reduce the volume of air ventilating the room. Still under positive temperature differences, the Archimedes number indicates an equal interaction ventilation when $Ar^{0.5}=0.45$, wind-driven when $Ar^{0.5}$ is inferior to that value, and buoyancy-driven when $Ar^{0.5}$ is superior to 0.45. When the temperature difference is negative, the effects are always constructive, which results in the combined effect to be always reinforcing the ventilation for all the Ar values.

Relating the previously exposed examples with this thesis, the major difference is the fact that there are no other examples where model validation was applied to the measurement results obtained. This fact reinforces the motivation of this thesis since the studies on the SS NV depth effectiveness are few, and the ones where those effectiveness results are compared with simulation models (model validation) are practically non-existent.

4 Methodology

After some introductory experimental work around the available experimental material (mainly temperature and CO_2 sensors), came the possibility to define the characteristics of the case-studies. In this section there is the explanation and characterization of the case-studies, the sensors setup schematics and the information used on the energy simulations tool.

4.1. Case-studies

Attending to the objectives of this thesis, three different rooms were selected to be studied in order to better conclude about the capabilities of SS NV on several types of offices. A large one, a medium one and a long narrow one. Given these characteristics they were respectively named “Large”, “Medium” and “Long” offices. For this thesis, more important than the floor area is the distance from the single-sided natural ventilated façade to the opposite wall, this being the best indicator of the depth range of the incoming ventilative air.

The offices are situated inside FCUL facilities, in the city of Lisbon near the urban area of Campo Grande (Latitude 38.76 N; Longitude 9.16 W). Large office is situated in the second floor of C1 building (total of 6 floors), with the exterior façade oriented towards NNW. Medium office is part of the second floor of C8 building (total of 5 floors), with the windows oriented towards SSE. As with Long office, this one is also part of C8 building, but in this case it is situated on the first floor with the opening façade oriented towards ENE. All three rooms were made air tight to ensure the mitigation of the infiltration air flows from outside and that all the ventilation occurring in the given room were due to the SS NV opening. This included the sealing of doorways and all ventilation grilles.

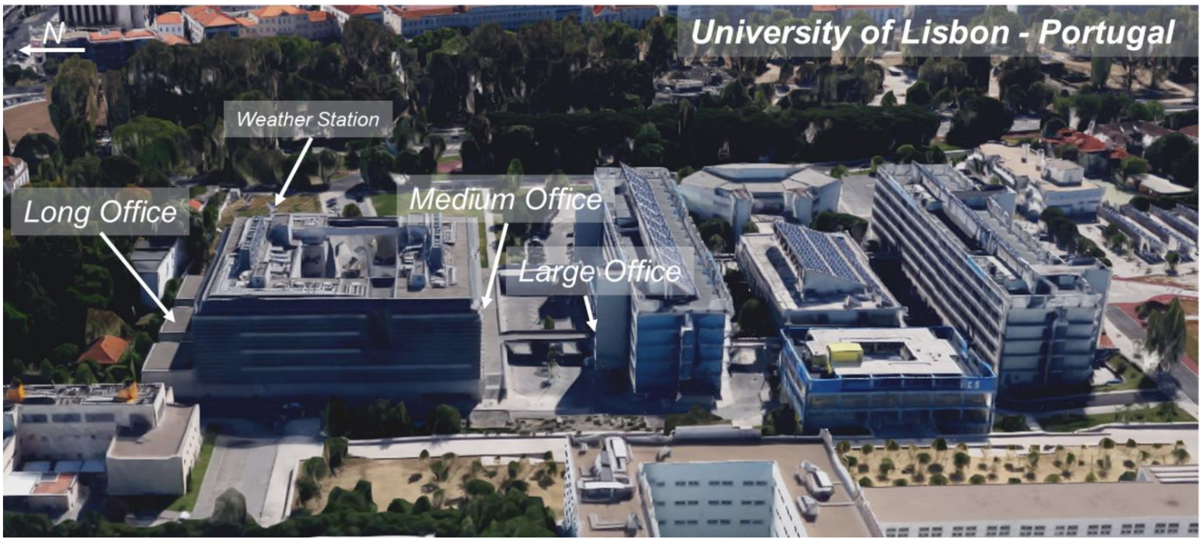
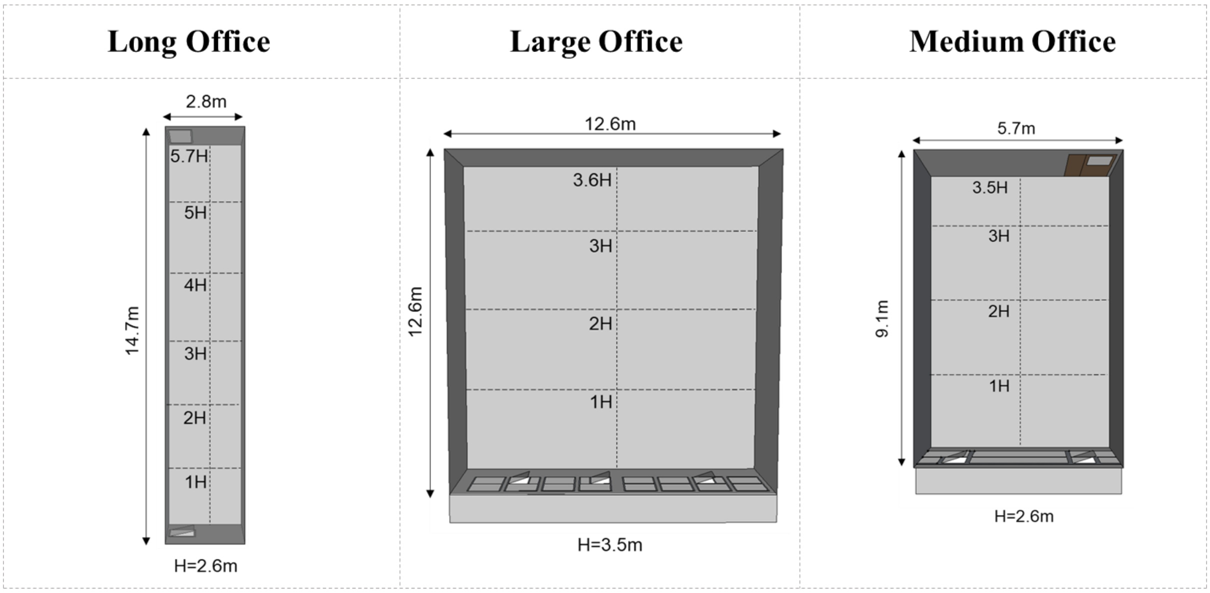


Figure 4.1 Location of the three case-studies and weather station, on FCUL Campus – Lisbon. Note: Weather Station is where Outside Temperature, Global Horizontal and Diffuse Horizontal Irradiance were measured. Wind direction and velocity were measured on each office’s exterior façade.

Relatively to the characteristics of the case-studies, on Figure 4.2 there is an exposition of those, completed by Table 4.1. Long office has 5.7H and is 14.7 m long and 2.8 m wide. Large office has 3.6H and has 12.6 m by 12.6 m. Medium office has 3.5H and is 9.1 m long and 5.7 m wide. Note that all the case-studies have depths larger than the 20 ft (roughly 6 m) and 2.5H mentioned on the legislations, in order to check if those are undoubtfully suitable or not. There are also photos of the case-studies to give a better understanding of how the experimental work was developed (Figure 4.3 to Figure 4.5).



Long Office | **Large Office** | **Medium Office**

Figure 4.2 Internal dimensions of the studied rooms.

Other characteristics of the experiments not perceptible by the figures are presented on the following table (Table 4.1), such as the opening area ratio (ratio between the opening area and the floor area), occupation and internal gains density.

Table 4.1 Specifications of some of the characteristics of the case-studies.

Office	Height (m)	Area (m^2)	Opening Area Ratio	Occupation	Internal Gains (W/m^2)
Large	3.5	158	1.0%	30 avg. (19-44)	25
Medium	2.6	52	1.2%	7	27
Long	2.6	41	1.5%	6	28

The photos presented next (Figure 4.3 to Figure 4.5) are here with the objective of allowing a better understanding and visualization of the case-studies and the experimental setup.

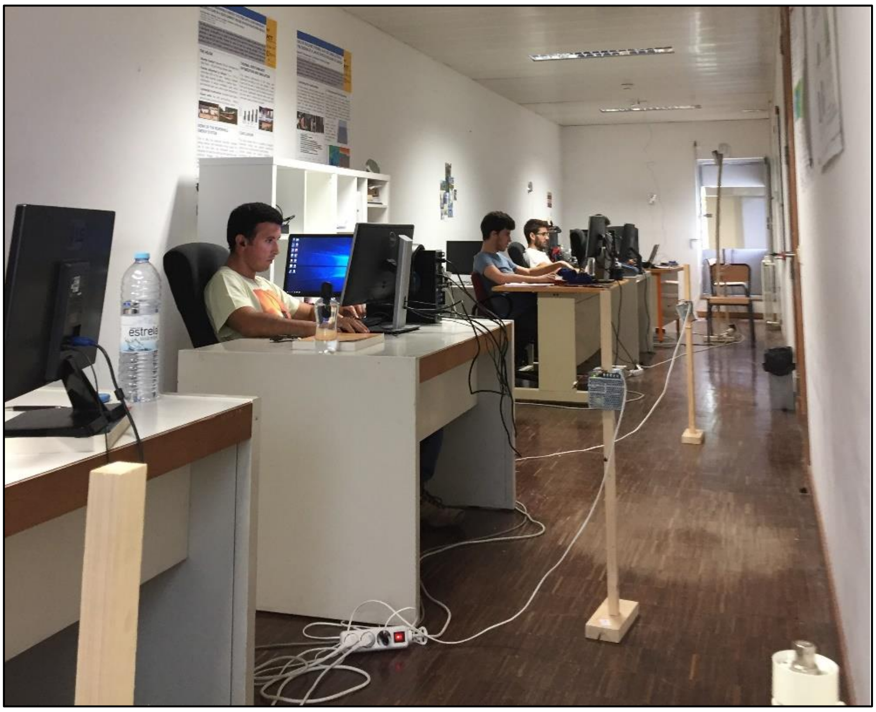


Figure 4.3 Long Office inside view during the measurements.

From the previous figure, it is possible to notice the distribution of the sensors along the room's depth. Long Office had 6 occupants and an internal gains density of 28 W/m^2.

Figure 4.4 Large Office inside view during the measurements.

Large Office presented a variable occupancy of between 19 to 40 people inside, averaging 30 over the experimental time. The average internal gains for this case-study were 25 W/m^2.

Figure 4.5 Medium Office inside view during the measurements.

To allow a similar value of internal gains density on Medium Office when compared to the other two cases, to complement the ceiling lighting, 7 people, and the electric equipment, 3 additional lamps were added with the resulting power of around 300 W (3 times 100 W), giving an extra of 6 W/m^2 increasing the total value to 27 W/m^2 (more comparable to the 25 and 28 W/m^2 of the other case-studies). Other than that, the opening area ratio (total opening area divided by floor area) had also comparable values ranging between 1.0% and 1.5% (Large and Long offices, respectively).

4.1.1. Experimental Setup

Several kinds of sensors were used in the experimental tests, therefore, in Table 4.2 there is a description of the sensors used and its specifications. There is also a group of schematics showing the sensors disposition in all the three case-studies.

Table 4.2 Specifications of the measurement sensors used.

Sensor		Measurement	Specifications	
F900 S-P Airflow Sensor		Wind speed	Range	0.15-10 m/s
			Accuracy	±0.05 m/s or 10% or 1% full-scale (which one is greater)
EKO Instruments	(MS-802 Pyranometer)	Global Horizontal Irradiance	Range	0-4000 W/m^2
			Accuracy	±2 W/m^2
	(MS-56 Pyrheliometer)	Diffuse Horizontal Irradiance	Range	0-4000 W/m^2
			Accuracy	±2 W/m^2
		Direct Normal Irradiance	Range	0-4000 W/m^2
			Accuracy	±1 W/m^2
CO$_2$ Meter (K-33 ELG)		Carbon dioxide (indoor)	Range	0-10000 ppm
			Accuracy	±30 ppm ±3%
		Temperature (indoor)	Range	-40 to 60 ºC
			Accuracy	±0.4 ºC at 25 ºC
HOBO U-12 013 (complemented with:)		Temperature (indoor)	Range	-20 to 70 ºC
			Accuracy	±0.35 ºC (0 to 50 ºC)
Telaire 7001		Carbon dioxide (indoor)	Range	0-2500 ppm
			Accuracy	±50 ppm or 5% of the measurement (which one is greater)

To measure the variables selected, the sensors were installed on positions that would give a good distribution of the needed variables among the room. The way the office furniture and construction were displayed imposed some restrictions on the places available to install the sensors. That being considered, the disposition of the sensors follows the schemes presented on Figure 4.6, each one representing the related case-study. Note that on Large Office the sensors were not only placed in depth but also in a perpendicular direction to the façade to give a better visualization of the lateral variations on the room given its large dimensions. On the other two case-studies, that effect was not considered to be of such relevance since variations with depth were the main interest and these rooms did not have such large width dimensions as the previous one. Most of the sensors installed are at 0.7 m since this is the average height of the occupied zone (considering that people are seated at offices), and the other sensors that are at 2.0 m were included to allow conclusions on the stratification of the air inside the rooms.

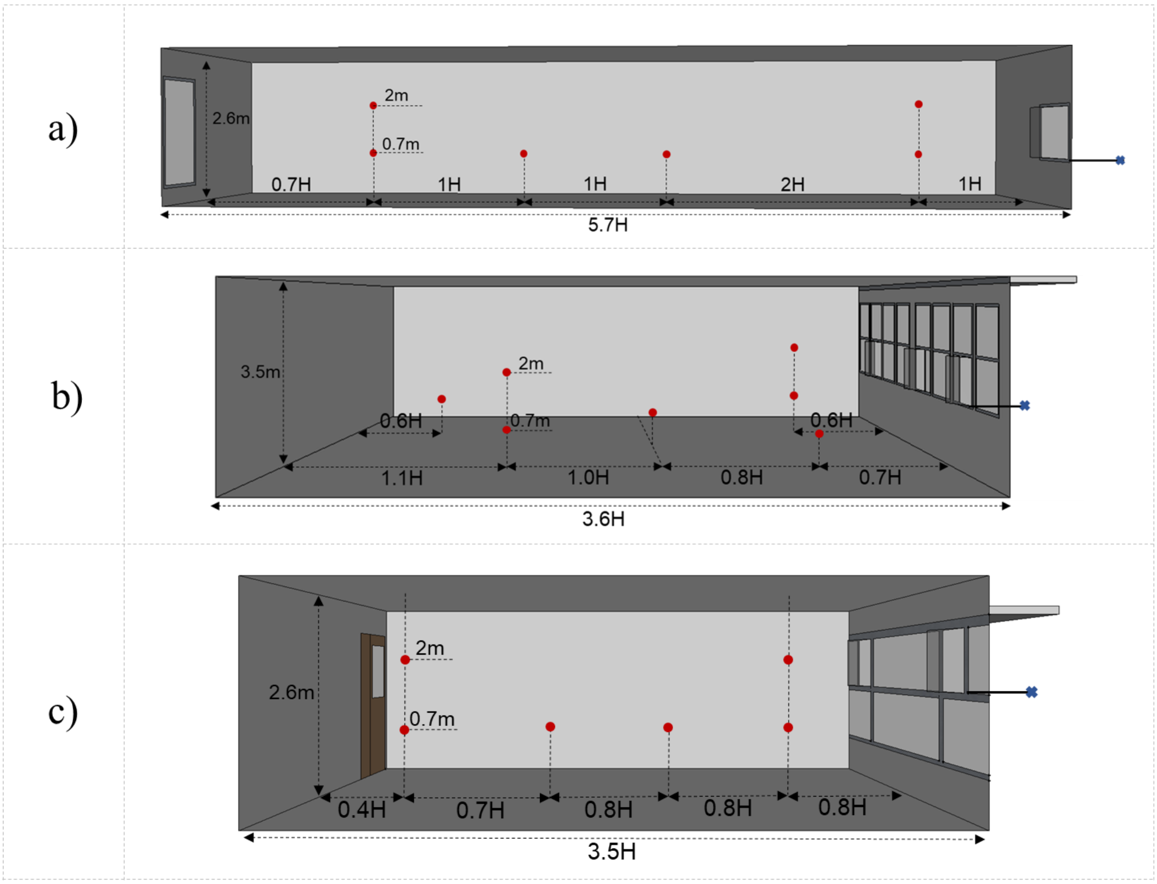


Figure 4.6 Sensors location during the experiments. **a)** Long Office; **b)** Large Office; **c)** Medium Office. **Note 1:** Red indicates Temperature and CO_2 measurements, while Blue represents the outside measurements of global and diffuse irradiance sensors as well as the temperature, wind speed and wind direction. **Note 2:** The distances are not drawn at scale.

Other than the sensors presented on the previous figure (measuring CO_2 and temperature), all the remaining variables were measured relatively to the room being studied. Explicitly, all radiation measurements were done in the Solar Campus Weather Station (Figure 4.1), but wind variables and both CO_2 levels and outside temperature were measured on the outside of the façade of each case-study (represented as the blue cross near the windows, on Figure 4.6).

4.1.2. EnergyPlus Simulations

To allow the validation of the experimental results, and since there are a lot of topics to specify in a simulation model, this section lists the acknowledgments that were considered in the simulations of the three case-studies as well as the outputs obtained from the simulations.

The first step is to build the geometrical model of the simulated rooms. These geometrical models were drawn in the software SketchUp with the Legacy OpenStudio plugin (optimization for applications on EnergyPlus). The divisions modeled in each one of the three simulations contain not only the case-study rooms, but also the adjacent floors, rooms, corridors and divisions (when needed). Figure 4.7 to Figure 4.9 show the models drawn in SketchUp for the three case-studies. The adjacent rooms that were using HVAC, were modeled considering the HVAC systems.

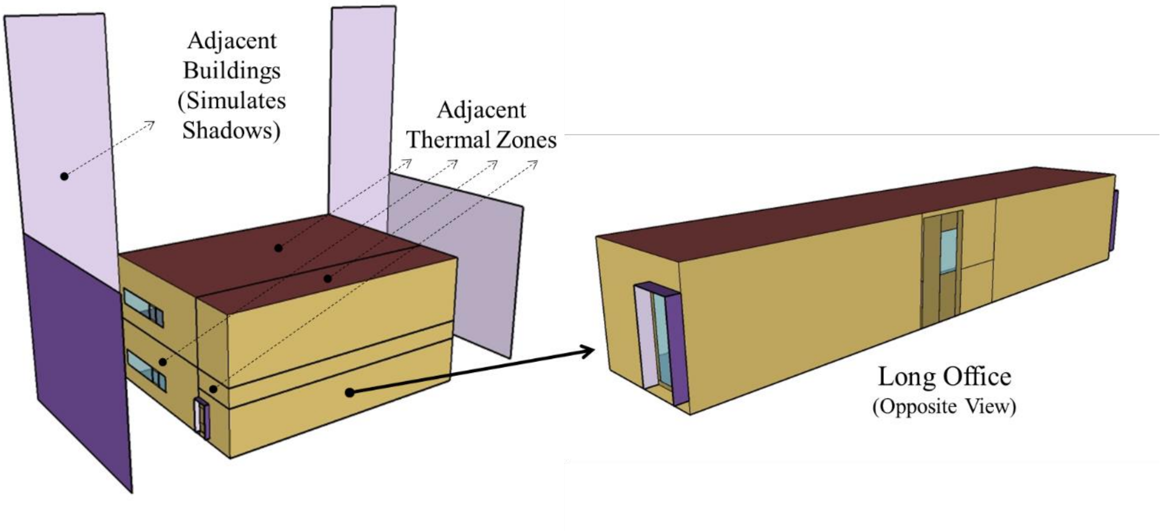


Figure 4.7 EnergyPlus Long Office models visualized on SketchUp.

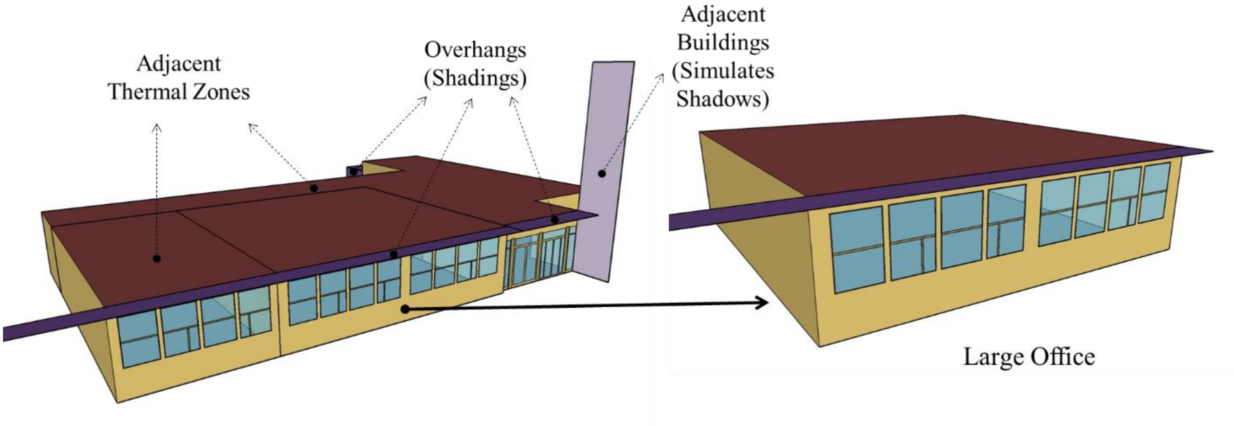


Figure 4.8 EnergyPlus Large Office models visualized on SketchUp.

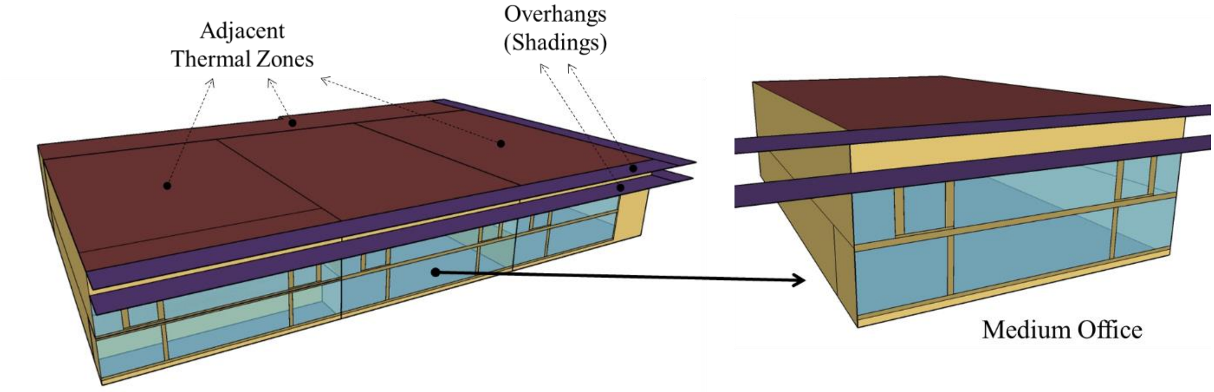


Figure 4.9 EnergyPlus Medium Office models visualized on SketchUp.

With the Legacy OpenStudio plugin for EnergyPlus, there is the easiness of defining thermal zones (as opposed to simple divisions only), which are the key factor to analyze energy systems in buildings. Then, there is the advantage of making those zones immediately recognizable as thermal zones by EnergyPlus, allowing the users to quickly proceed to other aspects of the energetic model. After having the thermal zones defined, it matters the most to state how they interact with each other and with the exterior. These are called the outside boundary conditions and need to be defined for all the surfaces present on the thermal zones of a geometry model. Outside boundary conditions were then defined as “Outdoors” when the surface is in contact with the exterior, “Ground” when in contact with the ground, “Surface” when in contact with another thermal zone (with a matching surface), and finally “Adiabatic” in the vast majority of the non-mentioned cases (e.g. when the surface being defined was already at the limits of the geometrical model and further away from the case-study room). On this thesis, Medium and Large offices ceilings and floors were modeled with periodic boundary conditions. This means that they were simulated like there was a top and bottom floor with the exact same characteristics, and simulating that there are heat flows between those floors and the one being studied, without the need to draw those floors on SketchUp. When modeling a surface in contact with the ground, an input of the monthly average temperatures of the soil at 2 meters depth was given to EnergyPlus, and the floor constructive solution was defined as 0.05 m of screed (top layer), followed by 0.10 m of ground slab and 0.25 m of riprap, and finally 1.6 m of soil (to make the totality of the 2 meters thickness considered). This method was presented in N. M. Mateus *et al.* [23], where it was proven efficient and a simpler alternative to the “Slab” method present in EnergyPlus code.

After these steps, the constructive solutions of the models need to be given as inputs to EnergyPlus. The most relevant constructions used for this thesis are presented on Table 4.3.

Table 4.3 Constructive solutions of the most relevant surfaces for the three offices. Note: * - Interior Ceiling and Interior Floor have the same constructive solution with the layers in opposing order.

Office	Surface	Layering Order	Material	Thickness (m)	Conductivity (W.m^{-1}.K^{-1})	Density (kg/m^3)	Specific Heat (J.kg^{-1}.K^{-1})
Long and Medium	Exterior Wall	Outside ↓ Inside	Concrete	0.120	0.7	1600	2000
			XPS	0.030	0.034	35	1200
			Plaster	0.020	0.9	1900	2000
			Brick	0.200	0.6	1600	2000
			Stucco	0.020	0.5	1200	800
	Interior Wall		Stucco	0.020	0.5	1200	800
			Brick	0.110	0.6	1600	2000
			Air	0.030	0.023	1.2	1000
			Brick	0.110	0.6	1600	2000
			Stucco	0.020	0.5	1200	800
	Interior Ceiling/ Floor*		Wood	0.080	0.14	550	1750
			Concrete	0.300	0.9	1900	2000
			Stucco	0.020	0.5	1200	8000
	Door		Wood	0.025	0.15	608	1630
Large	Exterior Wall	Outside ↓ Inside	Brick	0.110	0.89	1920	790
			Concrete	0.110	1.4	2450	900
			Gypsum	0.019	0.16	900	1090
	Interior Wall		Gypsum	0.015	0.16	900	1090
			Brick	0.110	0.89	1920	790
			Gypsum	0.015	0.16	900	1090
	Interior Ceiling/ Floor		Light-weight Concrete	0.100	0.53	1280	840
	Door		Wood	0.025	0.15	608	1630

Accordingly to Figure 2.3, the inputs given to EnergyPlus are Location, Envelope Elements (Geometry and Constructive Solutions), Thermal Zones, Internal Gains (including lighting, electronic equipment and people), Zone Surface Infiltration, and the Weather File. On the case of our study, no climatization equipment was used, since we were dealing with NV. It remains to specify the internal gains, surface infiltration and weather files used when modeling the three case-studies.

The internal gains given as input to the software were collected at several instants during the experimental work, this being related to people (occupancy), ceiling lights and socket electricity (computers, desk lamps, etc.). The values were given as a function of time to EnergyPlus although, for presentation, a better indicator to compare these offices is the internal gains density (W/m^2). Long office had an average value of 28 W/m^2, while Large had 25 W/m^2 and Medium had 27 W/m^2. These values are comparable which means that despite the different dimensions of the offices they represent similarly operating situations. The activity values and the CO_2 related to the people were defined accordingly to [24].

Zone surface infiltration were defined with the EnergyPlus object “ZoneInfiltration:DesignFlowRate”. On this object, for each office, values of air changes per hour were defined as 0.5 ACH to all the zones, accordingly to the typical office building values.

The weather file used was adapted from a typical weather file for Lisbon, with the addition of the measured values of wind velocity, dry bulb exterior temperature and solar radiation during the experiments. With this adaptation the weather file becomes more realistic because as the real data of the days when the studies occurred. The other variables present on weather files and not mentioned here remained relative to the typical year in Lisbon [25].

The next step was the definition of the natural ventilation processes occurring during the experiments (and on this case simulations). For this situation, there is an available object on EnergyPlus library called “ZoneVentilation:WindandStackOpenArea”, which includes the effects of both components of NV (wind and stack). The parameters needed are the opening areas of the windows, the opening effectiveness (C_w), which is a value that has to do with the direction of the incident wind on the façade (wind component related), the height difference (D_H), which represents the vertical placement of the windows on the façade (stack component related), and the discharge coefficient (C_D) related to the stack effect of the wind. The values of C_w and C_D used were based on [26].

There was also the definition of the remaining needed objects like schedules (time tables representative of inputs that were variable on time), internal mass (accounting for all the indicated furniture), and run period (time date of when the measurements were made, to relate this period with the available weather file data), to enable the simulation. The object “ZoneAirContaminantBalance” allows CO_2 levels to be modeled.

After all these steps and a few others with less relevance, one can simulate and choose the outputs that are obtained after each simulation from a list. The most relevant outputs for these simulations are zone temperatures and zone levels of CO_2. These two are the outputs that will allow to conclude about the air flow penetration depth for each of the three open plane office spaces studied.

5 Results and Analysis

After the experiments and the download of all the obtained values, the analysis of the results is here addressed. For both measured and simulated experiments the analysis is exposed in the next subchapters. There is also an introductory analysis of how the ACH were calculated (Equation (5.1) and Equation (5.2)).

To obtain some conclusions about the air changes per hour, these calculated values are going to be compared with those presented in [9]. This will determine whether the minimum (in Portugal) ACH are or are not achieved in the three case-studies. The method for calculations used is the one used by EnergyPlus, and is represented on Equation (5.1) and Equation (5.2). The first equation calculates the air flow that enters the room (Q [m^3/s]), and accounts with both components of natural ventilation (stack and wind), where $\left(C_w A_{op} W_s\right)$ is related to the wind effect and $\left(C_D A_{op}\sqrt{2gD_H\left|\frac{T_{zone}-T_{outside}}{T_{zone}}\right|}\right)$ relates to the stack effect. The second equation converts Q [m^3/s] in ACH [h^{-1}], for this being a standardized unit related to time instead of volume (which allows the comparison among rooms with different volumes).

$$Q = \sqrt{\left(C_w A_{op} W_s\right)^2 + \left(C_D A_{op}\sqrt{2gD_H\left|\frac{T_{zone}-T_{outside}}{T_{zone}}\right|}\right)^2} \tag{5.1}$$

$$ACH = Q \times \frac{3600}{V_{room}} \tag{5.2}$$

Where:

Q – Volumetric Air Flow Rate (m^3/s);

C_w – Opening Effectiveness;

A_{op} – Opening Area (m^2);

W_s – Wind Speed (m/s);

C_D – Discharge Coefficient;

g – Gravitational Acceleration (m/s^2);

D_H – Heigth Difference (m);

T_{zone} – Zone temperature (K);

$T_{outside}$ – Outside Dry Bulb Temperature (K);

ACH – Air Changes per Hour (h^{-1});

V_{room} – Room Volume (m^3).

Other conclusions are related to the temperature and CO_2 levels distribution on the rooms, this implicates that the values measured by each sensor are going to be compared with the other sensors on the same case-study. EnergyPlus model validation conclusions are based on the relations between simulated and measured results for average room temperature/CO_2 levels.

5.1. Measurements Results

Firstly, the nomenclature used to indicate the sensors needs to be explained. The logical way of looking into it is as follows:

- The last part on the name of each sensor represents the height at which it was installed, for example a sensor with "_2.0" on its name is located at 2.0 m meters from the ground.

- The exterior façade is considered as 0H (which gives the opposing façade to be located at 3.5H (medium office), 3.6H (large office) and 5.7H (long office)). For this case when a sensor has something like "2.5H_0.7" on its name it means that it is located at 0.7 m and at 2.5H from the exterior façade.

- Lastly, when standing inside the room facing the exterior façade, L represents the sensors that are on one's left side, C represents the centered sensors and R represents the sensors on the right side. This nomenclature happens only on Large Office and gives that when a sensor is called something like "R2.5H_0.7" it means that the sensor is on the Right side of the room, at the height of 0.7 m and at a 2.5H distance from the façade where there are windows.

Note that all the values on Subchapter 5.1 are presented (for each instant) after the application of a weighted average considering the four previous values, the four next values and the value itself. This helps smoothing the curves on the graph, which allows a better understanding of the information represented.

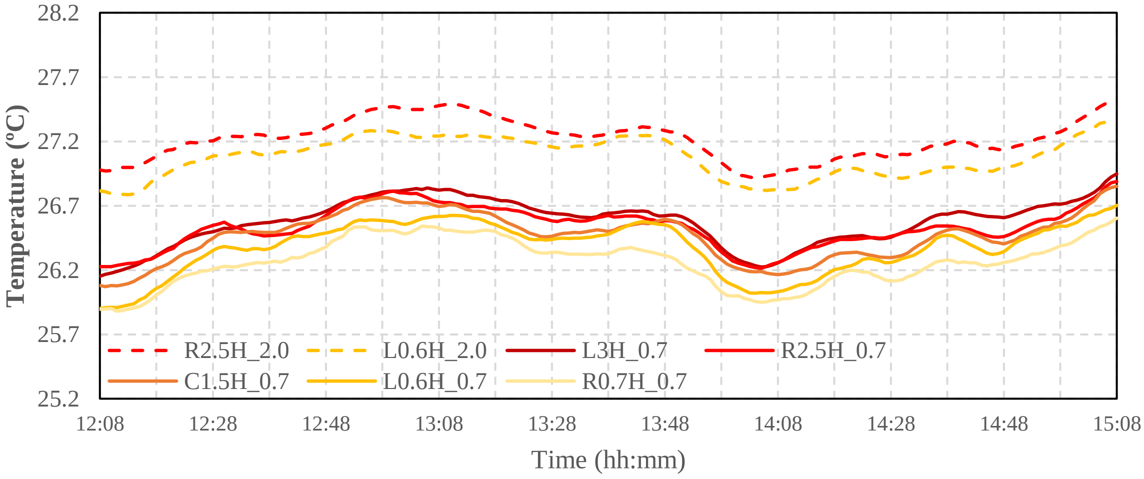


Figure 5.1 Large Office temperature values at the location of the various sensors, both at 0.7 m and 2.0 m.

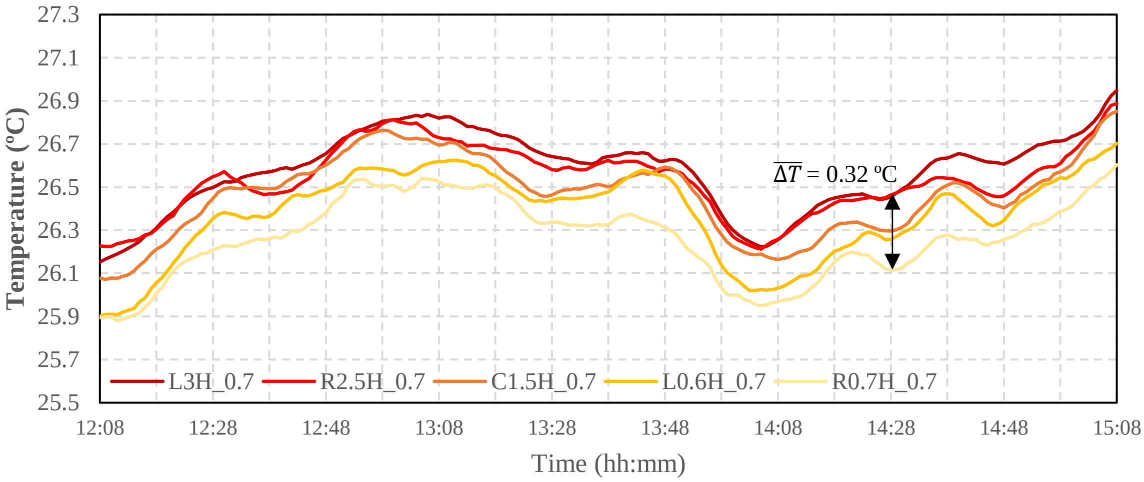


Figure 5.2 Large Office temperature values at the location of the various sensors at 0.7 m.

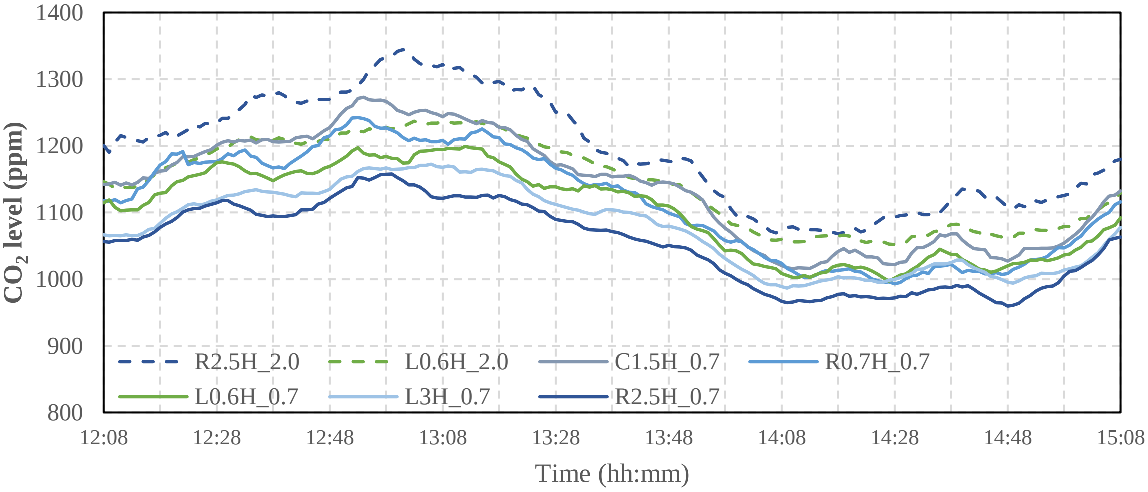


Figure 5.3 Large Office CO_2 values at the location of the various sensors, both at 0.7 m and 2.0 m.

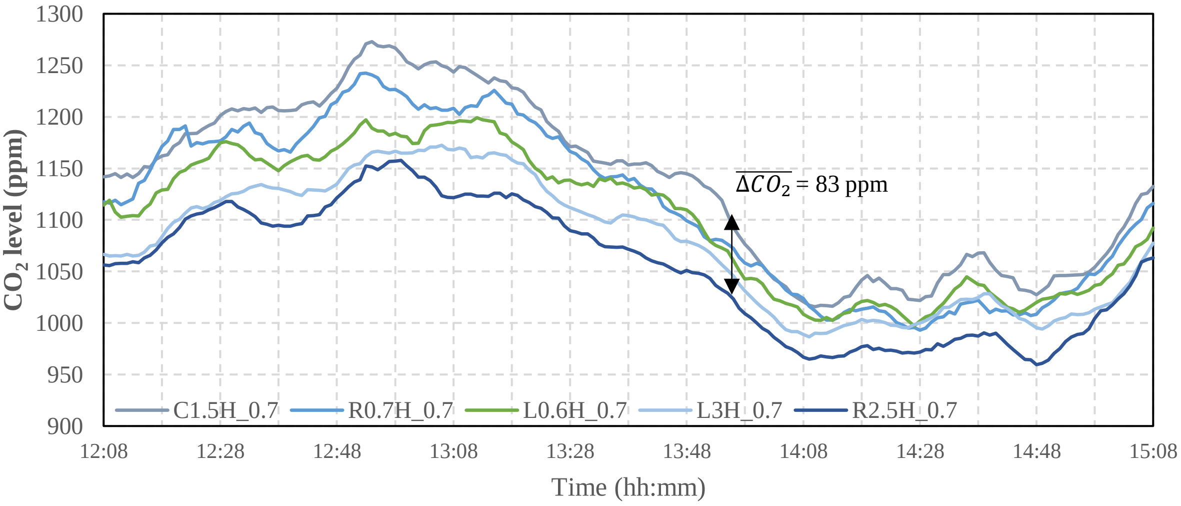


Figure 5.4 Large Office CO_2 values at the location of the various sensors at 0.7 m.

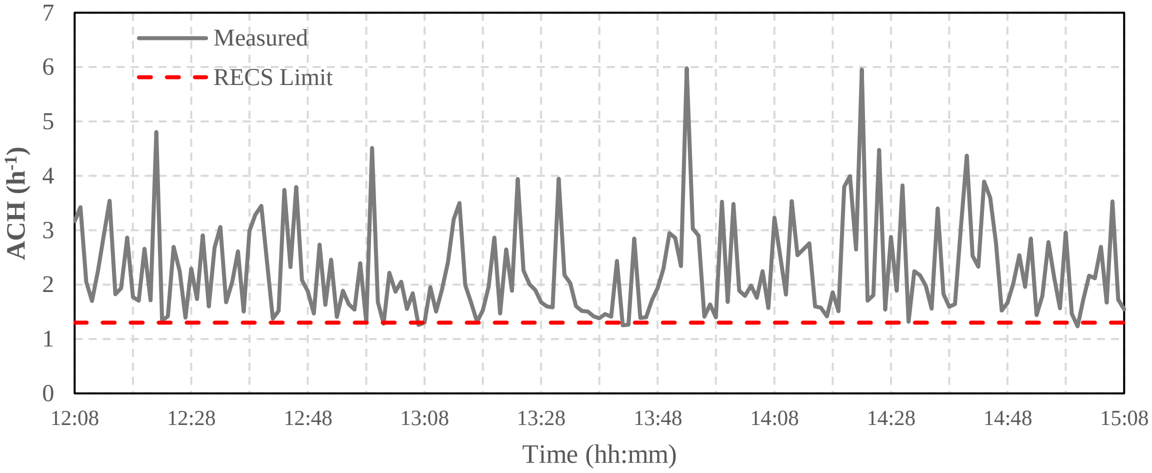


Figure 5.5 Large Office Air Changes per Hour in comparison with RECS limit.

Regarding Large Office, from Figure 5.1 and Figure 5.2, it is possible to observe two distinct relevant effects. Air stratification can be noticed on the first one, and on the second one it is shown that the air was getting a bit hotter as the distance from the windows increased. Despite that, it is a low variation in temperature, since the average difference between the minimum and maximum temperature registered at the height of the occupied zone (0.7 m) was only 0.32 ºC. At this point the ventilative strategy used looks effective.

As with CO_2 levels the analysis is similar. Figure 5.3 shows that at 2.0 m the concentration of CO_2 in the air is tendentially higher than on the other sensors' locations (0.7 m). At 0.7 m, as better perceived on Figure 5.4, the average difference between maximum and minimum CO_2 levels measured is just 83 ppm, which is a practically not even noticeable difference by the human. That gives that the SS ventilative strategy applied to Large Office proved effective at removing this air contaminant at least until 3H from the façade.

Finally, analyzing room air renovations rate (see Figure 5.5) it shows that almost all the time the limit was respected. On this case, the minimum ACH was only below or equal to RECS limit at 5 separate minutes, which gives a time percentage of 2.8% below (or equal) to the limit. This is not an alarming case, because 2.8% is a low percentage, and the values on those 5 minutes were almost at the limit level.

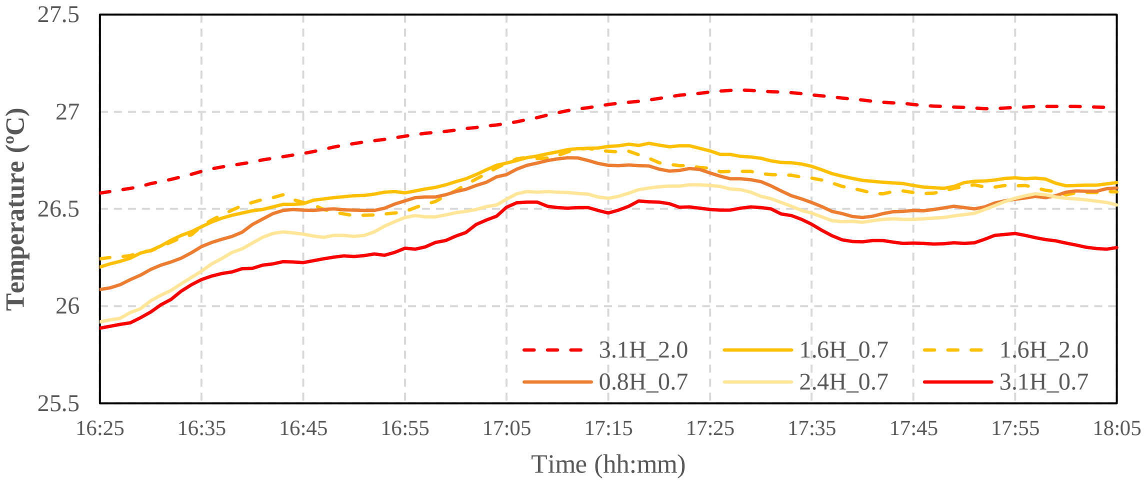


Figure 5.6 Medium Office temperature values at the location of the various sensors, both at 0.7 m and 2.0 m.

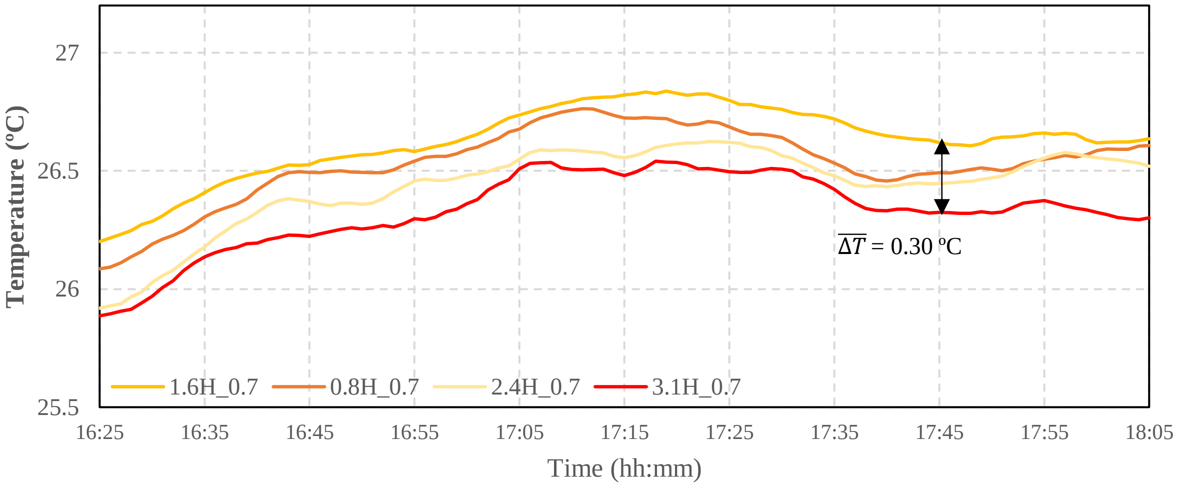


Figure 5.7 Medium Office temperature values at the location of the various sensors at 0.7 m.

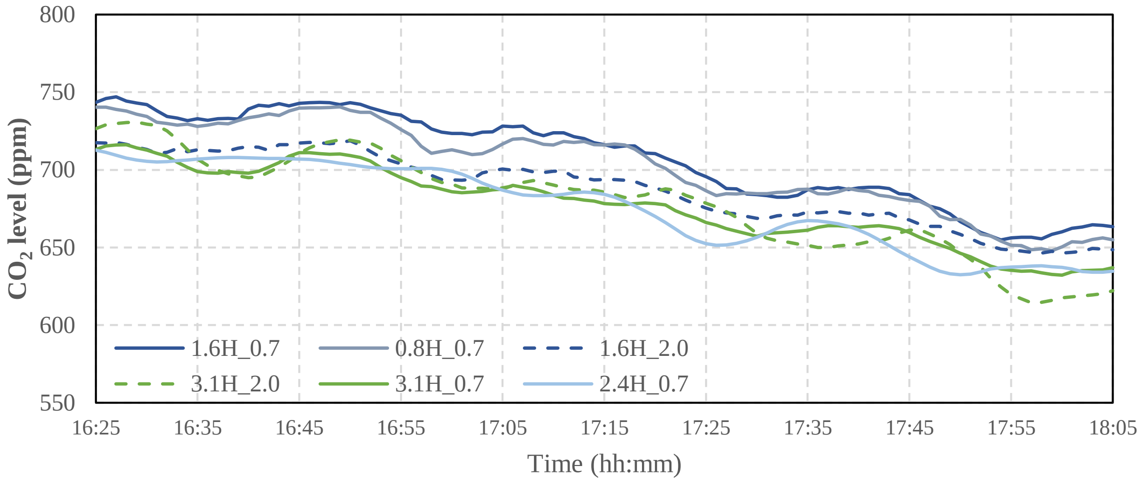


Figure 5.8 Medium Office CO_2 values at the location of the various sensors, both at 0.7 m and 2.0 m.

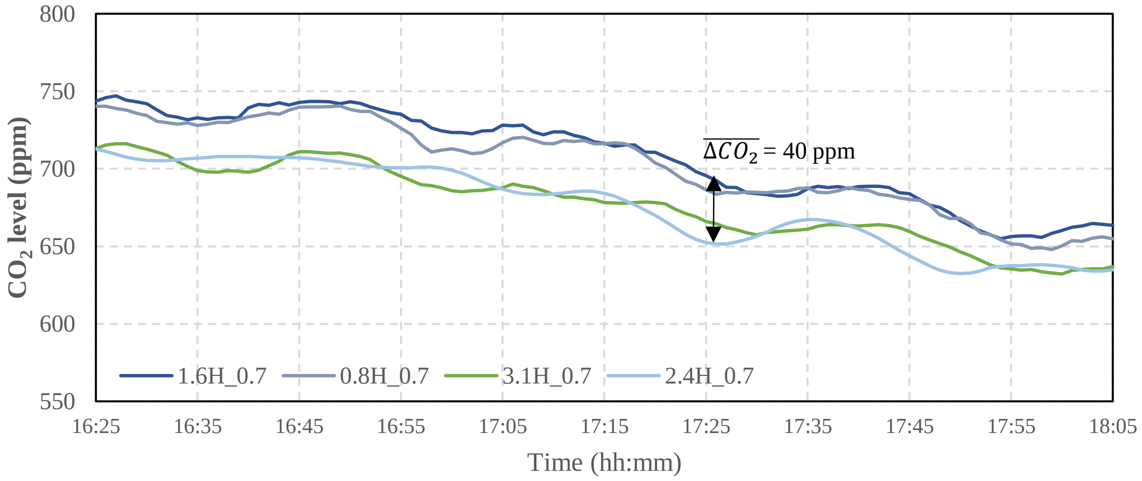


Figure 5.9 Medium Office CO_2 values at the location of the various sensors at 0.7 m.

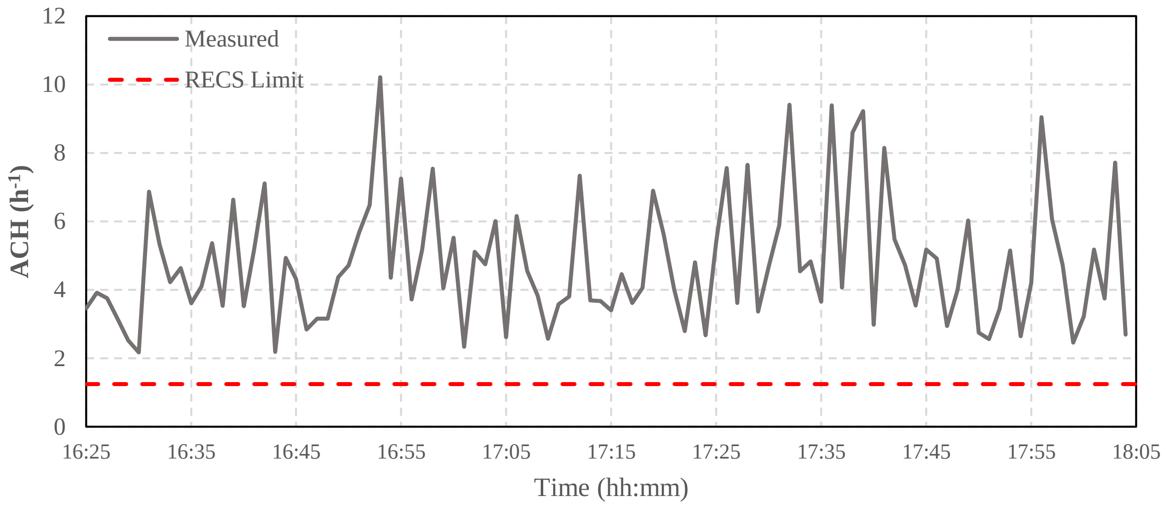


Figure 5.10 Medium Office Air Changes per Hour in comparison with RECS limit.

Similarly to Large Office, Figure 5.6 shows that the stratification effect is present also in Medium Office, although on sensor 1.6H_2.0 the temperatures measured are tendentially lower than on sensor 1.6H_0.7. This might have been induced by air recirculation given the proximity to the windows. Nonetheless, Figure 5.7 indicates that on the occupied zone the thermal differences are also very low (0.30 ºC), this indicates comfort temperatures among the first 3.1H of the room, given that such temperature difference is hard to notice by a human.

Figure 5.8 shows that in terms of CO_2, there is no stratification. This means that the air is enoughly well mixed in terms of this contaminant. Accordingly, Figure 5.9 reinforces this point since on the occupied zone, the average maximum difference on CO_2 levels was just 40 ppm. Looking into Figure 5.10, the ventilative strategy has proven sufficient in terms of ACH (always within the RECS limit), demonstrating that SS NV can in some cases guarantee the air flow renovations, avoiding any artificial system. Given the previous conclusions about these last 5 figures (Related to Medium Office), this case-study results show that the SS NV can work until 3.1H at least.

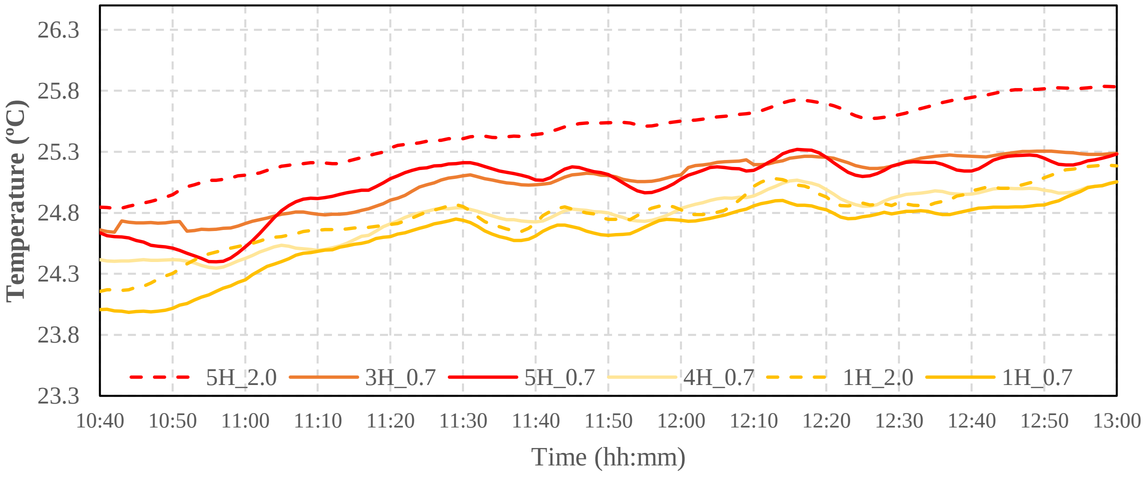


Figure 5.11 Long Office temperature values at the location of the various sensors, both at 0.7 m and 2.0 m.

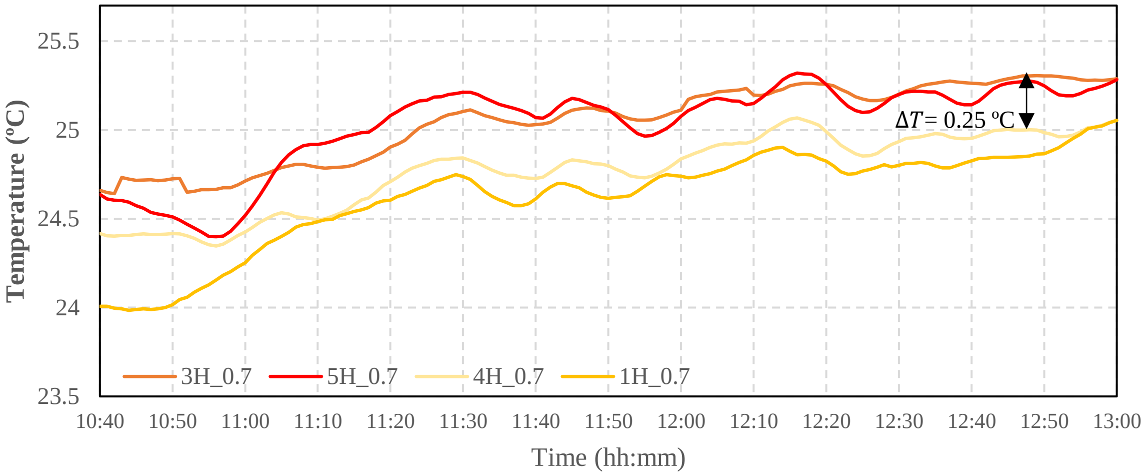


Figure 5.12 Long Office temperature values at the location of the various sensors at 0.7 m.

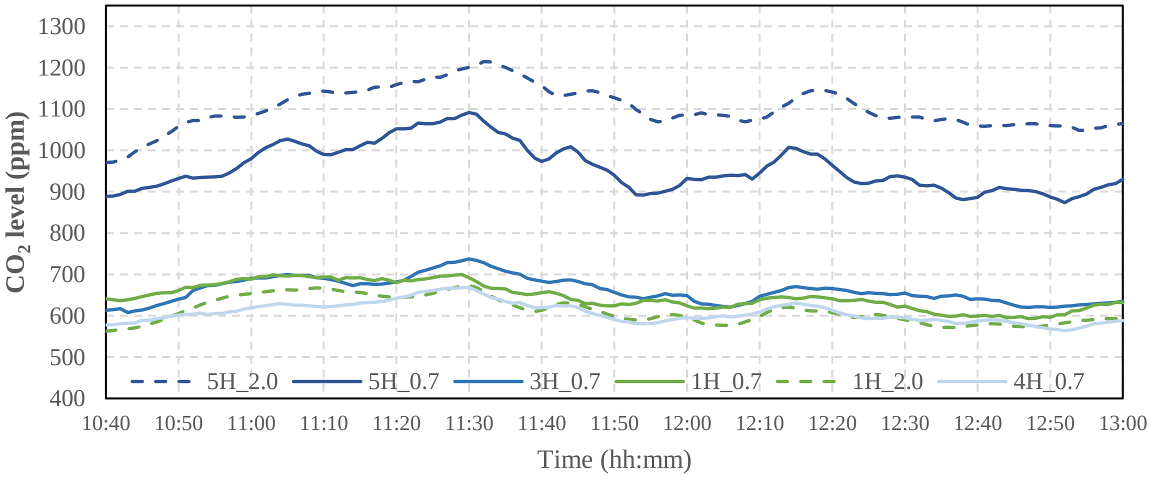


Figure 5.13 Long Office CO_2 values at the location of the various sensors, both at 0.7 m and 2.0 m.

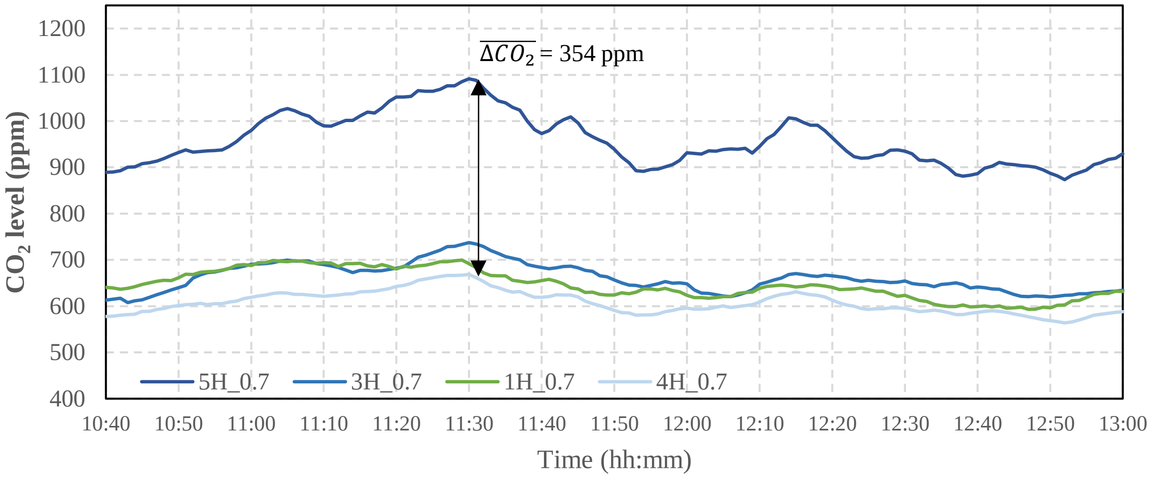


Figure 5.14 Long Office CO_2 values at the location of the various sensors at 0.7 m.

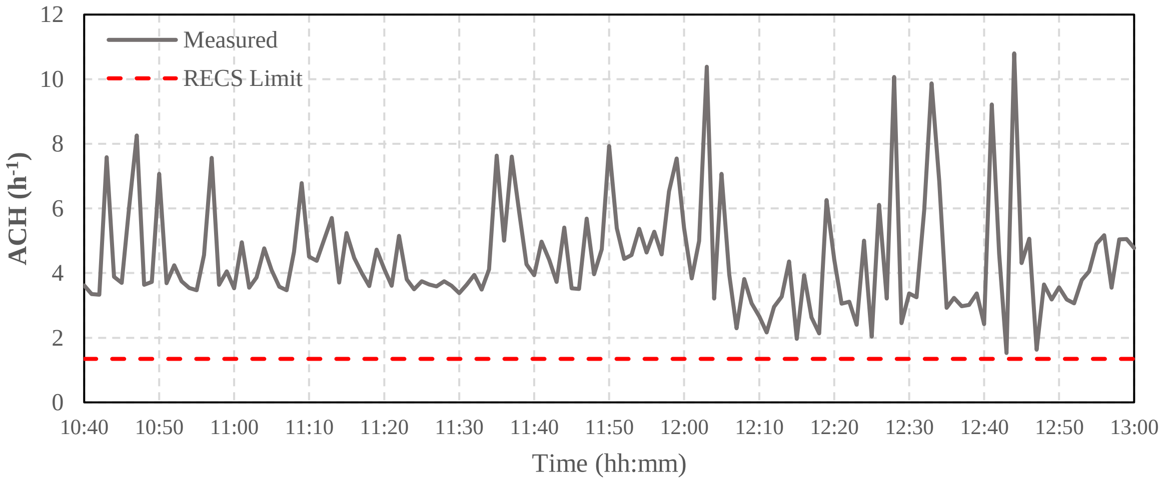


Figure 5.15 Long Office Air Changes per Hour in comparison with RECS limit.

Finally, with Long Office the situation is different from the two previous offices. There is still an effect of temperature stratification (Figure 5.11 and Figure 5.12) on the deepest side of the office (façade opposed to the window) noticed on the sensors 5H, but there is an anomaly on the expected behavior of sensor 3H: it registers higher values than 4H. This happened because sensor 3H_0.7 had to be placed closer to a computer than any of the other sensors, caused by the setup of the desks on the office. If we ignore that sensor and admitting that those values are not too trustable for the given reason, we can notice a big increase on temperatures between sensor 4H to 5H. Even on the latter values (when the experiment was closer to stabilization than ever) this difference was sometimes larger than 0.25 ºC in just one floor to ceiling distance. However, to avoid jumping to fast conclusions, one needs to analyze CO_2 levels as well.

Looking into Figure 5.13 and Figure 5.14, it is immediate that there is something interesting to be noticed. Long Office values of CO_2 show that there is clearly a stagnation zone near 5H away from the façade. This stagnation zone is then characterized by a thermal difference of at least 0.25 °C and roughly 350 ppm, in a distance of only 2.6 m (1H for Long Office).

Despite the previous results, the ACH on Long Office were also within the recommended RECS values during all the experience, proving again that ACH are not the main problem when studying SS NV in this kind of offices. Another worth mentioning fact, is that in all the three rooms the levels of CO_2 were always below the NV limit defined by EN 15251 of 1625 ppm [27].

5.2. EnergyPlus Model Validation

On this chapter, the way to obtain conclusions about the results is through calculation and comparison of some error indicators. The selected indicators are average error, average difference, maximum average difference, average bias and maximum average bias. These error indicators were based on [23], where all but average error have the same expressions. On the mentioned work the error would be calculated as shown on Equation (5.3). This occurs because opposingly to this thesis, what happened on the work mentioned was that it was relative to daily temperature variations (large temperature variations) and, to avoid dividing by negative values, the authors came with a normalized expression for the calculation of the error by the difference of the maximum and minimum measured values. Since on this thesis the differences between maximum and minimum measured were not comparable to the ones of a daily variation, it was considered more suitable to apply a simpler expression as shown on Equation (5.4).

$$Avg.Error_{daily}\ (\%) = \frac{100}{n} \times \sum_{i=1}^{n} \left| \frac{Sim_i - Meas_i}{Meas_{max} - Meas_{min}} \right| \tag{5.3}$$

$$Avg.Error\ (\%) = \frac{100}{n} \times \sum_{i=1}^{n} \left| \frac{Sim_i - Meas_i}{Meas_i} \right| \tag{5.4}$$

$$Avg.dif.\ (℃/ppm) = \frac{\sum_{i=1}^{n} |Sim_i - Meas_i|}{n} \tag{5.5}$$

$$Avg.\ bias.\ (℃/ppm) = \frac{\sum_{i=1}^{n} (Sim_i - Meas_i)}{n} \tag{5.6}$$

After the presentation of Figure 5.16 to Figure 5.21 that show the relation between Measured and Simulated values over the time of the experiments there is a summary on Table 5.1 with the resultant error indicators calculated for each of the three case-studies.

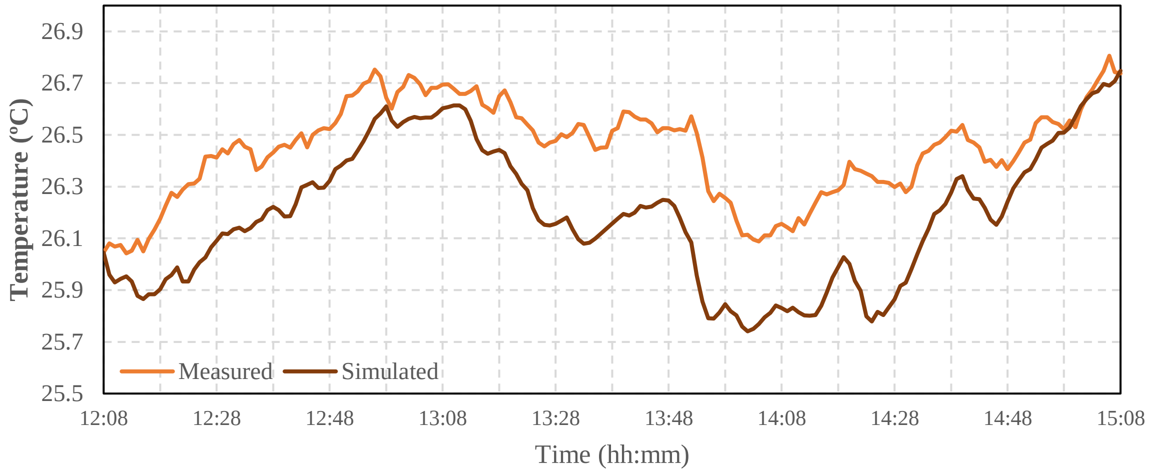


Figure 5.16 Large Office temperature comparison between Measured and Simulated values (°C).

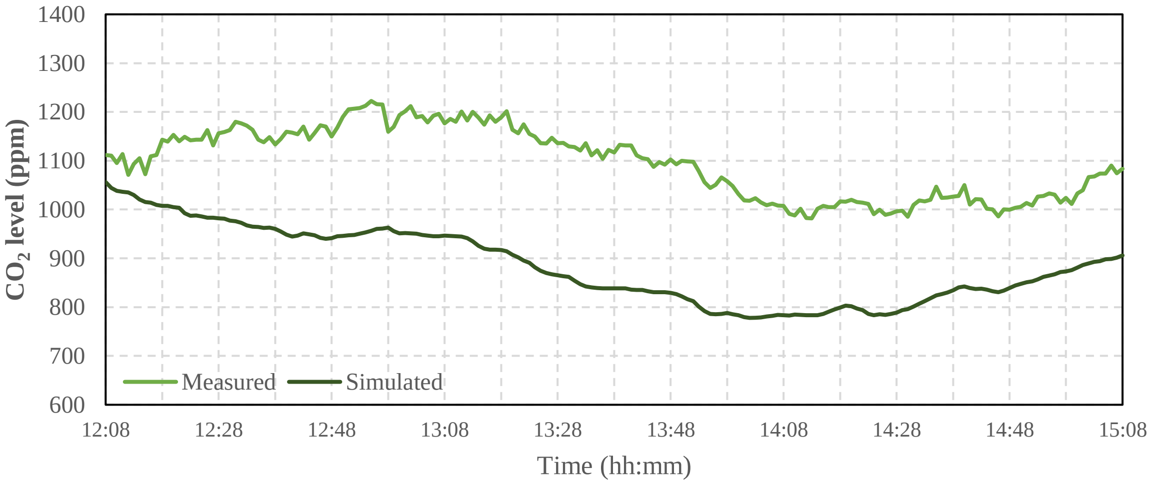


Figure 5.17 Large Office CO_2 levels comparison between Measured and Simulated values (ppm).

Large Office simulation presents a high accordance with real measurements when the topic is temperature. However, the CO_2 levels obtained from the simulation are significantly lower than the measured ones. One cause for this discrepancy might be that this was the Office with the higher occupation and the only one where people were free to leave and enter. Despite extreme care to open and close the door as fast as possible when someone was leaving or entering, this situation might explain this discrepancy.

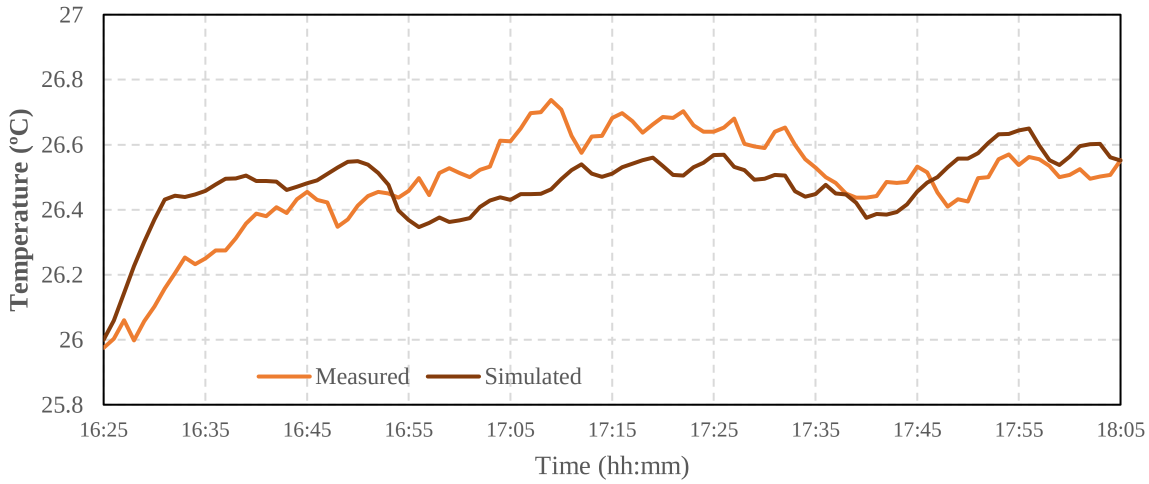


Figure 5.18 Medium Office temperature comparison between Measured and Simulated values (°C).

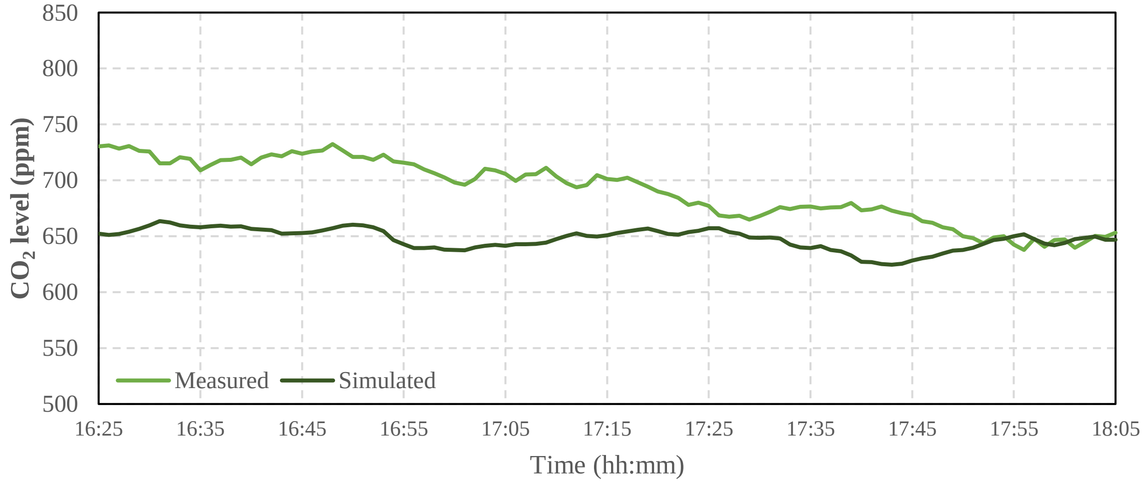


Figure 5.19 Medium Office CO_2 levels comparison between Measured and Simulated values (ppm).

On Medium Office, both graphs show good relations between measurements and simulation. Figure 5.18 represents a good interaction between the two curves, while Figure 5.19 also shows that the model could more or less predict the CO_2 behavior on the room, ending with pretty accurate values at the last 10 minutes of the experience.

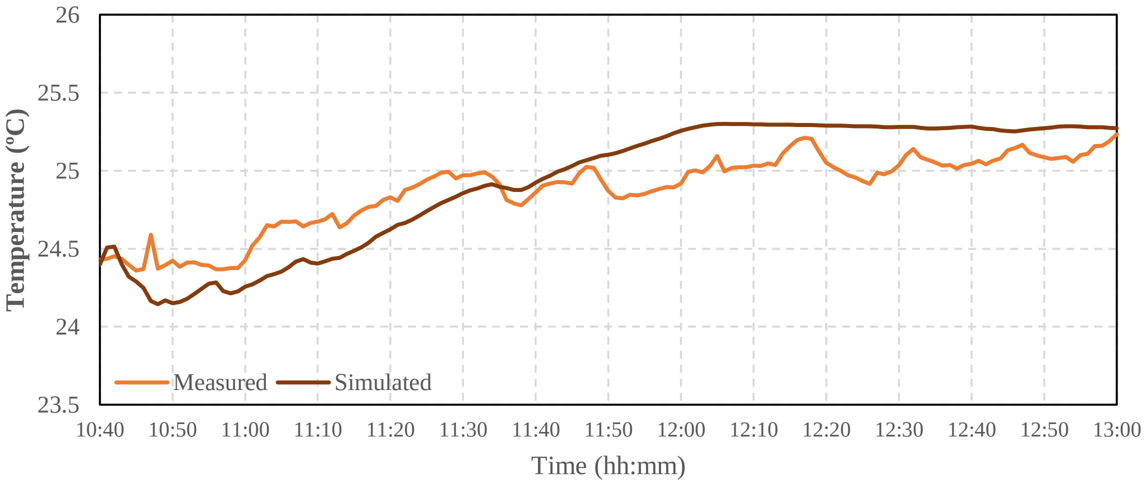


Figure 5.20 Long Office temperature comparison between Measured and Simulated values (°C).

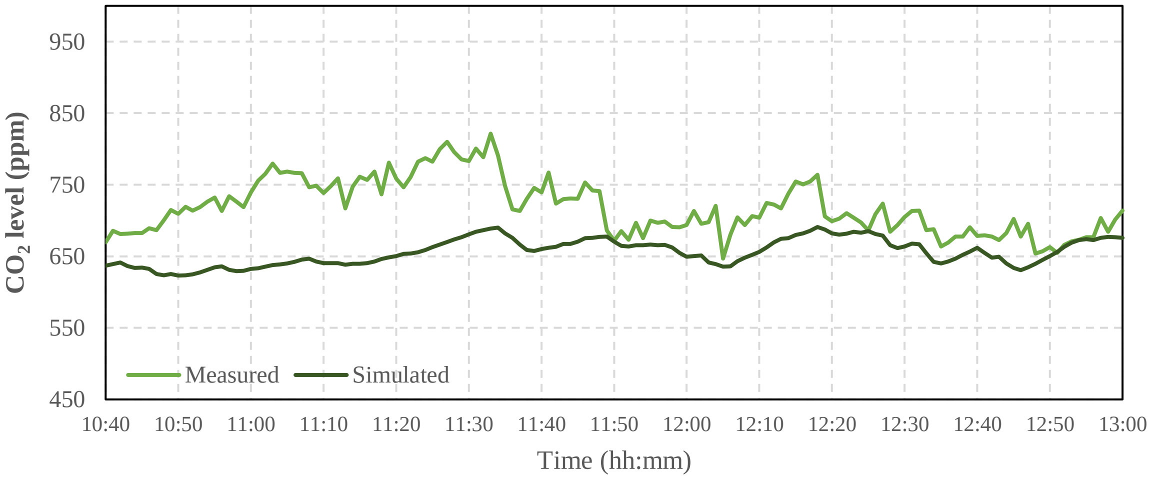


Figure 5.21 Long Office CO$_2$ levels comparison between Measured and Simulated values (ppm).

Lastly, on Long Office comparison between Measurements and Simulations, this was shown to not be the worst case, with both temperature and CO$_2$ showing similar tendencies and close curves. Generically, the mentioned situation with Large Office (people leaving and entering) caused that model to be the worst, even when compared to Long Office (the one shown to have stagnation problems in real life measurements). The error indicators related to the comparison between Simulated and Measured results are then presented next, on Table 5.1.

Table 5.1 Error indicators calculated for comparison between Measured and Simulated results of the three case-studies.

	Temperature (°C)					**CO_2 (ppm)**				
Office	Avg. Error (%)	Max. Error (%)	Avg. Dif. (°C)	Max. Avg. Dif. (°C)	Avg. Bias (°C)	Avg. Error (%)	Max. Error (%)	Avg. Dif. (ppm)	Max. Avg. Dif. (ppm)	Avg. Bias (ppm)
Large	1.0	2.1	0.26	0.56	-0.26	19.4	26.2	212	295	-212
Medium	0.4	1.0	0.12	0.27	-0.01	6.2	10.9	44	80	-43
Long	0.8	1.7	0.20	0.42	0.05	8.5	18.2	63	142	-63
Average	**0.7**	**1.6**	**0.19**	**0.42**	**-0.07**	**11.4**	**18.4**	**106**	**172**	**-106**

Reinforcing what was seen on the graphs present on this chapter (EnergyPlus Model Validation), the Office with the best relation between simulation and measurements was Medium Office with an average error of just 0.4% on temperature values and 6.2% on CO_2 values. While the worst was Large Office with respective values of 1.0% (which is good), and a relevant 19.4% when analyzing CO_2 levels. Long Office presents 0.8% and 8.5% respectively. Focusing into the average values obtained, one can observe that the average maximum error for the 3 case-studies never surpassed 1.6%, which is considered to be a low value. The same cannot be said about CO_2 (18.4% average maximum error), although having obtained values of average error lower than 10% regarding Medium and Large offices.

6 Conclusions and Further Developments

Nowadays, typical SS NV offices have large glazed areas and almost every day the HVAC is working at cooling the space (even in winter). The glazed areas enable large solar gains, which increase the cooling HVAC loads and lead to higher electrical bills. This acts as one of the most relevant motivations to study this subject.

The development of this work has shown that SS NV is an important strategy to consider when analyzing office buildings, the obtained results reveals that is possible to obtain a good performance, in terms of thermal comfort and promoting good indoor air quality. However, despite the good results, the strategy has shown limitations and needs further are more expensive studying to allow firmer conclusions.

Following, are the answers to the research questions presented on Chapter 1.

- What is the typical penetration depth of SS NV offices?

The results obtained from this work, indicate that for Large and Medium Offices the NV ventilation was effective until at least 3H, while for Long Office it was shown that somehow between 4H and 5H the effectiveness of this strategy starts to drop, making it unviable at 5H derived to the CO_2 stagnation zone and the slight increase on temperature.

- Are the current limitations (from CIBSE and the 20 ft rule) well defined, or do those need further studying and a possible reformulation?

This is the real question that motivated this work and all the experimental process was driven through answering to this. As mentioned in the last question, the results obtained allow the conclusion that the current limitations are definitely conservative when comparing the 2.5H of CIBSE with the 4H of Long Office and (at least) 3H of Medium and Large Offices. Since the work developed in this thesis is just a primarily approach to this subject, it does not prove that the limits are not well defined, however it can give the idea that these limits need more studying and that they are probably stricter than they should be. The objective of this thesis was not to prove that these limits are wrong, but to prove that more testing would be suitable.

- What is the typical precision that a trained thermal simulation engineer can expect to obtain for the simulation of a SS NV Office?

The last topic to conclude about is about the capability shown by EnergyPlus to model this kind of offices (SS). Justifying the discrepancies between Large Office's values of simulated and measured CO_2 with the allowance for people to leave and enter at their will, since this factor was not implemented on EnergyPlus (opening of the door was not taken into consideration because there was the attempt at minimizing this effect by closing the door as fast as possible during the experiment), one can observe that the other two models shown low values of error (<10%) and can be considered well validated. Relatively to temperature, the three models have shown average errors lower or equal to 1%, which reinforces the capability of EnergyPlus to model this kind of spaces.

The further developments suggested are the continuous investigation of a large number of SS NV offices, by credited entities on real office buildings. There is no better way to study and conclude about this subject than going into the real office buildings and do proper analysis. If proven that the limits are too strict, increasing these limits could have a huge positive impact on the energetic consumption of office buildings, by allowing high performance NV systems (or even hybrid systems working with mechanical and natural ventilation).

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