

AIRTIGHTNESS CONTRIBUTION FOR A SUSTAINABLE BUILDING STOCK IN THE CONTEXT OF SOUTHERN EUROPE

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A thesis submitted in partial fulfilment of the requirements for the degree of
DOCTOR OF PHILOSOPHY IN CIVIL ENGINEERING

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MAY 2022

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Ao Afonso

ACKNOWLEDGEMENTS

Aos meus orientadores, obrigado pela oportunidade de me deixarem e fazerem evoluir ao longo desta viagem.

Ao Professor Doutor Nuno Manuel Monteiro Ramos, pela visão, incentivo, paciência e lições passadas.

Ao Professor Doutor Ricardo Manuel dos Santos Ferreira de Almeida, pela razão, clareza, apoio e disponibilidade.

À Professora Doutora Maria Manuela de Oliveira Guedes de Almeida, pela postura construtiva e conhecimentos transmitidos.

À Irene, ao Martin, e à Lígia, pelo espírito colaborativo e pela marca que deixaram neste percurso.

Ao Luís e ao João, pela amizade e motivação, por estarem presentes e acreditarem.

À Ana pelo Afonso. Ao Afonso pelo sorriso e alegria.

Aos meus pais, por tudo.

The author would like to acknowledge the support of FCT - Fundação para a Ciência e a Tecnologia, the funding of the Doctoral Grant PD/BD/135162/2017, through the Doctoral Programme EcoCoRe. Base Funding - UIDB/04708/2020 and Programmatic Funding - UIDP/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC).



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ABSTRACT

With the urgent need to reduce energy use in heating buildings, standards, regulations, and national codes have become increasingly stricter. As heat transfers by air change rates have been earning increased importance in the energy performance of building envelopes, there is a need for constraints on air exchanges above the thresholds established for health and indoor air quality (IAQ). Therefore, energy and health are two conflicting issues in the air change rate strategy. In Europe, the northern countries have a clear objective of energy conservation. In them, the awareness of airtightness translates into a high level of regulation and implementation across the Architecture, Engineering, and Construction (AEC) industry.

Meanwhile, the southern counterparts lag, as they experience a more complex challenge by having predominantly passive ventilation strategies and milder climates. The subsequent lax approach has several consequences on indoor environmental quality (IEQ). To adopt nearly-Zero Energy Buildings (nZEB), an adapted approach to the latter countries is in dire need if building energy performance, and IEQ are to coexist in harmony.

The present thesis proposes and develops a methodology for classifying and defining the adequate air permeability of naturally ventilated buildings in mild climate countries typical of southern Europe, aiming to fulfil knowledge gaps in three main aspects of airtightness research: (1) experimentation and measurement methods, (2) simulation and modelling tools, and (3) policy and performance frameworks. In all these aspects, the aim was to adapt current practices to the context of southern Europe by providing solutions that better conciliate the existing methodologies to the challenges and needs of the context in study.

In its initial part, this thesis provides theoretical knowledge on ventilation systems, infiltration, airtightness and their respective influencing factors. Alongside, a state-of-the-art review focuses on the three main aspects: measurement techniques, protocols, and the uncertainty on experimentation results; types of airflow models and the reliability of the input data for simulation; airtightness requirements, performance characterization, and sustainability-related issues of envelope airtightness technology.

Next, the contributions are then divided into three Chapters, each about one of the three main aspects. The first focuses on the experimental assessment of building airtightness by evaluating the airtightness performance of envelope solutions and assessing the reliability of quantitative and qualitative evaluation frameworks on leakage paths. The second develops numerical simulation of airtightness impact on ventilation by determining the effects of different configurations of air leakage paths, changing airtightness levels, and detailing input data on air change rates. The third develops a methodology towards an airtightness performance labelling strategy for a sustainable building stock. It applies it in a restricted scope by recommending envelope airtightness performance ranges, developing a user-friendly tool to check the airtightness compliance of dwellings, and assessing the life cycle impacts of applying full envelope airtightness solutions.

Important conclusions are taken from the results of the performed research. While most of the interpretation of the results is bound to the constraints of the used case studies and input data, they support the scalability of the developed methodologies and provide ground for a broad range of future works.

KEYWORDS: Airtightness; Air change rate, Ventilation and Infiltration; Blower-door measurements and uncertainty analysis; Airflow modelling; Probabilistic approach and Machine Learning; Life-cycle assessment and Life cycle costing.

RESUMO

Com a necessidade urgente de reduzir o consumo energético no aquecimento de edifícios, normas e regulamentações têm-se tornado mais exigentes. A importância crescente das transferências de calor por trocas de ar no desempenho energético de edifícios, cria a necessidade de implementação de restrições às mesmas acima dos valores mínimos por razões de saúde e qualidade do ar interior. Desta forma, os desafios relativos a energia e saúde estão em conflito na estratégia de renovação do ar interior. Na Europa, os países do norte têm um objetivo claro, a conservação de energia. Nestes, a consciencialização para a estanquidade ao ar traduz-se num elevado grau de regulamentação e implementação nas indústrias de arquitetura, engenharia e construção.

Por contraste, nos países do sul, o tópico permanece secundário e raramente abordado de forma sistemática. De facto, nestes países o desafio é mais complexo, por derivado dos climas mais amenos, os parques habitacionais terem estratégias de ventilação predominantemente passivas. A subsequente abordagem negligente tem várias consequências para a qualidade do ambiente interior (QAI). Para a adoção de edifícios com necessidades quase nulas de energia (nZEB), uma abordagem adaptada a estes últimos países é necessária, para que o desempenho energético e a QAI possam coexistir em harmonia.

A presente tese propõe e desenvolve uma metodologia para classificar e definir a permeabilidade ao ar adequada de edifícios naturalmente ventilados em países de clima ameno típicos do sul da Europa, com o objetivo de preencher lacunas de conhecimento em três aspetos principais da pesquisa em estanquidade ao ar de edifícios: (1) métodos de experimentação e medição, (2) simulação e ferramentas de modelação (3) regulamentação e avaliação de desempenho. Em todos estes aspetos pretendeu-se adaptar as práticas atuais ao contexto do sul da Europa, proporcionando soluções que melhor conciliem as metodologias existentes aos desafios e necessidades do contexto em estudo.

Na sua parte inicial, esta dissertação fornece conhecimentos teóricos sobre sistemas de ventilação, infiltração e estanquidade. Paralelamente, uma revisão do estado da arte foca os três aspetos principais: técnicas de medição, protocolos e a incerteza sobre resultados de experimentação; tipos de modelos de fluxo de ar e a incerteza nos dados de entrada para simulação; requisitos de permeabilidade ao ar, caracterização de desempenho e questões relacionadas à sustentabilidade de tecnologias de estanquidade em envolventes de edifícios.

A seguir, as contribuições são divididas em três capítulos, cada um pertencente a um dos três aspetos principais. O primeiro enfoca a avaliação experimental da estanquidade da construção, avaliando o desempenho da estanquidade de soluções de envolvente e avaliando a fiabilidade de metodologias de avaliação quantitativa e qualitativa. O segundo visa a simulação numérica do impacto da estanquidade na ventilação, avaliando os efeitos das diferentes configurações dos caminhos de infiltração, da alteração dos níveis de estanquidade e do detalhe dos dados de entrada, nas taxas de renovação de ar. O terceiro desenvolve uma metodologia para uma estratégia de rotulagem de desempenho da estanquidade, para um parque habitacional mais sustentável. Aplica-a assim a um âmbito restrito, recomendando intervalos de desempenho, desenvolvendo uma ferramenta prática de verificação de conformidade e avaliando os impactos do ciclo de vida da aplicação de soluções de estanquidade à envolvente de edifícios.

Conclusões importantes são tiradas dos resultados da pesquisa realizada. Embora a maior parte da interpretação dos resultados esteja restringida aos casos de estudo usados e dados de entrada, as metodologias desenvolvidas fornecem bases para generalização e para uma ampla gama de trabalhos futuros.

PALAVRAS-CHAVE: Estanquidade; Renovação de ar, Ventilação e Infiltração; Medições por porta ventiladora e análise da incerteza; Modelação de fluxos de ar; Abordagens probabilísticas e Aprendizagem Computacional; Avaliação de ciclo de vida e análise de custos de ciclo de vida.

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

ACH	Air change rate
ACH _{50/n50}	Air change rate at a pressure difference of 50 Pa
ADPE	Abiotic depletion potential non-fossil
ADPF	Abiotic depletion potential fossil
AEC	Architecture, engineering and construction
A _{env}	Envelope area
AF	Floor area
AFN	Airflow Network
AIM-2	Alberta Air Infiltration Model
AIVC	Air Infiltration and Ventilation Centre
ANOVA	Analysis of Variance
AP	Acidification potential of land and water
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BES	Building Energy Simulation
C	Airflow coefficient
CB	Categorical Boosting
CED	Cumulative Energy Demand
CFD	Computational Fluid Dynamics
CH	Ceiling height
CO ₂	Carbon dioxide
Com	Compliant dwelling
CP	Compactness
CS	Chi-square
CV	Cross-validation
DEF	Default mode
DT	Decision Tree
EBC	Energy in Buildings and Communities Program
ELA	Effective leakage area
ELE	Electrical appliances
EN	European Norm
ENT	Entrance door
EP	Eutrophication potential
EPBD	Energy Performance Building Directive
EPD	Environmental Product Declarations
EPP	Energy payback period
EPS	Expanded Polystyrene
ES	Number of exposed vertical surfaces
EU	European Union
EWDI	Excessive winter death index
FLUID	Fluid applied exterior air barrier
FORM	First-Order Reliability Method
FVM	Finite Volume Method

GHG	Greenhouse Gas Emissions
GWP	Global warming potential
HAC	Heating and air conditioning elements
HRV	Heat recovery ventilation
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IPMA	Portuguese Institute for Sea and Atmosphere
IRP	Internal reference pressure
ISO	International Organization for Standardization
IWLS	Iterative Weighted Least Squares
KS	Kolmogorov-Smirnov
LARWK	Liquid-applied polyurea waterproofing membrane
LBL	Lawrence Berkeley Laboratory
LBNL	Lawrence Berkeley National Laboratory
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LHC	Latin Hypercube
LHS	Latin Hypercube Sampling
LIG	Lighting
LL	Lower limit
LSF	Light Steel Framing
MAE	Mean absolute error
MECH	Mechanically fastened exterior air barrier
MSE	Mean squared error
MV/ MEV	Mechanical Ventilation
n	Airflow exponent
n ₅₀	Air change rate at 50Pa of pressure difference
NCd	Non-compliant by default dwelling
NCE	Non-compliant by excess dwelling
ND	Number of vertical ducts
NDIR	Nondispersive infrared
NF	Number of floors
NIST	National Institute of Standards and Technology
NPV	Net Present Value
NRPE	Non-renewable primary energy
NV	Natural Ventilation
nZEB	Nearly Zero Energy Building
ODP	Depletion potential of the stratospheric ozone layer
OLSu	Ordinary Least Square based on the uncertainty on airflow measurements
OLSy	Ordinary Least Square based on the distance to the regression line
OPE	Openings
OSB	Oriented Strand Board

P()	Probability
PD	Panofsky Dutton
PDF	Probability density function
P-G	Pasquill-Gifford
PLU	Plumbing
POCP	Formation potential of tropospheric ozone photochemical oxidants
PP	Payback period
PVC	Polyvinyl Chloride
REM	Air leakage that remained at the end of the reductive sealing campaign
RF	Random Forest
RS	Roof slope
RSL	Reference Service Life
SIP	Structural Insulated Panel
SMOTE-NC	Synthetic Minority Oversampling Technique for Nominal and Continuous features
SR	Side ratio
SV	Support Vector
SVR	Support vector regressor
TPE	total primary energy
UK	United Kingdom
UL	Upper limit
USA	United States of America
UV	Ultraviolet
VAT	Value-added tax
WFJ	Wall/floor joints
WLOC	Weight Line of Organic Correlation
WOJ	Wall/openings joints
WPC/Cp	Wind pressure coefficient
WRJ	Wall/roof joints
WWJ	Wall/wall joints
XGB	Extreme Gradient Boosting
ZEB	Zero Energy Building
α /WSC	Wind shear coefficient/Location/Terrain
η	Nominal efficiency

1

INTRODUCTION

1.1. BACKGROUND AND MOTIVATION

The airflow across building envelopes remains a central topic to consider on the Energy Performance of Buildings Directive (EPBD) [1]. In its most recent edition [2], the commitment of the European Union (EU) on developing a "sustainable, competitive, secure and decarbonized energy system" is more refined than ever. In agreement with the 2015 Paris Agreement on climate change [3], both existing and new buildings are primary targets to address this challenge.

The built environment represents around 40% of the final energy use in the EU [4], and 27% of it is associated with the residential sector alone [5][6]. In this sector, 64% of the total energy consumption relates to space heating, and the annual heating energy loss due to air change rates (ACH) is 35% of the delivered energy for conditioning [7][8]. There is consensus that carbon dioxide emissions could be reduced up to 20% if the built stock was to comply with minimum air change rate levels [8].

Regulating levels of pollutants demand a minimum threshold of airflow, and handling heat transfers calls for constraint on additional air changes above the ones established for health and indoor air quality (IAQ) related matters. Therefore, energy and health are two conflicting issues in the air change rate strategy. The southern European building stock is dominated by naturally and adventitiously ventilated dwellings, in contrast with mechanically or balanced ventilated ones, representing most of the housing stock in northern and central Europe [9]. The first referred ventilation strategies solely depend on the natural forces of temperature gradient and wind. Thus, accomplishing the minimum threshold is a more significant challenge in the first than in the latter ventilation strategies.

In the last decade, the rate of implementing regulation ruling airtightness performance in the Architecture, Engineering and Construction (AEC) industry has increased consistently, mainly in countries with colder climates, typical of central and northern Europe [10]. Because of the struggle referred to in the last paragraph, nowadays, airtightness of dwellings experiences omission, facultative status or partial consideration on most of the existing mandatory energy performance certification programs in the EU [11]. This situation is particularly prevalent in southern and eastern country members [12].

Even though the climate is milder in these countries, mainly in southern Europe, data shows that energy poverty can still significantly impact [13]. With a 25.9% excessive winter death index (EWDI) compared to the 13.9% average, Portugal is a case study in this regard [14], alongside 56% of the enquired reporting very cold and very hot sensations in winter and summer, respectively [15]. These results come after considering adaptation over time and acclimatization processes, showing that it is a conscious decision to save income by not conditioning the indoor environment. Thus, the focus, at least in the southern European context, must be concentrated in passive systems, in which the envelope airtightness is included, rather than active ones.

In countries with mandatory airtightness compliance, the respective implementation suffers from several simplifications that are impactful at a practical level in different magnitudes. As the research topic relies on fluid dynamics, these assumptions are generally accepted for practical reasons and to avoid high computational costs. They encompass standards regarding measurement methods [16], established simulation software for design and retrofitting [17], and criteria in setting limits for the airtightness performance of dwellings [18].

Regarding EU national requirements on measurement methods, most of the existing ones address whole building airtightness, resulting in several drawbacks [19]–[21]. An example is the performance of separate building systems and components staying unknown. Therefore, a retrofitting plan may be compromised from the start as main leakage paths may be disregarded [22][23]. It is exceedingly relevant in the southern EU states, where buildings need greater attention in assessing their airtightness when retrofitting since, in most, airtightness awareness was not present during construction. This approach aligns with the growing interest for different types of construction from the traditional, such as modular ones, marked by increasingly complex buildings envelope systems, that bring their challenges [24][25].

Concerning simulation software, some of the main reasons for the simplifications and assumptions relate to [26][27][28][29]: the obtention of accurate data for practitioners' libraries, which are economically expensive and labor intensive; the availability and quality of meteorological data through time and land cover; the usual aim of the simulation being the obtention of inputs for energy efficiency estimation, which means that the focus is on average values rather than on fluctuations of airflow through time, more appropriate in assessing indoor air quality. While the emphasis leans on active elements to provide ACHs levels in the northern counterparts, the southern EU countries are majorly dependent on the variability of natural forces. Thus, giving detail to the latter adds to better predictions of ACHs.

Criteria on airtightness performance, particularly an upper airtightness limit, are defined at a national level and empirically [18]. They are commonly a compromise between the interests of AEC industry agents and regulatory agencies that intend to address energy and constructability concerns jointly. Some countries establish prescriptive paths during construction or retrofitting, and others develop static limits based on a single dwelling characteristic, usually the ventilation strategy [10]. There are two main faults to the current approaches. They do not have a pure scientific base for defining limits that support proper decision making. They lack the flexibility of boundaries by inputting too few features, thus restricting their adaptation to distinct dwelling characteristics and conditions.

The hypothesis is that by addressing the mentioned themes, one can improve the reliance on airtightness and air permeability research in practical applications and overcome the disparate approaches between EU country members by bridging, with proper adaptations, the northern Europe initiatives to the context of southern Europe. It would significantly contribute to the EU's ambition to attain a sustainable building stock and a correct implementation of nearly Zero Energy Buildings (nZEB) in its proper form for the southern countries [2].

1.2. OBJECTIVES AND METHODOLOGY

The main objective of the present thesis is to propose and develop a methodology for classifying and defining the adequate air permeability of naturally ventilated buildings according to technical, economic, and environmental criteria, which in the future may support the recommendation of optimal airtightness ranges. The focus and applicability of the developed work targets mainly mild climate countries of the southern European context. It accomplishes

a structure conveniently prepared, with few adjustments, for application in similar research topics.

After defining the thesis objective, a thorough review of the literature delineated the limitations of the current state of the art and identified the knowledge gaps. The broad scope narrowed to three axes, each encompassing secondary objectives. The first and second axes explore the reliance on airtightness and air permeability research in practical applications through experimentation characterization and numerical simulation. The third axis targets airtightness requirements implementation, life cycle assessment (LCA) and cost-of-life analysis. Each axis focuses mainly on specific methodologies and applies them to case studies to fulfil the proposed secondary objectives. They are as follows.

1. Experimental assessment of buildings airtightness:

- Evaluate the airtightness performance of an envelope solution for modular buildings;
- Assess the reliability of quantitative and qualitative evaluation frameworks on air leakage paths.

2. Numerical simulation of airtightness impact on building ventilation:

- Assess the effect of different configurations of air leakage paths and the impact of changing airtightness levels on ACHs;
- Evaluate the impact of meteorological variability and increased detailed methodologies in quantifying air change rates in a representative case study of a naturally ventilated dwelling.

3. Airtightness performance and compliance for a sustainable building stock:

- Contribute to the definition of recommended envelope airtightness performance ranges in the context of southern Europe;
- Develop a tool that allows a practitioner to check the airtightness compliance of dwellings regarding health and energy efficiency issues, both in design and retrofit scenarios;
- Assess the life cycle impacts of applying full envelope airtightness solutions in dwellings labelled as having excessive heat losses by air change rates.

1.3. OUTLINE AND THESIS OVERVIEW

The present document has a structure of six main Chapters:

- Chapter 2 comprises research context and general literature review following the current Chapter. It predominantly focuses on providing context regarding airtightness, infiltration, and airflow control in buildings. It assembles definitions and metrics while a review of influencing factors and experimental data is put together. In addition, it provides a thorough inspection of existing national frameworks regarding the residential buildings' airtightness regulatory context, followed by increasing contextualization addressing the following research Chapters. Finally, it compiles a summary of knowledge gaps. The work developed in this Chapter contributed to a publication in an international peer-reviewed journal [10].
- Chapter 3 focuses on experimental campaigns in lightweight residential buildings. Structural Insulated Panels (SIPs) are tested in a laboratory and in-situ conditions to assess their applicability regarding airtightness. The in-situ tests are performed in different construction stages to evaluate the impact of construction works on the airtightness performance during the operational phase of the building. In a second stage, a comprehensive reductive sealing campaign is performed in a building with the same envelope constructive solution, simulating a thorough assessment of an existing leaky building. The campaign focused on quantifying the contribution of each type of air leak to the whole building infiltration, qualitatively identifying the main contributors, and evaluating the impact of using different regression methods on the uncertainty of the measurement data. The Chapter wraps with the final remarks found in these works and the main possible applications in the existing practice. The work developed in this Chapter contributed to publications in an international conference [30] and in a peer-reviewed journal [31].
- Chapter 4 targets numerical aspects of airtightness and air permeability, mainly through simulation. A simple case study is modelled with existing software, to assess the impact of different configurations of air leakage paths on ACHs and the effect of changing airtightness levels on the air change rates provided by mechanical ventilation. The second case study addresses the impact of intra-hour variability of meteorological data and changing atmospheric stability in the ACH and intermediate outputs. As these topics go beyond the existing models' capabilities, the second case study relies on implementing a single zone model for data pre-processing and airflow mass calculation through an iterative process. The Chapter concludes with the main findings of the

developed research in both these case studies and proposes future research paths. The work developed in this Chapter contributed to publications in international peer-reviewed journals [32][33].

- Chapter 5 tackles airtightness policy structure, based on optimal airtightness ranges and a life cycle assessment approach on residential buildings, with methodologies, that although applicable for any location, particularly focus on the southern European mild climate and the case studies used in the present thesis. To the expressed end, a building sample representative of the built stock is used to stochastically create a simulated dataset for a timeframe representative of the heating season. Identifying the top-performing dwellings allows one to outline optimal performance ranges according to dwelling and terrain characteristics. The implemented methodology further applies to train and tune classification and regression models that make part of a proposed airtightness compliance tool. The same dataset serves as input to characterize the life cycle impact and life cycle cost of different airtightness solutions for dwellings with a broad array of characteristics. The Chapter ends with the main conclusions of the developed work and suggests regulatory action paths.
- Chapter 6 compiles the main conclusions of the thesis, highlighting the pertinence of the experimental, numerical, and policy main results and their interpretation. It mainly provides the findings of the proposed methodology for integrating an airtightness framework for the southern European mild climate conditions. Topics that undermine generalization and topics that add value to the current research are covered. These are candidates for future research and present themselves as opportunities to acquire theoretical knowledge and provide the ground for the methodology deployment in technological applications.

2

LITERATURE REVIEW

2.1. VENTILATION AND AIRTIGHTNESS

2.1.1. VENTILATION SYSTEMS AND INFILTRATION

Air flows into and out of a building through pressure differentials across the envelope air paths. Purposeful withdrawal and admission of air into a building goes by ventilation, subdividing into natural, mechanical and hybrid. The first produces air exchanges through passive elements such as grilles and other planned openings, while the second encompasses energy-dependent equipment, such as fans [34]. Hybrid ventilation denotes the combination of natural and mechanical strategies with control switching [35].

Air exchanges through background unintentional leakages are mentioned as infiltration when the airflow is from the outdoors into the building and exfiltration the other way around. Together they are referred to solely as air leakage or infiltration. The infiltration rate through a building envelope is dependent on [35]: size and distribution of air leakage paths; flow characteristics of the leakage paths; and the pressure difference across the leakage paths. Figure 2.1 represents typical leakage paths in buildings.

These unintentional air paths follow the same rules of natural ventilation, therefore driven by natural produced pressure differentials [36]. The occurring natural forces that induce pressure differentials in buildings envelopes are the wind and the air density gradients caused by temperature differences between the indoor and outdoor air, commonly referred to as thermal buoyancy. The mechanical forces comprise operating ventilation fans.

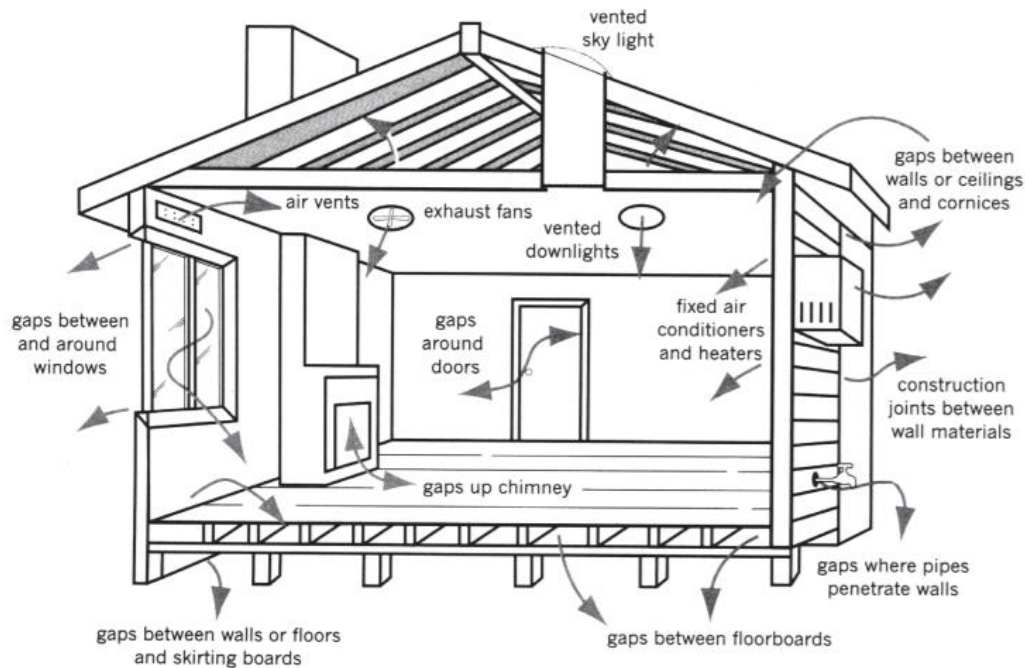


Figure 2.1. Typical air leakage paths in buildings [37]

Thermal buoyancy pressures, also known as the stack effect, occur due to warm air being less dense than colder air, resulting in hotter air rising and colder air sinking. In the heating season, the cooler air infiltrates through the bottom and the warmer air exfiltrates through the top of the enclosure. This mechanism reverts when the indoors is cooler than the outdoors.

Although air density is a function of temperature, humidity ratio and barometric pressure, humidity has a negligible impact compared to the other two, and barometric pressure only has significance in tall buildings [36]. The stack pressure grows with increasing temperature differences between the inside and the outside and taller envelopes [38] (Figure 2.2a).

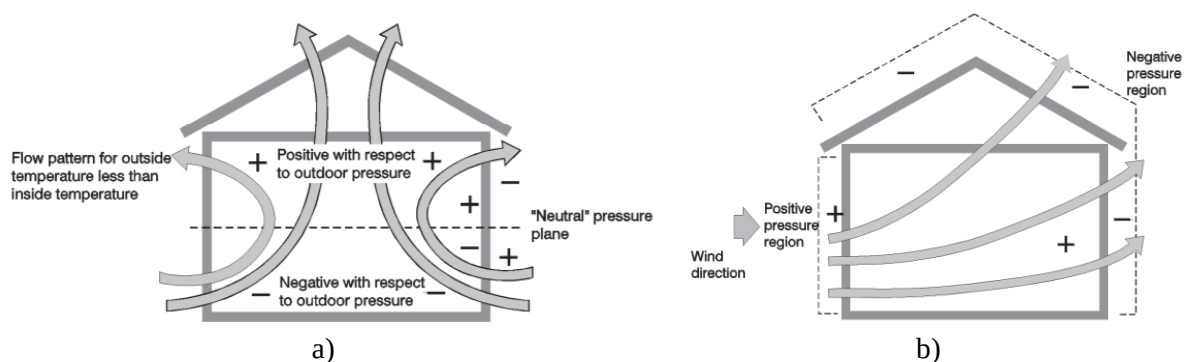


Figure 2.2. Airflow and positive (+) and negative (-) envelope pressures resulting from single mechanisms: a) thermal buoyancy; b) wind [39]

Wind creates a pressure distribution on the envelope of a building, causing air to enter it through the upwind faces and exit it through the leeward faces. Wind pressure on surfaces strongly depends on its direction, speed, surface orientation and surrounding conditions [36] (Figure 2.2b). Bernoulli's equation and local wind pressure coefficients apply to calculate the pressures on the building surfaces [40]. The local shelter effect reduces the wind pressure due to reduced wind speed, and therefore, the greater the building exposure, the stronger the wind effect.

The two introduced mechanisms do not act independently and cannot be directly added. Their combined effect is never more significant than the one resulting from the addition of each alone [41]. The distribution of intentional and unintentional air paths on the building enclosure and building geometry and irregularities in the flow itself influences their interaction. Different distribution patterns can cancel or add to each other for fixed effects of wind and buoyancy.

For natural ventilation systems, the challenge is correctly positioning and sizing the openings while considering and assessing the infiltration effect to avoid over-ventilation, making the performance of natural ventilation systems more reliable and stable. In buildings with leakier envelopes, higher and less stable air flow volumes will occur, frequently resulting in higher heating or cooling loads and consequently higher energy expenses and possible IAQ complications.

Inclusion of pressure regulators in the ventilation openings of natural ventilation systems is among the most common actions to minimize abnormal wind and stack pressures [36]. As a rule of thumb, generally, the wind effect dominates natural ventilation systems when wind speeds are higher than three or four meters per second (Figure 2.3).

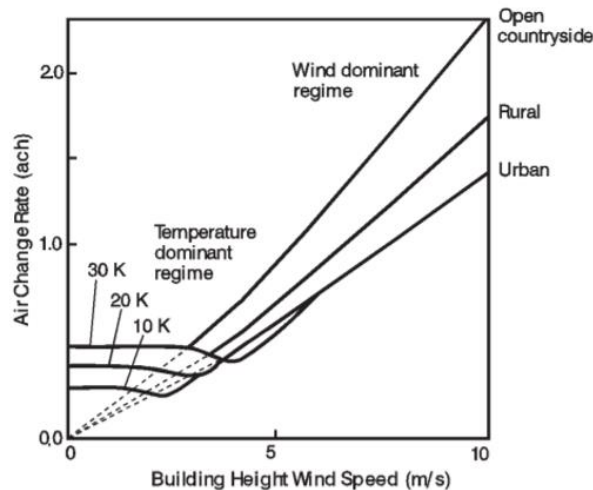


Figure 2.3. The relative importance of wind and stack effect on air change rates (ACH) [39]

Mechanical equipment for air supply or exhaust and vented combustion devices induces artificial pressures on a building envelope. Considering mass conservation, the sum of air flows in and out of a building must balance. A building provided with mechanical exhaustion will force the inflow at openings that otherwise may act as outflow. When the mechanical system is operating for airflow supply, the opposite occurs.

Depending on the given configuration, mechanical ventilation systems can pressurize or depressurize the building. Another critical topic is moisture flow. In cold climates and during the heating season, pressurized buildings will force hotter air to cross the envelope in the direction of colder surfaces and interfaces, which may cause condensation in its inner structure. The same occurs with depressurized buildings and when the indoors is cooler than the outdoors, as in the case of hot and humid climates. This condensation phenomenon compromises envelope durability and performance and enhances organic development such as mold [42].

If the envelope is leaky in buildings with mechanical systems, the dimensioned admission or extraction openings will underperform [43][44]. It will frequently cause the complete Heating, Ventilation, and Air Conditioning (HVAC) setup to not match the design aims, resulting in insufficient heating and cooling capacities, requiring supplementary energy to meet the defined targets or less acceptable standards of operation [36]. The same occurs on balanced ventilation systems, of both mechanical supply and exhaust, with increased noticeability when energy or heat recovery are present. Ductwork segments in the unconditioned zones of the building are of particular importance regarding airtightness [45].

The referred complications are increasingly prevalent in leaky buildings. On a similar note, leaks on air supply ducts tend to depressurize a building and leaks on return ducts tend to pressurize it when they are not inside the conditioned zone [46]. Figure 2.4 shows schematics of mechanical ventilation systems.

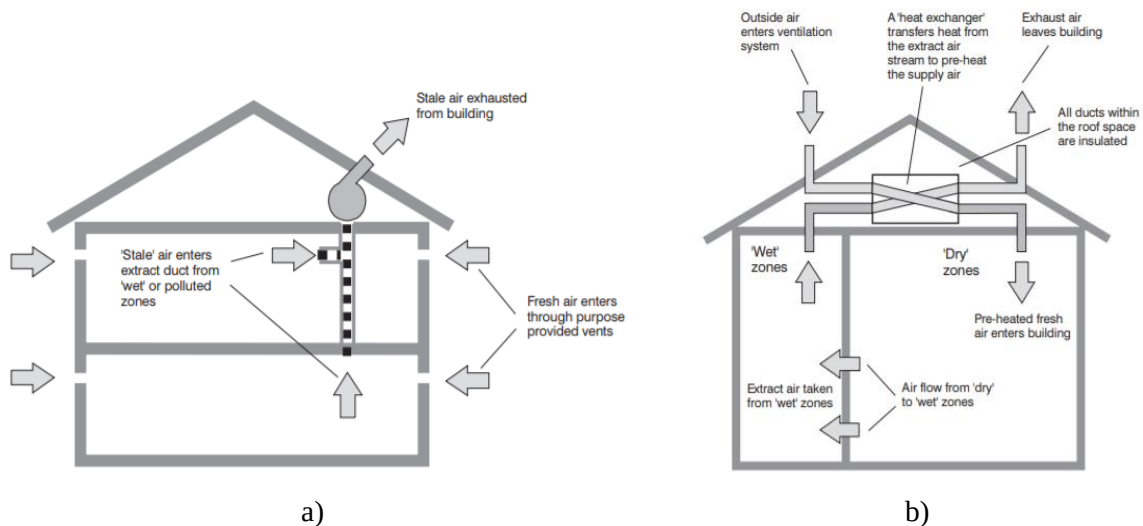


Figure 2.4. Schematics of mechanically ventilated envelopes: a) mechanical extract system; b) balanced mechanical system [39]

2.1.2. AIRTIGHTNESS IN BUILDING PERFORMANCE

Airtightness is the term used to refer to the resistance of air exchanges through unintentional air paths [47]. It represents a flow rate for a given reference pressure divided by a building scale metric. The reference metric for the air pressure difference is often 50 Pa when assessing airtightness. The building size scaling is, commonly, the building volume, the envelope area or the floor area [48].

By inducing pressure differences high enough to neglect the effect of natural pressure variations across the building envelope, airtightness measurements are theoretically not dependent on climatic conditions. On that behalf, airtightness is the most valuable property for the air leakage characterization and comparison of existing buildings. It is also broadly used in the modelling and quality control of new constructions and assessing interventions in the built environment [48]. Thus, ventilation and airtightness play a synergistic role in the developed air change rates in an envelope. Figure 2.5 portrays a scheme on the synergy between ventilation and airtightness in buildings.

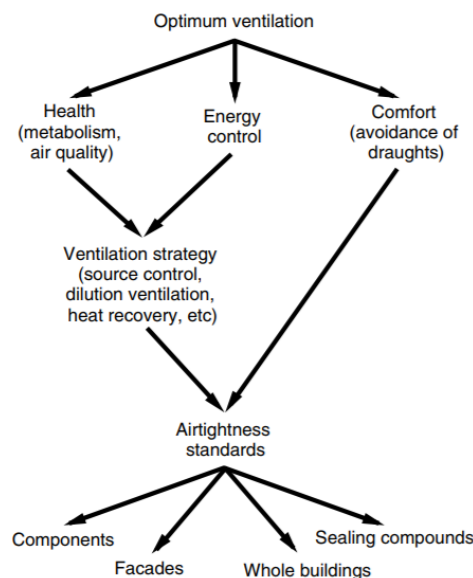


Figure 2.5. The synergy between ventilation strategy and airtightness requirements [49]

Ventilation strategies have distinct relationships with envelope airtightness. Natural ventilation, either with or without point extraction, has a greater performance variability than mechanical ventilation. Because of that fact, the airtightness limits of buildings with natural ventilation systems do not need to be as strict as those of buildings with mechanical ones. Also, air leakage can impact equipment life expectancy. Therefore, designers aim for high levels of airtightness in buildings with mechanical ventilation systems. Figure 2.6 displays suggested airtightness levels for different ventilation strategies, emphasizing the relationship between these two variables in a building.

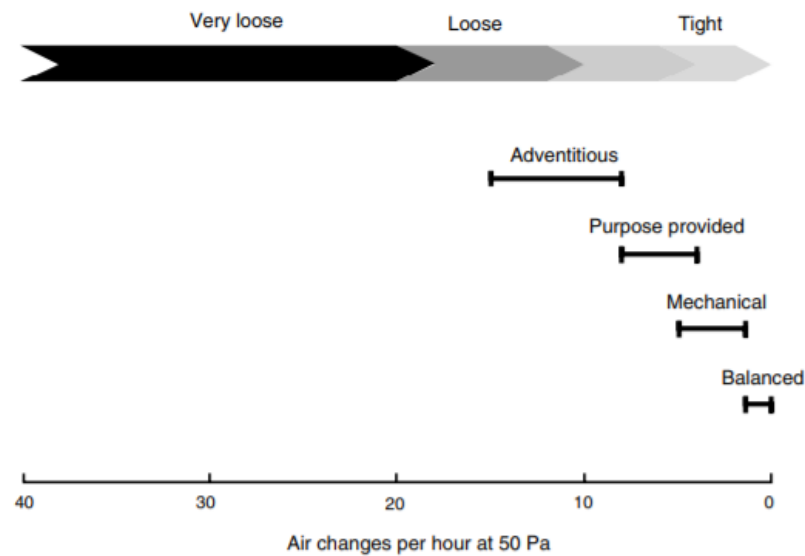


Figure 2.6. Airtightness levels suggested for different ventilation strategies [49]

Building airtightness influences aspects that concern people, buildings and the environment [50]. People prioritize solutions that provide safety, health, comfort and affordability [42]. Initial, running and decommissioning costs of the solutions implemented to control the air leakage will impact the affordability of different strategies [51].

Health issues are mainly related to indoor air quality [52][53]. The goal is to avoid odours and high concentrations of air pollutants, impacting occupants' comfort, environmental satisfaction, health and work performance [54][55]. The tightening of building envelopes without a proper assessment of the ventilation system may decrease the dilution and removal of potentially toxic gases [56][57][58]. As very airtight envelopes can result in less dilution of air pollutants when ventilation systems do not work as desired, leaky envelopes underperform when the outdoor environment is the source of contaminants and odors, such as in high-density populated cities [59].

Human comfort issues comprise the acceptability of thermal, acoustic, and humidity environments [60]. Comfort and health are closely related since temperature and humidity affect factors, such as mold growth in building surfaces, pests and allergies, the proper perception of the indoor environment, and respiratory systems complications [61][62]. Air leakage is also a potentiator of local thermal discomfort in draughts [63] and acoustic discomfort associated with sound leakage [64]. Figure 2.7 portrays a workflow of the

mechanisms and sources affecting pollutant concentration and how they affect IAQ and, consequently, the health and comfort of the occupants.

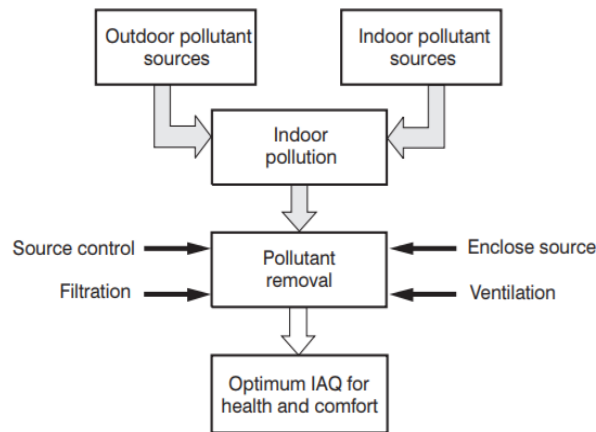


Figure 2.7. Optimum IAQ for health and comfort scheme [49]

Buildings require durable materials and energy-efficient solutions and strategies [65]. The efficiency of HVAC operating systems is likely to be negatively affected by unintentional air exchanges [66][67]. Ultimately, this translates into higher costs, primary energy needs and environmental pollution. A not so direct effect on energy loads is the reduction in the thermal insulation performance that transported moisture and air currents often breed [68][69][70]. Commonly the characterization of air leakage paths also maps moisture condensation incidence and location [71][72][73].

Regarding environmental issues, the primary energy use during the operation phase is more significant than that during the stages of construction and decommissioning [74]. Still, a sustainable approach should tackle both the embodied and operational primary energy.

2.1.3. AIRTIGHTNESS INFLUENCING FACTORS

Factors influencing building airtightness are important in the definition of statistical models and therefore in creating strategies and conditions to meet desired values or in estimating envelope airtightness of similar buildings. Multiple regression analysis [75], Spearman's ranking correlation [76], ANOVA tests [77] and t-tests [78] are among the most commonly used primary analysis tools for finding significant factors influencing airtightness [79]. According to

Canadian and French studies, dwellings structure type, building age, height, volume, floor area, climate, and insulation levels are the best predictors of airtightness levels [80][75].

- Geometry and building type

The number of significant envelope penetrations and total frame length show a positive correlation to infiltration in buildings [81][82][83][84]. Prefabrication in factory conditions improves airtightness performance compared to in situ construction [81]. In several studies, prefabricated houses measured roughly half the leakage of timber frame detached homes constructed in situ [24][75][85].

- Target and supervision

Aiming for airtightness already during the design phase is very important to achieve the desired performance [86][87]. It is the case of houses equipped with different types of ventilation systems. In homes with mechanical ventilation, the average air permeability is lower than that of naturally ventilated dwellings [78][82]. Assessing the design target should happen during the construction stage and not only at the commissioning stage [88]. A study on low-energy wood frame houses reports a 20 to 30% reduction in airtightness performance from the wind-barrier finishing stage to the commissioning stage [89]. Even though finishing works typically improve airtightness levels, further works, such as HVAC equipment installation, can compromise the improvements and even reduce the envelope performance compared to that at a previous stage [90]. Energy-efficient rated homes scored more airtight than the average home [91], and low-income households tend to have higher air infiltration [91][92].

- Materials and technology

Often asymmetries in building techniques and airtightness regulations are the causes for different performance degradation over time [93][94]. In the United States (US), this degradation averages a 15% increase over a decade [85][95].

Ageing by hygrothermal cycles concluded that construction materials and application methods significantly affect the durability of airtightness [96][97]. Experiments showed a reduced impact on the air barrier membranes performance [98]. Measurements on air barriers by plastering revealed a more pronounced reduction of the airflow resistance [99]. Other studies find similar results [100][101].

Chamber tests comparing modular envelope panels without and with sealing actions showed reductions over 96% of airflow crossing the specimens [97]. This type of panel is prone to moisture accumulation in the insulation layer [71], impacting serviceability. Laboratory tests found that air permeability at the material level is independent of the moisture content to a certain threshold [102]. Comparison with in situ results showed that the moisture content reduced the overall airtightness performance by 30%. Laboratory measurements commonly differ significantly from those performed in situ [103].

- Climate

Despite climate zone variations having reduced impacts since test standard rules and guidelines ensure independence [16], airtightness values differ significantly [85]. These discrepancies are primarily associated with airtightness design consideration and distinct used construction techniques. The greater awareness of airtightness concerns in severe climate zones, because of the more significant impact of air leakages, leads to seeking and applying more effective building technologies and strategies to cope with it. Climate is, therefore, not an influencing factor by itself but rather a potentiator of others.

Primary factors refer to those embedded in design stage decision making. Secondary factors are consequential to the primary ones (Figure 2.8).

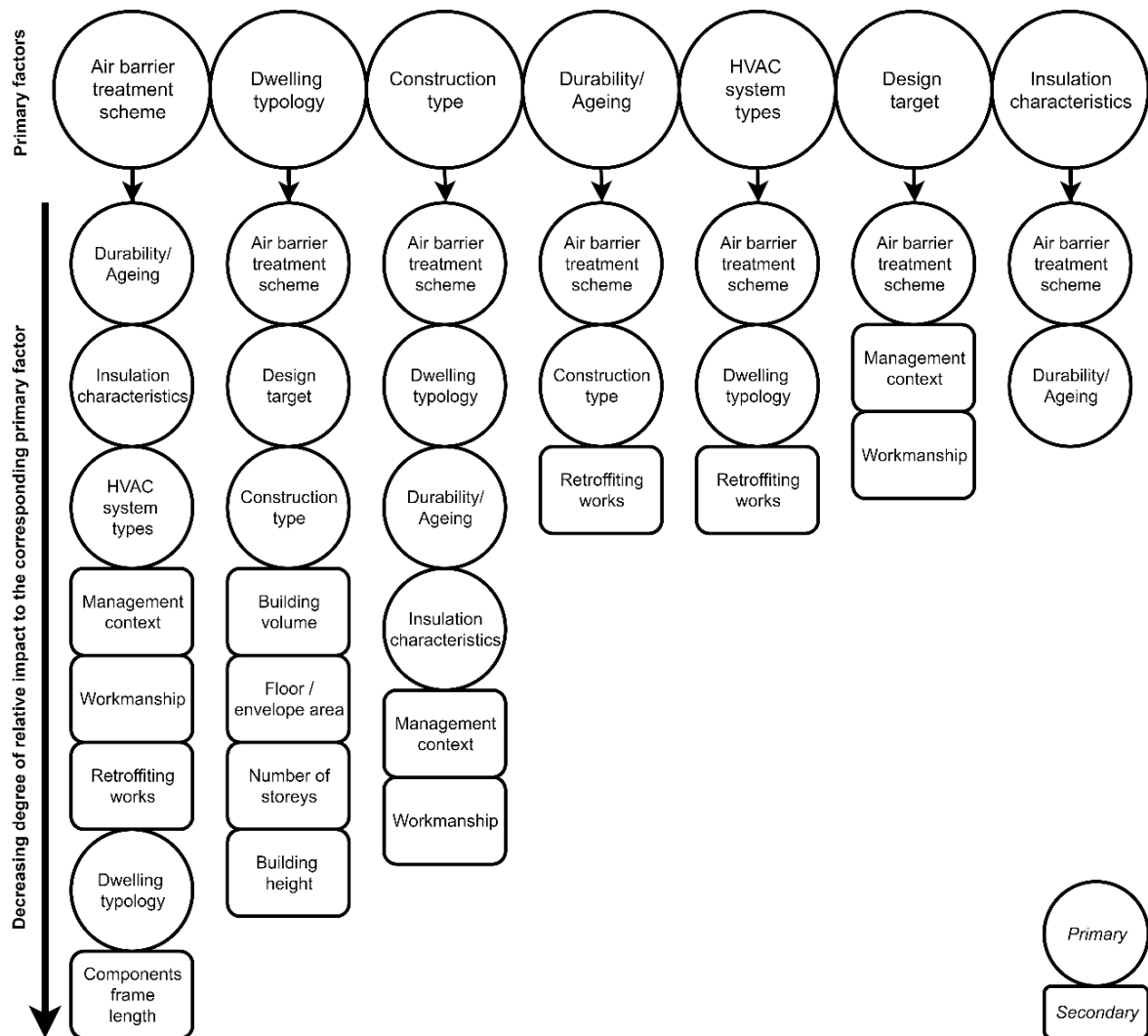


Figure 2.8. Primary and secondary factors related to whole building airtightness performance [10]

2.2. MEASURING AIRTIGHTNESS

When quantifying airtightness, one is inducing an air pressure differential between physically separated volumes and measuring the airflow rate across an opening or several openings in the material, component or assembly dividing them [35].

Physically, airflow is either laminar, turbulent or in the transition zone, depending on the disturbances in the path of the circulating air. Under commonly occurring conditions, turbulent air flows develop in large openings while smaller openings have air flows progressively more laminar. Most of the time, the air changes occur between fully turbulent and fully laminar zones, i.e., in the transition zone. An air flow is characterized by its discharge coefficient, which is not

constant between building openings because of the variation of their geometry and is not constant in the same opening over time because of the varying induced pressure [104][105].

The analysis of whole envelopes with multiple air leakage paths introduces extra hardness on locating and characterizing the respective properties of each, thus supporting the use of more practical generalizations [16]. This Chapter explores the measurement techniques current state of development and discusses their potentials and limitations.

2.2.1.MEASUREMENT TECHNIQUES

2.2.1.1.Quantitative methods

The most common approach to airtightness quantification is in the form of a power law [106]. Several other equations, such as the quadratic law, were also developed to fulfil the same purpose [107]. However, theoretical analysis, laboratory measurements, and field tests assure that the power law describes the natural conditions with increased accuracy, producing better results at low pressures [108]. The power law is the equation used to describe building airtightness on several standards, such as ISO 9972:2015 [16] (Eq. (2.1)).

$$Q = C(\Delta P)^n \quad (2.1)$$

Q	airflow through opening (m ³ /s)
C	airflow coefficient (m ³ /(s·Pa ⁿ))
ΔP	pressure difference (Pa)
n	airflow exponent (-)

The experimental method specified in this standard to assess airtightness is the external fan pressurization test, also known as the blower door test [109][110]. In the blower door test, an opening, usually a door or window, serves as a frame for installing an adaptive structure. A fan connected to a manometer is attached. Calculating air flows for several theoretically uniform static pressure differentials allows the extrapolation outside the measurement range to assess the leakage under natural conditions. The pressure differentials are theoretical since the thermal buoyancy between indoors and outdoors and the changing wind conditions can significantly affect the test results. The test is only valid if the natural pressure readings on each side of the building do not exceed prerequisite values. The higher the airflow rate, the less airtight the

building is for a specific pressure difference. Figure 2.9 provides further comprehension of the equipment setup used in the test.



Figure 2.9. Typical blower door equipment apparatus

The standard refers to three methods. While the test procedure is the same, the sealing of components and systems is distinct. Method 1 requires the sealing of mechanical ventilation and air conditioning terminal devices, while natural ventilation openings shall be closed when possible. The objective is to assert the performance of the whole building in use. Method 2 also requires sealing all the intentional openings referred to in Method 1. The purpose is to assess the building envelope performance. Method 3 involves adapting intentional openings following the policy in a specific country where the test is undergoing.

While airtightness measurements often apply to whole building envelope assessment, they can also evaluate individual components or adjacent volumes. Additionally, in situ airtightness measurement of components can be achieved through the reductive sealing technique [102] or a collection chamber [25]. In reductive sealing, the deduction of successive sealing of individual components enables quantifying their respective impacts. As for the latter, the tester positions a collection chamber over the element for which the airtightness is unknown.

The collection chamber equivalent in laboratory conditions is named test chamber. Laboratory conditions ensure more control over the studied components, as natural conditions impact is

close to null. Standard EN 12114:2000 [111] provides a methodology and test procedure for this kind of test.

As discussed in 2.1.2, airtightness measurement results do not represent buildings' actual air change rates. Extrapolation is necessary to pressure levels corresponding to those induced by natural conditions [112]. Among other methods for estimating air change rates at natural conditions, direct quantification is possible using a tracer gas measurement [113][114]. According to ASTM-E741 [115], the calculation of hourly air changes can follow three different test methods: concentration decay, constant injection, and constant concentration. The literature indicates that the most consensual method for calculating the ACH is the concentration decay test method [116][117]. In the concentration decay method the tracer gas is injected and allowed to mix with the air inside the enclosure [118]. Tracer gas measurements are greatly dependent on the weather conditions during the test and take longer to perform than pressurization tests [119]. The descriptions and workflows presented in [113] give a broader interpretation of the available methods.

2.2.1.2. Qualitative methods

Knowing the locations of air leakages is no less essential than quantifying the airtightness of envelopes or components in the infiltration assessment of buildings. Pressurization techniques often accompany air leakage locations methods for qualitative evaluation. Infrared thermography uses thermal radiation to detect leakage paths [120]. The admission or expulsion of cold air through leaking will cool the surrounding surfaces revealing the air paths where air leakage occurs [121]. If the outdoors is colder than indoors and the location test occurs indoors, the fan should depressurize the envelope to identify the colder spots due to leakage. If the location test occurs outdoors, the fan should pressurize the envelope to identify the hot exfiltrated air locations. Despite the refinement of the technique, it can often be confused with other thermal inducing phenomena, i.e., thermal bridges. To minimize these issues, the method is most effective the greater the temperature difference between indoors and outdoors during the test procedure.

Smoke is also an effective qualitative indicator of air leakage locations [24]. Circulating the smoke source near potential leak paths will drive the smoke flow through them. Pressurizing the envelope will significantly improve the flow identification.

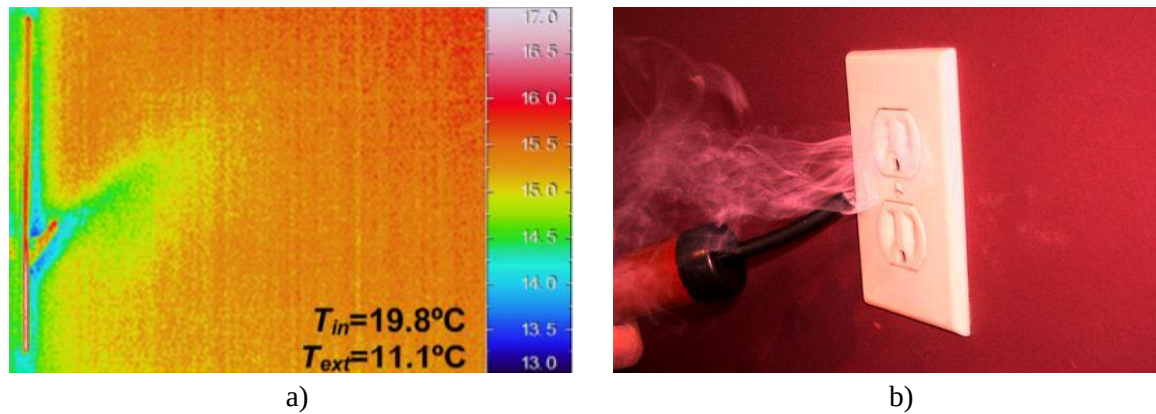


Figure 2.10. Leakage location techniques: a) thermography in roller shutter handle [121]; b) ongoing smoke test [122]

The ultrasound reduction method addresses air leakages qualitatively and quantitatively [123]. The inside of the envelope receives an acoustic source. At the same time, the building is pressurized, and a group of microphones in the exterior recognizes the sound leakages, thus indicating the air leakage paths locations and quantifying their contribution.

2.2.2. CURRENT MEASUREMENTS PROTOCOLS

Some differences exist between the measurement protocols and standards of different regions. In European countries, the measurement framework relies on EN ISO 9972:2015 [124], previously EN 13829:2000 [125], as the main focus is assessing whole building airtightness. Different standards may apply in the USA and Canada [126]–[130]. This number of alternatives is related to a greater focus on the detailed specifications on implementing air barriers [131] and air permeability performance [132] required by the national building codes [133][134][131].

Despite the international standard [124] clearly states the actions on sealing and closing of different building components for the various test methods, in most of the countries, there are national guidelines with either additional requisites on methodology and building preparation, such as France [135], or checklist documents helping the interpretation of specific measurement methods, such as Germany [136].

The metric used to report airtightness is one of the main differences between setups. This issue compromises the characterization and comparison of built stocks [137][138]. Table 2.1

summarizes prevalent metrics. They derive from the combination of airflow rate at an established pressure difference, predominantly 50 Pa, and a building geometry variable.

Table 2.1. Prevalent metrics on building airtightness performance

Classification parameter	Description	Unit	Formula	
n_{50} , ACH50 air change rate	Airflow through the building envelope at 50 Pa of pressure difference divided by the building volume.	$[h^{-1}]$	$n_{50} = \frac{Q_{50}}{V}$	(2.2)
q_{50} air permeability	Airflow through the building envelope at 50 Pa divided by the envelope area.	$[m^3/(hm^2)]$	$q_{50} = \frac{Q_{50}}{A_{env}}$	(2.3)
w_{50} specific leakage rate	Airflow through the building envelope at 50 Pa of pressure difference divided by the floor area.	$[m^3/(hm^2)]$	$w_{50} = \frac{Q_{50}}{A_{floor}}$	(2.4)
ELA effective leakage area	The area of an orifice which would have the same leakage as the building at P_r pressure difference assuming a flow at 50 Pa of pressure difference.	$[m^2]$	$ELA = \frac{Q_{50}}{C_D} \sqrt{\frac{\rho}{2P_r}} \cdot 10000$	(2.5)
NLA normalized leakage area	ELA normalized with the floor area of the building.	$[-]$	$NLA = \frac{ELA}{A_{floor}}$	(2.6)
C_D	discharge coefficient (-)			
P_r	reference pressure (Pa)			
ρ	density of the air (kg/m^3)			
Q_{50}	airflow through the building envelope at 50 Pa of pressure difference (m^3/h)			
V	dwelling volume (m^3)			
A_{env}	dwelling envelope area (m^2)			
A_{floor}	dwelling floor area (m^2)			

Table 2.2 highlights the most relevant information on the different analyzed measurement protocols and related data acquisition. Regarding acceptable test conditions, all the standards establish a combination of rules regarding wind, temperature, and building height [139][140][105].

Table 2.2. Compilation of test standards, guidelines, and methodologies on measurement data acquisition by analyzed countries with an established database

Country	United Kingdom	France	USA	Canada	Czech Republic	Germany	Belgium	Spain
Current test standard	BS EN ISO 9972:2015 [124]	NF EN ISO 9972:2015 [141]	ASTM E779-19 [127] ASTM E1827-11 [126] sp: single point tp: two points	CAN/CGSB-149.10 [129]	ČSN EN ISO 9972:2017 [142]	DIN EN ISO 9972:2018 [143]	NBN EN ISO 9972:2015 [144]	UNE EN ISO 9972:2019 [145]
National guidelines	TSL1:2016 [146]	FD P50-784:2016 [135]	2018 IECC [134]	NBC 2015 [147]	ČSN 73 0540-2:2011 [148]	EnEV 2014 [149] DIN 4108-7:2011 [150]	STS-P 71-3:2014 [151]	None
Test conditions	Wind Temperature Height	Wind Temperature Height	E779: Height Temperature E1827: Wind Temperature	Wind	Wind Temperature Height	Wind Temperature Height	Wind Temperature Height	Wind Temperature Height
Method/ Building preparation	Method 2 Instructions on temporary sealing according to method 2 are present in the national guidelines	Method 3 Additional instructions on temporary sealing and guidelines on air leakage location	Permanent and temporary sealing actions in national guideline Additional instructions on the airtightness measurement standard	Permanent and temporary sealing actions in national guidelines Additional instructions on the airtightness test standard	Method 1 or 2 (preferred) No further instructions on national guidelines	Method 2 Instructions on temporary sealing according to method 2 are present in the national guidelines	Method 1 or 2 Instructions on temporary sealing according with method 1 or 2 and air leakage location identification are present in the national guidelines	Methods A and B *
Minimum initial and final baseline (duration)	10 points (30s)	10 points (30s)	E779: 5 points (10s) E1827: 1 point	1 point	10 points (30s)	10 points (30s)	10 points (30s)	10 points (30s)
Minimum test extent (duration)	7 points (-), equal steps < 10 Pa between steps Lowest $\Delta P > 10$ Pa or $5x \Delta p_0$ 50 Pa < Highest $\Delta P < 90$ Pa	10 points (10s), equal steps < 10 Pa between steps Lowest $\Delta P > 10$ Pa or $5x \Delta p_0$ 50 Pa < Highest $\Delta P < 100$ Pa	E779: Over 5 points (10s) 10 Pa < $\Delta P < 60$ Pa 5 to 10 Pa between steps E1827: Repeated sp (5x): 50 Pa Repeated tp (5x each): 12.5 Pa and 50 Pa	8 points (-) 15 Pa < $\Delta P < 50$ Pa 5 Pa between steps	At least 5 points (-), equal steps < 10 Pa between steps Lowest $\Delta P > 10$ Pa or $5x \Delta p_0$ 50 Pa < Highest $\Delta P < 100$ Pa	At least 5 points (-), equal steps < 10 Pa between steps Lowest $\Delta P > 10$ Pa or $5x \Delta p_0$ 50 Pa < Highest $\Delta P < 100$ Pa	At least 5 points (-), equal steps < 10 Pa between steps Lowest $\Delta P > 10$ Pa or $5x \Delta p_0$ 50 Pa < Highest $\Delta P < 100$ Pa	10 points (-), equal steps* 11 < $\Delta P < 65$ Pa
Regression method	Ordinary least squares	Ordinary least squares	Ordinary least squares	Weighted least squares	Ordinary least squares	Ordinary least squares	Ordinary least squares	Ordinary least squares
Pressure direction	Either or both	Either or both	E779: Both E1827: Either or both	Depress.	Either or both	Either or both	Either or both	Both
Metrics	q_{50} (m ³ .h ⁻¹ .m ⁻²)	q_{4-surf} (m ³ .h ⁻¹ .m ⁻²); n_{50} (h ⁻¹)	E779: EflA @ 4Pa (cm ²); N_{50} (h ⁻¹) E1827: q_{50} (m ³ .h ⁻¹ .m ⁻²)	ELA @10Pa(m ²); NLA (cm ² .m ⁻²)	n_{50} (h ⁻¹)	q_{50} (m ³ .h ⁻¹ .m ⁻²)	n_{50} (h ⁻¹) q_{50} (m ³ .h ⁻¹ .m ⁻²)	n_{50} (h ⁻¹) q_{50} (m ³ .h ⁻¹ .m ⁻²)
Accuracy of pressure measuring device	±1 Pa	±1 Pa	E779: ±5 % or 0.25 Pa, whichever greater E1827 sp: ± 2.5 Pa E1827 tp: ± 0.5 Pa	± 2 Pa	±1 Pa	±1 Pa	±1 Pa	±1 Pa
Accuracy of air flow measuring device	±7 %	±7 %	E779: ± 5 % E1827 sp: ± 5 % E1827 tp: ± 2 %	±5 %	±7 %	±7 %	±7 %	±7 %
Accuracy of temperature measuring device	±0.5 K	±0.5 K	E779: ± 1.0 K E1827 sp: ± 2.0 K E1827 tp: ± 2.0 K	± 1.0 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K

*Methodology used on the dataset of the INFILES project obliged to the standard current at the time: UNE EN 13829:2002 [152]

The standards guidelines in North America instruct on the statement of results in several different metrics and at distinct pressure differences. Still, the national codes require the input for energy certification to be at 50 Pa. Even though the metrics differ, if one intends to make cross-country comparisons of performance, theoretically, the derived quantities should be interchangeable with the direct measurement results. However, they depend on building dimensions, and national guidelines include differences in their assessment, which translates into the introduction of errors in the conversion process [153].

Beyond the minimum information established in the international standard ISO 9972 [124], some datasets include leak location information by including thermal imaging when possible, e.g., Spain [154], Canada [155] or the Czech Republic [153].

Thermography assessed the air leakage distribution in detached houses in Finland [156][157], which detected three typical air leakage paths: roof-wall joints, floor-wall joints, and window-wall joints. A study in 32 lightweight detached houses in Estonia [24] found air leakage paths at envelope joints, including doors and windows, and envelope penetrations, such as ventilation ducts, electrical sockets and switches, and plumbing installation.

France [135] and Belgium [151] have established extensive templates to assess air leakage location. They provide categories of possible leakage paths to allow standardization and ease later analysis [158]. In the case of France, with more than 200 thousand dwellings analyzed, the most frequently identified leak locations include floor-wall joints, rolling shutter casing, ventilation air terminal devices, electrical grids on external walls, and sliding doors [22][158].

When measurements are quantitative, they are mostly not extensive. The identified air leaks only represent a portion of the total air leakage area. Their quantification is essential when high leakage levels are still present, even after determining some of the most relevant air leakage paths [159]. One of the methods available for quantifying single components impact is the reductive sealing technique [49][48].

In studies performed in the UK [89][149][150], the leakage rates attributed to the background ranged from 45% to 75% after assessing permanent vents, windows, doors, their joints with the envelope, attic hatches, and several other joints. Still, some of these values may occur due to the additional challenges of air tightening commissioned buildings [23].

2.2.3. UNCERTAINTY OF AIRTIGHTNESS RESULTS

There are three standard error types when quantifying airtightness by fan pressurization tests: precision and bias errors on measurements and modelling errors on the used regressor [162][163]. Wind speed and direction fluctuations are the primary sources of precision and modeling errors [140].

The zero-flow measurements intend to tackle part of it, but still, for uncertainty purposes, the assumptions made show significant importance [164][165]. All the analyzed standards in the last Subsection require baseline zero-flow pressure readings, changing the demand on the number of points and reading duration [166][153]. Extended measurement periods, especially on high wind conditions, can substantially reduce the impact of zero flow approximation on the uncertainty of the test [164], as uncertainty is higher for lower pressure stations [165]. These issues add to the discussion concerning the adequate method for error estimation [165][20]. The consideration of higher numbers of measurement points also improves combined uncertainty results [167][168][162].

Certain components and interfaces can suffer a valve effect on one of the directions tested [169]. This effect was found in several studies [170][162][171][172]. With differences, up to 20% between pressure directions results, considering an average value between them seems to be the most reasonable approach to assess the envelope airtightness performance.

In addition to these errors, there is the influence of the tester behavior. It is the main reason behind certification programs for testers and quality management schemes [173][174]. During an in-situ measurement campaign of the contribution of different elements to the overall airtightness performance, one of the outputted characteristics widely used in building simulation is the ELA (Table 2.1). Usually, it characterizes envelope components air permeability, serving as input in airflow modelling. For its usefulness in scenarios design and comparison, libraries for quick access compile lists of calculated ELAs. Interesting examples can be found in AIVC [175] and ASHRAE [176] documentation.

The reliability of fan pressurization measurements has been the object of study for a while now [177][178]. The uncertainty in fan pressurization measurements is non-negligible in both the two measured variables: airflow volume and pressure differential [179][172]. In addition, the uncertainties are not constant in the pressure stations during a test [167][164].

A significant part of these uncertainties often goes unaccounted for with the regression method currently in place in the ISO 9972:2015, the Ordinary Least Squares (OLS). Regression is necessary to fit the relationship between the several measurements of airflow volume and pressure difference pairs during an airtightness test. It allows the extrapolation to pressure differences not contemplated during the measurements, either inside or outside the measured range. The OLS minimizes the distance between the airflow volumes and the fitted line, completely neglecting the uncertainty in the pressure difference. Additionally, it does not consider the uncertainty from the test equipment.

One of the main limitations found in the literature is that uncertainty estimation and propagation during data treatment is scarce [180][181]. More recently, the adoption of alternative regression models aims to tackle measurement uncertainty. Two examples are the Iterative Weighted Least Squares (IWLS) and the Weighted Line of Organic Correlation (WLOC). They include weighting the uncertainty for each pressure-airflow reading and considering more error sources in calculating the total uncertainty [19]–[21]. The weighting allows for addressing the non-constant uncertainties in both measured variables.

2.3. MODELLING AIRFLOWS AND AIRTIGHTNESS IMPACT

Air infiltration modelling is a fundamental tool both for new buildings design and for existing buildings retrofit. It contributes to predicting air change rates, indoor climate, energy-efficient conditioning and ventilation system conception [182]. Figure 2.11 presents a workflow regarding airflow modelling and building design.

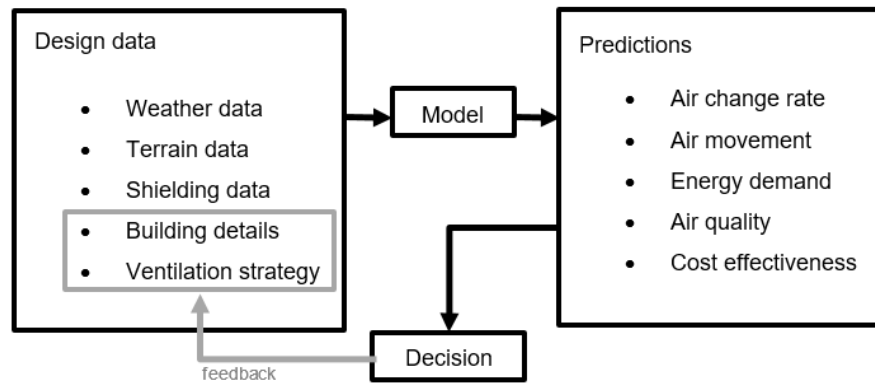


Figure 2.11. Airflow modelling workflow on the design process (adapted from [183])

An accurate calculation of the air infiltration requires the following data [35][183]: the time series of wind speed and direction and the indoors and outdoors air temperatures at the desired location; the location and flow characteristics of all openings on the envelope; the specific pressure distribution product of the climatic influence on the driving mechanism; the topography characteristics of the terrain where the building locates. Construction quality, manufacturing, and installation processes influence the characteristics of leakage paths [184]. This Chapter explores the current state of development of airflow modelling and its respective limitations.

2.3.1. TYPES OF MODELS

2.3.1.1. Empirical models

While in a simulated environment, one models different configurations of air leakage paths at will, a different scenario occurs when assessing an existing building. The models based on data resulting from pressurization tests are labelled as empirical models. They may take a simple mathematical link between infiltration and airtightness ratings, such as the Persily-Kronvall estimation model [185], or more complex structures that consider several dwelling features [80]. Building airtightness influencing factors are essential in the definition of statistical models and, therefore, in creating strategies and conditions to meet desired values or estimating the envelope airtightness of similar buildings. Airtightness research refers to the first approach as reducing pressurization data methods and the second as statistical methods, resulting in structured empirical knowledge.

Other empirical models allow for the direct use of single components flow coefficients and pressure exponents normalized by length or area [175][176]. The values are obtained through field and laboratory tests alike, allowing for consideration of workmanship and materials [186]. Airtightness data concerning windows, doors, component/wall interfaces, walls, ceilings and floors, ceiling/wall/floor interfaces, penetrations, fireplaces, flues, trickle ventilators, and vents are available for input [175]. The performance evaluation often considers different sealing solutions, insulation materials and geometric configurations effects [187].

2.3.1.2. Theoretical models

Theoretical methods are of accrued complexity when compared to empirical ones. They are the product of integral equations on fluid flows. Equations governing this type of model rely on mass, momentum, and energy balance. They address heating and cooling loads and the dependence of air change rates on the pressure difference across a building envelope, among other issues. Control volumes are assumed, and their boundaries are the control volume surfaces. When internal partitions have a small to insignificant influence on the air movement, the indoors can be accepted as a single zone [188]. Otherwise, a multizone model applies [189].

As empirical models, theoretical ones have different degrees of complexity. Regarding leakage input data, it ranges from single airtightness parameters, such as Effective Leakage Area (ELA) [190], to pressure function constants obtained in literature [36], and, in a more advanced approach, to the full description of air leakage paths [191].

Regarding climate data, the infiltration models can be climate independent [185], averaged climate-dependent over time [190] or continuous-time step climate-dependent [36]. It will affect infiltration modelling as well as energy modelling. Among the most used single zone models are the Lawrence Berkeley Laboratory (LBL) model [192] and the Alberta Air Infiltration Model (AIM-2) [188]. They are the source of the basic and enhanced models, respectively, described in ASHRAE Fundamentals [36]. The basic model computes airflow from an ELA at 4Pa. Weather stations provide temperature differences and wind speeds, while wind and stack coefficients are dependent on building height and sheltering effect. As for the enhanced model, additional factors apply in the calculation [193].

Another theoretical single zone model of relevance is the one prescribed by EN 15242:2007 [194], maintained in the current version, EN 16798-7:2017 [195]. This model is used in most

European national regulations to assess air change rate compliance, Portugal included [196]. Air change rates frequency will be closely dependent on wind speed cumulative distribution.

Small buildings such as typical single-family houses often discretize as a single zone, but more complex buildings need a different approach. While single zone models only create balances between a single internal zone and several indoor-outdoor flow resistances, multizone models also consider the flow resistance between internal partitions. One can view the multizone scheme as a grid of nodes, independent zones connected by flow paths that comprise resistances to airflow between them [35]. In each node, the pressure is considered homogeneous. The balance of forces between the internal zones requires an iterative solution that guarantees the mass balance. The tools capable of simulating one or multiple zones go by as Airflow Network (AFN) software.

The detailed flow structure within a single zone belongs in the dominion of microscopic flow solutions. They depend on the use of the Navier-Stokes equations, particularly the numerical technique of the Finite Volume Method (FVM) [35]. Examples are airflow velocity and spatial temperature distribution [52]. Reducing a volume to infinitesimal air elements is also possible by the use of Computational Fluid Dynamics (CFD) [197][198][199]. Bird et al. [200] provide a thorough explanation of the math of the transport phenomena. Table 2.3 structures different methods, their advantages, drawback and primary purposes.

While empirical models are primarily adequate for a general assessment, theoretical ones provide more accurate results. Regarding simulation and hypothesis testing for later application, single zone models are acceptable in calculating air change rates and further energy demand assessment. CFD coupling presents itself as a more powerful ventilation and thermal comfort design tool. It can model airflow and temperature spatial distributions without the computational power and time required by complete CFD modelling.

Table 2.3. Air infiltration models exhibit

Type	Method	Main advantage	Main drawback	Main purpose
Empirical	Pressure data reduction	No computing required	Highly unreliable	Retrofit Easiness
	Statistical	Characterization of built stock	Overfitting to the original dataset	Retrofit Identify infiltration characteristics
	Single components	Direct technical information	Outdated on present requirements	Design / retrofit Assess the quality of construction
Theoretical	Single zone	Compromise between empirical and theoretical	Only one zone modelled	Design / retrofit Energy demand
	Multizone	Prediction of air distribution patterns between designated zones	Substantial data is required to describe the flow	Design Decide ventilation strategies Model indoor air quality
	CFD coupling	Compromise between zones methods and CFD	Sensitive to discretization	Design Decide ventilation strategies Model indoor air quality Model thermal comfort

2.3.2.RELIABILITY OF THE INPUT DATA FOR SIMULATION

While empirical models often overfit the dataset they are generated from [201][88], theoretical models tend to be very sensitive to discretization [202]. Airflow models simplifications, either in the model architecture, either on the input data, populate all simulated scenarios and physical implementations in any research field. Following the line of thinking of 2.2.3, in modelling, accuracy issues regarding data on building leakage distribution, internal and external geometry properties, and weather are the most common basis of uncertainty [203].

Regarding meteorological variables, Building Energy Simulation (BES) and Airflow Network (AFN) software are often used with 1-hour readings or averages to compute airflow balances [204][205][206]. However, large time steps between readings can result in loss of information since the variability in the meantime is ignored, which is particularly important for wind direction and speed. Existing studies have already shown the importance of the time interval when calculating air infiltration in actual conditions [207][208].

Additionally, in the in-between, other parameters such as wind shear coefficients (α or WSC) and wind pressure coefficients (WPC), which significantly affect the air change rates, suffer from similar simplifications. The wind shear coefficient (α or WSC), or vertical wind profile

exponent, is used to convert measured wind speeds to estimated ones at different heights. Wind shear is dependent on atmospheric stability, surface roughness and height [209][210].

Atmospheric stability categorizes the level of atmospheric turbulence, the irregularity of air motion, at a given moment in a given location. Solar radiation adds instability by promoting vertical mixing, faster cooling grounds at night promote stable conditions, and a high enough wind speed will push the atmosphere to neutral conditions by eliminating any air stratification [211].

As atmospheric stability is dynamic over time, so is the wind shear coefficient. Still, in most BES and AFN models, the wind shear coefficient is often assumed to depend only on terrain conditions. It is thus considered constant over time, i.e., as neutral atmospheric stability. The AIM-2 model is an exception, as it considers two atmospheric stability classes in the input [188]. Despite the widespread use of this simplification, previous research shows ACHs monthly average variations up to 64% from summer to winter months [26] and even higher offsets in intraday variations [27].

Using fixed or variable exponents results in differences up to 1.24 times on ventilation airflows and 1.12 times on modelling energy saving potentials [212]. Moreover, different day periods recorded both under and overestimated ventilation performance. Overall, the differences found indicate that the simplification of considering a single atmospheric stability class can have an impact as high as that of wind pressure coefficients simplifications [213] since there is a cumulative effect, as the first impacts the latter.

Wind pressure coefficients result from the relation between the static and the dynamic pressures exerted by air density, wind speed and direction in a given point of the exposed building envelope. This balance also depends on the on-site conditions and building geometry [214].

Pressure coefficients induce high degrees of uncertainty in modelled airflows [28][29]. The output of simulation scenarios using values from measurements [215], databases [186], analytical models [214], among others, show considerable variation [216]. For simulation purposes, the input is often the surface average. Accuracy issues occur across different positions in a single façade [217] and at a single position over time [218]. Previous studies showed that ACHs calculated based on local coefficients oscillated between 0.23 and 5.07 times the ones calculated with surface averages [216].

Although possible, full-scale field measurement of the wind pressure coefficients requires considerable resources and is time-consuming [219]. Thus, most of the available data used in simulation come from wind tunnel studies on building models [220] or numerical models constructed on parametrical analysis of the first [221].

Due to the high number of influencing factors, obtaining reliable input data for simulation is constrained by the scope and extension of the developed studies [221]. Different models based on separate data sources, although modelling the same building and theoretical conditions, can present up to 40% variation in outputted ACHs on exposed structures and up to 100% in sheltered ones [29].

In the latest efforts, using some of the most recent highly detailed wind tunnel data [222], the use of established methods in the research area and new ones for the development of analytical models is providing prediction tools with higher degrees of accuracy [223][224][225]. These recent advances closely fit the training data. They, therefore, may not represent some factors combination, particularly concerning the impact of wind speed profile exponents in the spectrum of wind pressure coefficients.

2.4. AIRTIGHTNESS PERFORMANCE

2.4.1. AIRTIGHTNESS REQUIREMENTS ADOPTED IN DIFFERENT COUNTRIES

The EPDB does not make it mandatory to comply with particular requirements regarding building airtightness [226]. Consequently, discrepancies occur in their applications at a national level. As seen in Section 2.1, matching ventilation strategies with infiltration levels is a challenge. It has added complexity when variables such as climate ask for particular adaptations. For the past decade, the growing number of studies and research evidences the increasing interest in buildings' airtightness. Due to policies regarding the impact of air infiltration on buildings energy performance, regulations focused on guaranteeing minimum construction quality [153]. Several of these initiatives resulted in performing many measurements, and therefore, several countries developed programs to store them. The measurements stored in these have various purposes:

- When mandatory rules are in place, demonstrate compliance of the dwelling [227];
- Increase the accuracy and reliability of the estimates of building energy needs and ventilation performance [228];

- Provide datasets for modelling and designing tasks [75];
- Evaluate the relationships between dwelling characteristics and airtightness [79];
- Assess the quality of construction practices [18];
- Develop guidelines on best practices [229];
- Appraise the impact of singular measures in airtightness performance [63];
- Visualize trends through periods [93];
- Assess how the building stock progresses towards meeting energy performance milestones [230];
- Analyze different building stocks, i.e. between countries [231].

Criteria and nature of normative legislation closely relate to how and why the implementation of the current strategies unroll the way they do [226][232]. There are remarkable dissimilarities between each country approach, each with several exceptions to the norm and particular cases demanding strict or stricter requirements and control. Countries establish different criteria on limits or recommendations that often encompass:

- Integrated ventilation system type (natural, hybrid, mechanical and, in some cases, considering heat recovery), e.g., Germany [149];
- Dwelling typology (single-family or multi-family buildings), e.g., France [233];
- New or retrofitted dwelling, e.g., Switzerland [234];
- Energy performance label, e.g., Lithuania [235];
- Climate zone, e.g., USA [134];
- Ratios between different geometric properties, e.g., Denmark [236];
- A prescriptive path on air barrier detailing, e.g., Canada [147].

Some countries set limits, e.g., the United Kingdom and France. In contrast, others just set recommendations, e.g., Poland, default values, e.g., Belgium, Finland, or even no consideration, e.g., Greece and Hungary (Table 2.4).

Table 2.4. The regulatory approach on residential building airtightness in different countries (NV = Natural ventilation; MV = mechanical ventilation; HRV = heat recovery ventilation)

Country	Parameter	Units	Requirements	On-site testing	Comments	Ref.
Airtightness mandatory values						
Austria	n_{50}	h^{-1}	NV < 3 MV < 1.5	Not mandatory		[237]

Belgium – Brussels region	n ₅₀	h ⁻¹	< 0.6	Not mandatory	New dwellings	[238]
Bosnia	n ₅₀	h ⁻¹	NV < 3 MV < 1.5	Not mandatory		[239]
Croatia	n ₅₀	h ⁻¹	NV < 3 MV < 1.5	Not mandatory	Mandatory testing for NZEB	[240]
Czech Republic	n ₅₀	h ⁻¹	NV < 4.5 MV < 1.5 Heat recovery system <1	Not mandatory	Also, for retrofitted dwellings	[148]
Denmark	w ₅₀	l/(s·m ²)	A _{env} /A _{floor} ≤ 3: < 1 A _{env} /A _{floor} > 3: < 0.3	Not mandatory	Default value when testing is not conducted: 1.5 l/(s·m ²). Random checks are performed	[236]
France	q ₄	m ³ /(h·m ²)	Single-family < 0.6 Multi-family < 1	Mandatory	Alternatively, a certified airtightness quality management approach can be applied.	[233]
Germany	n ₅₀	h ⁻¹	NV < 3 (exceptions with active components < 1.5) MV < 1.5	Not mandatory	Favourable credits only if testing results comply with the benchmarks	[149]
Iceland	q ₅₀	m ³ /(h·m ²)	< 3	Not mandatory		[241]
Ireland	q ₅₀	m ³ /(h·m ²)	< 5	Mandatory		[242]
Latvia	q ₅₀	m ³ /(h·m ²)	NV < 3 MV < 2 Heat recovery system < 1.5	Not mandatory	Mandatory test only in the cases of EU co-financing for construction of new buildings or retrofitting of existing public buildings [243]	[244]
Liechtenstein	q ₅₀	m ³ /(h·m ²)	New buildings: NV < 2.4 MV < 1.6 Renovations: NV < 3.6 MV < 2.4	Not mandatory		[245]
Lithuania	n ₅₀	h ⁻¹	Class C: < 2 Class B: < 1.5 Class A: < 1.0 Class A+ and A++: < 0.6	Not mandatory	Mandatory for class A	[235]
Luxembourg	n ₅₀	h ⁻¹	NV < 3 MV < 1.5 Heat recovery system < 1	Not mandatory		[246]
Monaco	q ₄	m ³ /(h·m ²)	Single-family < 0.6 Multi-family < 1	Mandatory	Alternatively, a certified airtightness quality management approach can be applied	[247]
Montenegro	n ₅₀	h ⁻¹	NV < 3 MV < 1.5	Not mandatory		[248]

Netherlands	w ₁₀	dm ³ /(s·m ²)	<1	Not mandatory		[249]
Norway	n ₅₀	h ⁻¹	< 1.5	Not mandatory	Exceptions for specific typologies and uses	[250]
Russia	n ₅₀	h ⁻¹	NV < 4 MV < 2	Not mandatory	The developer must conduct mandatory settlement and instrumental control of the standardized energy indicators	[251]
Slovenia	n ₅₀	h ⁻¹	NV < 3 MV < 2	Not mandatory	Mandatory for buildings > 5000 m ²	[252]
Spain	n ₅₀	h ⁻¹	Compacity V/A _E ≤ 2: < 6 V/A _E ≥ 4: < 3	Not mandatory	Mandatory test only for dwellings ≥ 120 m ²	[253]
Sweden	q ₅₀	m ³ /(h·m ²)	< 0.6	Not mandatory		[254]
Switzerland	q ₅₀	m ³ /(h·m ²)	New buildings: NV < 2.4 MV < 1.6 Renovations: NV < 3.6 MV < 2.4	Not mandatory		[234]
United Kingdom	q ₅₀	m ³ /(h·m ²)	< 10	Mandatory	Notional recommended value: 5 m ³ /(h·m ²)	[255]
USA	n ₅₀	h ⁻¹	< 3 climate zone 3 to 8 < 5 climate zone 1 and 2	Mandatory (depending on the state-level speed of national energy code adoption)		[134]
Airtightness recommended values						
Poland	n ₅₀	h ⁻¹	NV < 3 MV < 1.5	Not mandatory		[256]
Airtightness default values						
Belgium (Flanders and Wallonia)	q ₅₀	m ³ /(h·m ²)	12	Mandatory, to improve from default values		[257]
Canada	n ₅₀	h ⁻¹	3.2 with basic air barrier specifications 2.5 with extra prescriptive details	Mandatory, to improve from default values	The focus is on the requirements of air barrier assemblies and details [131].	[147]
Estonia	q ₅₀	m ³ /(h·m ²)	Single-family: 6 Other buildings: 3	Mandatory, to improve default values		[258]
Finland	q ₅₀	m ³ /(h·m ²)	4	Mandatory, to improve from default values	New dwellings	[259]
No whole building values suggested or no consideration at all						
Albania			Malta			
Andorra			Moldova			

Belarus	North Macedonia
Bulgaria	San Marino
Cyprus	Serbia
Greece	Ukraine
Hungary	Portugal
Italy (except Trento and Bolzano regions)	Slovakia

The information provided in Table 2.4 supports the increased airtightness awareness in countries with colder climate conditions. On the opposite spectrum, in most Mediterranean countries, with milder climates, whole building airtightness has still not been the focus from a regulatory point of view (Figure 2.12). As the Excessive Winter Death Index (EWDI) is higher in most countries without airtightness requirements [14][13], the issue does not lose relevance with climate alone (Table 2.5).

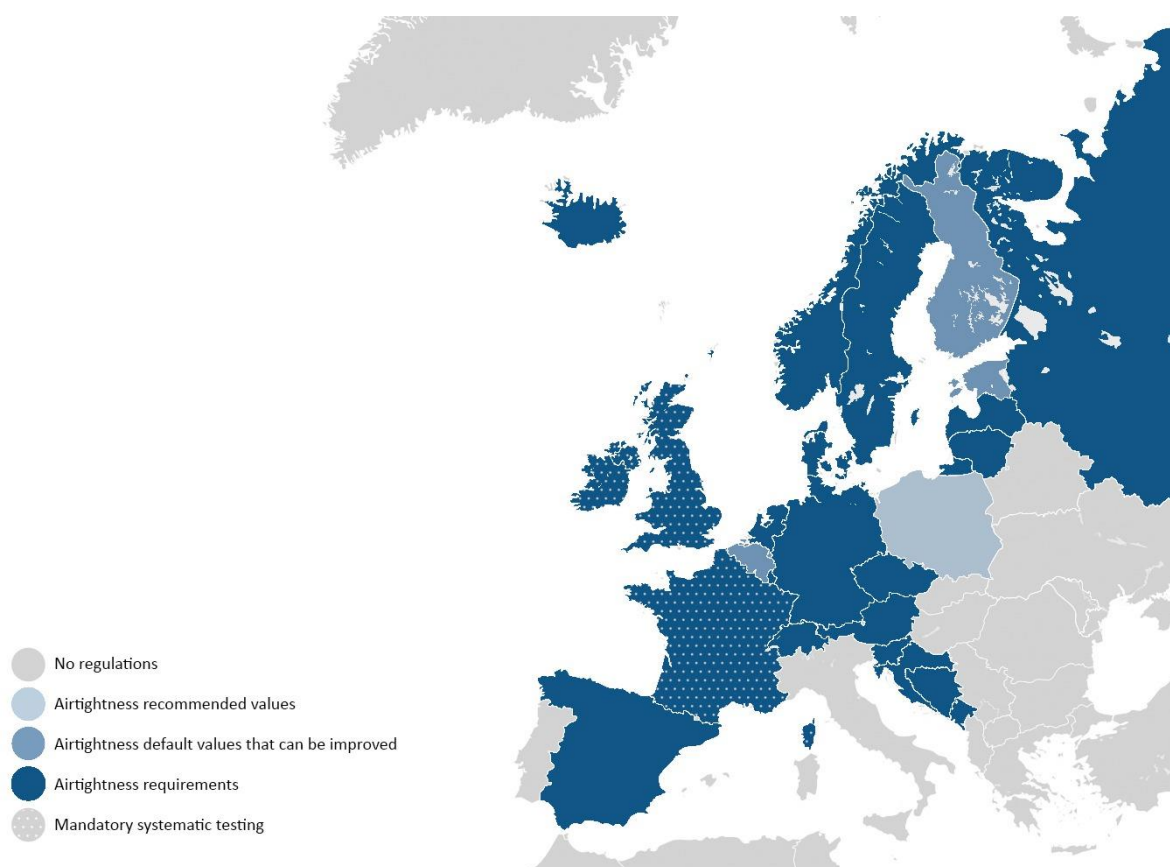


Figure 2.12. Airtightness regulatory context in Europe

Table 2.5. Final energy consumption on space heating in eastern and southern countries of the EU with no requirements on whole building airtightness (adapted from [5])

Country	Final energy consumption on space heating (%)
Bulgaria	54.3
Greece	56.2
Hungary	74.0
Italy *	67.5
Malta	15.1
Portugal	21.2
Romania	63.4
Slovakia	68.3
Spain **	43.4

* except Trento and Bolzano regions

** national-level requirements since late 2019

In the EU, Belgium [238][257] and Italy [260][261] experience different requirements regionally. In the Flanders and Wallonia regions of Belgium, default values are very unfavorable and can only be improved by way of measurements [86], resulting in a concealed encouragement for systematic testing. As a result, at the end of 2016, almost 90% of new residential buildings were tested [174].

In the United States, airtightness gets enforced by state governments [232] and cannot adopt more tolerant limits than those defined at the national level [262][134]. A similar rationale exists in Canada [147], where regions need to comply with the main guidelines of the national regulation. Energy calculation assigns default values if there is no measurement, similar to Belgium policy. It differs by requiring the usage of conforming air barrier assemblies [131] and on the provision and compliance of envelope detailing with prescriptive actions.

In countries with no requirements or recommendations, sometimes specific airtightness classes for several envelope building components, e.g., windows and doors, is required. One can consider their impact on the energy performance calculation, e.g. Portugal [196].

While the North American approaches lean towards prescriptive based methods, the European ones lean toward performance-based methods or a combination of the two. While generalization of good practices is an advantage of the prescriptive method, it leaves several impacting variables unaccounted, e.g., workmanship and actual performance of the envelope. Performance-based methods portray the reality of the built stock more accurately as they require performing tests.

The practices of the North American and European energy codes are converging. Canada and the United States will require mandatory testing of airtightness performance for all the energy labels in the performance-based approach. A review published in an international peer-reviewed journal provides additional details of these practices [10].

2.4.2.CHARACTERIZING AIRTIGHTNESS PERFORMANCE

Policies are increasingly striving for buildings higher energy performance, as the focus on European countries is converging to the nZEB [2]. Theoretically, controlling air infiltration by developing airtight envelopes is critical to avoid a profound impact on the energy demand of dwellings [70].

The energy demand of a dwelling is one of the variables that airtightness influences. The analysis of large national airtightness datasets can be useful to estimate the potential benefits of implementing airtightness improvements and the impact of energy policies on the energy performance of dwellings [263].

The energy impact of air infiltration has been a major driver for increasingly stricter building airtightness requirements [8][261][262], and emerging large datasets of measurement data ease the assessment of the trend of airtightness's weight on residential sectors' energy performance. The transition to mandatory requirements in the UK and France significantly improved airtightness levels stabilizing on the new limit in a few years after entry into force [266][158].

In Spain, in which airtightness was not a requirement until 2019, no significant improvement was observed over time [18]. If one assumes that ageing is associated with airtightness deterioration, these results hint at higher air leakage rates in newer buildings. The most probable cause points to the general disregard for the issue during the installation of building systems.

An EPBD energy certificate attributes a label to a dwelling regarding its energy performance and additional information related to a reference baseline [2]. Still, the information regarding air change rates is limited, usually delimited to compliance with an airtightness limit validated by a blower door test or a prescriptive path during construction [10].

By the analysis of Subsection 2.4.1, one perceives the heterogeneity of airtightness implementation in the EPBD framework. Regulations are inflexible in defining limits regarding details on characteristics and location of dwellings, and although empirically determined, upper

limits definition seem to follow a certain trend. While regulation lacks purely scientific support, there are developments in research towards its accomplishment [267][268][269][270].

Research on this topic commonly focuses on probabilistic approaches. The aim is to have an input dataset with enough variability on single features and their respective combinations to characterize a group of dwellings or buildings. The purposes range from addressing airtightness and ventilation performance to dwelling energy performance.

The first-order reliability method (FORM) applied to the analysis of infiltration in a low-rise building provided probability density functions of air change rates for different wind directions, based on climatic data, terrain data, airtightness performance and geometry of the building [105][271].

IEA EBC Annex 55 and Annex 58 aimed to provide reliable stochastic models based on databases or full-scale dynamic measured data. The models consider infiltration and apply sampling methods to probability distributions on input data [272][273]. A detailed study on the input parameters of AFN models used uniform distributions to portray the uncertainty in considering width and length of cracks, and pressure coefficient of exposed facades, among other variables. Sensitivity analysis found some of these among the most influential parameters, scoring higher than mechanical outflow ventilation and exterior temperature [274].

In research to assess the energy-saving potential of demand-controlled ventilation, a representative dwelling was used on stochastic analysis, applying, among others, intervals of façade orientation, wind pressure coefficients, and terrain roughness and normal distribution to the airtightness and length of ducts. This approach allowed the identification of the most robust ventilation strategy, i.e., the one experiencing less variability with changing environmental parameters, for heat loss and pollutant exposure synergy [275].

In the last decade, metamodels have gained a greater degree of application in topics related to the energy efficiency of buildings. These predictive models present themselves as natural additions to stochastic approaches [276][277]. Metamodels reduce simulation time cost and provide user-friendly tools in characterizing an existing dwelling or designing one [278][279]. The application of surrogate models allows one to classify the dwellings per the ventilation performance in each, emphasizing the added value of combining passive strategies with renewable and sustainable energy solutions [280].

A probabilistic approach of weather data and dwelling characteristics in the UK built stock found artificial neural networks to be the best predictors of indoor air quality parameters [281]. The probabilistic approach overpasses several limitations of learning algorithms, such as training ranges and limited datasets [282]. Gradient boosting models displayed higher accuracy than multivariate linear regression at predicting building ventilation potential in urban environments [283]. Random forests and support vector machines are some of the other applied surrogate models with high performance in predicting ventilation and energy performance [284] [285][286].

Research of the effect of building characteristics with heating and cooling loads showed random forests outperformed linear regressions in predicting their relationship, defending the first in complex applications [287]. Additionally, the authors highlight the implicit advantages of decision tree mechanisms in dealing with statistical assumptions, such as multicollinearity between input variables [288].

Recently, an optimization system for building envelope design, based on gradient boosting machines, was successfully applied, providing mean absolute errors below 3.5% between predicted and actual operative energy consumption [289]. Work on relating air infiltration predictions by converting ACH between 50 Pa and 4 Pa of pressure difference, based on the Persily-Kronvall model, only found modest coefficients of determination between actual and predicted values, despite the application of nonlinear fitting methods [290]. A regression tree designed from several CFD simulated values of ACH presented itself as a better substitute to the latter [291].

An SVR metamodel requiring 29 building parameter inputs predicted accurately the performance of approximately 50.000 detailed energy and airflow simulations [292]. Other implementations of SVR in building performance showed similar results [293][294]. The authors highlight that the developed model could form a comfort performance labelling program for naturally ventilated commercial buildings.

The connection between labelling schemes and meta-modelling seems encouraging, as when dealing with passive strategies, a single classification or regression output often does not compute a comprehensive characterization [292].

Still, a thorough literature review could only find one study [281] addressing infiltration and airtightness characteristics with detail and a broad scope on a built stock with Machine Learning

techniques. The study refers to the UK, in line with the northern European context. Similar approaches addressing the southern European context are lacking.

2.5. SUSTAINABILITY IN AIRTIGHTNESS

2.5.1. LIFE CYCLE ASSESSMENT IN THE AEC INDUSTRY

The AEC industry has one of the most impactful and challenging sustainability issues [295]. Environmentally, the sector is one of the heaviest on energy consumption and carbon emissions [296]. Economically, buildings are assets with high initial and operational costs and long life cycles [297]. Socially, as humans spend most of their time inside buildings, the challenges are numerous. They have deep implications in societies [298].

Among several reasons from which its structure and inefficiencies can be highlighted [299], the sector has one of the most substantial potentials on reducing greenhouse gas emissions (GHG) and cutting energy consumption [300].

Principles on sustainable construction encompass reusing and recycling resources, reducing their consumption, protecting natural systems, and eliminating toxic materials from the life cycle [301]. Life cycle assessment (LCA) establishes itself as a major tool, driving decisions and policies [302].

In the initial approach of the EPBD [303], priority was on energy efficiency measures, in the form of design or retrofit packages pointing to cost-optimality through the life cycle of reference buildings [304]. This trend focused on reducing energy consumption, and therefore, the consequent cut on carbon emissions resulted from the electricity mix provided by the energy carriers [305].

In the current version of the Directive [2], there is a shift to clean energy adoption, deployment of renewables, and general decarbonization of the building stock. This trend requires the nZEB and ZEB to focus significantly on carbon targets, not solely on energy ones [306][307][308].

Although the operational phase contributes the most to environmental impacts [309][310], the percentage of energy used in the production and construction phases increases as buildings get more energy-efficient [311]. The main causes are the decreased energy used during the operational phase, the increased embodied energy and carbon in specific materials, and the application of particular technologies, particularly HVAC equipment [312].

Embodied carbon and energy refer to the CO₂ emissions produced and the primary energy required, respectively, during the resource extraction, transportation, fabrication, assembly, disassembly and end of life disposal of a particular product [313]. Throughout the literature, one finds very high average values of GHG emissions, over 50%, and energy consumption, around 80%, associated with the operational phase of a conventional building [314].

Low energy buildings face a shifting paradigm. As the operational phase gets less impactful, higher embodied effects arise, such as increasing insulation levels and adopting new technologies on active systems [315][316]. Proportions go as high as 40% of embodied impact and as low as 60% of operational impact [317].

2.5.2. ENVELOPE AIRTIGHTNESS TECHNOLOGY

Airtightness implementation often adopts air barrier systems [318] dependent on air barrier materials, components and accessories. Air barrier materials include polyethene fibre wraps or gypsum plastering. Windows and doors are examples of air barrier components. Air barrier accessories refer to tapes and sealants, elements that maintain the airtightness performance in the penetrations and joints of air barrier materials and the joints between materials and components. Their performance relies on durability, compatibility and constructability as they are often complex regarding proper installation [229]. Figure 2.13 schemes the relationships between common air barrier elements.

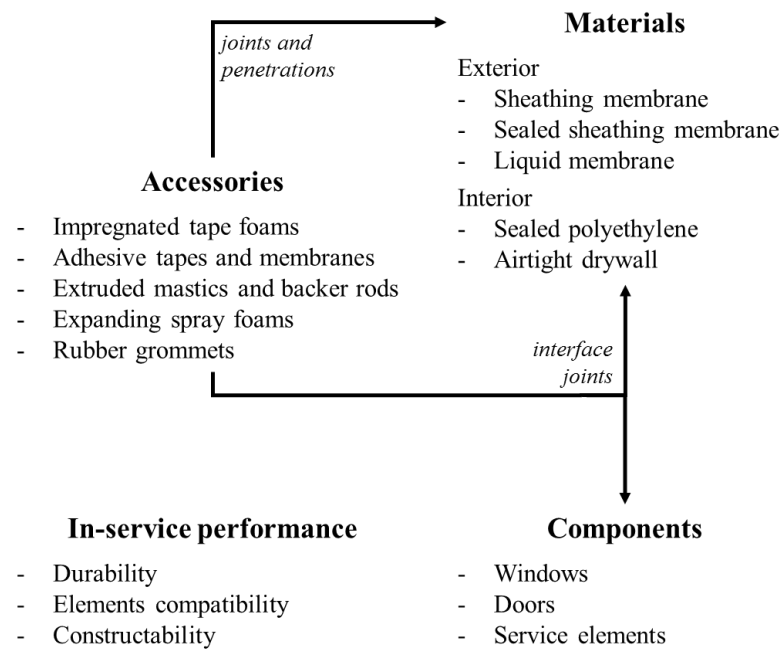


Figure 2.13. Relationships between elements applied in building air barriers (based on [229])

Constructability aspects feature design, detailing, construction sequencing and overall complexity of airtight solutions. They bring extra unpredictability to a craft already highly susceptible to the quality of the workmanship. Chemical incompatibility between elements is the main factor in reducing adhesion. The nature of the sealant, exposure to weather, imposed pressure, amplitude and frequency of movements, elements causing degradation, such as UV radiation, ozone, among others, the geometry of the interface and nature of their exposed layers, all influence the durability of a sealed interface [319][320][321].

A thorough study on the application of polyurethane foam on air leakage of joints found surface roughness, type of materials in contact and width of the joint to be the main contributors to the airtightness performance [322]. The planed timber joints performed better than the sawn ones by a factor of two, and mixed timber-PVC joints by a factor of three approximately. The failure rate of leakage paths on joints of 30 mm was 14.5% higher on average than 10 mm joints, reaching 50% in some cases. The authors indicate that moistening plastic surfaces before applying the foam increases surface bonding. The high variation between air leakage rates on theoretically equally treated specimens showed that the failure rate, more than the actual air leakage performance, is the main factor influencing the overall success of sealing implementation.

The results of a study of the window frame – cavity masonry wall interface found that, on average, plywood frame solutions performed substantially better than their counterparts [187]. Medium-density mineral fiber, and the application of plaster finishing only, were the worst performers. While polyurethane foams, backer rods and polyester foil all provided low air leakage values, the authors highlight the sensitivity to errors during installation as a challenge to overcome. Redundancy on air leakage path treatment, such as sealing interior and exterior simultaneously, and the further application of caulk in different materials interfaces, is indicated as mitigating this issue.

Laboratory results from another study show disparate values between sealing technologies, i.e. materials used in the sealing process, and techniques, i.e. how these materials were applied [323]. The size of self-expanding sealing strips needs to be carefully selected according to the joint width, as density will be affected. Their form of fixation strongly influences the performance of wind and vapor barriers. Higher distances on nails were associated with higher air leakage rates, as different pressurization modes will push the barrier against or away from the support layer. Continuous backer rods in steep angles perform worse than a non-continuous alternative. Tapes, wind barrier strips, and backer rods were the most airtight elements studied.

Regarding durability and ageing, tests on samples after an extended period, five months, of pressure differential, 150 Pa, and extreme temperatures, -20 to + 65 °C, found strengths and weaknesses between the different solutions [324]. Good performances were obtained regarding backer rods and rubber gaskets, counting that no stretching on application occurred since the material tended to its original length over time. Low levels of compression rate were associated with stability issues. Open-cell gaskets and mineral wool showed poor efficiency as air barriers but adequately filtered dust. Small cracks are identified in wood-aluminum joints when expanding urethane foam is used. Adhesive tapes and silicone sealing showed results unaffected by the extended period and the temperature ranges, but acrylic sealings lost adhesion when submitted to extended periods of +65 °C [100][96].

From the sealing methods studied in a laboratory setup for wall-component joints, only joints treated with mineral fiber failed to reduce the air leakage rate to negligible levels [325]. The use of backer rods, foils/wraps and polyurethane foams performed similarly. The foam solution was the less expensive method.

A study on the typical joints of timber frame buildings showed joints on corners of external walls and joints on inserting floors on exterior walls are the ones with the highest readings [103]. Correcting these discontinuities with self-adhesive tape showed good results. Authors point to difficulties in fixing these issues when prefabrication provides interior finishing. It notes that field conditions provide values up to ten times higher, thirty-five times in another study [326], than ones obtained in laboratory conditions. Additionally, it highlights the need to introduce a common framework on requirements for sealing elements, such as adhesion, tear resistance, elongation, and durability.

Partially due to the complexity of these relationships, partially due to a reduced embodied impact of these materials in the overall construction or retrofitting works, the study of the airtightness solutions regarding life cycle assessment is often overlooked. Usually, when reporting airtightness and air infiltration improvements, they come as a by-product of the consideration of works not primarily intended to target the issue [327]. When directly considered, the reductions in air change rates generally result from windows replacement [328].

In line with the identified disregard for the topic, Environmental Product Declarations (EPDs) related to complete airtightness solutions and sole elements are scarce [329]. It is thus a quite unfeasible task to assess distinct elements that constitute the air barrier in an LCA approach. Considering whole envelope airtightness solutions seems to be a more plausible path.

2.6. SUMMARY ON KNOWLEDGE GAPS AND RESEARCH PATHS

The present Chapter explored literature concepts and relationships, analyzed findings from previous studies, and identified knowledge gaps and needs to branch airtightness research and implementation in the southern European context. This Section revisits them more systematically:

- Subsection 2.1.3 and Section 2.2 highlighted gaps in experimental airtightness characterization. From the lack of awareness, construction in the southern European context disregards airtightness issues resulting in the existing built stock being in its greater majority unadapted to the topic. Identifying the air leakage locations and quantifying their impact is particularly relevant in this regional context. These issues have relevance in new building developments and building stock retrofit, with the latter

experiencing a gradual increase in global significance in the AEC industry in southern European countries in the last decade.

Additionally, as buildings become more complex and occupants more demanding, there is an obvious trend for smart design, supervised workmanship, and materials durability, especially in the design of buildings envelope systems, as is the case of modular envelope solutions. The performance of these solutions is not often adequate, and thus, a stronger focus on airtightness at the design phase could avoid costly operations on corrections in later stages. Although a measurement during the construction phase is an important reference for the overall building performance, it does not always indicate that airtightness can only improve in subsequent construction phases.

Regarding airtightness measurements, one of the main limitations found in the literature is that research studies concerning uncertainty estimation and propagation during data treatment are scarce. Recent developments show that the current data treatment disregards significant uncertainty during airtightness measurements. The undergoing progress in measuring airtightness brings an important potential contribution to the reliability of fan pressurization measurements and confidence in the subsequent data treatment. One questions if the combination of qualitative methods can provide an optimized sealing sequence for quantification of air leakage paths contributions and if the sealing sequence affects the uncertainty of results and the subsequent data treatment phase.

Chapter 3 will explore these knowledge gaps.

- Section 2.3 pointed limitations related to the simulation of ACHs through building envelopes. The airflow in countries of southern Europe is majorly dependent on the variability of natural forces. As the current focus of airflow simulation is on average values rather than on fluctuations through time, more appropriate in assessing indoor air quality, adding detail to the latter adds to better predictions of ACHs.

A proper airtightness performance mainly depends on settling in a range that ensures minimum ACHs for health reasons. The performing range must have low variability to avoid an extra impact on HVAC equipment's energy consumption and operating capacity. Therefore, in line with the previously proposed experimental limitations to be explored, it is essential to understand how different air leakage paths configurations and

airtightness levels influence building envelope ACHs in a southern European case study.

Additionally, the literature review shows that using hourly averaged meteorological data and wind shear and wind pressure coefficients dependent only on terrain characteristics may overlook variations in the overall ACHs. As one intends to maintain the ACH in a narrow range, a more detailed knowledge of its variability may provide ground for better design of natural ventilation systems.

Chapter 4 will address these issues.

- Section 2.4 explored current regulatory efforts and setups regarding airtightness implementation in the AEC industry and its sustainability aspects. The focus is mainly on the conditions that inhibit the proper adaptation of the existing practices to the southern European context.

All the studied setups use a one-variable approach. However, a combination of several variables already in use with others affecting the performance of natural and adventitious ventilation systems would be a better approach. Further performing feature importance would define a minimum complementary data setup that could guide future initiatives. Feature importance assesses the impact of each feature on the variability of air change rates, therefore, identifying those which can drop from future research as they show to be unimportant. Existing massive datasets with a high number of data categories serve as adequate input for this type of analysis, although statistical alternatives exist. Both are suitable as input in defining airtightness performance ranges. One can construct reliable predictive and labelling models on top of these datasets. Ultimately, properly defining airtightness requirements for southern Europe that bind with energy efficiency labelling would be an important milestone in the nZEB pursuit. It represents a window of opportunity to implement or enhance proper practices in these countries.

In addition to predictions, the results from such an instrument can potentially drive design and retrofitting paths regarding airtightness performance for sustainability. Section 2.5 reports significant disparities in materials airtightness performance in a controlled environment. One must assume that commercial products and systems are completely airtight when properly applied to create scenarios. Therefore, the main goal

is not to compare solutions but to assess which dwellings characteristics, along with airtightness performance, justify the implementation of airtightness technology regarding an LCA scope in the context of southern Europe.

Chapter 5 will develop on these opportunities.

For the research of the current thesis, the three identified research paths:

- experimental assessment of buildings airtightness;
- numerical simulation of airtightness impact on ventilation;
- and airtightness performance for a sustainable building stock,

were divided into seven Applications. The first two pursue the detailing of natural forces variability impacting airtightness and air change rates, while the third focuses in easing research deployment to policies and general society. For the reader's convenience, Table 2.6 maps these Applications across the research paths and identifies the main software tools that supported their development.

Table 2.6. Map of Applications, their chapters and main software tools, within the research paths

Research path	Research Application (A)	Chapter	Main software tools
Experimental assessment	A1 - Laboratory and in-situ airtightness performance	3.2	Excel FanTestic
	A2 – Quantitative and qualitative assessment of air leakage paths	3.3	
Numerical simulation	A3 – Air leakage paths configurations and airtightness levels	4.2	CONTAM CpCalc+ Excel FanTestic MATLAB
	A4 – Meteorological variability impact on air change rates	4.3	
Airtightness performance	A5 – Airtightness performance labelling strategy	5.2	Excel EasyFit Minitab MATLAB Python (Scikit Learn)
	A6 – Airtightness compliance tool for naturally ventilated dwellings	5.3	
	A7 – Life Cycle Assessment of airtightness solutions	5.4	

3

EXPERIMENTAL ASSESSMENT OF BUILDINGS AIRTIGHTNESS

3.1. CONTEXT

Addressing the real airtightness performance requires experimental assessment. Understanding the efficacy of different technologies and their respective application is the source of important knowledge for decision making on airtightness solutions. The present Chapter explores this branch of airtightness research.

As sustainability awareness increases in the AEC industry, adopting alternative building constructive systems gets additional focus. Such is the case of modular envelope solutions such as SIPs. A SIP is a sandwich structure composed of an insulating layer sandwiched between two layers of oriented strand board (OSB) or similar structural alternatives. Concerning airtightness, this type of envelope solution presents additional challenges compared to traditional ones, as discussed in Subsection 2.1.3. This envelope solution has a highly standardized construction procedure that should include a systematic detection and treatment of unintended leaks. To tackle these challenges, the case studies chosen for the experimental campaigns adopt this type of envelope solution.

The first Application (A1) assesses the performance of modular lightweight construction envelope solutions, SIPs, in a controlled environment in laboratory conditions and different construction stages through in situ measurements.

The second Application (A2) explores qualitative and quantitative assessment frameworks for air leakage characterization and subsequent data treatment. The case study evaluates the reliability of measurement techniques and discusses the application potential of different regression techniques for data treatment.

Sections 3.2 and 3.3 provide the methodology, results, and discussion on these Applications. Section 3.4 provides conclusions on the undertaken research.

3.2. LABORATORY AND IN-SITU PERFORMANCE BY CONSTRUCTION STAGE (A1)

The objective of Application A1 is to evaluate and discuss the airtightness performance of a SIP building envelope solution. It aims to:

- Compare the airtightness performance in laboratory and field application of the SIPs envelope solution;
- Assess the offset of airtightness between the finished wind barrier construction and commissioning stages.

3.2.1. LABORATORY AND IN-SITU METHODOLOGY

3.2.1.1. SIP case study

The SIP solution evaluated in this Application, A1, encompasses metal framing elements, a core of expanded polystyrene (EPS) and oriented strand boards (OSB) sidings. Figure 3.1 illustrates the composition and the assembly details. The constructive solution includes connection modules that fill the space between the metal frame profiles. At the connection between panels, the OSB sidings are theoretically in contact. Nevertheless, a continuous mastic strand on the exterior and interior sides seals all the joints to ensure the construction system's continuity and performance.

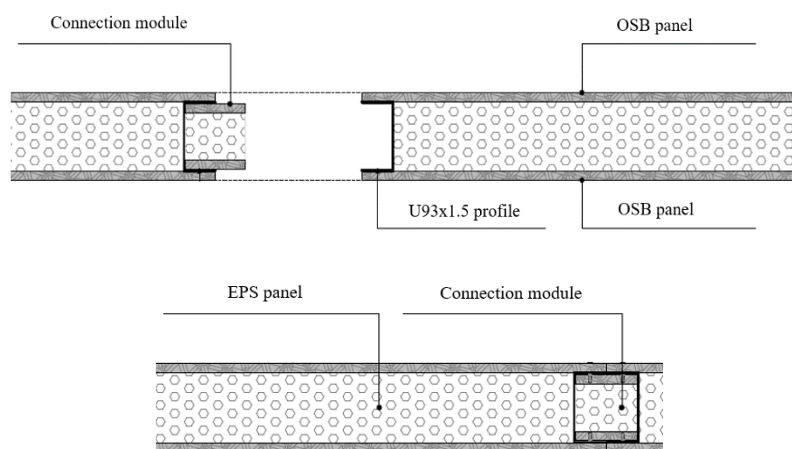


Figure 3.1. Details of the SIPs assembly

The dimensions of the specimen tested in the laboratory measurements was $360 \times 300 \text{ cm}^2$. After the initial assessment of the wall assembly, a $55 \times 70 \text{ cm}^2$ tilt and turn window was integrated into the setup for the second stage of the tests. Figure 3.1 shows the two laboratory SIPs specimens ready for testing. The interior surface remains unfinished, but the exterior finishing layer uses the same materials of the in-situ example: magnesium oxide-based boards, with a coating of synthetic mortar reinforced with a fiberglass mesh. The specimen has 9.6 linear meters of joints between panels and 2.5 linear meters of joints between the SIPs and the window.

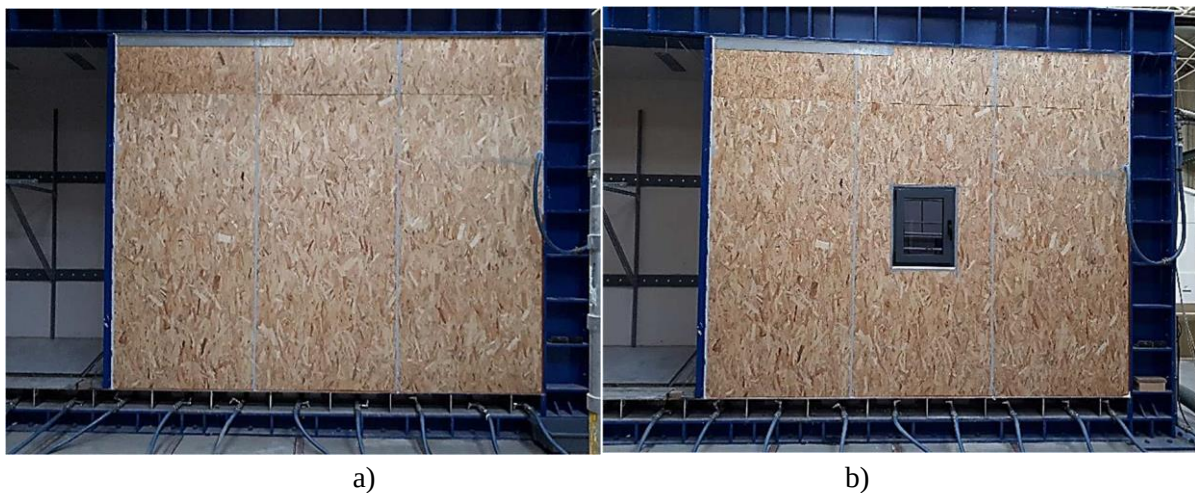


Figure 3.2. SIP modules tested: a) wall assembly; b) with a tilt and turn window

The in-situ case study corresponds to a single floor modular dwelling built in the north region of Portugal. The slab is made of reinforced concrete. SIPs compose the rest of the structure. As referred before, an additional exterior cover of magnesium oxide-based boards was added to the SIPs and covered by a synthetic mortar reinforced with a fiberglass mesh. On the interior side, a plasterboard finishing was applied. The same SIPs with an additional liquid waterproofing layer on the exterior surface constitute the roof. Except for the entrance door, all the exterior openings are double glazed side hung aluminum frames. There are mechanical exhausts in the bathrooms and kitchen, and there are grilles for fresh air admission in the living room and the laundry (Figure 3.3). Table 3.1 presents the dwelling relevant geometric properties.



Figure 3.3. In-situ case study: a) and b) exterior openings; c) and d) examples of air extraction and admission points.

Table 3.1. Modular home geometric properties

Floor area [m ²]	Volume [m ³]	Envelope area [m ²]	SIPs – windows joints length [m]	Internal SIPs joints length [m]
103.0	319.3	322.0	64.0	329.5

3.2.1.2. Laboratory and in-situ setups

The laboratory tests follow the procedure described in EN 12114:2000 [111]. The test starts by imposing three pressure pulses, 1.1 times higher than the maximum pressure difference, followed by increasing pressure levels up to a maximum of 1000 Pa, both for negative and positive pressures. At each step of the process, the corresponding airflow is measured. The pressure differences in the tests were 50, 100, 180, 320, 560, and 1000 Pa.

The measurements were performed under stable conditions with temperatures between 15 and 16 °C and relative humidity between 55 and 60%. An integrated electromechanical control system measures and records the test data. The pressure transducer measures a minimum of 50 Pa pressure difference with an accuracy of ± 5 Pa. The accuracies of the flowmeter and the anemometer are ± 0.05 l/min and ± 0.05 m/s, respectively.

In the in-situ case study, the airtightness measurements occurred during the construction and commission stages. The tests were performed with the blower door Retrotec1000 model, following the procedure described in the standard EN 13829:2000 [125].

In the measurement carried out at the construction stage, the whole envelope was assembled, and the exterior coating was applied. Nevertheless, the connection between the window frames and the interior plasterboards was not completely sealed. Additionally, no other penetrating elements in the exterior walls were installed, such as the electrical ones. Only method B of the EN 13829 was applied at the construction stage. At the commissioning stage, both methods A and B were used.

3.2.2. LABORATORY AND IN-SITU PERFORMANCE ASSESSMENT

3.2.2.1. Laboratory measurements

Figure 3.4 portrays the airflow per linear meter of internal joints for the test specimens with and without the window. Figure 3.4a displays pressurization measurement results. Figure 3.4b presents depressurization data. The contribution of the internal SIPs joints to the airtightness is $0.005 \text{ m}^3/(\text{h.m})$ at 50 Pa of a pressure difference. This result is approximately 30% below the average contribution found by previous authors for both horizontal and vertical joints [330]. Including a window to the setup increases the airflow volume to $0.0113 \text{ m}^3/(\text{h.m})$ at 50 Pa. The window permeability mainly justifies this. However, the different geometry of the SIPs-window joints compared to the internal SIPs joints is another factor to consider. Still, the results show a good performance throughout the range of studied pressure differences, never exceeding the DIN 4108-2 limit [331]. The acquired results prove the envelope system's reliability in creating airtight environments with no further addition of sealing elements.

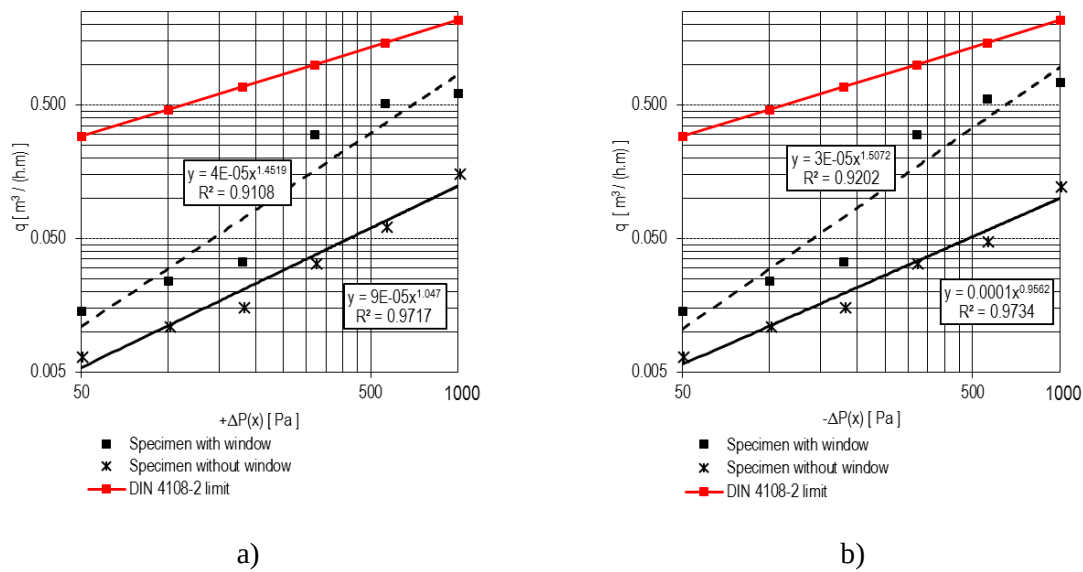


Figure 3.4. Airflow cross joints for the test specimens: a) at positive pressure differentials; b) at negative pressure differentials

3.2.2.2. In-situ measurements

Concerning the in-situ tests, Table 3.2 shows the ACH across the building envelope at 50 Pa divided by the indoor volume, n_{50} , for the different stages and scenarios under study. Each n_{50} portrays the average of one pressurization and one depressurization test. A very airtight building was expected after the laboratory results, particularly for method B measurements since the openings get sealed. Nevertheless, even for this situation, the n_{50} was 1.55 h^{-1} increasing to 1.98 h^{-1} when method A applied. This result is in line with findings published in a previous study about wind barriers on wood frame houses [102], where the field measurements largely exceeded the theoretical values found in the laboratory. Still, this data contrasts with the results found on reinforced concrete and masonry-built flats, representative of typical multi-family Portuguese buildings [82]. In that example, the airtightness averaged 6.8 h^{-1} .

Table 3.2. Air change rates and air permeability at 50 Pa during different building stages of measurements according to EN 13829:2000

Building stage	n_{50} [h ⁻¹]	q_{50} [m³/(h·m)]
Construction - method B	2.49	2.42
Commissioning - method A	1.98	1.92
Commissioning - method B	1.55	1.50

Moreover, the results show a 37.8% reduction of the envelope's air permeability, measured by method B, from construction to commissioning. As construction stage measurement underwent with finished exterior works, one can conclude that interior works on the envelope are not negligible for the final airtightness performance. The purpose provided openings contribution is 0.42 m³/h at 50 Pa, only 21% of the total air change rate, differing significantly from other values found in a similar study [326]. A contribution of 59% was found. In this case study, the air renovation mostly depends on the infiltration through envelope leaks. Theoretically, the infiltration should not be influenced joints between SIPs and joints between SIPs and windows, as in the less airtight value estimated in laboratory conditions, the influence never surpasses 1.5 % of the n₅₀ measured in situ.

3.2.3.COMPLIANCE AND DRAWBACKS

The SIP envelope system complies with the permeability requirements of the DIN 4108-2 standard. This construction system is an alternative to the traditional heavy construction solutions regarding airtightness performance.

One key factor influencing the airtightness of a building was the workmanship. Airtightness laboratory results should not be the only method to estimate/evaluate real case performance scenarios and should serve as an optimum benchmark for comparing and selecting building envelope solutions.

Unforeseen air paths, and others not studied in Application A1, as floor/exterior wall joints, electrical/plumbing/gas facilities, etc., substantially influence the overall airtightness performance. The next Application, A2, will focus on these types of unforeseen air paths.

3.3. QUANTITATIVE AND QUALITATIVE ASSESSMENT OF AIR LEAKAGE PATHS (A2)

The objective of Application A2 is to assess the reliability of quantitative and qualitative evaluation frameworks on air leakage paths with the reductive sealing technique, particularly aiming to:

- Make an in-depth discussion of the evaluation of air leakage paths, using a modular building as a case study;

- Check the strengths and weaknesses of using a smoke tracer as a qualitative technique for the detection of leaks;
- Evaluate the uncertainties resulting from applying standard and recently evaluated regression methods on variables of interest, such as airflow rates and effective leakage areas;
- Produce recommendations for the reliable application of the reductive sealing technique.

3.3.1.ASSESSMENT METHODOLOGY

3.3.1.1.Modular case study

The selected case study is a small modular building assembled with SIPs and light steel framing (LSF) (Figure 3.5), located in Porto, Portugal. The building is one floor only, with 33.6 m² of floor area and a volume of 85.7 m³, and the envelope solutions are common in this type of buildings. Figure 3.6 shows the design details of the exterior building components. In the exterior walls, SIPs have insulation boards of EPS 30 with a thickness of 153 mm. Standard U steel profiles filled with EPS 30 thermal insulation connect the SIPs. Extruded mastics on both faces seal the joints. The roof solution is similar to the wall solution, with an additional continuous liquid-applied polyurea waterproofing membrane (LARWK) on the exterior side. The interior side has a non-ventilated cavity with mineral wool boards and gypsum boards fixed to the LSF beams. The slab solution does not use SIPs. It encompasses the same type of LSF beams supporting a solution of OSB3 panel of 12 mm, 40 mm of mineral wool boards of 70 kg.m⁻³ with embedded OMEGA profiles for support, and an additional 25 mm OSB3 panel before the application of the floor finishing material. Regarding ventilation and airtightness, the building has a balanced mechanical system, and all the windows and doors have an air permeability of class 4 [332].

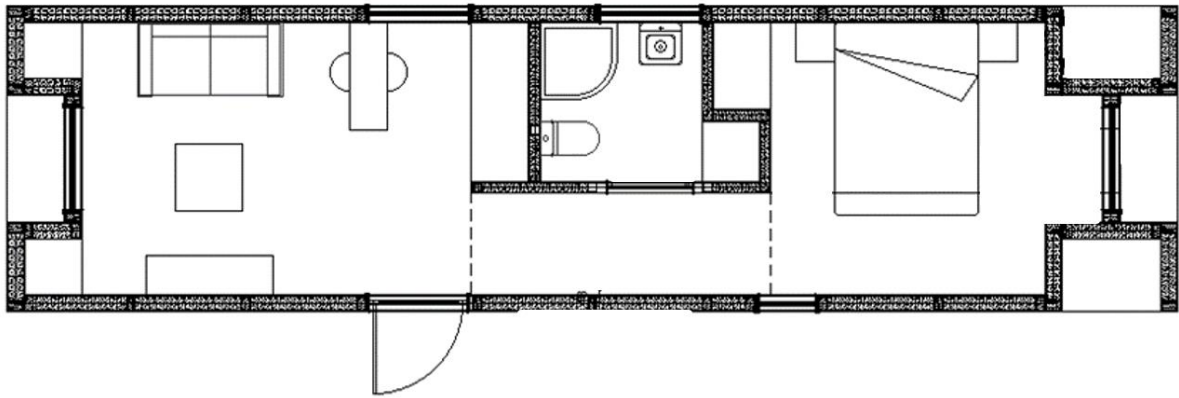


Figure 3.5. Floor plan of the modular building

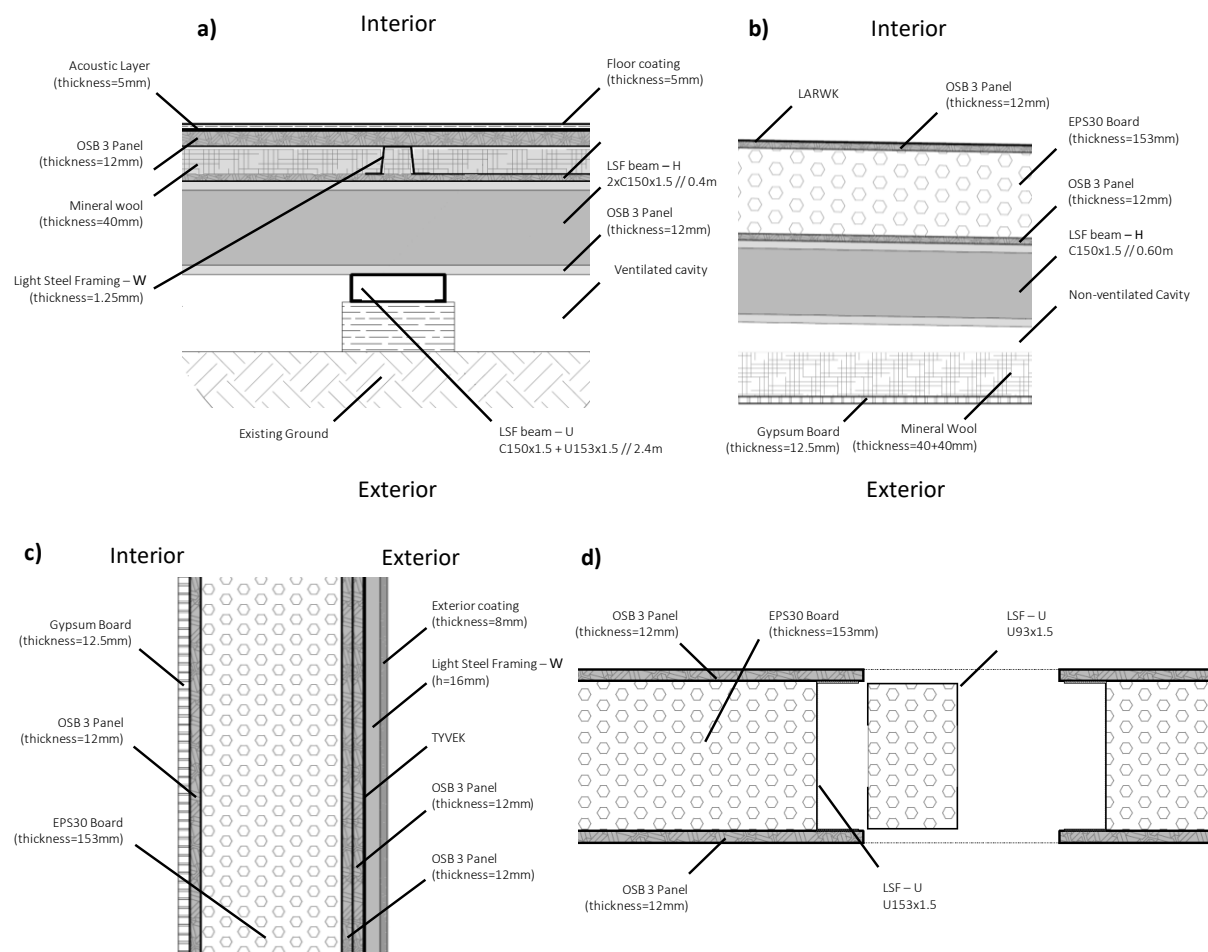


Figure 3.6. Design details of the exterior building components: a) floor, b) roof, c) exterior wall, and d) external SIP connection

3.3.1.2. Experimental campaign work plan

The work plan develops according to the following steps:

- Definition of a reductive sealing plan;

- Implementation of the in-situ testing campaign;
- Uncertainty analysis of the test results.

After a detailed inspection of the building, the reductive sealing plan was defined and included 11 steps. In each step, the temporary sealing was made with paint stripes and plastic coverings when seen appropriate. The steps were the following in a cumulative and progressive order of sealing:

- Default mode (DEF);
- Mechanical ventilation (MEV);
- Heating and air conditioning elements (HAC);
- Electrical appliances (ELE);
- Lighting (LIG);
- Plumbing (PLU);
- Wall/wall joints (WWJ);
- Wall/floor joints (WFJ);
- Wall/roof joints (WRJ);
- Wall/openings joints (WOJ);
- Openings (OPE);
- Entrance door (ENT).

The established methodology starts with sealing the referred elements at each step, followed by one pressurization and one depressurization test. A smoke tracer pressurization test for further air leakage detection follows in each step.

After the default step (DEF), the smoke tracer test identified the main leakage paths. The aim was to reduce the air leakage of the case study as much as possible and consecutively address similar types of air leakage paths: 1D – item/point leakage; 2D – linear leakage. As one progressively identifies the leaks, they are handled with similar types, i.e., identifying ELE and addressing LIG and PLU consecutively. While the openings, OPE, were recognized as one of the largest contributors, they were to be assessed sequentially to the entrance door, ENT, and this one needed to be last for access reasons.

All the tests for the determination of airtightness followed the ISO 9972:2015 [124] standard guidelines. The tester performs zero-flow pressure readings before and at the end of the pressure

station measurements, each time with a collection of 10 points and 30 seconds duration each. Pressure-flow couples were measured at 10 points, from 65 to 15 Pa, equally spaced, with 30 seconds each.

The chosen lower limit was to comply with the standard guidelines and the equipment's characteristics. Regarding the upper range, while the standard indicates it could go as high as 100 Pa in a single measurement, it only requires that the highest-pressure difference be recorded at a minimum of 50 Pa. As one intended to apply common procedures usually adopted by practitioners, the assumed value was 65 Pa.

Smoke tracer tests followed ISO 9972:2015 and ASTM E1186:2017 [333] guidelines. The building was pressurized at 100 Pa for 15 minutes with simultaneous smoke generation to allow for the homogenization of the smoke indoors and the taking of photographic evidence.

3.3.1.3.Campaign equipment

Figure 3.7 portrays the equipment used for the quantitative and qualitative airtightness assessment. For the proposed work, a Retrotec 1000 model, together with a DM-2 gauge, was used to collect pressure-flow couples and zero-flow pressure measurements. The gauge meter has a pressure resolution of 0.10 Pa and an accuracy of $\pm 1\%$ of the pressure reading or 0.15 Pa, whichever is greater [334]. With the used setups, the fan model has an accuracy of $\pm 3\%$ of the airflow measured [335], limited to readings above 10 Pa.

A Cameo Steam Wizard 2000 with slow fog served to detect air leakages visually. The overall airtightness of envelopes or components is critical in the infiltration assessment of buildings but knowing the locations of air leakages is also essential. Air leakage location methods used in conjunction with pressurization tests improve their identification. A smoke tracer is thus a useful qualitative indicator of air leaking locations.

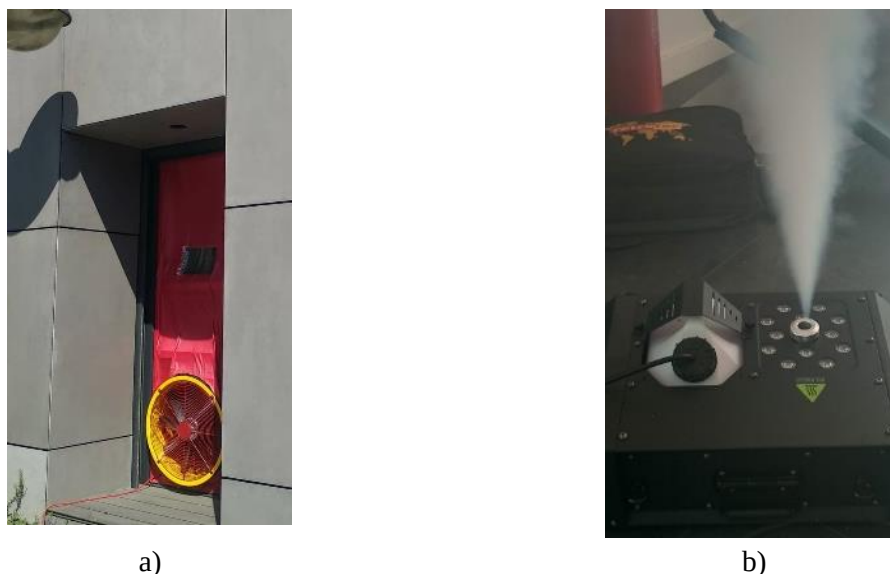


Figure 3.7. Equipment used on the campaign: a) blower-door apparatus; b) smoke generator.

During the campaign, an indoor temperature sensor and a nearby weather station provided continuous monitoring of interior (T_i) and exterior (T_e) temperatures, as well as wind speeds (v). The accuracy of the indoor sensor is ± 0.5 °C, and its resolution is 0.1 °C. Temperature sensors on the weather station have an accuracy of ± 0.3 °C and a resolution of 0.1 °C. The $v_{\min}$, v_{mean} and $v_{\max}$ represent the minimums, means and maximums, respectively, of the wind speed during the test periods. Table 3.3 synthesizes the measured variables.

Table 3.3. Registered weather conditions during the campaign measurements

	T_e [°C]	T_i [°C]	$v_{\min}$ [m/s]	v_{mean} [m/s]	$v_{\max}$ [m/s]
Minimum	20.4	23.6	0.1	0.6	0.7
Average	24.9	27.2	1.0	1.4	1.8
Maximum	31.2	31.9	2.0	2.5	3.1
Std. deviation	3.24	2.48	0.44	0.51	0.68

3.3.1.4. Measurement uncertainty analysis

The airflow coefficient before correction to standard conditions, C_{env} , represents, amongst the effect of indoor and outdoor air densities, the joint product of the discharge coefficient and the leakage area (Eq.(3.1)). ISO 9972 assumes the latter is equal to 1.0 more in line with leaks of reduced dimensions [336] and the assumption of the development of fully turbulent flow in the air leakage paths. It implies the edges of the air leaks dominate the airflow resistance [337]. As one intends on applying the ISO standard, one adopts this assumption in the present

Application. In Eq. (3.1) and (3.2), the T stands for the exterior temperature in depressurization mode and interior temperature in pressurization mode.

$$q = C_{env} \left(\frac{T_0}{T} \right)^{1-n} \Delta p^n \quad (3.1)$$

$$ELA = \frac{10q}{3.6} \sqrt{\frac{\rho_0}{2\Delta p}} = \frac{10}{3.6} C_{env} \left(\frac{T_0}{T} \right)^{1-n} \left(\frac{\rho_0}{2} \right)^{0.5} \Delta p^{n-0.5} \quad (3.2)$$

q	airflow volume at Δp (m ³ /s)
T_0	reference temperature of 20 °C (K)
T	given temperature (K)
n	airflow exponent (-)
C_{env}	airflow coefficient before correction to standard conditions of 20 °C (m ³ /(s·Pa ⁿ))
ELA	effective air leakage area at Δp pressure difference (cm ²)
ρ_0	air density at standard conditions of 20 °C (kg/m ³)
Δp	pressure difference (Pa)
C_D	discharge coefficient (-)

To evaluate the reliability of results, the standard regression method of the EN 9972:2015 and its respective approach to uncertainty calculation, here referred to as OLSy, underwent a comparison with two alternatives:

- OLSu, same regression method of OLSy, but the process of calculation grounds on the uncertainty found in the measured airflow rates and temperatures, instead of the distances between the measured airflow rates and the regression line;
- WLOC is a different regression method from OLSy and OLSu, as the calculation includes weights based on the uncertainty of readings of airflow rates, temperatures, pressure differentials, and a component for the zero-flow approximation.

The inclusion of OLSu serves as a benchmark for the total influence of the fan accuracy on the measurement uncertainty. Figure 3.8 presents a flow chart of the variables and calculation procedure for the uncertainty assessment.

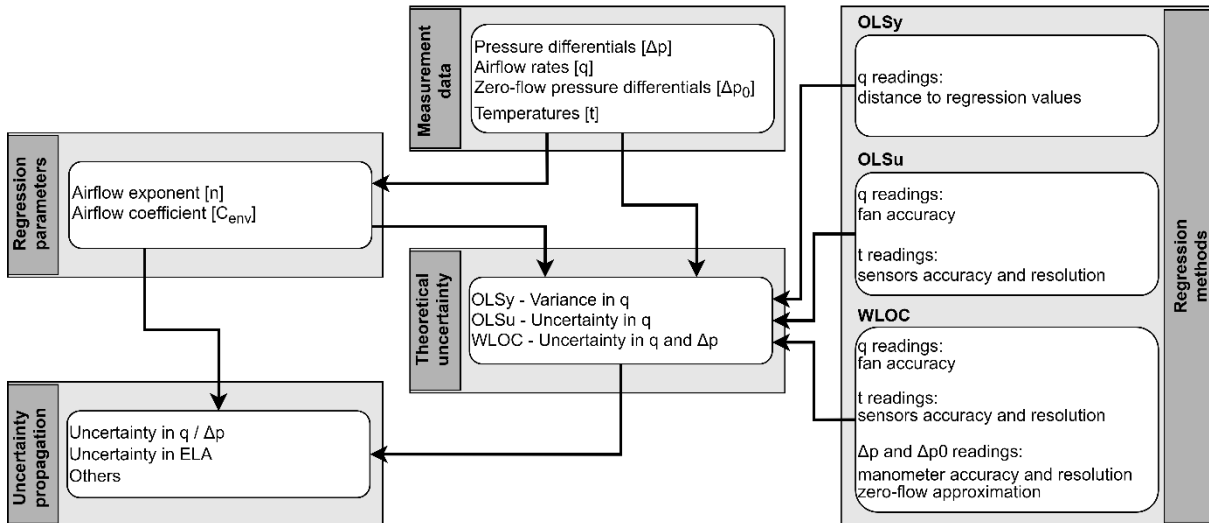


Figure 3.8. Uncertainty analysis procedure

The literature develops the full WLOC regression method structure [165][167][21]. For the airflow rate, both the fan and temperature sensors resolutions and accuracies account for the uncertainty. Eq. (3.3) represents the combined uncertainty of the different sources of errors considered for a depressurization test. The q_r is the airflow rate reading, q_m and q_{env} are the measured airflow rate and the airflow rate through the building envelope, respectively, resulting from corrections dependent on the interior and exterior temperatures. As for the pressure differential, both the gauge meter accuracy and resolution and the zero-flow approximation component account for the uncertainty (Eq. (3.4)) [163].

$$u(q_{env}) = \sqrt{\left(\frac{T_e}{T_i} \sqrt{\left(\frac{T_i}{T_0} u(q_r) \right)^2 + \left(\frac{q_r}{2T_i} \sqrt{\frac{T_i}{T_0}} u(T_i) \right)^2} \right)^2 + \left(\frac{q_m}{T_i} u(T_e) \right)^2 + \left(\frac{q_m T_e}{T_i^2} u(T_i) \right)^2} \quad (3.3)$$

$$u(\Delta p) = \sqrt{u^2(\Delta p_m) + u^2(\Delta p_{0m}) + u^2(\Delta p_{0a})} \quad (3.4)$$

$u()$	uncertainty
q_{env}	airflow rate through the building envelope (interior/exterior air density correction) (m ³ /h)
T_e	exterior temperature (K)
T_i	interior temperature (K)
T_0	absolute temperature at standard conditions of 20°C (K)
q_r	airflow rate readings (m ³ /h)
q_m	airflow rate corrected to standard temperature (air density correction to 20 °C from interior (pressurization)/ exterior (depressurization) temperatures (m ³ /h)
Δp	resulting pressure difference after all corrections (Pa)
Δp_m	measured pressure difference of q-Δp pairs (Pa)
Δp_{0m}	measured pressure difference during zero-flow (Pa)
Δp_{0a}	zero-flow approximation component (Pa)

The accuracy and resolution uncertainties of the used equipment assume uniform distributions. The standard deviation on zero-flow pressure approximates a normal distribution, as pointed in recently developed work [164][19]. These sources of error and their joint uncertainty apply in quantifying weights for the application of WLOC.

Following the measurements linearization and the application of the two methods, error propagation of the regression parameters was applied to estimate the total uncertainty of the variables of interest. In Eq. (3.5) and (3.6), T stands for the exterior temperature in depressurization mode or interior temperature in pressurization mode. As the regression parameters are correlated, a term including their respective covariance is added.

$$u(q) = \sqrt{\left(C_{env} \Delta p^n \left(\frac{T_0}{T} \right)^{1-n} \ln \left(\Delta p \frac{T}{T_0} \right) u(n) \right)^2 + \left(C_{env} \Delta p^n \left(\frac{T_0}{T} \right)^{1-n} u(\ln(C_{env})) \right)^2 + \left(\frac{C_{env}(n-1)}{T} \Delta p^n \left(\frac{T_0}{T} \right)^{1-n} u(T) \right)^2 + 2 \left(C_{env} \Delta p^n \left(\frac{T_0}{T} \right)^{1-n} \right)^2 \ln \left(\Delta p \frac{T}{T_0} \right) u(n) u(\ln(C_{env})) r(n, \ln(C_{env}))} \right)} \quad (3.5)$$

$$u(ELA) = \sqrt{\left(2.155 C_{env} \Delta p^{n-0.5} \left(\frac{T_0}{T} \right)^{1-n} \ln \left(\Delta p \frac{T}{T_0} \right) u(n) \right)^2 + \left(2.155 C_{env} \Delta p^{n-0.5} \left(\frac{T_0}{T} \right)^{1-n} u(\ln(C_{env})) \right)^2 + \left(2.155 \frac{C_{env} \Delta p^{n-0.5}(n-1)}{T} \left(\frac{T_0}{T} \right)^{1-n} u(T) \right)^2 + 2 \left(2.155 C_{env} \Delta p^{n-0.5} \left(\frac{T_0}{T} \right)^{1-n} \right)^2 \ln \left(\Delta p \frac{T}{T_0} \right) u(n) u(\ln(C_{env})) r(n, \ln(C_{env}))} \right)} \quad (3.6)$$

$u()$	uncertainty
q_{env}	airflow rate through the building envelope (interior/exterior air density correction) (m ³ /h)
T_e	exterior temperature (K)
T_i	interior temperature (K)
T_0	absolute temperature at standard conditions of 20°C (K)
q_r	airflow rate readings (m ³ /h)
q_m	airflow rate corrected to standard temperature (air density correction to 20 °C from interior (pressurization)/ exterior (depressurization) temperatures (m ³ /h)
Δp	resulting pressure difference after all corrections (Pa)
Δp_m	measured pressure difference of q-Δp pairs (Pa)
Δp_{0m}	measured pressure difference during zero-flow (Pa)
Δp_{0a}	zero-flow approximation component (Pa)
T	interior(pressurization)/ exterior(depressurization) temperature (K)
n	air flow exponent (-)
C_{env}	air flow coefficient before correction to standard conditions (m ³ /(s·Pa ⁿ))
$r()$	correlation coefficient

The previous equation provides results on the uncertainty of the airflow rate and ELA for pressurization or depressurization modes separately. To provide a single result characterizing the leakage path, one needs to average the two results (Eq. (3.7)).

$$u(ELA) = \sqrt{\frac{u(ELA_d)^2 + u(ELA_p)^2}{4}} \quad (3.7)$$

$u()$	uncertainty
ELA	effective leakage area (cm ²)
ELA_d	effective leakage area in depressurization (cm ²)
ELA_p	effective leakage area in pressurization (cm ²)

In the process of reductive sealing, the value at each step must subtract from the preceding sealing step (Eq. (3.8)). As the results of airflow rates from one step to the other are dependent on the prior results, the uncertainties must combine to compute the error of the airflow rate offset for each step (Eq. (3.9)). To further understand the calculations on the used regression methods, refer to Annex A2.

$$ELA_{step,i} = ELA_{i-1} - ELA_i \quad (3.8)$$

$$u(ELA_{step,i}) = \sqrt{u(ELA_{i-1})^2 + u(ELA_i)^2} \quad (3.9)$$

$u()$	uncertainty
$ELA_{step,i}$	effective leakage area in sealing step i (cm ²)

3.3.2. EXPERIMENTAL RESULTS

3.3.2.1. Quantitative analysis

Table 3.4 shows the results of the airflow rate in each step of the reductive sealing for a pressure difference of 50 Pa (q_{50}). All the values correspond to the average of pressurization and depressurization tests. The results are the product of applying both regression methods, and the corresponding difference between them shows in percentage. Regarding the average airflow values, the results have negligible differences between OLS and WLOC, never exceeding 0.64 m³h⁻¹ and averaging 0.17 m³h⁻¹. It is in line with previous applications of this methodology [179][21]. Individual airflow rate - pressure difference pairs for the different sealing steps during depressurization (D) and pressurization (P) tests are present in Annex A2.

Table 3.4. Average q_{50} results and their difference for the sealing steps using OLS and WLOC

	DEF	MEV	HAC	ELE	LIG	PLU	WWJ	WFJ	WRJ	WOJ	OPE	ENT
OLS [m^3h^{-1}]	802.36	689.66	552.27	487.98	440.61	437.40	401.87	353.95	291.33	269.98	145.01	51.32
WLOC [m^3h^{-1}]	802.16	689.43	552.16	487.97	440.11	436.76	401.48	353.86	291.41	270.03	145.03	51.32
Difference [%]	0.02	0.03	0.02	0.00	0.11	0.15	0.10	0.02	0.03	0.02	0.01	0.01

3.3.2.2. Qualitative analysis

The smoke tracer allows pinpointing the precise location of some air leaks. The most relevant ones were: MEV and HAC – through ceiling penetrations; ELE and LIG – through the electrical technical board and the connection with the shutters; OPE and ENT – through the joints.

Figure 3.9 portrays the main air leakage paths found with the smoke tracer.

Although the smoke tracer technique provides important visual data, the procedure encountered some difficulties. The main one occurs when there is a cladding system on the façades that include an air gap. In this case, the smoke can move through the air layer between the structured insulated panels and the cladding itself, hiding the precise location of the air leakage paths or even leading to false conclusions. An example is the smoke that appeared in the perimeter of the roof area. Despite an apparent substantial reduction in the WWJ and WFJ sealing steps, identifying the origin at the walls or floor interfaces of the envelope was not feasible.

Other methods, such as thermography, if the temperature gradient is adequate [121], could provide a good complement for the qualitative assessment. Still, because of the low temperature difference between indoor and outdoor during the measurement campaign, this method was not applied, as it would not produce suitable results.

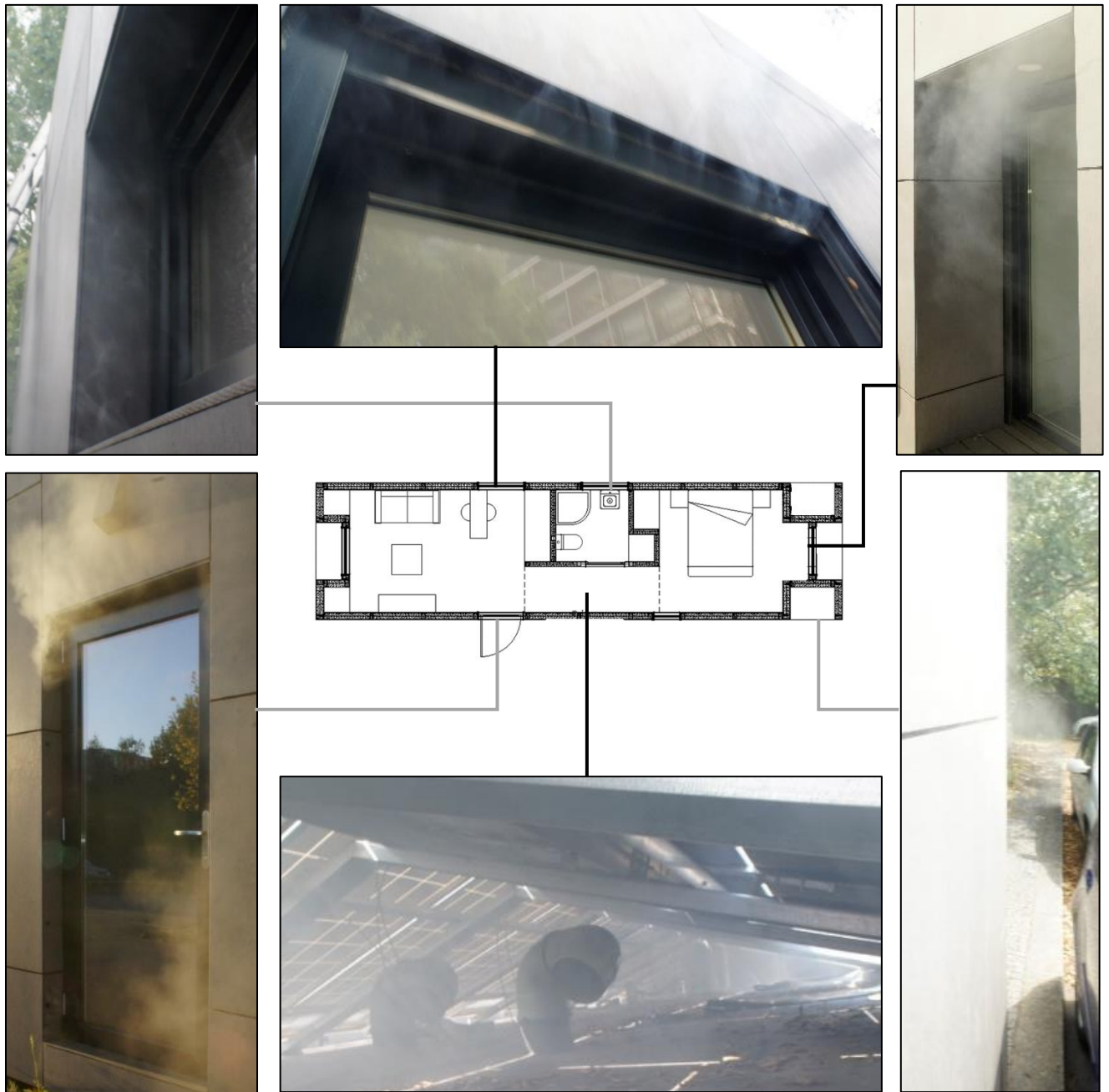


Figure 3.9. Compilation of identified air leakage path locations throughout the reductive sealing campaign: top left – bathroom window perimeter; top centre – shutters on opening in the kitchenette; top right – perimeter on the opening of the bedroom; bottom left – the frame of the entrance door; bottom centre – diffuse smoke over the roof; bottom right – the edge of the door giving access to the electrical board.

3.3.2.3. Regression parameters

On average, the values of the regression parameters experience a low difference between the OLS and WLOC regression methods, 0.42% for n and 0.98% for C_{env} . Figure 3.10 and Figure 3.11 represent the calculated values and uncertainties on n and C_{env} , respectively, obtained using

the OLSy, OLSu and WLOC regression methods. The ranges provided result from the application of a positive and negative boundary ($y - u(y)$; $y + u(y)$) around the calculated values.

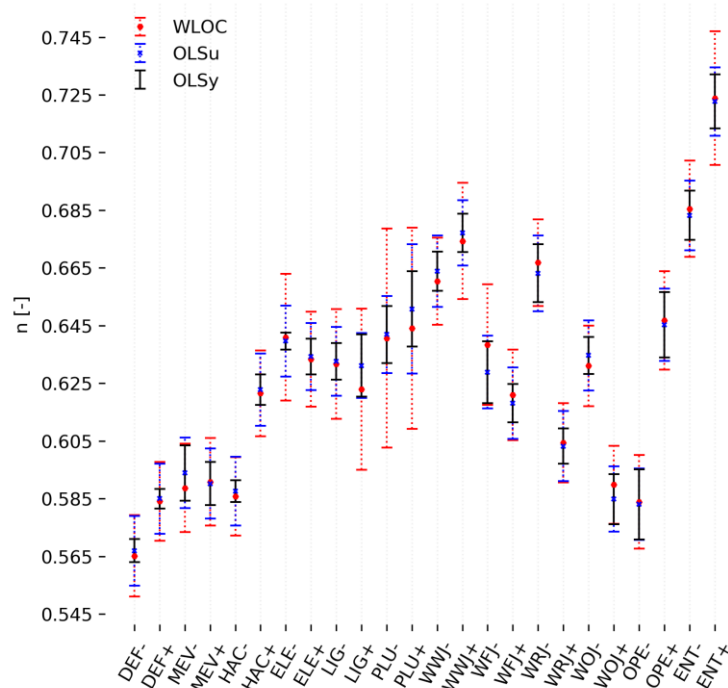


Figure 3.10. Calculated uncertainty of n values in each campaign measurement using OLSy, OLSu, and WLOC (+ pressurization / - depressurization)

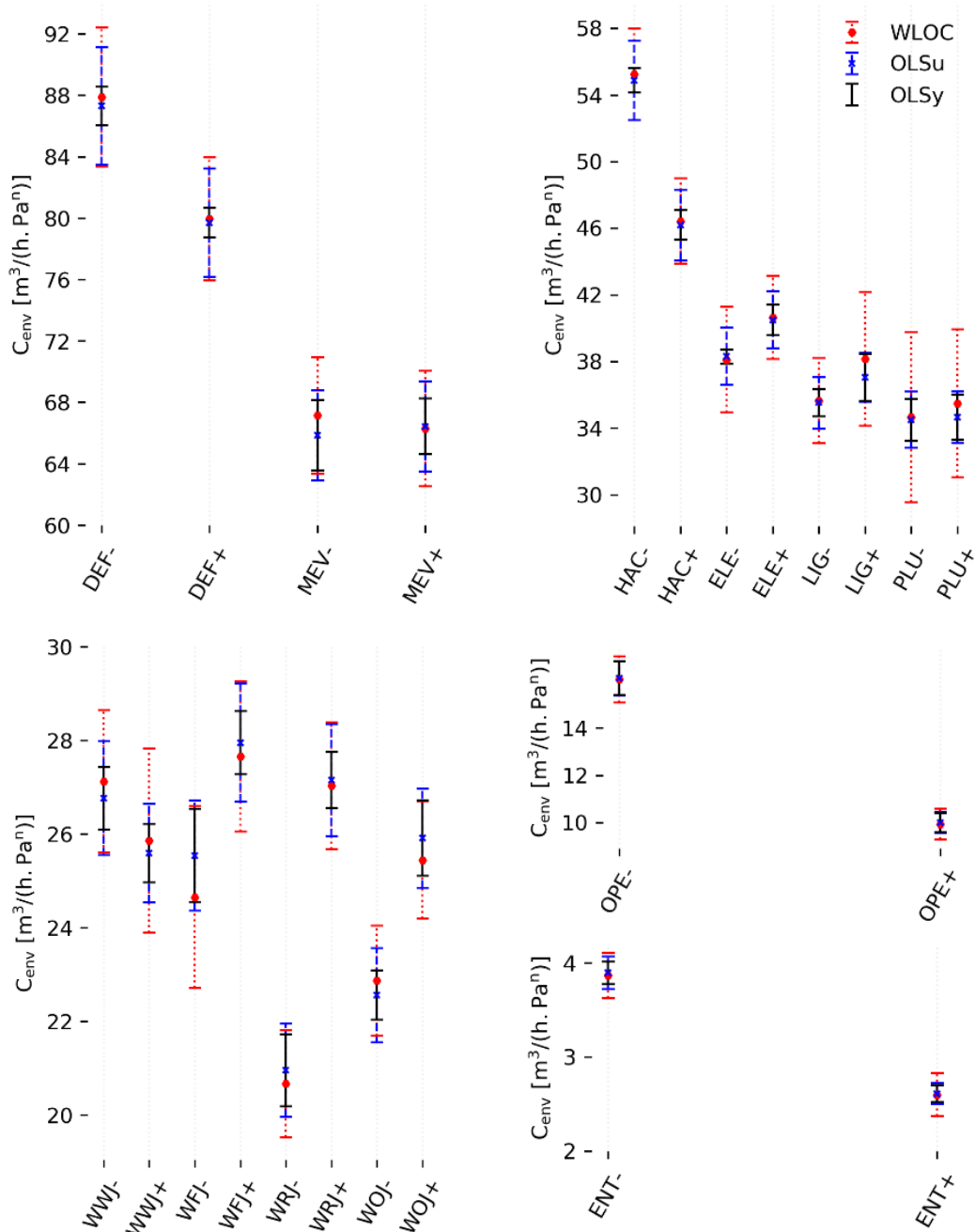


Figure 3.11. Calculated uncertainty of C_{env} values in each campaign measurement using OLSy, OLSu, and WLOC (+ pressurization / - depressurization)

The average uncertainty of n was 0.009, 0.012 and 0.019 for OLSy, OLSu, and WLOC, respectively. For C_{env} , the uncertainty, in the same order, averages 0.58, 0.95, and 1.41 $m^3h^{-1}Pa^{-n}$. The phenomenon was expected since OLSu includes additional sources of error compared to OLSy, particularly relative to airflow and temperature readings.

The WLOC method adds to OLSu the contribution of pressure differential readings, including the direct effect of wind with the zero-flow approximation component. A simple linear model $\varepsilon = (0.11 + 0.98\sigma)$ was a proper predictor of this component [19], being σ the standard deviation of the measured zero-flow pressure points. As the points distribution tested significant for normality [164], considering an interval containing 50% of its values results in $\varepsilon/1.35$.

The difference between WLOC and OLSu is thus highly influenced by the wind. Figure 3.12 confirms the almost linear correlation between the difference in uncertainty when using WLOC and OLSu at 4 Pa of pressure difference and the zero-flow approximation component.

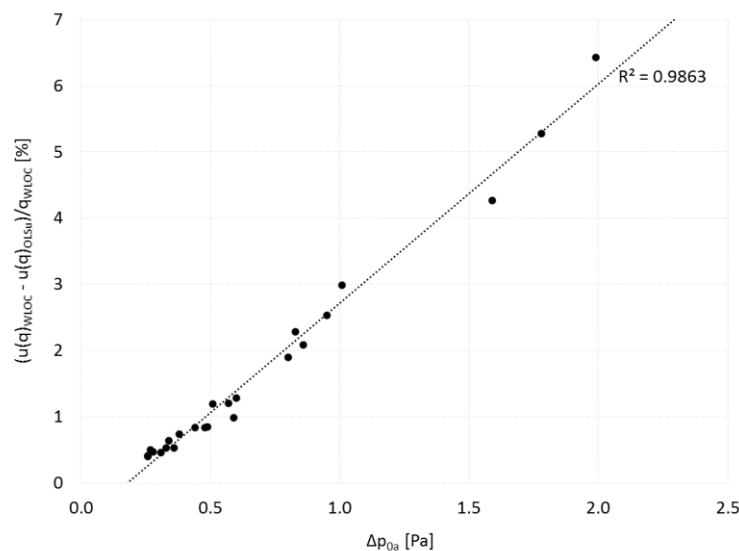


Figure 3.12. Correlation between the difference in uncertainty when using WLOC and OLSu at 4 Pa of pressure difference and the zero-flow approximation component

The normal distribution of the zero-flow pressure points is confirmed by the results of the Kolmogorov-Smirnov ($D = 0.17$, $p = 0.08$) and Shapiro-Wilk tests ($D = 0.91$, $p = 0.25$), in line with previous findings in the literature [164]. Table 3.5 portrays the ratios between the considered regression methods. They represent the number of times the uncertainty of a certain regression method. In this case, the number of times OLSu and WLOC fit in the uncertainty calculated by the defined base regression method, OLSy. The average values are in fair accordance with mean results from the most comprehensive study to date on the subject [21].

Table 3.5. Average uncertainty ratios of OLSu and WLOC to OLSy for both regression parameters

Regression parameter	Airflow direction	Average ratio			
		Literature $u(\text{OLSu})/u(\text{OLSy})$ [21]	$u(\text{OLSu})/u(\text{OLSy})$	Literature $u(\text{WLOC})/u(\text{OLSy})$ [21]	$u(\text{WLOC})/u(\text{OLSy})$
n	-	1.67	1.59	2.17	2.16
	+	1.57	1.27	1.86	1.99
C_{env}	-	1.49	1.83	2.27	2.74
	+	1.36	1.52	2.07	2.33

3.3.2.4. Airflow rates and leakage areas

One must analyze the error propagation to establish an accurate level of uncertainty of variables dependent on the parameters exposed in the last Subsection, such as airflow rates and effective leakage areas. As previously discussed, the partial (OLSu) or complete (WLOC) components concerning accuracy and resolution of the used equipment, pressure gauge, fan and thermometers, together with the input of zero-flow approximation, were used to compute the theoretical uncertainties. Figure 3.13 reports the distribution of average uncertainties on airflow rates of the sealing steps at several pressure differences. Note that using the average significantly reduces overall uncertainty on variables of interest (see Eq. (3.7)).

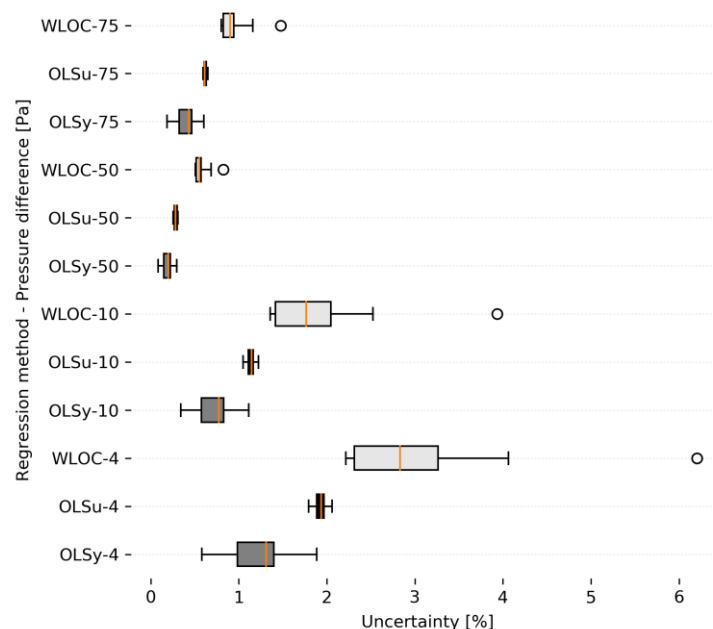


Figure 3.13. Uncertainty distribution on airflow rates (q) of the sealing steps at several pressure differences for the considered methods

Different methods observe significant variations. As expected, WLOC provides higher calculated uncertainties than the other two methods, on average, 2.6 and 1.7 times greater than OLSy and OLSu, respectively.

The rather compact distribution of values in OLSu is the result of considering the accuracy and resolution range of the fan and temperature sensors readings as the only ones impacting the uncertainty of results. In other words, the OLSu is the method with the highest independence from pressure readings uncertainty. The pressure components considerably influence the other two methods. In OLSy, the value is dependent on a regression line that uses pressure readings as input. In WLOC the uncertainty is controlled by the accuracy and resolution of the manometer and the zero-flow approximation component. These aspects contribute to the higher dispersion of the results obtained with these methods.

Regarding ELAs and focusing on average values of the 12 pairs of tests, the uncertainty for changing pressure differences remains low despite the regression method used. The maximum uncertainty occurs at 4 Pa of pressure difference when using the WLOC regression method, averaging 3.0%, 1.9%, and 1.2% for WLOC, OLSu and OLSy, respectively. As reported in previous studies, the minimum values always happen at the centroid of the measured pressures, 40 Pa, as reported in previous studies [21].

3.3.3.DISCUSSION ON EXPERIMENTAL RESULTS

3.3.3.1.Contribution of air leakage paths

The valving effect, identified in the results, gives strength to using the average of pressurization and depressurization tests when assessing airtightness performance. This phenomenon is particularly relevant in naturally ventilated buildings where pressure modes simultaneously occur at different envelope parts.

Considering average values of airflow rates and neglecting any uncertainty in measurements, one can quantify the contribution of each type of air leakage path to the overall airtightness of the case study. The air leakage that remained at the end of the reductive sealing campaign refers to solely as REM (Figure 3.14).

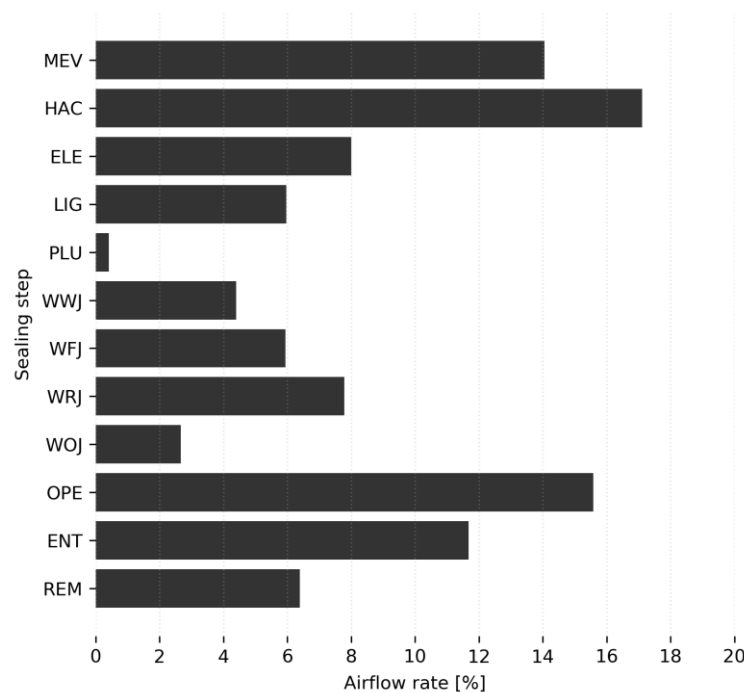


Figure 3.14. The average contribution of each type of air leakage path to the overall airtightness performance. The remaining airflow rate refers to as REM

Types of air leakage paths observed significant dispersion of the airflow rate between them. It is in line with findings in previous studies, and the relative contributions are in fair agreement with a reported range of results [181][159]. For instance, if one compares ceiling details data, equivalent to the sum of LIG and WRJ, the test results pointed to a 14% contribution to the total air leakage against an average of 18% found in the literature [181]. Mechanical ventilation MEV was 14% compared with 13% of the literature [159], and heating and air conditioning elements were 17% against 15% reported in [181].

3.3.3.2.Reductive sealing cumulative effect

Subsection 3.3.2 showed that the airflow and ELA uncertainty of individual sealing steps have different impacts depending on the used regression methods, but generally small, even at low pressure differences. However, applying a reductive sealing technique implies that any current result depends on earlier results. Therefore, incrementing the number of sealing steps adds additional uncertainty to future results. Some sealing steps were grouped based on three premises to evaluate the cumulative effect:

- the type of air leakage paths share characteristics regarding geometry and overall behavior;
- the sealing steps are consecutive;
- the interpretation of the results becomes tangible to grasp and provides relevant meaning.

The last point refers to the proportionality of measured ELA and the accompanying uncertainty range. In fact, in some sealing steps, the calculated ELA is rather small, and as the reductive sealing unfolds, the uncertainty range assumes a value several times higher than ELA itself. This way, ELE/LIG/PLU were grouped, seen as wall penetrations, WWJ/WFJ/WRJ/WOJ were grouped, regarded as joints in assemblies or between assemblies and envelope components (Table 3.6).

Table 3.6. Cumulative uncertainty of the ELA, in %, for the sealing steps of the reductive sealing campaign, at five pressure differences often used to express the variable, with the three considered regression methods

Sealing step	Pressure difference	OLSy [%]	OLSu [%]	WLOC [%]
MEV	4	7.0	13.9	17.2
	10	4.5	8.9	11.4
	50	1.3	2.5	4.7
	75	3.0	5.8	7.7
	100	4.4	8.4	10.5
HAC	4	7.1	14.7	17.7
	10	4.3	9.0	11.3
	50	1.2	2.3	4.3
	75	2.6	5.3	7.0
	100	3.7	7.5	9.4
ELE/ LIG/ PLU	4	8.3	15.8	24.1
	10	5.3	10.1	16.4
	50	1.6	2.8	5.8
	75	3.7	6.7	9.9
	100	5.3	9.7	14.0
WWJ/ WFJ/ WRJ/ WOJ	4	10.3	19.4	28.3
	10	5.6	10.4	16.4
	50	1.2	2.1	4.3
	75	2.5	4.6	6.8
	100	3.4	6.2	9.1
OPE	4	11.0	20.5	30.9
	10	6.5	12.0	19.1
	50	1.6	2.8	5.6
	75	3.5	6.2	9.2
	100	4.8	8.7	12.4
ENT	4	13.2	24.6	37.0
	10	8.0	14.8	23.8
	50	2.2	3.7	7.5
	75	4.7	8.5	12.5
	100	6.7	12.0	17.2
Average	4	9.9	18.8	27.5
	10	6.0	11.2	17.4
	50	1.6	2.8	5.6
	75	3.5	6.4	9.2
	100	4.9	9.0	12.7

Notice that the smaller the ELA offset between steps, the bigger the relative impact of the uncertainty on the calculated value. It shows that while the regression method highly influences the uncertainty range for each sealing step, the planning of the reductive sealing campaign, such

as the sealing step order, is the main factor impacting the attained levels of uncertainty. Therefore, a good definition of the order of the sealing steps is crucial to improve the reliability of the results. To that end, the qualitative assessment of the air leaks, i.e., by smoke tracer, could help assert the order of sealing by identifying the main contributors to the air leakage of the building.

3.3.3.3. Absolute and normalized ELAs

While for retrofitting decision-making, airflow rate measurements and leakage location assessments may be enough, for design purposes and scenarios simulations, the use of ELA provides more reliable results. Figure 3.15 provides data for the considered groups of air leakage paths at a reference pressure of 4 Pa. Most of the existing datasets and libraries provide ELA values at 4 Pa since it is closer to the common pressure difference experienced by a building in real conditions.

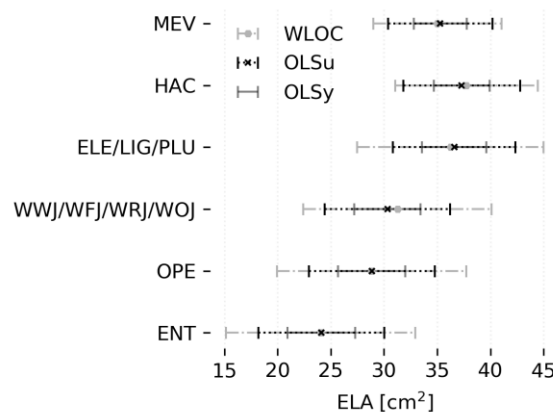


Figure 3.15. Cumulative uncertainty of the ELA, in cm^2 , for the considered groups of sealing steps, at 4 Pa of pressure difference, with the three considered regression methods

The literature shows that the WLOC regression method better approximates the observed values to the calculated ones. With this in mind, and aiming to obtain standard values for types of leakage paths, the ELA at 4 Pa for the different groups is normalized by its proper metric (Table 3.7). The ranges obtained with WLOC are, on average, 2.8 times wider than the ones obtained with OLSy (Figure 3.16). Another interesting conclusion is that in absolute values, the

uncertainty tends to stabilize in the later steps of the campaign. The bigger contributions occur early.

Table 3.7. Normalized ELA and lower and upper bounds (in cm^2) for each type of air leakage path considering OLSy and WLOC at a reference pressure of 4 Pa

Group	Qty.	Metric	Contribution [%]	OLSy				WLOC			
				ELA	Unc.	Lower bound	Upper bound	ELA	Unc.	Lower bound	Upper bound
MEV	4	item	14.1	35.29	2.48	8.203	9.441	35.00	6.03	7.244	10.257
HAC	4	item	17.1	37.30	2.63	8.667	9.984	37.74	6.70	7.762	11.110
ELE/	19	item	8.0	36.59	3.02	0.983	1.160	36.23	8.75	0.805	1.317
LIG/	17		6.0			0.819	0.967			0.671	1.098
PLU	7		0.4			0.139	0.164			0.114	0.187
WWJ/	40.8		4.4			0.141	0.173			0.116	0.208
WFJ/	38.3	lm	5.9	30.32	3.11	0.203	0.249	31.27	8.85	0.167	0.299
WRJ/	38.3		7.8			0.266	0.327			0.219	0.392
WOJ	35.1		2.7			0.100	0.122			0.082	0.147
OPE	25.6	lm	15.6	28.85	3.17	1.003	1.251	28.82	8.90	0.778	1.473
ENT	5.9	lm	11.7	24.10	3.17	3.548	4.623	24.06	8.90	2.569	5.586

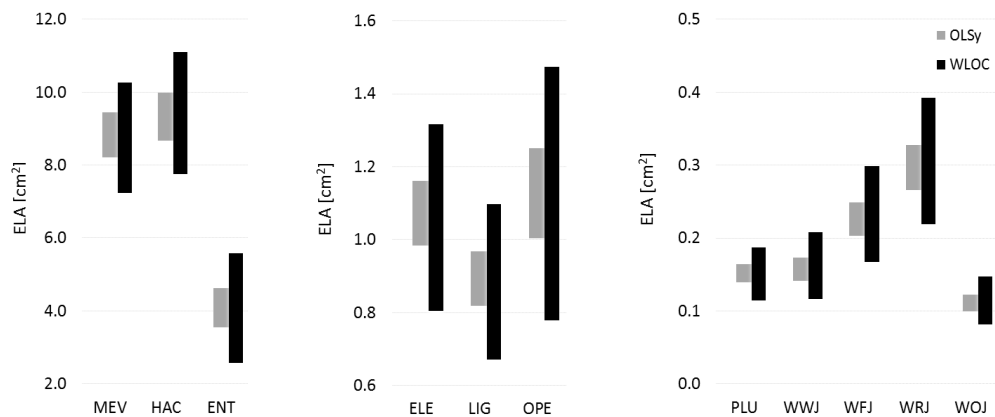


Figure 3.16. Normalized ELA ranges for each air leakage path considering OLSy and WLOC at a reference pressure of 4 Pa

Direct comparison with the previously referred libraries available in the literature is limited. Despite considering the same reference pressure and discharge coefficient, most values assume an airflow exponent equal to 0.65. Still, as an example, the value obtained for the entrance door, ENT, was 24.1 cm^2 , close to the maximum suggested in the ASHRAE library, 27 cm^2 [176].

3.4. EXPERIMENTAL APPLICATIONS FINAL REMARKS

The Applications of the present Chapter pursued a further understanding of the airtightness performance of envelope solutions for lightweight constructions. In addition, the reliability of the results of a reductive sealing application was analyzed by comparing different regression methods.

From Application A1, one concluded that although the envelope component, SIP, as a whole solution has an adequate airtightness performance complying with internationally recognized standards, the process of construction and the handling of detailing between panels connections and interfaces with other envelope elements can be tricky. The disparate airtightness performances found between the construction stage, finished envelope with no purpose provided air barrier, and a commissioning stage clearly shows that interior works are not negligible. The produced results indicate that the final airtightness performance is the product of the combined effects of elements and materials both at an envelope's exterior and interior interfaces. It implies the occurrence of complex airflow paths along its depth.

In-situ applications revealed that too many factors in real buildings make the final airtightness performance too reliant on chance or the combination of the proper application of the several envelope components, both in the exterior and interior interfaces. This fact points to another issue. If the airtightness is dependent on complex interactions between envelope elements, it may be compromised soon by subsequent user intervention or the durability of the materials themselves. Incorporating a purpose provided air barrier solution could mitigate these risks while providing additional assurance of reliable performance over time.

Application A2 corroborated these findings as the contribution of none of the eleven considered types of air leakage paths exceeded 18% of the total air change rate. One can conclude that, in this kind of construction, air leakage experiences high dispersion among materials and components of the building envelope. Over 93.5% of the airflow leakage was properly identified in the case study. The identified valving effect strengthens the need to average the results of pressurization and depressurization tests.

A smoke tracer is notably advantageous for retrofitting planning and avoiding comprehensive intervention. Still, there is no qualitative assessment method without limitations and assessing walls with exterior cladding can be tricky.

Applying different regression methods returned small differences in average values but substantially different uncertainty values. On average, WLOC calculated uncertainty of airflow rates is 2.6 and 1.7 times higher than the uncertainty calculated with OLSy and OLSu, respectively. The correction of zero-flow measurements is highly impacting the uncertainty of the results. The zero-flow approximation component proved to be relevant, as the dispersion of values between measurements in WLOC was substantially superior to OLSy.

The results confirmed that proper planning regarding the order of sealing steps benefits the quality of a reductive sealing campaign results. The strategy should be assessing less impacting air leakage paths first to control and minimize the uncertainty accumulation effect. The qualitative assessment, i.e., by smoke tracer, could help define the order of the sealing steps by identifying the main contributors to the air leakage of the building. Putting similar air leakage paths' types in a consecutive order also improves results' reliability. It allows adjoining sealing steps for proper data analysis.

On average, at a reference pressure difference of 4 Pa, the sealing step uncertainty averaged 9.9%, 18.8%, and 27.5% for OLSy, OLSu, and WLOC, respectively. At 50 Pa difference, the percentages were 1.6%, 2.8% and 5.6%. By considering a greater number of error sources, WLOC should be the preferred regression method. In that regard, even though a greater variability on the building performance will result from its application, the simulated air leakage outputs will be more reliable, providing added value either for a risk analysis or establishing performance ranges.

Overall, although the current international standard details thoroughly building preparation and measurement procedures, results show that the performance of envelope solutions is complex and that improvements to the current data treatment are possible and advisable. The proposed improvements and acquired results from the Applications of the present Chapter support both:

- straightforward decisions for interventions in existing buildings, i.e., quick decisions of which air leakage paths to treat;
- confidence intervals for subsequent airflow modelling, i.e., uncertainties on ELAs tackle part of air leakage paths discretization in simulation scenarios.

While the developed Applications in this Chapter allowed one to propose several recommendations to assess air leakage paths in building envelopes, creating a full methodology

with potential for generalization for dwellings with various characteristics requires additional research.

4

NUMERICAL SIMULATION OF AIRTIGHTNESS IMPACT ON VENTILATION

4.1. CONTEXT

Planning and comparing scenarios for designing and retrofitting building envelopes regarding ventilation strategies requires numerical simulation. These simulations must attend to airtightness, and therefore, infiltration.

Leaky envelopes often experience high ACHs variability in naturally ventilated dwellings and partial disruption of the function of HVAC equipment in mechanically ventilated dwellings. Therefore, the relationships between air leakage paths configurations and airtightness levels are essential in defining adequate airtightness performances that do not obstruct ventilation strategies. Additionally, the most common aim of numerical simulation regarding ACHs is integrating energy efficiency estimation. Thus, the focus tends to be analyzing average outputs, frequently neglecting the time-fluctuation of the parameters. Focusing on average values results from the several simplifications and assumptions made in AFN models, making a more detailed analysis often unreliable.

While these assumptions may have a reduced impact for energy efficiency purposes, the same is not true for the correct operation of ventilation strategies. The more dependent the ventilation strategy is on the variability of natural forces, the higher the impact on its operation performance, as in the case of naturally ventilated dwellings, typical of southern Europe built stocks. To tackle these challenges, the numerical Applications adopt this type of envelope solution.

The first Application (A3) compares the measurement results on airtightness and infiltration of a real case study with numerical simulations in a southern European climate context. Several

configurations provide a wider scope for further findings on the effect on ACHs of different air leakage paths configurations and changing airtightness levels.

The second Application (A4) explores the ACHs variability over time for a representative dwelling of the Portuguese built stock. This variability is further dependent on additional meteorological data variability and changing atmospheric stability. An airflow model was developed for the simulations, which included additional details necessary to study these impacts, as it was not possible to implement using existing publicly available software. Subsection 4.3.1.3 thoroughly explains it.

Section 4.2 focuses on Application A3 and Section 4.3 on Application A4. Section 4.4 provides conclusions on the undertaken research.

4.2. AIR LEAKAGE PATHS CONFIGURATIONS AND AIRTIGHTNESS LEVELS (A3)

The objective of Application A3 is to evaluate the effect of changing geometry and airtightness characteristics on ventilation strategies and outputted ACHs. It aims to:

- Assess the impact of different configurations of air leakage paths on ACH;
- Estimate the effect of changing airtightness levels on the air change rates provided by a mechanical ventilation system.

4.2.1. CHARACTERIZATION OF THE CASE STUDY

The current Application used experimental results of a real case study for input and compared them with multizone AFN simulations to study different scenarios. The real case study refers to a suite comprising a bedroom and bathroom of an apartment in Porto, Portugal. Figure 4.1 informs on the arrangement of both compartments, while Table 4.1 presents their floor areas and volumes. There is mechanical extraction ventilation (MEV) with air exhaust in the bathroom. The air supply takes place through unintentional air leakage paths.

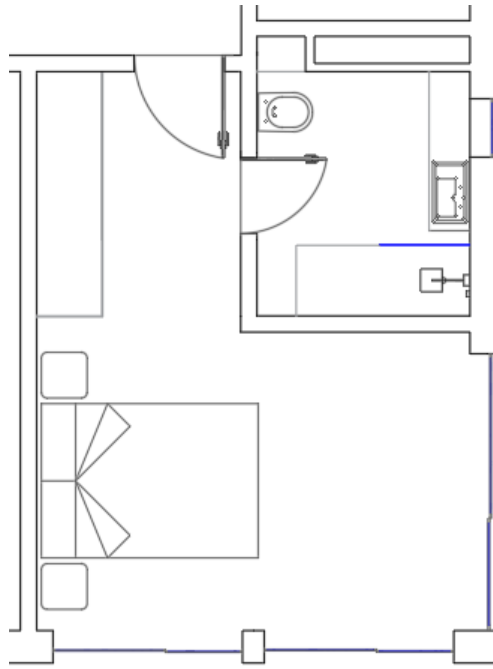


Figure 4.1. Studied compartments

Table 4.1. Characteristics of the two compartments

Compartment	Type of Window	Floor Area [m ²]	Volume [m ³]
Bedroom	Windows frame double slide	18.3	46.9
Bathroom	Single windows frame side hung	5.0	12.8

The assessment of the ventilation performance took place in the months of July and August. Nondispersive infrared (NDIR) sensors monitored the CO₂ concentration (Table 4.2) in two compartments of the case study.

Table 4.2. Specifications of the equipment used in the experimental campaign

Equipment	Accuracy	Range	Resolution	Delay
CO ₂ NDIR sensor	±25 ppm or ±3% (0–2000 ppm) ±30 ppm or ±3% (2000–5000 ppm)	0 to 5000 ppm	1 ppm	3 min to 90% of accuracy

During the CO₂ measurement campaign, the door connecting the bedroom to the rest of the apartment remained shut when not in use. Blower-door tests with a Retrotec Model 1000 fan [335], coupled with a DM-2 gauge [334], determined the compartments ACH₅₀. The accuracies of the equipment are ±3% of the reading, and ±1% or 0.15 Pa, whichever is greater, respectively.

The tests followed method A of the standard EN 13829 [125], performing depressurization and pressurization measurements. The final ACH_{50} is the average of those.

The concentration decay test method using the occupant-generated CO_2 as a tracer gas determined the ACH value of the compartments. Measurements occurred for different ventilation configurations in standard conditions of use: with MEV on and MEV off. When MEV is on, it has a maximum extraction volume of $98 \text{ m}^3/\text{h}$. The estimate of the CO_2 production used the methodology proposed by Coley and Beisteiner [338]. The average night production of CO_2 was $5.97 \text{ cm}^3/\text{s}$. The value used for the external CO_2 concentration was 350 ppm, as assumed in ASTM-D6245 [339]. An on-site outdoor CO_2 monitoring campaign validated this value for two weeks, with an average value of 348 ppm. During the two months of the campaign, ACH measurements occurred daily as recommended in the standard ASTM-E741 [115].

The desirable properties for a tracer gas can be found in the literature, identifying different suitable types of gases, although none meets all the requirements. Metabolic CO_2 is considered a good option as a tracer gas [338][340].

4.2.2.METHODOLOGY FOR THE AFN SIMULATIONS

Afterwards, numerical simulation performed an in-depth analysis of the case study. The selection of the software considered the following points, according to the recommendations stated by Orme and Leksmono [175]:

- The application of multizone modelling, since the case study required two zones - the bedroom and the adjacent bathroom;
- The input of structured data related to climate and weather, such as long-term meteorological data files [341], air leakage characteristics, from component airtightness databases [342], and wind pressure coefficients, in the form of fully developed profiles [221];
- The modelling of air handling systems since mechanical ventilation is present in the bathroom.

Since it fulfils all these conditions, the CONTAM software was chosen [191]. It has numerous applications in modelling ventilation strategies, energy impacts [343], and contaminant

dispersion [344]. This software also enables importing data from several sources, easing the creation and comparison of scenarios.

4.2.2.1. Considered scenarios

One devised a simulation plan based on two main steps to address the Application purpose. Figure 4.2 shows a schematic representation of the simulation plan.

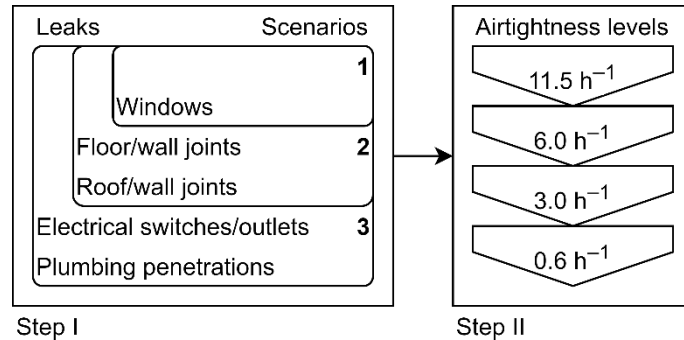


Figure 4.2. The plan for simulation

- Step I: Changing air leakage paths configurations

The impact of air leakage distribution on the ACH considered three scenarios, all assuming the same airtightness level (11.5 h^{-1}). The scenarios vary in the number of types of air leakage paths, and MEV is off. Scenario 1 only considers the windows. Scenario 2 encompasses windows and joints of floor/wall and roof/wall. Lastly, Scenario 3 includes all of the air leakage path types of Scenario 2, plus electrical switches and outlets and plumbing penetrations. The focus on constructing these scenarios is the progressive shifting from a concentrated infiltration to a more dispersed one.

- Step II: Changing airtightness levels

Changing the ACH_{50} , therefore, altering the total Effective Leakage Area (ELA), enables evaluating the impact on the ACH, both with and without mechanical extraction (MEV). For that, using the three modelled scenarios to assess changing air leakage paths configurations, four levels of ACH_{50} were now defined, each resulting from a different source: the blower-door measurement, 11.5 h^{-1} ; a mid-range requirement for dwellings with natural ventilation, 6.0 h^{-1} ; a mid-range requirement for dwellings with mechanical extraction ventilation [49], 3.0 h^{-1} ; and the passive house requirement on airtightness [166], 0.6 h^{-1} .

4.2.2.2. Modelling air leakage paths

The intention of using a case study and measurements was to have results on the performance of a real setup and to use those results as input data for a simulation. Simulating with this input data allows its comparison with measurements results, supporting a partial validation of the assumed discretization and additional trust in simulation results for the other equated scenarios.

As most of the leakage paths are located randomly, in a real case, it is an almost impossible task to address each leakage path individually and identify its respective characteristics. Construction quality, manufacturing, and installation processes influence the characteristics of leakage paths [184]. For that reason, when dealing with these input data, commonly, extensive libraries of effective leakage areas (ELAs) on typified air leakage paths are used, such as the ones present in ASHRAE [176] and AIVC [186].

For AFN simulations, the scenarios consider a total ELA as individual leakage characteristics are not known. An ELA is the area of a circular sharpened edge orifice that would leak the same volume of air as a particular tested specimen when pressurized to a reference pressure difference [192]. In other words, it represents an overall quantitative effect of the airflow paths. The three analyzed scenarios assume the measured airflow of 50 Pa for both compartments. The total ELA calculates from that airflow volume (Eq. (4.1)), and, as such, it is the same for the three scenarios. The discharge coefficient for this case study assumes the value of 1.0, typical of small openings.

$$ELA_r = 10000Q_r \frac{\sqrt{\rho/2\Delta p_r}}{C_D} \quad (4.1)$$

ELA_r	effective air leakage area at a reference pressure difference (cm ²)
Q_r	airflow volume at Δp_r (m ³ /s)
ρ	air density (kg/m ³)
Δp_r	reference pressure difference (Pa)
C_D	discharge coefficient (-)

To apply a relative weight to the contribution of each type of leak to the overall performance, the libraries available on the National Institute of Standards and Technology (NIST) were used to quantify the elements airflow value [342]. As all the values suggested in those libraries are

based on a pressure difference of 4 Pa, the calculated total ELA needs to be converted (Eq.(4.2)). The values base on a discharge coefficient of 1.0 and an airflow exponent of 0.65.

$$ELA_{r,2} = ELA_{r,1} \frac{C_{D,1}}{C_{D,2}} \left(\frac{\Delta p_{r,2}}{\Delta p_{r,1}} \right)^{n-0.5} \quad (4.2)$$

$ELA_{r,i}$ equivalent air leakage area at reference pressure difference $\Delta p_{r,i}$ (cm²)
 $C_{D,i}$ discharge coefficient at reference pressure difference $\Delta p_{r,i}$ (-)
 n airflow exponent (-)

The ELAs in these libraries are normalized by an interface metric (usually area, length, or item), meaning that only by multiplying it does one get the entire ELA of a specific air leakage path ($ELA_{r,i}$) (Eq.(4.3)). Table 4.3 presents the air leakage paths types used in the simulation of the three scenarios and their respective normalized ELAs. One must perform the transformation shown in Eq.(4.4) to maintain the proportionality, and subsequently, the airtightness level to be the same in all scenarios.

$$ELA_{r,i} = ELA_{r,n} \cdot I \quad (4.3)$$

$$ELA_{r,p,i} = \frac{ELA_{r,total} \cdot ELA_{r,i}}{\sum_{i=1}^j ELA_{r,i}} \quad (4.4)$$

$ELA_{r,i}$ effective leakage area at a reference pressure difference of type i air leakage path (cm²)
 $ELA_{r,n}$ effective leakage area at a reference pressure difference normalized by an interface (cm²/metric)
 I interface metric of a type of air leakage path (usually m², m, item)
 $ELA_{r,p,i}$ proportional effective leakage area at a reference pressure difference of type i air leakage path (cm²)
 $ELA_{r,total}$ effective leakage area at a reference pressure difference based on measurement results (cm²)

Table 4.3. Equated types of air leakage paths and their considered normalized ELA ($ELA_{r,n}$) based on best estimate values [342]

Scenario		Code-Type of Air Leak	$ELA_{r,n}$
1	2	A—Windows, double horizontal slider, aluminum, weather-stripped	0.72 cm ² /m
		B—Windows, casement with weather-stripping	0.24 cm ² /m
	3	C—Joints, sole plate, floor/wall, caulked	0.8 cm ² /m
		D—Joints, ceiling wall	1.5 cm ² /m
		E—Electrical outlets/switches, no gaskets	2.5 cm ² /item
		F—Piping/Plumbing/Wiring penetrations, caulked	2.0 cm ² / item

The ELA of a particular type of air leakage path ($ELA_{r,p,i}$) varies between scenarios, as the increasing consideration for additional types of leakage changes the relative contribution of each ELA (Table 4.4). Air leakage interface metric indicates the extension of the leakage, linear meters (m) or the number of items, and envelope orientation is either south or east. Figure 4.3 illustrates the scenario with the highest number of types of air leakage paths (scenario 3). It includes the mechanical extractor (MEV) in the bathroom.

Table 4.4. Air leakage type, metric, extension, envelope orientation, and relative importance in ELA percentage of the modelled scenarios. Relative elevation refers to the mid-height of the air leakage path to floor level

Air Leakage Path Type	Interface Metric	Interface Extension		Relative Elevation [m]	Envelope Orientation	Scenario ELA %		
		Bedroom	Bathroom			1	2	3
A	m	8.8		1.0	South	30.0	15.2	9.5
		8.8		1.0	South	30.0	15.2	9.5
		10.7		1.0	East	36.6	18.4	11.5
B			3.0	1.3	East	3.4	1.7	1.1
C		4.0		0.0	South		7.7	4.8
		2.9		0.0	East		5.6	3.5
			2.1	0.0	East		4.0	2.5
D		4.0		2.56	South		14.3	9.0
		2.9		2.56	East		10.4	6.5
			2.1	2.56	East		7.5	4.7
E1/E2	item	2/2		0.3/1.1	South			14.9
		1/1		0.3/1.1	East			7.5
F			5	5x0.5	East			15.0

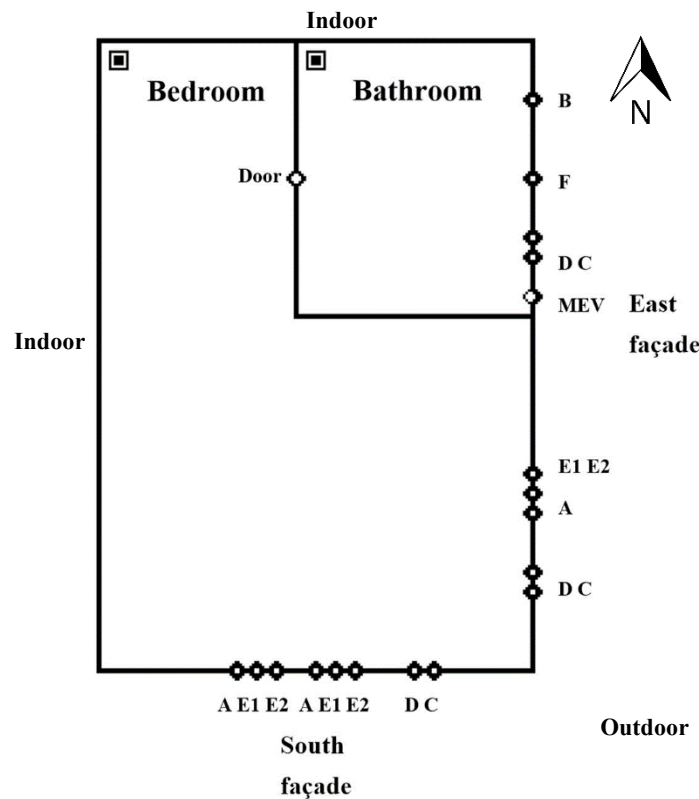


Figure 4.3. Representation of the CONTAM model of the most comprehensive scenario (Scenario 3) with mechanical extraction ventilation (MEV) added. For leakage type code, refer to Table 4.4. For additional characteristics on the air leakage paths and respective weight on the total ELA, refer to Table 4.3.

The door connecting the two compartments has a cross-sectional area of 1.4 m^2 and is considered open in the simulations. Since one assumes all the other openings as small, the discharge coefficient and the flow exponent are the ones defined in the ASHRAE libraries [342].

The simulation period was the same as July–August's measurement campaign. Spatial interpolating public weather data outputted hourly averaged air temperature, wind speed and direction [341] (Figure 4.4). The wind pressure coefficients were estimated using the methodology proposed by Swami and Chandra [221]. The manufacturer provided the performance data of the extraction fan of the bathroom.

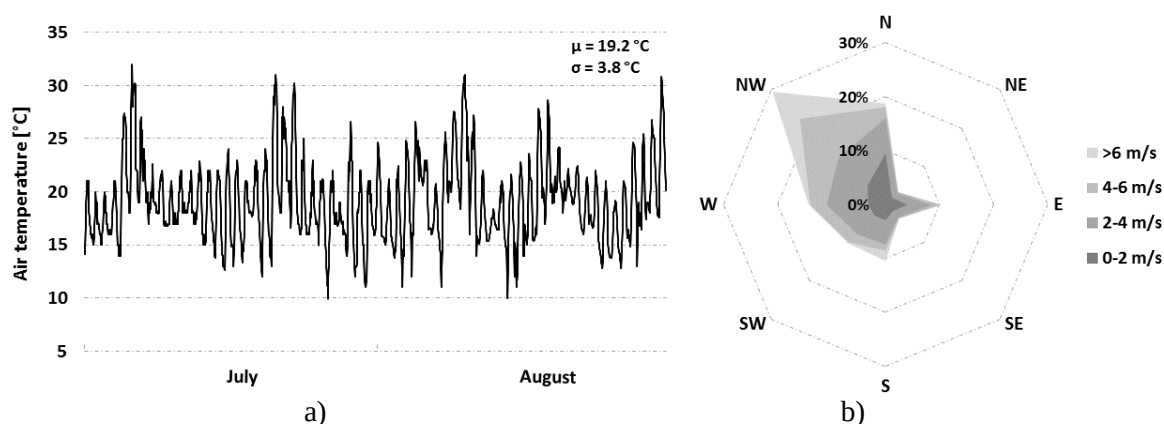


Figure 4.4. Hourly averaged climatic data [341]: a) exterior air temperature; b) wind speed and direction frequency

Uncertainty related to measurement results and simulation assumptions is not insignificant. Still, the current study is not compromised by it, as the aim is to compare results between scenarios with disparate characteristics. Therefore, one considers average measurement results, and coherently, average values of the library on ELAs.

4.2.3. RESULTS AND DISCUSSION ON THE REAL CASE STUDY AND SIMULATED SCENARIOS OUTPUTS

4.2.3.1. Real case study measurements

Table 4.5 presents the experimental results of the blower-door test (ACH_{50}) and the tracer gas measurements (ACH) carried out in the two compartments separately.

Table 4.5. Average ACH and ACH_{50} results

Compartment	MEV on ACH [h^{-1}]	MEV off ACH [h^{-1}]	ACH_{50} [h^{-1}]
Bedroom	0.78	0.15	-
Bathroom	4.21	0.13	-
Total	1.52	0.15	11.50

With MEV on, the ACH of the Bedroom and Bathroom reaches 0.78 h^{-1} and 4.21 h^{-1} , with the overall renovations standing at 1.52 h^{-1} . This value is the result of volume averaging.

As minimum ACH for indoor air quality in residential buildings often range from $0.4\text{--}0.8\text{ h}^{-1}$ [9], when the MEV is off, the results are particularly low, 0.13 h^{-1} and 0.15 h^{-1} , for the Bathroom and the Bedroom, respectively. The ACH_{50} measured for the ensemble of the two compartments was 11.5 h^{-1} , which is in line with the upper values obtained in the study of Ramos et al. [82].

As literature defends [336], one would expect the ACH to be higher than the one measured with this airtightness level. The most likely reason for this phenomenon is that the case study has the envelope facing south and east, and the most predominant wind directions in this location are north, northwest and west.

4.2.3.2. Air leakage distribution effect

The ELA_{50} calculated from the blower door test results was 206.99 cm^2 . After conversion to ELA_4 , it totals 141.71 cm^2 . Regarding the results of the simulations, Figure 4.5 portrays the evolution and distribution of the ACH in each of the three modelled scenarios, considering MEV off and hence natural ventilation conditions. The ACH only exceeds 1.2 h^{-1} in three instances and for very short periods. The ACH suffers significant variations during the simulated period in all three scenarios, as peak values occur often. The boxplot representation shows the increasing trend for higher ACH values as leakage air paths adopt a more dispersed configuration (scenario 3).

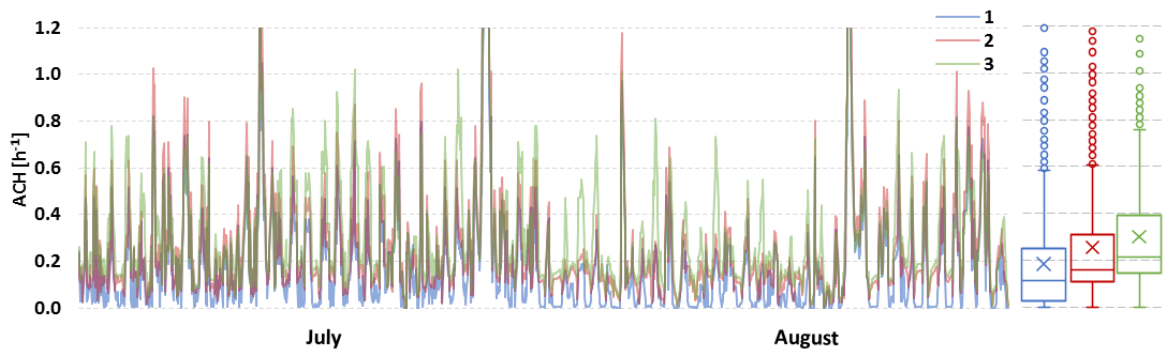


Figure 4.5. Hourly averaged ACH for the simulated period and boxplot representation in the three modelled scenarios with natural ventilation conditions; scenarios - 1 (blue) - 2 (red) – 3 (green)

Table 4.6 informs on the average, the standard deviation, the maximum, and the interquartile range (IQR) for each scenario. There is an average ACH increase from Scenario 1 to Scenario 2 of 38.0% and from Scenario 1 to Scenario 3 of 62.6%. Still, the highest variation in ACH and the maximum resulting values do not occur in Scenario 3. Despite having a wider IQR, it presents the lowest maximum ACH. Scenario 2 shows the highest maximum ACH and the highest variance. Figure 4.6 illustrates these trends.

Table 4.6. Statistical data of the ACH for the three modelled scenarios

ACH [h^{-1}]	Scenario		
	1	2	3
Average	0.185	0.254	0.301
Std. Dev.	0.239	0.275	0.243
Maximum	2.246	2.748	2.235
IQR	0.226	0.198	0.248

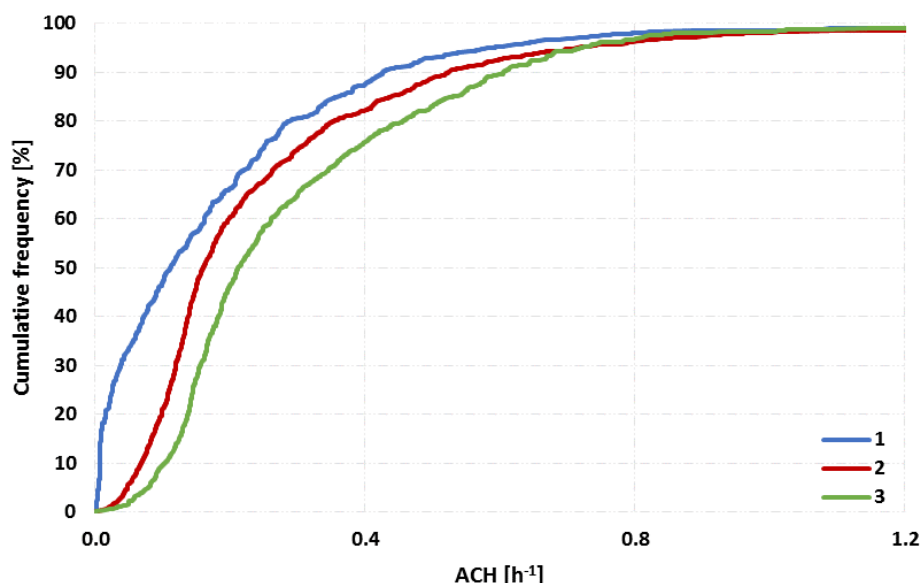


Figure 4.6. Cumulative frequencies of ACH for the modelled scenarios on air leakage paths configuration; scenarios - 1 (blue) - 2 (red) – 3 (green)

As the configuration of air leakage paths gets progressively more dispersed, the sweeping effect of air movement from the Bedroom to the Bathroom gets reduced. In Scenario 1, 23.6% of the infiltrating air through the Bedroom gets exfiltrated through the Bathroom. In Scenario 2 and 3, this value reduces to 13.7% and 9.5%, respectively. The value found in Scenario 1 agrees with the tracer gas measurements, which indicated that 24.2% of the infiltrating air through the Bedroom extracts through the Bathroom.

4.2.3.3. Airtightness levels effect

In the second step of the research, four levels of airtightness were applied in the three scenarios. This variation allowed assessing the impact of airtightness levels on the air change rates, with and without the mechanical extraction activated in the Bathroom. As airtightness levels change,

the total ELA considered for simulation was also modified. For the four levels of airtightness, Table 4.7 presents the resulting ELA_4 after airflow volume transformation and conversion to 4 Pa of pressure difference.

Table 4.7. Airflow data transformation and conversion for the four airtightness levels

ACH_{50} [h^{-1}]	Q_{50} [m^3h^{-1}]	ELA_{50} [cm^2]	ELA_4 [cm^2]
11.5	687.1	209.1	143.2
6.0	358.2	109.0	74.6
3.0	179.1	54.5	37.3
0.6	35.8	10.9	7.5

For the cases with MEV off, as expected, all scenarios show a significant reduction in the resulting ACH as airtightness increases (Figure 4.7). For visualization purposes, outliers were not included in it.

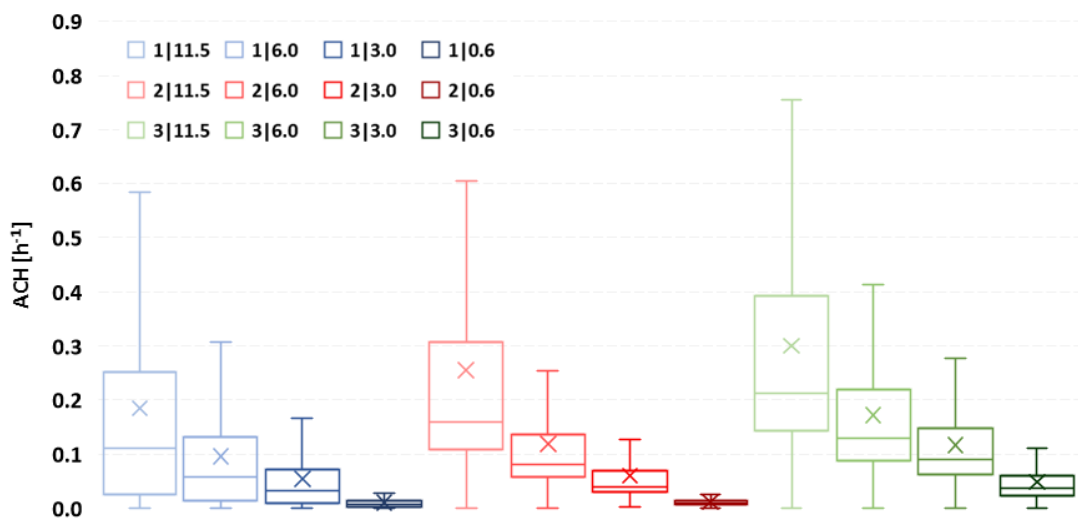


Figure 4.7. ACH distribution in the different configurations of air leakage paths for the four airtightness levels considered (Scenario|ACH₅₀ (h^{-1})); scenarios - 1 (blue) - 2 (red) – 3 (green)

Average ACH values fall in a higher proportion in Scenario 3 than in any other. When the airtightness level increases in that scenario, the average ACH drops by 57, 68 and 41%. For Scenario 1, the average decreases by 52, 56 and 18%, and in Scenario 2, it decreases by 47, 50 and 20%.

As the envelope gets more airtight, the ACH distribution experiences fewer disturbances for all the air leaks configurations considered. The behavior of the three less airtight levels (11.5/6.0/3.0 h⁻¹) shows a similar evolution regarding the proportionality of ACH distribution between configurations. When the envelope is very airtight (0.6 h⁻¹), the most dispersed configuration of air leakage paths, Scenario 3, shows a less significant relative contraction on the ACH distribution compared to the others.

Scenario 2 shows a more significant concentration of values from one airtightness level to the next. It may indicate the higher impact of increasing airtightness levels on the stack effect contribution for ACH. It is the scenario that puts the most relative importance in floor/wall and wall/ceiling joints, maximizing the effect of the indoor height.

Figure 4.8 shows the ACH averages and standard deviations for the different simulated cases. For the cases with MEV on, as supposed, the values of ACH experience less dispersed distributions than those without MEV. As the envelope becomes more airtight, the ACH distribution deviates less from its average, confirming that mechanical ventilation provides more consistent ACH when paired with tighter envelopes.

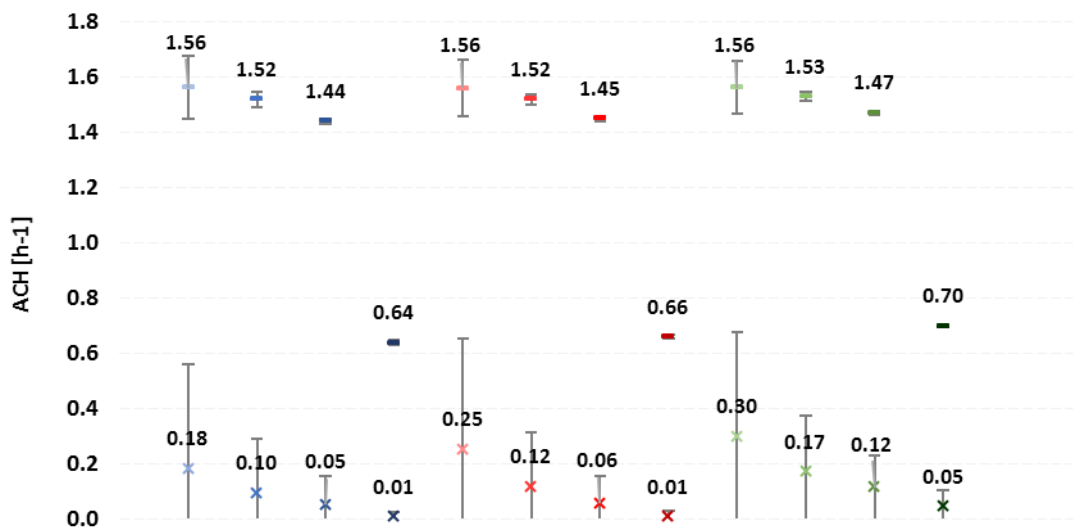


Figure 4.8. Average (labels) and standard deviation of ACH values: MEV on (dash) – MEV off (cross); scenarios - 1 (blue) - 2 (red) – 3 (green); lighter to darker color grade with increasing airtightness levels

For these modelled cases, with MEV on, the effect of changing air leakage paths configurations can be considered negligible since, for all of them, the average ACH evolution is practically the

same as the airtightness level increases. This result reinforces the need to assess airtightness performance when designing HVAC systems. For distinct levels of airtightness, ventilation elements, when active, will induce specific ranges of pressure differentials on building envelopes. The resulting ACH average and range will vary as ventilation equipment operates at different airflow volumes with dissimilar pressure differentials.

In all scenarios, there is a significant reduction of the average ACH from an ACH_{50} of 3.0 to 0.6 h^{-1} . When MEV is on, the performance curve of the extractor in the Bathroom drives the ACH. In other words, it regulates the relationship between the induced pressure differential on the envelope and the extracted air volume. For the case of Scenario 2 with ACH_{50} of 3.0 h^{-1} , the average pressure differential of the air leakage paths is 17.3 Pa, and the Bedroom – Bathroom sweeping effect is apparent, as can be seen in Figure 4.9. The contribution of infiltration through the Bedroom totals 86.7% of the $89.5 \text{ m}^3\text{h}^{-1}$ exhausted through the Bathroom extractor.

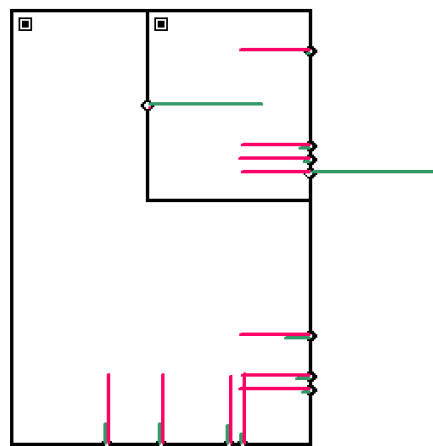


Figure 4.9. CONTAM simulation results for Scenario 2 assuming an ACH_{50} of 3.0 h^{-1} : relative quantities of airflow volumes and direction (green bars); relative pressure differentials and pressurization mode (red bars)

4.3. METEOROLOGICAL VARIABILITY AND ATMOSPHERIC STABILITY (A4)

The objective of Application A4 is to develop an increasingly comprehensive methodology for modelling the intra-hour variation of air change rates, including the effect of changing atmospheric stability. Ultimately it quantifies and compares their impact in intermediate outputs and ACHs. The author develops a single-zone airflow model that includes the additional details necessary to study these impacts, as it was not possible to implement using existing publicly available software. The Application aims to:

- Include meteorological variability in the quantification of wind shear coefficients, in contrast with only terrain dependent ones;
- Use 10-minutes readings of meteorological variables in comparison with hourly readings or averages;
- Implement the stochastic nature of meteorological variables in contrast with averaged input.

4.3.1.METHODOLOGY

4.3.1.1.Considered setups

The methodology establishes four setups (AveT, ReaT, ReaTM, DisTM). Each defines different approaches in combining meteorological data and meteorological variability. The order of the setups intends to isolate and portray the effect of accrued complexity. Figure 4.10 provides a flowchart of the complete methodology, including the different pre-processing steps required by each setup.

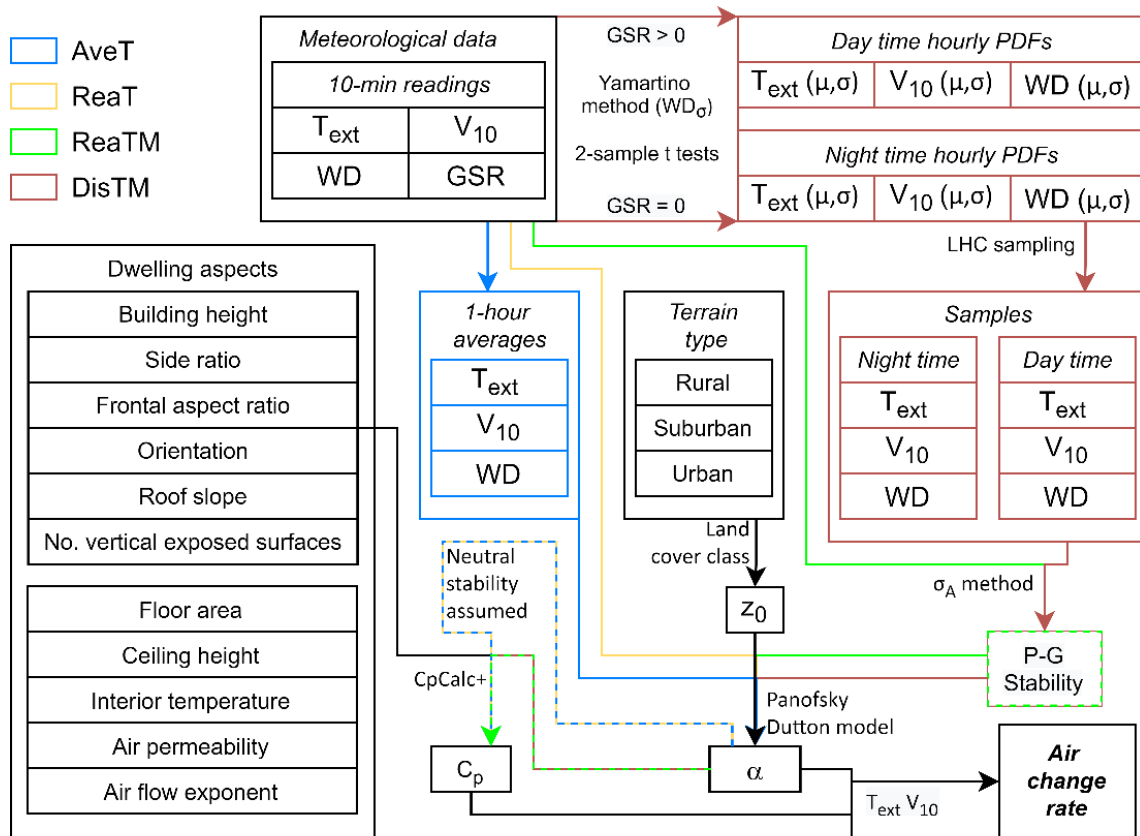


Figure 4.10. Flowchart of the methodology

The AveT setup considers hourly averaged meteorological data. The second setup, ReaT, differs from the previous by using the 10-min readings in the meteorological data. The wind shear coefficients in both setups are based only on terrain features. In other words, it assumes neutral atmospheric stability. Comparing these two setups allows one to perceive the effect of the time step.

The third setup, ReaTM, differs from ReaT by considering the variability in the meteorological component required to quantify the wind shear coefficients. Comparing the two setups exposes the importance of considering variable atmospheric stability conditions.

In the last setup, DisTM, a stochastic approach is implemented to consider the meteorological variability. To that end, the simulation includes hourly distributions of all the meteorological input variables. The comparison between DisTM and ReaTM shows the effect of considering stochastic meteorological inputs.

The stochastic analysis implemented in DisTM requires the definition of hourly probability density functions (PDFs). Wind speed commonly follows Weibull distributions [345] in larger time frames, and air temperatures follow distributions close to normal [346]. For lower time frames, such as one hour time steps, the probability of events can be assumed as constant. Therefore, this setup considers the hourly uniform distributions for exterior air temperature, wind direction, and wind speed.

The pseudo-random numbers from the assumed uniform distributions are then obtained through Latin Hypercube Sampling (LHS), using the Mersenne Twister generator with a fixed seed [347][348]. A correlation matrix between T_{ext} , WD, and V_{10} is calculated and inputted in the sampling process for each hour.

Figure 4.11 provides data on this regard for four hours with exceptionally high variability. The sample size is 50 elements, at which no hour exceeded the variability of a 500 elements sample in more than 2.15%.

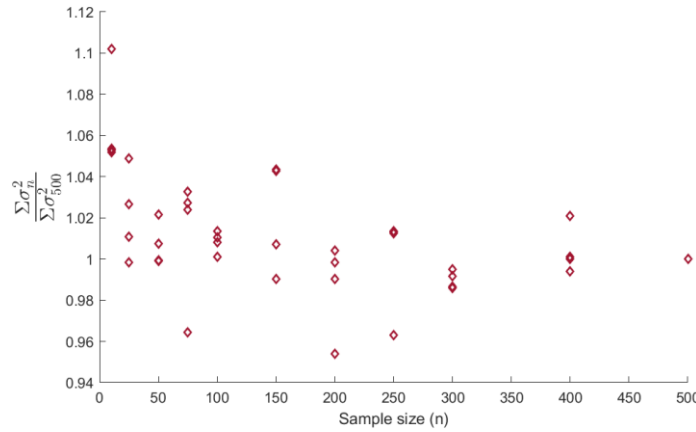


Figure 4.11. The variance of meteorological variables as a function of sample size normalized to the variance of the maximum tested sample size

4.3.1.2. Input data pre-processing

In preprocessing, to obtain the standard deviation of the wind direction, the Yamartino method is used [349][350] (Eqs. (4.5)-(4.8)).

$$\sigma_A = \sigma_{WD} = \arcsin(\epsilon) \left[1 + \left(\frac{2}{\sqrt{3}} - 1 \right) \epsilon^3 \right] \frac{180}{\pi} \quad (4.5)$$

$$\epsilon = \sqrt{1 - (s_a^2 + c_a^2)} \quad (4.6)$$

$$s_a = \frac{1}{6} \sum_{i=1}^6 \sin \theta_i \quad (4.7)$$

$$c_a = \frac{1}{6} \sum_{i=1}^6 \cos \theta_i \quad (4.8)$$

$\sigma_A = \sigma_{WD}$	the standard deviation of the horizontal component of the wind direction at a particular hour (°)
s_a	average of the sines of the wind angle readings at a specific hour (rad)
c_a	average of the cosines of the wind angle readings at a specific hour (rad)
θ_i	wind angle reading at i time (°)

Afterwards, to classify the atmospheric stability, the hours must classify into daytime or nighttime. Positive GSR values correspond to the day, while null values are nighttime. This distinction further affects how the applied σ_A method estimates the Pasquill-Gifford (P-G) stability classes [211]. The σ_A method is a lateral turbulence method, which uses as inputs the scalar mean wind speed (V_{10}) in combination with the standard deviation of the horizontal component of the wind direction (σ_{WD}) [351]. The initial category estimates (Table 4.8) need wind speed adjustments based on daytime and nighttime and occurring wind speed (Table 4.9).

Table 4.8. Initial estimates of P-G stability categories according to the standard deviation of wind azimuth angle [351]

Initial estimate of P-G stability category	Standard deviation of wind azimuth angle σ_A (°)
A	$22.5 \leq \sigma_A$
B	$17.5 \leq \sigma_A \leq 22.5$
C	$12.5 \leq \sigma_A \leq 17.5$
D	$7.5 \leq \sigma_A \leq 12.5$
E	$3.8 \leq \sigma_A \leq 7.5$
F	$\sigma_A \leq 3.8$

Table 4.9. Corrections of P-G stability categories according to the wind speed at 10 meters from the ground during daytime and nighttime [351]

	Initial estimate of P-G stability category	v_{10} [m/s]	Final estimate of P-G stability category
Daytime	A	$v_{10} < 3$	A
	A	$3 \leq v_{10} < 4$	B
	A	$4 \leq v_{10} < 6$	C
	A	$6 \leq v_{10}$	D
	B	$v_{10} < 4$	B
	B	$4 \leq v_{10} < 6$	C
	B	$6 \leq v_{10}$	D
	C	$v_{10} < 6$	C
	C	$6 \leq v_{10}$	D
	D, E or F	Any	D
Nighttime	A	$v_{10} < 2.9$	F
	A	$2.9 \leq v_{10} < 3.6$	E
	A	$3.6 \leq v_{10}$	D
	B	$v_{10} < 2.4$	F
	B	$2.4 \leq v_{10} < 3$	E
	B	$3 \leq v_{10}$	D
	C	$v_{10} < 2.4$	E
	C	$2.4 \leq v_{10}$	D
	D	Any	D
	E	$v_{10} < 5$	E
	E	$5 \leq v_{10}$	D
	F	$v_{10} < 3$	F
	F	$3 \leq v_{10} < 5$	E
	F	$5 \leq v_{10}$	D

From the available models used for wind speed extrapolation, the Panofsky Dutton (PD) model [352] was chosen as it shows one of the highest accuracies [353][354]. This model uses the power law equation (Eq. (4.9)), Irwin approximations of atmospheric stability and stability length to calculate wind shear coefficients [209] (Eqs. (4.10) to (4.20)). The power law in vertical wind profiles approximates the logarithmic law. Because true profiles are often too complex because of non-uniform terrain, the power law is an acceptable approximation of the

latter. It, therefore, is usually applied in engineering practice [352]. More recent research supports this approach [355][356]. Stability length depends on the surface roughness (z_0) [357] and curve-fitting constants on stability classes [358] (Table 4.10). As only the layer closer to the surface is of interest, for the geometric height ($\bar{z}$) h_2 was considered at 50 m from the ground [210]. The value of h_1 corresponds to measured wind speed height, 10 meters from the ground.

$$v_z = v_1 \left(\frac{h_z}{h_1} \right)^\alpha \quad (4.9)$$

$$\alpha = \frac{\phi_m \left(\frac{\bar{z}}{L} \right)}{\ln \left(\frac{\bar{z}}{z_0} \right) - \psi_m \left(\frac{\bar{z}}{L} \right)} \quad (4.10)$$

$$\bar{z} = (h_1 h_2)^{0.5} \quad (4.11)$$

Stable conditions ($\bar{z}/L > 0$):

$$\phi_m \left(\frac{\bar{z}}{L} \right) = 1 + 4.7 \left(\frac{\bar{z}}{L} \right) \quad (4.12)$$

$$\psi_m \left(\frac{\bar{z}}{L} \right) = -4.7 \left(\frac{\bar{z}}{L} \right) \quad (4.13)$$

Neutral conditions ($\bar{z}/L = 0$):

$$\phi_m \left(\frac{\bar{z}}{L} \right) = 1 \quad (4.14)$$

$$\psi_m \left(\frac{\bar{z}}{L} \right) = 0 \quad (4.15)$$

Unstable conditions ($\bar{z}/L < 0$):

$$\phi_m \left(\frac{\bar{z}}{L} \right) = \left(1 - 15 \left(\frac{\bar{z}}{L} \right) \right)^{-1/4} \quad (4.16)$$

$$\psi_m \left(\frac{\bar{z}}{L} \right) = -\ln \left(\frac{(\zeta_0^2 + 1)(\zeta_0 + 1)^2}{(\zeta^2 + 1)(\zeta + 1)^2} \right) - 2(\arctan(\zeta) - \arctan(\zeta_0)) \quad (4.17)$$

$$\zeta = \left(1 - 15 \left(\frac{\bar{z}}{L} \right) \right)^{1/4} \quad (4.18)$$

$$\zeta_0 = \left(1 - 15 \left(\frac{z_0}{L} \right) \right)^{1/4} \quad (4.19)$$

$$L = \frac{1}{a(z_0)^b} \quad (4.20)$$

v_z	wind speed at height h_z (m/s)
v_1	wind speed at height h_1 (m/s)
α	wind shear coefficient (-)
$\bar{z}$	geometric mean height (m)
ϕ_m, ψ_m	Monin-Obukhov universal stability functions (-)
L	Monin-Obukhov length (m)
z_0	surface roughness length (m)
ζ, ζ_0	Obukhov stability parameters (-)
a, b	curve-fitting constants on stability classes (-)

Table 4.10. Curve-fitting constants on stability classes [358]

Final estimate of P-G stability category	a [-]	b [-]
A	-0.0875	-0.1029
B	-0.03849	-0.1714
C	-0.00807	-0.3049
D	0	0
E	0.00807	-0.3049
F	0.03849	-0.1714

The considered surface roughness was 0.1, corresponding to an exposed building, in line with the surface roughness at the weather station site and Corine Land Cover (CLC) classification [359].

The CpCalc+ [214] software calculates wind pressure coefficients. An entire collection of wind pressure coefficients outputs for each wind shear coefficient associated with each atmospheric stability class. In CpCalc+, each surface is discretized by a 10x10 points mesh equally spaced, subsequently averaged for inclusion in the air infiltration balance. The wind shear coefficients were limited to the range 0.1 to 0.4 since these are the confidence limits defined in CpCalc+. The values refer to angle steps of 45°, and a linear interpolation within each 45° was assumed to obtain the 1° step values for the 360 possible angles. Annex A4 compiles the outputted tables.

4.3.1.3. Airflow rates modelling

A numerical single-zone model of a single-family dwelling with natural ventilation, combining stack ducts and a leaky envelope, was developed to simulate the several setups. Figure 4.12 shows a schematic representation of the model. The scheme describes a profile of parametrized exposed surface areas of a two-story dwelling and the respective input data required to calculate air change rates.

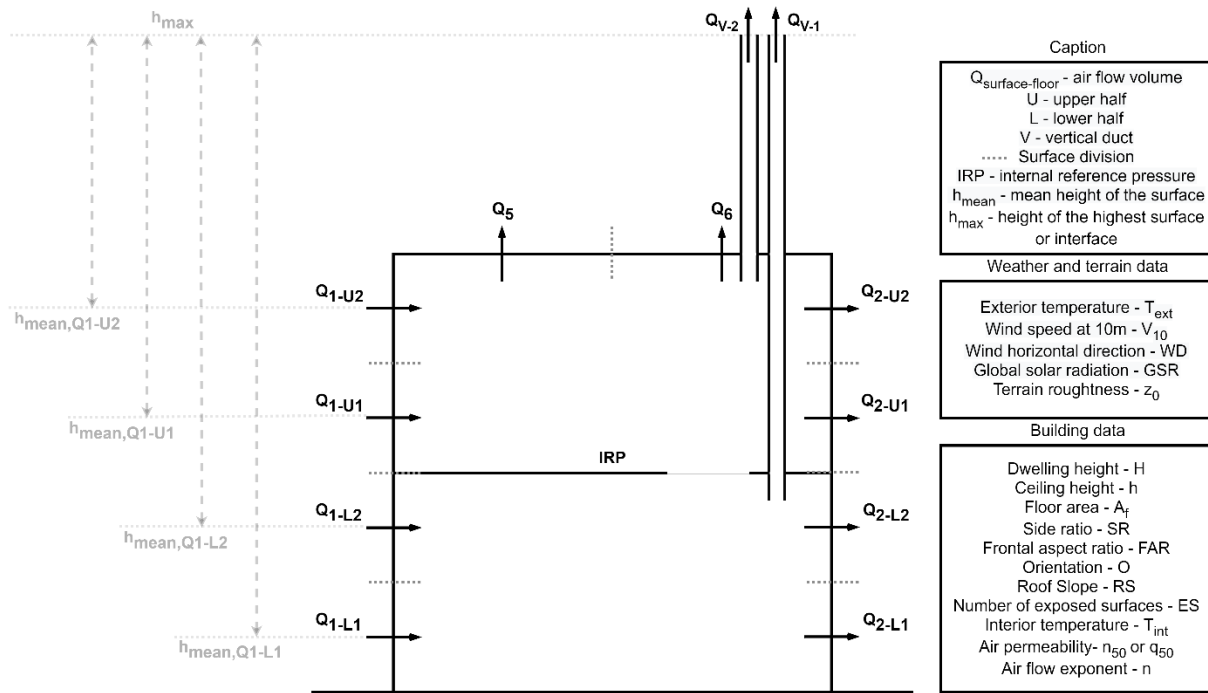


Figure 4.12. Schematic profile of the parametrized exposed surface areas and respective required input data

The first number in the terminology of each envelope surface refers to 1 – windward wall; 2 – leeward wall; 3 – wall to the right of the windward wall (clockwise); 4 – wall to the left of the leeward wall (counterclockwise), following the structure applied in AIVC documentation [186]. L1 and L2 refer to the lower and upper halves of the ground floor, respectively, while U1 and U2 refer to the lower and upper halves of the first floor, respectively. Surfaces 5 and 6 refer to the two roof halves, and V-1, V-2 to the duct connecting to the ground and first floor, in that order.

The process presented for airflow convergence has the same architecture of the iterative method of EN 15242:2007 [194], transposed as method 1 in the current version, EN 16798-7:2017 [195] (Eqs. (4.21) to (4.23)). The IRP found at convergence corresponds to the internal pressure at the defined height at that instant in time. A gradient descent method [360] performs the iterative process. It is available through the MATLAB Optimization Toolbox [361].

$$\Delta P_{r_i} = P_{r_{i,ext}} - P_{r_{i,int}} \quad (4.21)$$

$$P_{r_{i,ext}} = \rho_{a,ref} \frac{T_{ext,ref}}{T_{ext}} \left(\frac{1}{2} C_{p_i} v_{site}^2 - g(h_{mean,i} - h_{max}) \right) \quad (4.22)$$

$$P_{r_{i,int}} = IRP - g(h_{mean,i} - h_{max}) \rho_{a,ref} \frac{T_{ext,ref}}{T_{int}} \quad (4.23)$$

ΔP_{r_i}	pressure difference at surface i (Pa)
$P_{r_{i,ext}}$	external pressure at the surface i (Pa)
$\rho_{a,ref}$	air density of dry air at the reference temperature of 20 °C (kg/m ³)
$T_{ext,ref}$	external reference temperature of 20 °C (K)
T_{ext}	external temperature (K)
C_{p_i}	wind pressure coefficient at surface i (-)
v_{site}	wind speed at upper height of surface i (-)
g	gravity acceleration (m/s ²)
$h_{mean,i}$	mean height of surface i from ground level (m)
h_{max}	height of the exit of the vertical duct from ground level (m)
$P_{r_{i,int}}$	internal pressure at the surface i (Pa)
IRP	internal reference pressure (Pa)
T_{int}	internal temperature (K)

The modelling of the airflow paths is based on one-way power laws for the volume flow ($Q = C \cdot \Delta P^n$) and the calculation of Eq. (4.24) to (4.31), following an iterative process for the airflow convergence. The power law is the equation adopted in most international standards regarding airtightness testing. Additionally, experimental campaigns suggest that the power law produces better results than the quadratic law at lower pressures [108][362]. The formulation background is available in ASHRAE documentation [363].

As computed in Eq. (4.24) to (4.26), the airflow coefficient (C) can be expressed as a function of air permeability, envelope area, pressure differential at which the air permeability was measured, and airflow exponent. The use of the air permeability rate (q_{50}) instead of the air change rate (n_{50}) allows establishing a relationship between airtightness performance and envelope surface areas (Eq. (4.26)). For each exposed surface, the airflow is calculated.

$$ELA_{50} = \frac{Q_{50}}{C_{D50}} \sqrt{\frac{\rho}{2 \cdot 50}} \quad (4.24)$$

$$Q_{50} = q_{50} A_{env} \quad (4.25)$$

$$Q_{\Delta P_i} = C(\Delta P_i)^n = C_{D50} ELA_{50} \sqrt{\frac{2 \cdot 50}{\rho}} \left(\frac{\Delta P_i}{50}\right)^n = Q_{50_i} \left(\frac{\Delta P_i}{50}\right)^n = \frac{q_{50} A_{env_i}}{50^n} \Delta P_i^n \quad (4.26)$$

ELA_{50}	effective leakage area at 50 Pa of pressure difference (m ²)
Q_{50}	airflow volume at 50 Pa of pressure difference (m ³ /h)
C_{D50}	discharge coefficient at 50 Pa of pressure difference (-)
ρ	air density (kg/m ³)
q_{50}	air permeability at 50 Pa of pressure difference (m ³ /(h·m ²))
A_{env_i}	area of surface i of the envelope (-)
Q_{r_i}	airflow volume at r Pa of pressure difference in surface i of the envelope (m ³ /h)
ΔP_{r_i}	pressure difference at surface i (Pa)
C	airflow coefficient (m ³ /(s·Pa ⁿ))
n	airflow exponent (-)

The pressure difference in each surface (ΔP_{r_i}) is computed from Equation (4.29)), which, besides the wind (Eq. (4.27)) and stack (Eq. (4.28)) effects, also includes the internal reference pressure (IRP), required to guarantee the convergence in the airflow volume.

$$\Delta P_{wi} = \frac{p_{ref} \cdot M}{2 \cdot T_{ext}} C_{pi} \left(v_{10} \left(\frac{\delta_{met}}{H_{met}} \right)^{\alpha_{met}} \left(\frac{H_i}{\delta} \right)^{\alpha} \right)^2 = \frac{176.49}{T_{ext}} C_{pi} \left(v_{10} \left(\frac{\delta_{met}}{H_{met}} \right)^{\alpha_{met}} \left(\frac{H_i}{\delta} \right)^{\alpha} \right)^2 \quad (4.27)$$

$$\begin{aligned} \Delta P_{si} &= -9.81(h_{mean,i} - h_{max}) \frac{p_{ref} \cdot M}{R} \left(\frac{1}{T_{ext}} - \frac{1}{T_{int}} \right) \\ &= -9.81(h_{mean,i} - h_{max}) 352.98 \left(\frac{1}{T_{ext}} - \frac{1}{T_{int}} \right) \end{aligned} \quad (4.28)$$

$$\Delta P_i = \Delta P_{wi} + \Delta P_{si} + IRP \quad (4.29)$$

ΔP_{wi}	pressure difference at surface i due to the wind effect (Pa)
T_{ext}	external temperature (K)
C_{pi}	wind pressure coefficient at surface i (-)
v_{10}	wind speed at 10 m of height or the height it was measured (m/s)
δ_{met}	atmospheric boundary layer thickness at the location of the meteorological station (m)
H_{met}	height of the meteorological station (m)
α_{met}	wind shear coefficient at the location of the meteorological station (-)
H_i	height of surface i of the envelope (m)
δ	atmospheric boundary layer thickness at the location of the dwelling (m)
α	wind shear coefficient at the location of the dwelling (-)
$\Delta P_{sr,i}$	pressure difference at surface i due to the stack effect (Pa)
$h_{mean,i}$	mean height of surface i from ground level (m)
h_{max}	height of the exit of the vertical duct from ground level (m)
IRP	internal reference pressure (Pa)
T_{int}	internal temperature (K)

Replacing Equation (4.29) into Equation (4.30), one obtains the airflow at each surface. For each time step, the ACH is the sum of either the positive, from outdoor to indoor, or the negative, from indoor to outdoor, surface airflows divided by the dwelling interior volume (Eq. (4.31)).

$$Q_{\Delta P_i} = C(\Delta P_i)^n = \frac{q_{50} A_{env,i}}{50^n} (\Delta P_{wi} - \Delta P_{si} - IRP)^n \quad (4.30)$$

$$\sum Q_{\Delta P_i} = 0, \text{ for } Q_{\Delta P_i} > 0 \cup Q_{\Delta P_i} < 0: ACH = \frac{\sum Q_{\Delta P_i}}{V} \quad (4.31)$$

ACH	air change rate (h ⁻¹)
V	internal volume (m ³)

4.3.1.4. Developed airflow model assumptions

The use of the developed model requires the acceptance of several assumptions. These are often adopted or available in airflow analysis software [205][206]. They are as follows:

- Internal partitions and furniture are ignored;
- As each component is rarely solely addressed when measurements are performed, their contribution to the whole building airtightness is unknown. Therefore, the air permeability is uniformly distributed along the exposed surfaces. It is a feature often available in airflow analysis software [205][206];
- Each vertical exposed surface divides horizontally in half at each floor to better identify possible changes in the flow direction, ease the pairing of wall sections with available WPCs, and overall increase the detailing. Consequently, the h_{mean} of each wall section occurs at an elevation of 25% and 75% of the ceiling height (Figure 4.12). They correspond to the mid-height of each of the parametrized sections;
- The atmospheric pressure is considered 101.325 kPa, and dry air is assumed when considering air densities. As temperature differences are already taken into account, a change from 0% to 100% relative humidity has a residual impact on air density, i.e., at a temperature of 293.15 K, it corresponds to a change of 0.84% in the air density, at 283.15 K, the difference in air density is of 0.48%, and at 273.15 K, it reduces to 0.23%. The air density ratios at different atmospheric pressures, for a 10 K range (indoor-outdoor) of temperature, if one considers the ranges between 97.000 kPa and 101.325 kPa, and between 101.325 kPa and 104.000 kPa, respectively, result in 0.0768% and 0.0144% discrepancies in comparison with static atmospheric pressure. These lower and upper limits portray the boundaries between which the atmospheric pressure at sea level usually varies;
- The IRP found at convergence corresponds to the internal pressure at the chosen height for the combination of natural forces at that moment.

4.3.1.5. Meteorological data

The meteorological data used in the present Application comes from the Porto/Pedras Rubras weather station, near Sá Carneiro Airport, in the northern region of Portugal. The station locates at a latitude of 41.2335, a longitude of -8.68133 and an altitude of 63 m. It is part of a broader governmental network of the Portuguese Institute for Sea and Atmosphere (IPMA) for weather forecasting, representing the typical weather conditions in the Metropolitan Area of the Porto region. Table 4.11 shows the four variables used in this research, the sensors and respective ranges and accuracies.

Table 4.11. Variables and sensors characteristics at the weather station

Variable	Sensor	Range	Accuracy
Text	Vaisala HMP155	-80 ... +60 °C	±0.2 °C
V ₁₀	Vaisala WAA15A	0.4 ... 60 m/s	±0.17 m/s
WD	Vaisala WAV15A	0 ... 360°	±3.0 °
GSR	Kipp & Zonen CM11	0 ... 1400 W/m ²	±3.0 %

The temperature (T_{ext}) and solar radiation (GSR) sensors are installed at 1.5 m from the ground, while the readings on wind speed (V_{10}) and direction (WD) occur at 10.0 m from the ground. The analysis used the 10-minutes interval data collected between the 1st of January 2015 and the 31st of December 2015. The referred interval corresponds to the shorter time step usually available at the meteorological weather stations that make up the national network of IPMA. A shorter time step would allow one to observe the wind speed and direction changes even more accurately. Still, one must compromise between the available datasets and the computing capacity.

4.3.1.6. Representative dwelling as a case study

The current Application considers a low-rise building representative of the Portuguese stock to showcase the proposed objectives. The number of floors, floor area and ceiling height corresponds to the averages of a dataset of reference buildings used in previous studies [364][306]. The case study has two floors, a floor area of 126.5 m² and a ceiling height of 2.63 m. Additionally, the side ratio is 1:1, the frontal aspect ratio is 1:1, and the roof is double pitched with 20° slopes.

The airtightness characteristics were defined from a compilation of Portuguese studies [82][365][366][367], leading to an average n_{50} of 7.60 h⁻¹. Since the pool of studied houses is quite limited, 72 elements, the whole collection was applied. Still, as over 96% of the Portuguese built stock is below four floors [368], and low-rise buildings are those with less than 15 meters height above ground, the current approach is deemed acceptable.

As adopting a specific air leakage configuration was not relevant for the study, one considered the scenario of uniformly distributed air permeability. It is a typical routine where a tester performs only whole building blower door measurements.

Regarding dwelling features, being the side ratio 1:1, all vertical surfaces exposed, and the roof slope 20°, the envelope area yields approximately 234 m², and the conversion to q₅₀ results in 10.8 m³/h·m².

The airflow coefficient (C) weights according to the contribution of each exposed surface. Since the side ratio is 1:1, 10.52 m³h⁻¹Pa⁻ⁿ convey to each split of vertical envelope surface areas in each floor, and each half of the roof represents 34.05 m³h⁻¹Pa⁻ⁿ. The airflow exponent (n) is 0.67, corresponding to a combination of laminar and turbulent flows [36], as recommended by ASHRAE [363] when measurement data is unavailable.

Two vertical ducts apply, one per floor. Their pressure drop is defined as medium, typical of ducts with diameters between 125 mm and 200 mm and a free flow area equal to or greater than 70%. With these characteristics, the airflow coefficient is equal to $44.2/(1.93+0.14 \cdot L)^{0.5}$, where L is the length of the vertical duct [196]. The airflow exponent (n) for these elements is 0.5 [369].

As occupants strive for thermal comfort, the interior temperature modelling uses the adaptive method proposed in EN 16798-1:2019 [370] for thermal comfort in free-running buildings.

The considered heating season was from the 1st day of October to the 30th day of April, in line with the Portuguese regulation for the buildings energy efficiency [371]. During this period, when the exponentially weighted running mean of the daily mean external air temperature (T_{rm}) is above 10°C, the considered interior temperature is 19°C. When T_{rm} goes below 10°C, the interior temperature is 18°C.

In the cooling season, the interior temperature is $T_i = 0.33T_{rm} + 18.8 - 3$, corresponding to the lower limit of Category II of acceptability. Figure 4.13 portrays these temperatures daily for the whole year.



Figure 4.13. Daily mean interior temperature (T_i), mean exterior temperature (T_{em}), and running mean exterior temperature (T_{rm}) for the whole year

4.3.2. RESULTS AND DISCUSSION ON SIMULATED SETUPS

4.3.2.1. Time step effect

Table 4.12 presents the descriptive statistics on the ACH results obtained for the whole year in each setup. The differences between the setups are not significant, particularly concerning measures of central tendency. This situation occurs because of the data grouping for the whole year, and thus, relevant information ends up lost. These results highlight the importance of considering the intra-hour variability if one intends to perceive the variations between the outputs of the setups.

Table 4.12. Descriptive statistics of the results of the setups for the whole year dataset

ACH [h^{-1}]	Mean	Std. Dev.	Min	1%	5%	25%	Median	75%	95%	99%	Max
AveT	0.527	0.275	0.045	0.155	0.227	0.332	0.459	0.649	1.080	1.481	2.282
ReaT	0.530	0.282	0.010	0.142	0.219	0.332	0.459	0.653	1.093	1.516	2.444
ReaTM	0.517	0.285	0.010	0.145	0.218	0.323	0.436	0.635	1.093	1.516	2.444
DisTM	0.517	0.285	0.003	0.146	0.218	0.322	0.435	0.633	1.093	1.515	2.440

The results of the comparison between AveT and ReaT setups are analyzed first. These two setups assume neutral conditions, corresponding to P-G stability class D, which, when combined with a terrain roughness of 0.1 m, results in a wind shear coefficient of 0.185. Figure 4.14 presents the comparison between the air change rates in the two setups for the first 72 hours of the dataset.

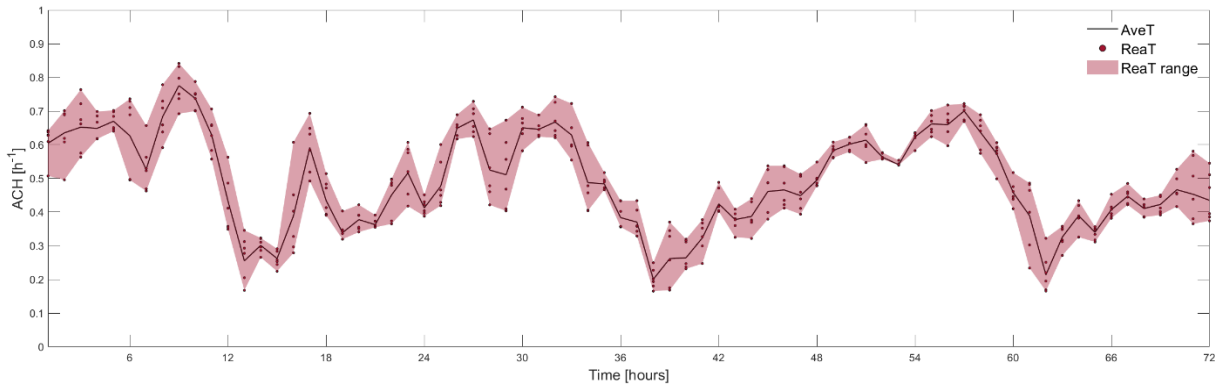


Figure 4.14. Air change rates (ACH) in AveT and ReaT setups from the 1st to the 3rd of January

The scatter points correspond to the 10-min readings simulated in ReaT and expose the variability in the ACH values for each hour. The magnitude of this effect distributes randomly throughout the dataset.

Regarding the whole year, Figure 4.15a presents the relative differences in the calculated ACH between using the hourly averages (AveT) or the 10-min time step readings (ReaT) of the meteorological data (sample size=52560). Figure 4.15b portrays the hourly ACH standard deviations using the ReaT setup (sample size=8760).

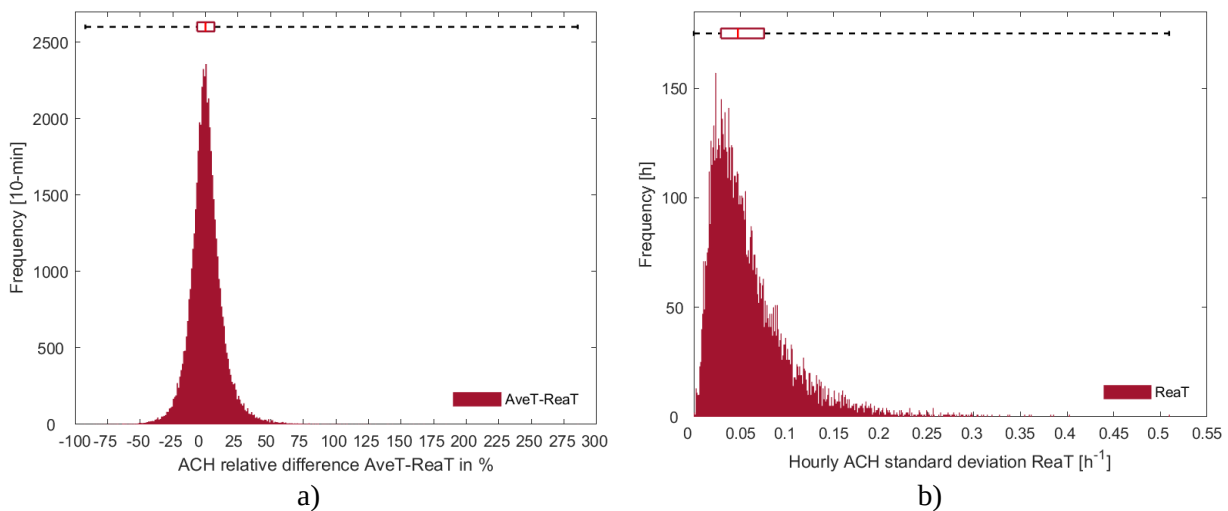


Figure 4.15. Comparison between AveT and ReaT setups: a) air change rates (ACH) relative difference; b) hourly air change rates (ACH) standard deviation in ReaT setup

The relative differences in ACH distribution are nearly symmetrical, with 50% of the occurrences within -6.3% and 6.9%, between the 1st and 3rd quartiles. However, the 5% and 95% quantiles experience differences below -18.6% and above 22.5%. Observing Figure 4.15b,

50% of the hours throughout the year have standard deviations between 0.025 and 0.065 h⁻¹, corresponding to the range of the 25% quantile to the 75% quantile. The median standard deviation is 0.040 h⁻¹. At the 95% quantile, the standard deviation reaches 0.126 h⁻¹.

4.3.2.2. Atmospheric stability effect

The introduction of variable atmospheric stability conditions produces changes in the calculation of the WSCs and consequently in the WPCs. While AveT and ReaT consider unchanging neutral conditions, in ReaTM and DisTM, one of the following situations of the P-G stability classification can occur: unstable conditions (classes A, B and C); neutral conditions (class D); or stable conditions (classes E and F). The subsequent analysis is only on ReaT and ReaTM to isolate the effect of considering a variable atmospheric stability classification.

Table 4.13 exposes the effect of considering meteorological variability in the computation of WSCs and WPCs. For example, WPCs of the windward vertical exposed wall, for a wind angle incidence of 0°, are presented: Cp1L refers to the lower floor, and Cp1U to the upper floor.

Table 4.13. Whole year occurrences of P-G stability classes in ReaTM setup and their effect over wind shear coefficients (WSCs) and wind pressure coefficients (WPCs) (terrain roughness of 0.1 m)

P-G stability	Occurrences	WSC [-]	Cp1L [-]	Cp1U [-]
A	2507	0.104	0.655	0.755
B	1394	0.112	0.653	0.746
C	2802	0.131	0.643	0.723
D	30204	0.185	0.594	0.661
E	10130	0.344	0.261	0.473
F	5523	0.591	0.078	0.403

Neutral conditions (class D) are the most common and occur 57.47% of the time, while unstable atmosphere occurs in 12.75% (classes A, B and C), and the remaining 29.78% correspond to stable conditions (classes E and F). When the atmospheric stability tends to unstable conditions, the reduction of wind speed with height is less pronounced, and therefore the WSCs decrease when unstable conditions are present. Reversely, in stable atmospheric conditions, the wind effect decreases as the vertical reduction of wind speed is more drastic, and therefore higher WSCs occur. The WPCs reflects this effect. As the wind effect loses relevance, from unstable to stable atmospheric stability conditions, the WPCs experience a progressive reduction.

Since the difference between ReaT and ReaTM is the consideration of atmospheric stability classes other than neutral, when comparing both setups, the differences lie in the group of the non-neutral occurrences, which were 42.53% of the total. Table 4.14 presents a descriptive statistic of the differences in non-neutral occurrences.

Table 4.14. Descriptive statistics of the relative differences between ReaT-ReaTM setups

Δ ACH	Mean	Std. Dev.	Min	0.01	0.05	0.25	Median	0.75	0.95	0.99	Max
ReaT-ReaTM [%]	-4.4	22.1	-71.9	-45.8	-34.6	-18	-8.5	8.2	37.4	59.2	122.7
ReaT-ReaTM [h^{-1}]	-0.031	0.095	-0.361	-0.27	-0.202	-0.082	-0.029	0.023	0.131	0.207	0.31

As the mean of the ACH differences tends to negative values (-0.031 h^{-1}), it indicates that the entire year's atmospheric stability skews for stable conditions in the studied location. The standard deviation is 0.095 h^{-1} , and the differences ranged between -0.20 and $+0.13 \text{ h}^{-1}$, at the 5 and 95% quantiles, respectively.

Figure 4.16 informs on these impacts. Hour zero corresponds to midnight on the 1st of January. During the nighttime, the ACHs in ReaTM are consistently lower than in ReaT, with stable conditions predominant (blue rectangle). During the daytime, unstable atmospheric conditions result in higher ACH in ReaTM (red rectangle). When neutral conditions occur during an entire hour, the ranges of ReaTM and ReaT overlap (green rectangle).

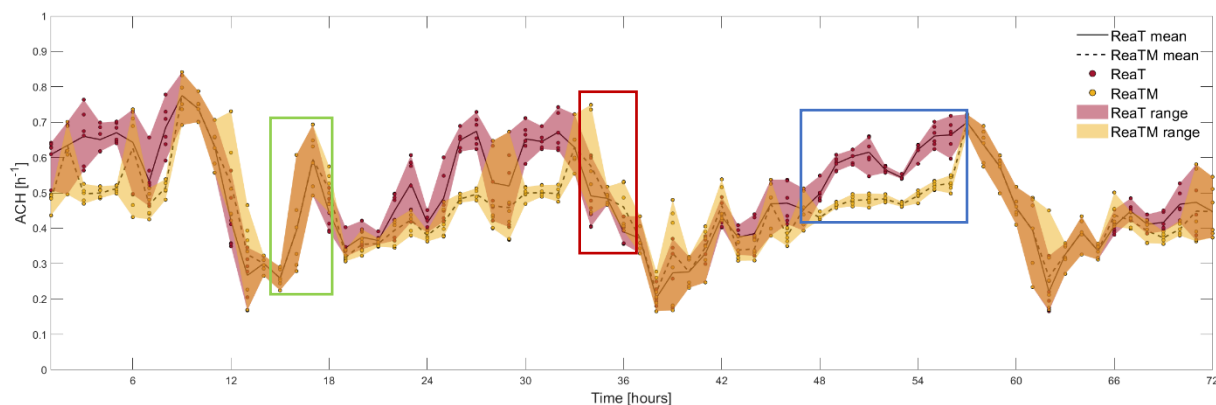


Figure 4.16. Average air change rates (ACH) and respective confidence bands in the ReaT and ReaTM setups from the 1st to the 3rd of January of the meteorological dataset

Another interesting finding spotted in Figure 4.16 is that generally, neutral conditions are more sensitive to the time step effect than stable conditions. For those hours, the readings experience

greater dispersion (blue rectangle). On the other hand, the atmospheric stability effect gains significance over the time step effect for more modest wind speeds when unstable conditions are present (red rectangle).

Additionally, the pressure differences across the parametrized surfaces observe these effects. Hours 34 (Figure 17a) and 52 (Figure 17b) represent unstable and stable atmospheric stabilities in ReaTM, respectively. For reference, the surface nomenclature can be consulted in Figure 4.12 and the paragraph immediately afterwards.

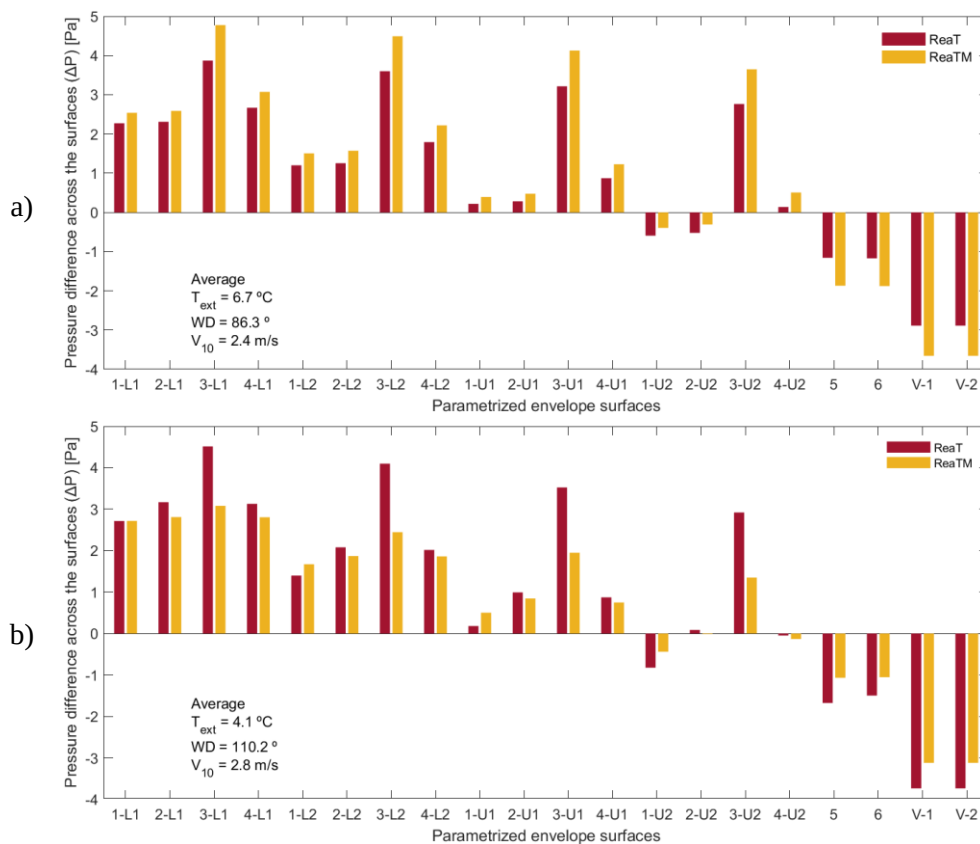


Figure 17. Pressure differences across the parametrized envelope surfaces for specific hours in the ReaT and ReaTM setups: a) hour 34 in class C, unstable conditions; b) hour 52 in class E, stable conditions. ReaT represents static class D, neutral conditions.

From neutral to unstable conditions, the wind shear coefficient gets smaller, increasing the wind pressure coefficients, resulting in increments in the occurring pressure differences across the envelope (Figure 17a). From neutral to stable conditions, the greater wind shear coefficient develops decreasing wind pressure coefficients, which reflects the decline in the occurring pressure differences across the surfaces of the envelope (Figure 17b). Figure 4.18 reports on

ACH differences in ReaT-ReaTM for the occurrences classified as non-neutral in the latter (sample size=22353) and divided by stability class for the whole year.

Figure 4.18 reports on ACH differences in ReaT-ReaTM for the occurrences classified as non-neutral in the latter (n=22353) and divided by stability class for the whole year.

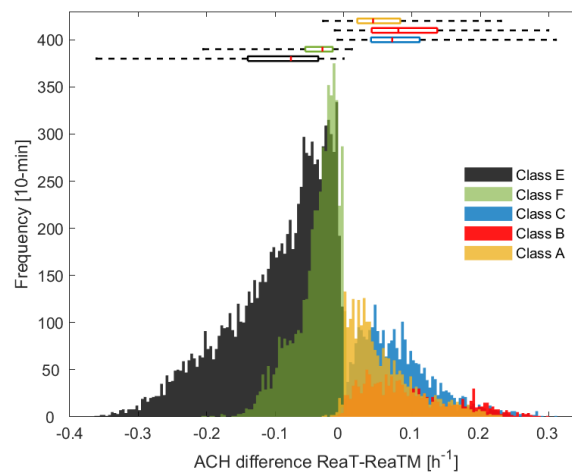


Figure 4.18. Air change rates (ACH) differences between ReaT-ReaTM setups for the readings classified with non-neutral atmospheric stability

In some occurrences, the ACH from neutral to stable conditions increases and decreases from neutral to unstable conditions. The exterior temperature is higher than the interior temperature in all these occurrences. Therefore, the stack effect counters the wind effect ascendant movement, resulting in partial or total vertical flow inversion. With this rationale, one understands that, by locking one of the effects and steadily increasing the other, it withers until the forces cancel each other before the ACH grows.

4.3.2.3. Stochastic modelling effect

Figure 4.19 portrays the effect of introducing a stochastic nature in the input data using the 1st to the 3rd of January as an example. As can be seen, the DisTM setup results in a wider hourly ACH range for most of the hours.

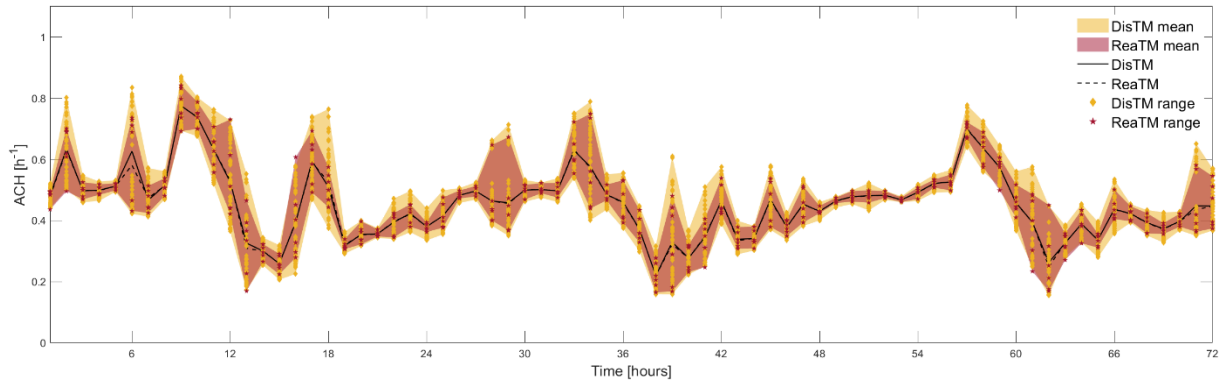


Figure 4.19. Air change rates (ACH) ranges, averages, and scatters in the ReaTM and DisTM setups from the 1st to the 3rd of January of the used meteorological dataset

As expected, the stochastic modelling of the meteorological variables does not significantly affect the P-G classification since a significant difference would indicate a distortion from reality. The most substantial changes from ReaTM to DisTM occur in class D with a decrease of 0.24% and in class F with an increase of 0.19% (Figure 4.20a). The minor differences found give robustness to applying uniform distributions to the meteorological variables.

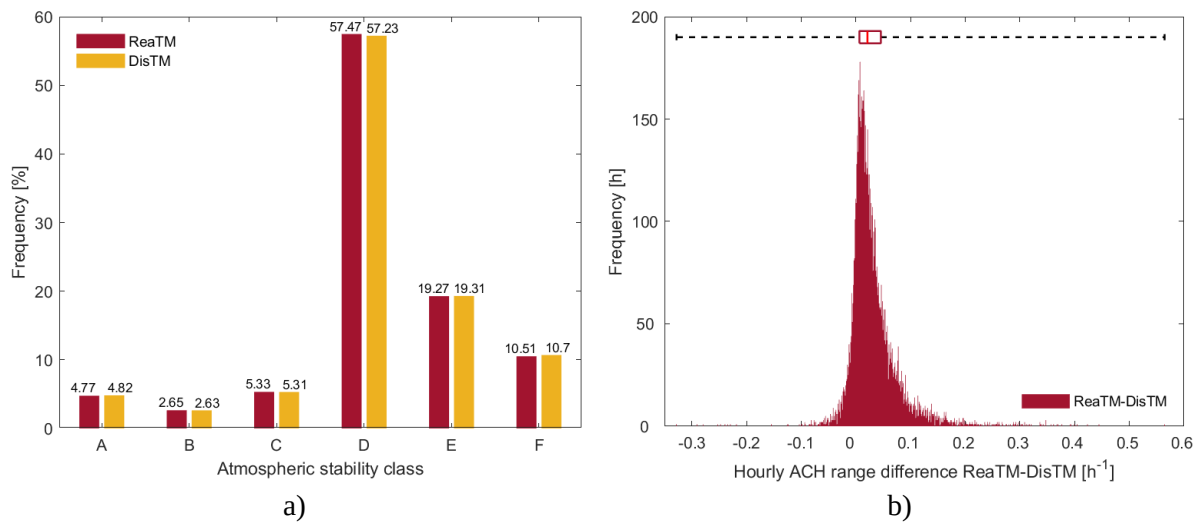


Figure 4.20. Comparisons between ReaTM and DisTM setups: a) occurrence of Pasquill-Gifford (P-G) stability classes; b) hourly air change rates (ACH) range difference

The comparison between ACH in ReaTM and DisTM by location measures is inappropriate since the aim is to consider other possible intra-hourly occurring phenomena. As Figure 4.20b shows, the use of hourly uniform distributions confers a rather lognormal distribution of the

relative differences in ACH ranges. The median of the relative differences between the two setups increased 19.6%, while the mean increased 29.3%.

Still, a percentage of the hours in DisTM results in narrower outputted ACH ranges than in ReaTM (14.3%). Details on two particular hours are presented in Figure 4.21, representing the advantages and limitations of considering hourly distributions. Cp1 refers to the windward wall, Cp2 to the opposite leeward wall. Cp3 and Cp4 refer to the lateral walls. The L and U refer to the lower floor and upper floor, respectively.

Figure 4.21a shows that a reading far from the others results in the assumed uniform distribution not including it. For Cp1, Cp2, and Cp4, the range of DisTM is more comprehensive than that of ReaT. For Cp3, the range of DisTM is one-third of that of ReaT.

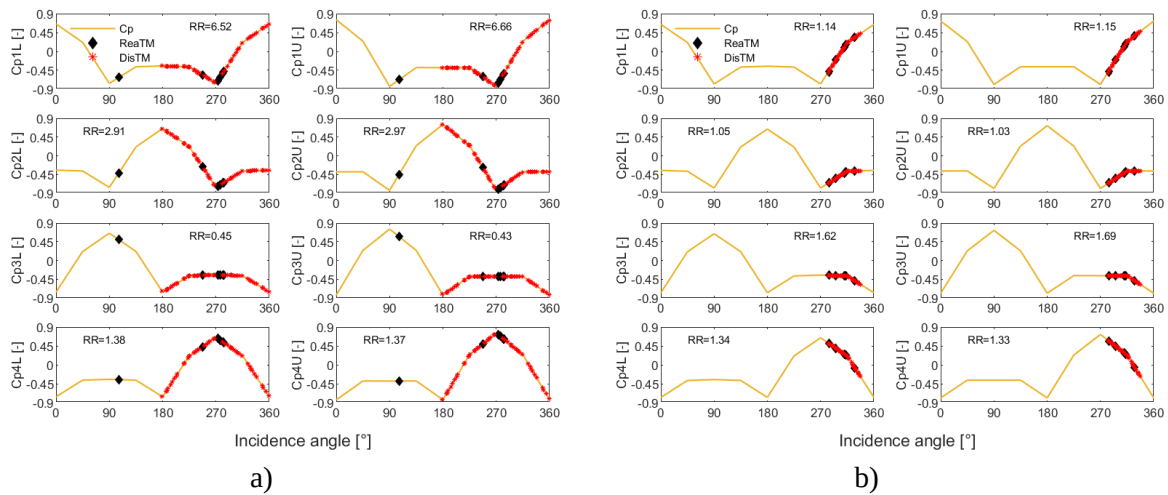


Figure 4.21. Comparison of wind pressure coefficients (WPCs) of the vertical exposed surfaces for ReaTM and DisTM setups in the hour 160 (a) and hour 138 (b) of the used meteorological dataset; RR refers to range ratio

Figure 4.21b portrays the advantage of using the uniform distributions, as the sampled meteorological values result in wind pressure coefficients along, between, and slightly over the ReaTM readings range. As these represent over 86.6% of the hours in the whole studied year, it seems a reasonable trade-off.

4.3.2.4. Combined effect

The step-wise increment in complexity from one setup to the following made it possible to single out the impact of each effect in the intra-hour dispersion of the air change rates. Comparing the outputted ACH of the first setup, AveT, with the full proposed methodology, DisTM, highlights the full scope of the disparities. Figure 4.22 shows for the first 72 hours of the dataset the hourly averages resulting from the AveT setup and the hourly averages and ranges resulting from the DisTM setup. The averages of the two setups experience significant differences, with DisTM consistently outputting lower ACH during nighttime and higher in daytime periods.

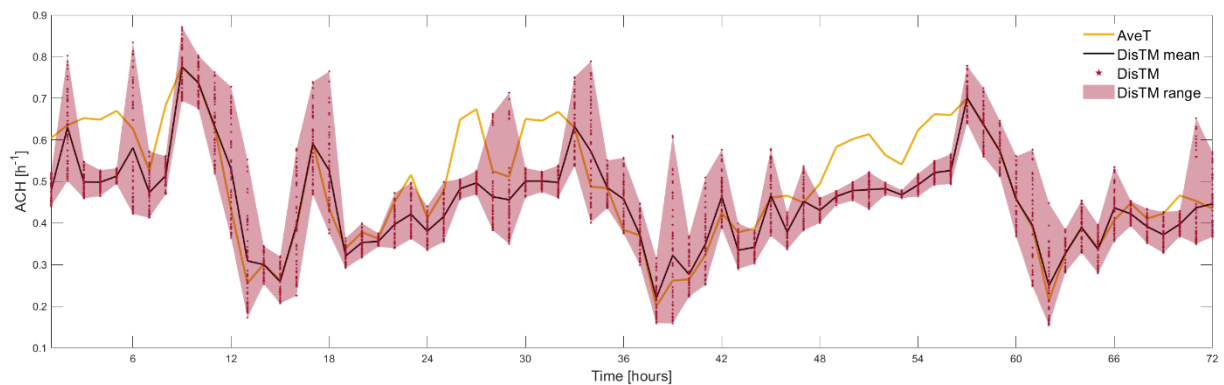


Figure 4.22. Average air change rates (ACH) in AveT and DisTM setups, range band, and scatter in DisTM from the 1st to the 3rd of January of the meteorological dataset

4.4. NUMERICAL APPLICATIONS FINAL REMARKS

The Applications of the present Chapter pursued a further understanding of how the airtightness levels, the configuration of air leakage paths, and the discretization of airflow modelling impact the variability of ACHs through time and the performance of ventilation strategies.

The case study of Application A3 represents a common Portuguese situation with highly permeable envelopes. Several conclusions arise from the discussion on the outputs of the different simulated configurations and the measurements of the real case study:

- Results from simulation on the studied dwelling presented a low average air change rate associated with highly variable hourly values. Tracer gas measurements in the case study showed that most of the air that infiltrates through the bedroom also exfiltrates in it. The sweeping effect from the bedroom to the bathroom only occurred when MEV was on;

- Although there are limitations on comparing real data with simulation results, as there is uncertainty in measurements and discretization in the input data, a significant accord between estimate values of ACH on measurement results and one of the scenarios is found. Scenario 1 (1.56 h^{-1}), corresponding to air leaks concentrated in fewer locations, showed significant agreement with the obtained in-situ results (1.52 h^{-1}). With MEV off, the simulation output was 0.19 h^{-1} , and CO_2 measurements resulted in 0.15 h^{-1} ;
- The distribution of the ELA through different leakage path configurations is an impactful factor when addressing ACH. From the most concentrated air leakage path configuration to the most dispersed one, Scenario 1–3, there is an increase of around 63% of the ACH;
- The adequate design of ventilation systems depends on prior knowledge of the airtightness level, as the whole system performance depends on it. In Scenario 1, with the ELA concentrating in windows and doors, an ACH_{50} change from 11.5 to 0.6 h^{-1} results in an 0.92 h^{-1} ACH drop.

The results confirmed that the relation between airtightness and air change rates should be carefully analyzed. The identification and sealing of air leakage paths, and further testing in the case study, would give additional data for input and comparison with simulation results. Although not being in the aims of Application A3, it would be an interesting methodology to develop and apply in the future. Together with the consideration of uncertainties, in the case of sensitivity analysis, the methodology used in this research could be generalized to increasingly complex and comprehensive case studies.

Complementarily, the work presented in Application A4 evaluated the effect of atmospheric stability and intra-hour variability of meteorological variables in quantifying air change rates of buildings with natural ventilation and leaky envelopes. The analysis and comparison of the different simulated setups allowed one to extract meaningful conclusions. They are as follows:

- Using 10-min readings instead of hourly meteorological data in ACH simulations detected a time step effect showed, in this case study, by an hourly standard deviation of ACH between 0.025 and 0.065 h^{-1} (between the 25% and 75% quantiles) while at the 95% quantile the standard deviations reached 0.126 h^{-1} ;

- Atmospheric stability classes showed to change outputted results significantly. Approximately 43% of the time was in non-neutral conditions. The hourly ACH relative differences between a setup with neutral atmospheric conditions and another setup admitting varying atmospheric conditions averaged -0.031 h^{-1} , with a standard deviation of 0.095 h^{-1} . At the 5% and 95% quantiles, the ACHs differences were -0.202 h^{-1} and 0.131 h^{-1} , respectively;
- The similar results found for the atmospheric stability classification when using deterministic versus stochastic meteorological variability gives robustness to the application of hourly uniform distributions to the meteorological variables considered;
- From deterministic to stochastic meteorological variability, the average ACH range increased by an average of 29.3%. Still, in 13.4% of the events, the hourly ACH ranges were narrower in the stochastic simulation setup due to the limitation of the hourly uniform distributions in encompassing all the 10-min readings of these hours.

The methodology detailed and discussed in this work considers shorter time steps and the effect of changing atmospheric stability to evaluate the fluctuations in environmental conditions that influence infiltration driven air change rates in building envelopes. Using hourly distributions and stochastic sampling ensures that the values between and others potentially occurring around the boundaries are considered for ACH calculation, providing a more exhaustive approximation of the actual conditions.

While for a year-long joint observation, these findings do not significantly change the central tendency of the ACH, they provide important information on the intra-hour dispersion. It can be helpful to predict better hourly ranges of performance that can have multiple applications in the ventilation strategy, either in the design stage or in the optimization of the performance of an existing building.

The generalization of the methodology includes the definition of additional combinations of building geometries and terrain roughness, assessing the impact on results of using alternative formulations, such as the quadratic equation in modelling airflow paths, and the logarithmic law in vertically extrapolating wind speeds, and analyzing the correlation between meteorological variables and pressure distribution along the building facade.

The conclusions from Application A3 highlight the relevance of Application A1 and A2. The airtightness level and the configuration of the air leakage paths are significant in the produced air change rates. Therefore, quantifying and locating the air leakage paths brings relevant information on designing and retrofiting scenarios. Application A4 showed that the detail on meteorological datasets and respective treatment for simulations also significantly impact the air change rates variability over time.

Even though one hopes to pave the way for increasingly accurate simulated air change rates for the context of naturally ventilated dwellings, as of today, some important issues in the present state of air infiltration research prevent the generalization of the full methodology of Application A4:

- The category boundaries of the σ_A method require adjustments according to the site roughness, and the roughness length is typically not uniform in all directions at the measuring site;
- While CpCalc+ provides an interesting tool to obtain the wind pressure coefficients with changing wind shear coefficient, its use is limited to some predefined standard geometries and specific ranges of wind shear coefficients, particularly the upper limit cap.

5

TOWARDS AN AIRTIGHTNESS PERFORMANCE LABELLING STRATEGY FOR A SUSTAINABLE BUILDING STOCK

5.1. CONTEXT

Chapters 3 and 4 focused on research that can contribute to the improvement of airtightness applications in naturally ventilated dwellings, which are the predominant typology in southern European countries. The literature review revealed a generalized lack of airtightness awareness in these countries, which translates into a lax approach to the issue. This Chapter provides valuable insights for implementing airtightness requirements in the referred countries at a potential regulatory scope. The developments are presented in three Applications (A5, A6, and A7).

Application A5 schemes and introduces a probabilistic approach in defining an airtightness performance labelling strategy for dwellings in the southern European context. This labelling strategy depends on the potential performance ranges that were attained by gathering data from a dataset representative of a built stock in the same context and applying smart sampling techniques to represent the dwellings characteristics and their respective combinations adequately. A rationale on lower and upper limits for air change rates is defined, and dwellings are labelled accordingly.

Because of the issues referred to in the last paragraph of Subsection 4.4, while relying on the single zone airflow model used in Application A4, in Application A5, adjustments are made in the input data and pre-processing to encompass a broader scope of dwelling features. It is a needed step to fulfil the proposed objectives.

Application A6 explores and develops an airtightness compliance tool based on the information gathered from the dataset created in Application A5, namely: dwellings and terrain characteristics, the respective air change rate outputted time series, and the labels attributed to them. The proposed tool aims to be user-friendly and applicable to designing and retrofitting naturally ventilated single-family dwellings regarding airtightness.

Identifying airtightness performance ranges and developing a compliance tool for a wider range of the referred aspects can result in complete guidelines and operating user-friendly tools, respectively, with potential application in national policies regarding airtightness and ventilation performance of naturally ventilated buildings.

Application A7 assesses the life cycle impacts of applying full envelope airtightness solutions in a subset of dwellings labelled as the worst performers regarding energy efficiency in Application A5. To that end, one must assume that a heating system equips each of the dwellings. In these conditions, both energy and environmental performance can be evaluated, alongside a Life Cycle Cost assessment.

Sections 5.2, 5.3, and 5.4 focus on Applications A5, A6, and A7, respectively. Lastly, Section 5.5 provides conclusions on the undertaken work.

5.2. PERFORMANCE LABELLING STRATEGY APPLIED TO THE AIRTIGHTNESS OF NATURALLY VENTILATED DWELLINGS (A5)

The objective of Application A5 is to contribute to the definition of airtightness requirements in the context of southern Europe by establishing a methodology and applying it to a case study. A probabilistic approach using a single zone model based on method 1 of the standard EN 16798-7:2017 [195] was used in this Application. The basis of the developed model is exposed in Application A4, while Subsection 5.2.1.3 details the changes made to it to enable the analysis. Application A5 aims to:

- Define a representative sample of the built stock to establish reliable dwelling characteristics, and analyze data from a meteorological station to assess the average outdoor conditions during the heating season;
- Evaluate the airtightness performance in a dataset representative of a predominantly naturally ventilated residential built stock, particularly Portuguese single-family

buildings, in the context of southern Europe mild climates, specifically the Metropolitan Area of the Porto region in the north of Portugal;

- Develop a labelling strategy based on airtightness performance and propose airtightness performance ranges for the subset of analyzed dwellings.

5.2.1. METHODOLOGY FOR THE STATISTICAL APPROACH

5.2.1.1. Dwellings sample characterization

As data regarding airtightness characterization is rather limited in Portuguese studies, one performs a joint analysis with Spanish ones. Assessing the latter supports evaluating their similarity with the results of the first, allowing the possibility of using a more suitable dataset to generate the input sample for simulation.

Table 5.1 presents statistical information on samples of buildings tested for airtightness in main studies of Portugal and Spain. While the differences between periods of construction present no clear trend [18][372], renovations seem to improve airtightness performance, even if often marginally because airtightness is not directly addressed [82].

Table 5.1. Summary of dwellings n_{50} characteristics of airtightness studies performed in Spain and Portugal

Country	Sample size	Period	Renovation	Minimum	Average	Maximum	Std. Dev.	Ref.
Portugal	7	1991	No	4.4	7.5	12.9	2.6	[365]
	24	1972	No	3.6	8.9	15.6	3.1	[82]
	25	1972	Yes	3.2	6.8	13.1	2.7	[82]
	2	<1960	No	7.5	8.4	9.3	0.9	[366]
	2	<1960	Yes	5.5	5.9	6.2	0.4	[366]
	12	1961-1990	No	2.4	7.1	20.0	5.3	[367]
Total	72	All	All	2.4	7.6	20	3.3	-
Spain	45	1991-2012	No	3.2	5.7	8.7	1.7	[77]
	2	1961-1990	Yes	3.2	3.9	4.7	0.7	[12]
	11	1991-2012	No	2.6	6.7	13.4	2.6	[12]
	7	<1960	Mixed	5.1	5.8	10.1	1.8	[372]
	46	1961-1990	Mixed	3.0	7.6	14.7	2.7	[372]
	106	1991-2012	Mixed	2.7	6.6	15.6	2.4	[372]
	225	Together	Mixed	~2	8.4	~38	4.2	[373]
	111	Together	Mixed	1.2	7.1	21.8	3.7	[18]
	18	Together	Mixed	1.4	6.1	12.4	2.9	[18]
Total	571	All	All	1.2	7.4	~38	3.4	-

Spain recently completed the INFILES project [374]. The project compiles most of the presented data of the studies performed in Spain, and the executed sampling scheme aimed to obtain a representative sample of the national built stock.

When one plots its data with the Portuguese collected studies, it shows that the studied dwellings have very similar overall distributions. This similarity implies that the construction technology and practices of the built stock are quite identical between the countries (Figure 5.1). The p-value of the two independent samples t-student test supports this conclusion (Table 5.2).

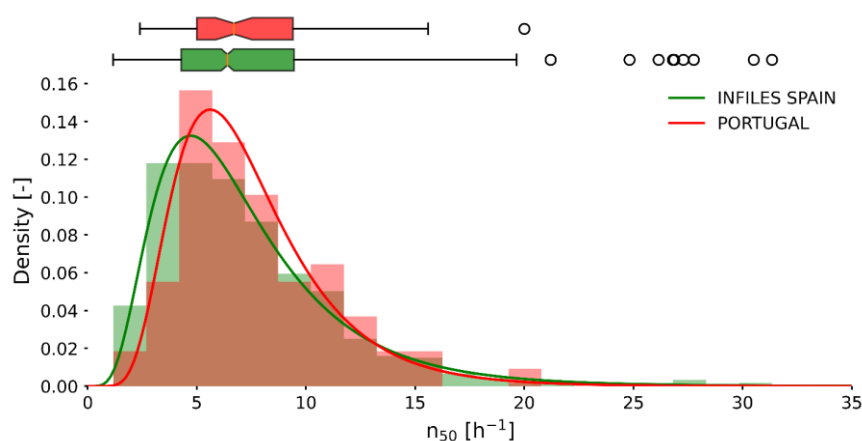


Figure 5.1. n_{50} distributions of INFILES project and the compiled Portuguese studies

Table 5.2. Comparison of n_{50} distributions between the INFILES project and the compiled Portuguese studies

Samples	N	Mean	Std. Dev.	Mean Std. Error.	LogN p-value	2-sample t p-value
INFILES project	792	7.30	4.25	0.15	KS (0.86) CS (0.46)	0.48
PT studies	72	7.61	3.50	0.41	KS (0.99) CS (0.93)	

The distribution of airtightness values presents positive skewness [158][81][80], justifying their non-normality [77]. These similarities support using the INFILES project data in the subsequent analysis.

The extracted data encompasses floor area, envelope area, volume, air change rate at 50 Pa and airflow exponent. The envelope area and volume apply to converting the air change rate at 50 Pa to air permeability at the same pressure difference. The ratio of volume by floor area computes the corresponding ceiling height.

A fitness test was performed to find the best distribution type for these continuous variables. Kolmogorov-Smirnov (KS) and Chi-Square (CS) tests failed to reject the hypothesis of the variables following lognormal distributions. Therefore, distributions of this type apply to fit these variables (Table 5.3).

Table 5.3. Details on the continuous variables regarding dwelling characteristics and evaluation of their respective distributions fitness

Continuous variable	Typology	N	Mean	Median	Std. Dev.	Fitness	p-value
Floor area (AF) [m ²]	Single	75	150.47	129.24	70.13	LogN	KS (0.78) CS (0.19)
Ceiling height (CH) [m]	Single	75	2.64	2.62	0.28	LogN	KS (0.64) CS (0.61)
Airtightness at 50Pa (n ₅₀) [h ⁻¹]	Single	150	6.45	5.65	3.50	LogN	KS (0.62) CS (0.37)
Air flow exponent (n) [-]	Single	150	0.60	0.60	0.04	LogN	KS (0.52) CS (0.56)

Several categorical variables were considered in agreement with representative reference dwellings of the Portuguese built stock [364] to achieve a higher diversity of terrain and dwellings characteristics. These characteristics relate to terrain (α), side ratio (SR), roof slope (RS), number of exposed surfaces (ES), number of vertical ducts (ND), and number of floors (NF). Table 5.4 compiles the considered categorical and continuous variables for sampling.

Table 5.4. Geometry, terrain and airtightness variables considered

Categorical variables	Levels
Location/Terrain (α)	0.14 / 0.22
Side ratio (SR)	1:1 / 2:1
Roof slope (RS)	0° / 20°
No. exposed vertical surfaces (ES)	2 / 3 / 4
No. vertical ducts (ND)	2 / 3 / 4
No. floors (NF)	1 / 2
Total of combinations	144
Continuous variables	Distribution
Floor Area (AF) [m ²]	LogNormal
Ceiling Height (CH) [m]	LogNormal
Airtightness at 50Pa (n ₅₀) [h ⁻¹]	LogNormal
Air flow exponent (n) [-]	LogNormal

Regarding terrain characteristics, two terrains are examined ($\alpha = 0.14$; $\alpha = 0.22$) corresponding to rural and urban surroundings, respectively, according with ASHRAE Fundamentals [363]. The orientation of the house is 0°, north. Three configurations applied regarding the number of exposed vertical surfaces (ES): 4, 3, and 2 ES. The west wall has no air exchanges in the three ES configurations, and the west and east walls have no exchanges in the two ES configurations.

The levels of the categorical variables result in a total of 144 combinations. Figure 5.2 depicts the relationship between SR and NF when quantifying envelope geometry.

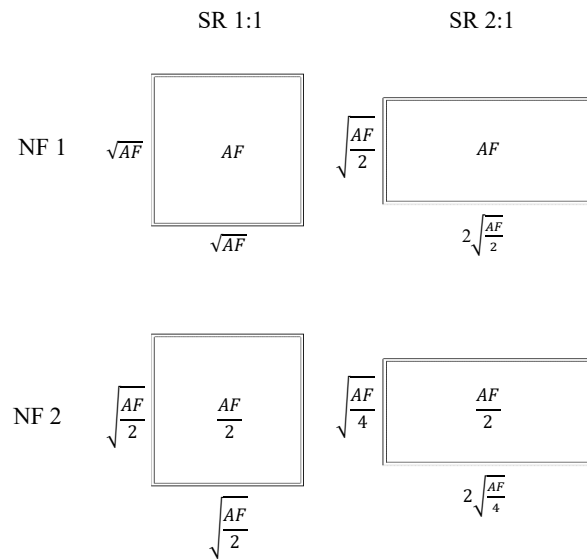


Figure 5.2. Geometry relationships between SR, NF, and AF

Since one aims to portray a significant number of combinations between these variables, a Latin Hypercube Sampling (LHS) was performed to represent the sampling space, as it outperforms simple Monte Carlo sampling [347][348].

This technique allows inputting a correlation matrix alongside the original data, preserving the existing significant correlations in the output sample [375]. The Spearman correlation coefficient addressed the effect of correlation between the variables. Correlations were statistically significant at the 5% significance level between AF and n_{50} and between n_{50} and n (Table 5.5). A decrease in n represents an increasing dominance of laminar flow over turbulent, typical of broader airflow paths.

Table 5.5. Correlation matrix of the continuous variables considered with the upper triangle indicating the p-values for statistical significance and the lower triangle pointing the Spearman correlation

coefficient				
p\ p-value	AF	CH	n₅₀	n
AF	1	0.57	0.00	0.74
CH	-0.05	1	0.84	0.21
n₅₀	-0.30	-0.02	1	0.01
n	0.03	-0.10	-0.20	1

The LHS method generated 300 dwellings, corresponding to different combinations of the continuous variables. The group of 300 is then combined with the 144 possible combinations of the categorical variables creating a dataset of 43200 unique single-family dwellings for simulation.

The achieved sample characterizes most of the diversity and combinations of geometry and airtightness characteristics of the Portuguese residential building stock of single-family dwellings. Even if it refers to single-family buildings with one or two floors only, which is not a complete representation of the existing dwellings in the Portuguese built stock, single-family dwellings represent over 86% of the residential stock [368]. For this subset, over 44% and over 47% have one and two floors, respectively, totaling over 91% of the total single-family dwellings.

5.2.1.2. Meteorological data and indoor environment characterization

The used meteorological data comes from the same weather station as the one used and described in Application A4, Subsection 4.3.1.5, located in the Metropolitan Area of the Porto region in the north of Portugal.

For reasons of computational cost, a representative month of the heating season was chosen, from the 1st of February to the 2nd of March of 2015, totaling 30 consecutive days. The raw data was recorded at a time-step of 10 minutes but averaged hourly by the same reasoning, totaling 720 hours (Figure 5.3).

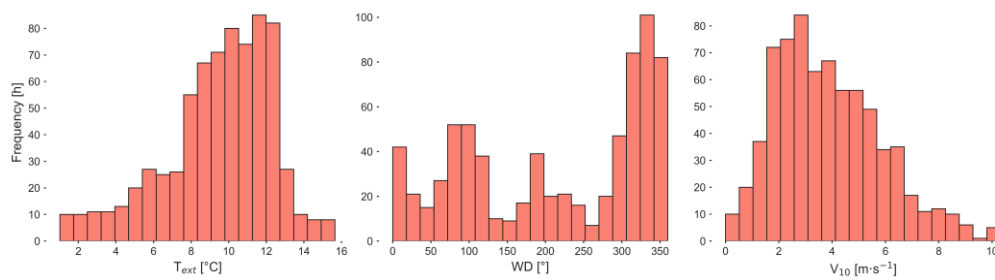


Figure 5.3. Hourly averaged distribution of the meteorological variables from the 1st of February to the 2nd of March of 2015

Concerning the indoor environment, the interior temperature was set to 18 °C, following the operative temperature established by EN 16798-1 for category III in residential buildings during the heating season [370].

5.2.1.3. Input libraries and airflow balance

The single-zone model based on method 1 of the standard EN 16798-7:2017 [195] developed in Application A4 allows one to apply a probabilistic approach that was not possible to implement using existing publicly available software such as CONTAM. The ACH calculations occur in the 43200 individual dwellings (300 x 144) for the 720 hours considered, resulting in the simulation of 31104000 events.

The model considers the dwelling a single zone and calculates the ACH by balancing the air mass flow rate. Subsection 4.3.1.3 of Application A4 details the model, while Subsection 4.3.1.4 explores its assumptions and limitations.

Still, as seen in Subsection 4.4, the generalization of the full preprocessing to a wider range of dwellings and terrain characteristics requires input data that is not available till the present day. This data refers to WPCs and their relation with changing category boundaries of the σ_A method regarding atmospheric stability. Because of this limitation, some changes need to be implemented to fulfil the objectives of this Application. However, the model and the convergence engine itself remain unchanged.

Regarding wind pressure coefficients (WPCs), the tables available in AIVC documentation [186], specific for low rise dwellings, were used. These tables divide buildings by SR and sheltering level. For this Application, from that particular document, the designated exposed

dwelling WPCs tables apply for a rural location, and for an urban site, the semi-sheltered ones apply. Concerning the roof slope, one used the flat roof WPCs tables for the defined roof slope of 0°, and the tables designated for roof slope till 30°, for the defined roof slope of 20°. As these tables only account for 45° steps, a linear interpolation within each of them was assumed to obtain the 1° step values for the remaining of the 360 possible angles.

5.2.1.4. Rationale on air change rate limits

As presented in Subsection 1.1, maintaining favorable ACHs in a dwelling is a matter of balance between meeting minimum thresholds for the great majority of the time and avoiding high ACHs for energy efficiency. Regarding health concerns, the minimum limits imposed or recommended by different countries greatly diverge [9], ranging from 0.3 h⁻¹ to 1.0 h⁻¹ limits (Table 5.6).

Table 5.6. Minimum ventilation rates in dwellings (adapted from [9])

Country	Minimum ACH for dwellings [h ⁻¹]
Czech Republic	0.3
Finland	0.5
France	0.5 ⁽¹⁾
Germany	0.4 ⁽¹⁾
Greece	0.7
Hungary	0.6 ⁽¹⁾
Italy	0.3
Lithuania	0.5
Netherlands	1.0
Norway	0.5 ⁽¹⁾
Portugal	0.4
Romania	0.5 ⁽¹⁾
Slovenia	0.5
United Kingdom	0.45 ⁽¹⁾

⁽¹⁾ 120 m² of floor area and a ceiling height of 2.5 m

In Portugal, by 2020, this limit is 0.4 h⁻¹ in the heating season and 0.6 h⁻¹ in the cooling season [196]. By mid-2021, legislation changes indicate that if the mean ACH is below 0.5 h⁻¹, it should be considered 0.5 h⁻¹ for calculating heat transfers by ventilation [376]. If it is above 0.6 h⁻¹, it should be regarded as 0.6 h⁻¹. For the present research, the minimum ACH considered was 0.4 h⁻¹. The upper limit, related to excessive heating loads due to heat transfers by air change rates, was defined at 0.7 h⁻¹. The defined ACH lower and upper limits at the EU level correspond to the default predefined ventilation airflow rates for residential buildings of categories IV and I,

respectively, of EN 16798-1:2019 [370]. These categories relate to indoor environmental quality and occupants' expectations.

Figure 5.4 schemes a flowchart of the rationale for establishing airtightness performance ranges. Since the system is passive, dwellings with different geometry, airtightness, and terrain characteristics, perform disparately. For example, dwellings of a particular group where the wind speed has a high impact will experience high ACH dispersion. Therefore, their ability to fulfil the intended range of ACH in a certain percentage of time will be diminished, compared with dwellings from another group where this impact is lower. The top-performing dwellings in the first group will have a share of time between 0.4 h^{-1} and 0.7 h^{-1} ACH lower than the top-performing dwellings in the second group. For this reason, for applying the labelling procedure, the dataset divides by the most impactful categorical variable found by feature selection.

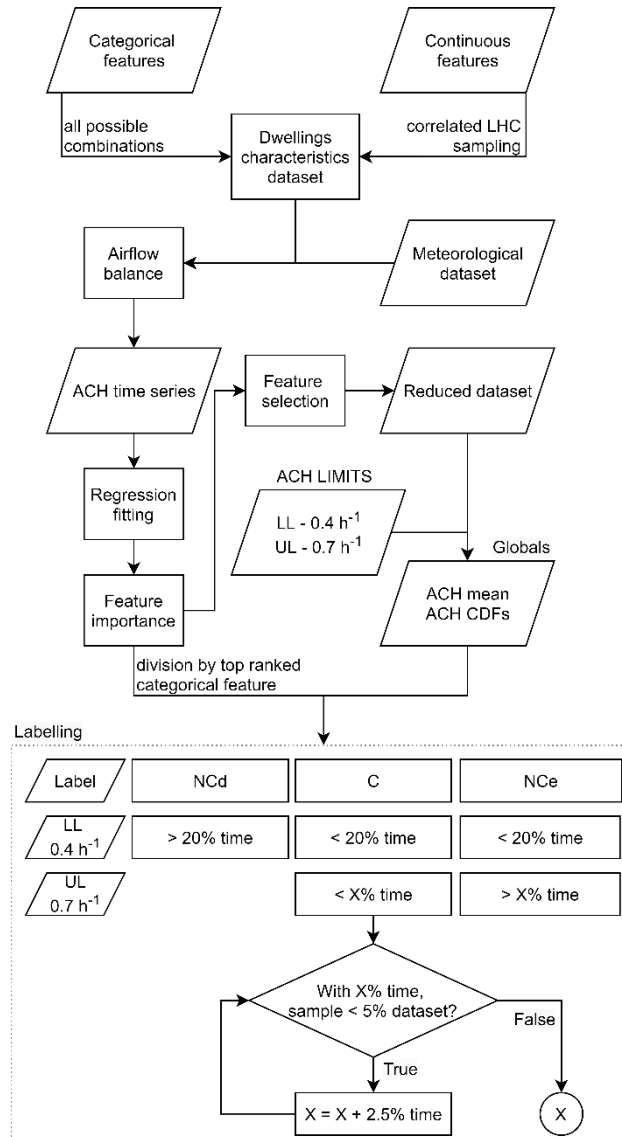


Figure 5.4. Flowchart on processing inputs, manipulating time series, and labelling dwellings performance

For the labelling strategy, the dwellings are grouped according to the percentage of time they are below, between, and above the proposed ACH lower and upper limits as non-compliant by default (NCd), compliant (Com), and non-compliant by excess (NCe), respectively. The following rules apply (Labelling block in Figure 5.4):

- Those with an ACH below 0.4 h⁻¹ more than 20% of the time are labelled as non-compliant by default (NCd). This percentage is of category II of EN 16798-1 standard on the expected rate of dissatisfied occupants based on CO₂ levels [370]. From 1000 ppm, around 20% of users are expected to feel dissatisfied with the indoor air quality [377];

- After applying the NCd threshold, the criterion shifts to the percentage of time the ACH is above the 0.7 h^{-1} upper limit for the remaining dwellings. Steps of 2.5% in time above this upper limit increment until a sample size of 5% of the initial dataset gets encompassed. This group of dwellings is labelled as compliant (Com), and they are the top performers;
- The remaining dwellings are labelled as non-compliant by excess (NCe).

5.2.2. RESULTS AND DISCUSSION ON THE STATISTICAL APPROACH

5.2.2.1. Exploratory data analysis

Figure 5.5 explores the correlations between variables. Figure 5.5a) presents a plot matrix of the ACH and meteorological variables of the 720 hours for the first dwelling simulated. Figure 5.5b) informs on the ACH and continuous variables regarding dwellings characteristics of the 300 sampled with Latin Hypercube (LHC) in the first discrete combination for the first hour of the studied dataset.

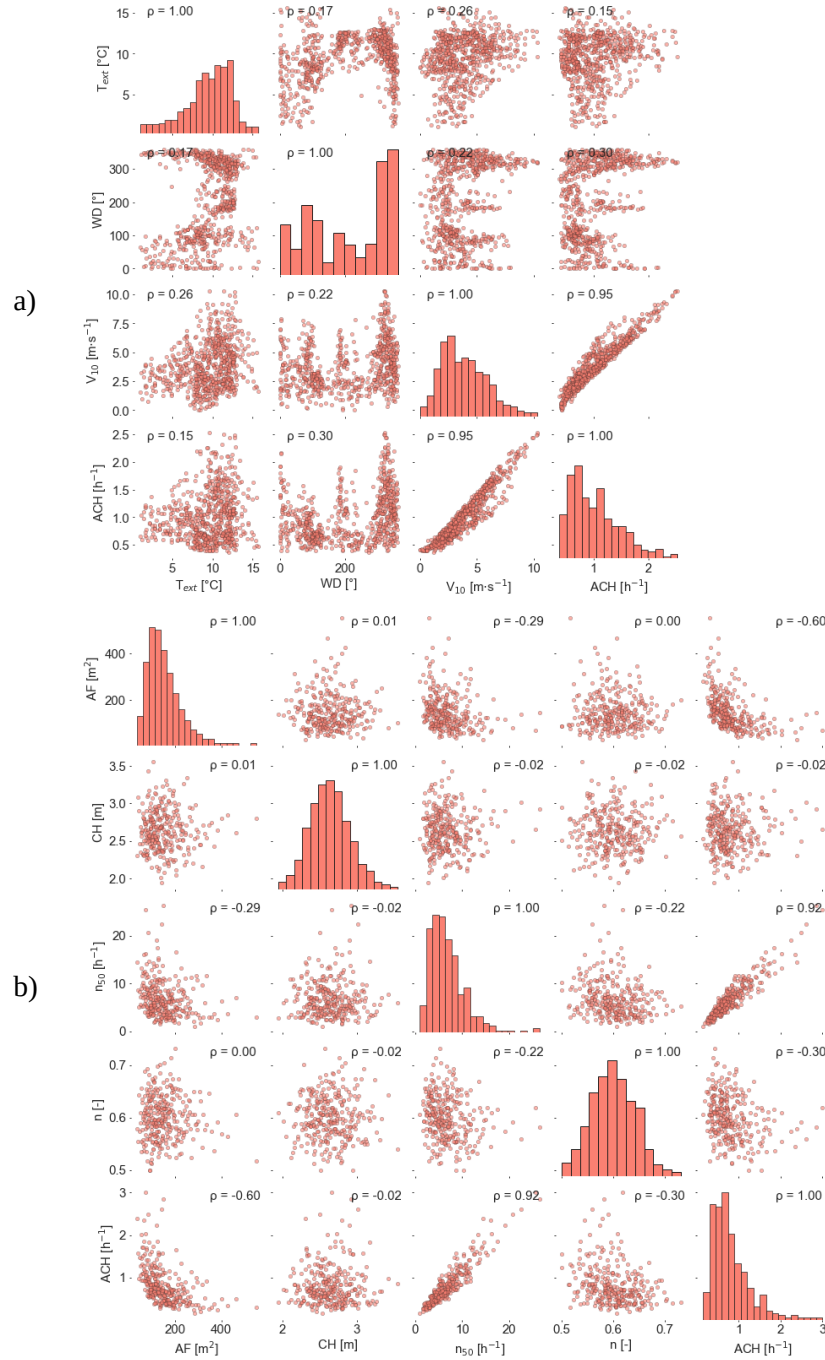


Figure 5.5. a) Matrix plot of the meteorological variables and response for the first parametrized house (AF=88.9 m²; CH=2.95 m; n_{50} =10.2 h⁻¹; n =0.5; α =0.14; SR=1:1; RS=0°; ES=2; ND=2; NF=1); b) Matrix plot of the sampled 300 dwelling continuous variables for one of the discrete combinations (α =0.14; SR=1:1; RS=0°; ES=2; ND=2; NF=1) for the first hour of the studied dataset

Several significant correlations are present between predictors despite none reporting an absolute Spearman correlation coefficient above 0.26 between meteorological predictors and above 0.29 between dwelling predictors. Regarding correlations between predictors and ACH,

the wind speed and n_{50} show the highest scores, followed by AF. As WD presents no monotonicity in its distribution, the coefficient presents no relevant information.

The demonstrated strengths of the correlation between variables and response give a general view of the importance of each variable for the resulting ACH in the whole dataset. Still, the ones shown only relate to the specific geometrical and airtightness characteristics of a small portion of the dataset indicated in the caption of Figure 5.5. A feature importance analysis allows one to grasp the influence of the variables in the produced ACHs.

5.2.2.2. Feature selection by importance

Feature selection encompasses a set of tests that score the impact of each of the input variables, often referred to as features, in the variability of the outputted ones, ACH in this particular instance.

As a first indicator, one-way ANOVAs applied. One visualizes in Figure 5.5 that the response distribution has significant positive skewness presenting a long right tail. As the airflow follows an exponential law by applying a natural logarithm to the ACH before performing the analysis, one brings the response closer to a Gaussian distribution giving robustness to the test. Table 5.7 informs on these statistics between different categories in each categorical variable, normalized to the maximum. Figure 5.6 pictures the overall f-statistics of the categorical variables, normalized to the max.

Table 5.7. One-way ANOVAs between the levels within the considered categorical variables normalized to the maximum

Variable	Level	ACH mean [h^{-1}]	ACH std. dev. [h^{-1}]	F-stat levels normalized
Location (α)	0.14	0.747	0.550	1.000
	0.22	0.534	0.344	
Side ratio (SR)	1:1	0.619	0.444	0.039
	2:1	0.662	0.495	
Roof slope (RS)	0°	0.654	0.479	0.015
	20°	0.627	0.462	
No. exposed surfaces (ES)	2	0.625	0.477	0.038
	3	0.639	0.461	
	4	0.659	0.474	
No. vertical ducts (ND)	2	0.583	0.447	0.100
	3	0.643	0.469	
	4	0.696	0.489	
No. floors (NF)	1	0.558	0.417	0.913
	2	0.724	0.506	

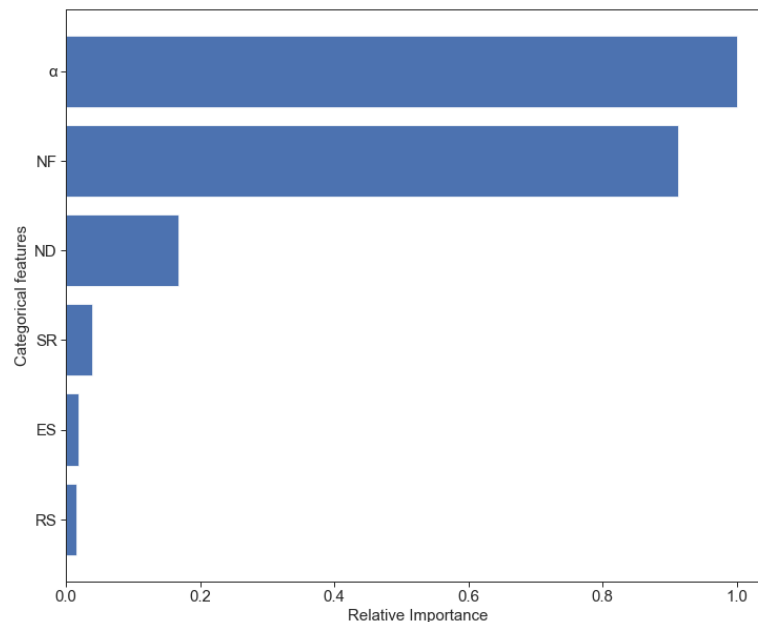


Figure 5.6. ANOVA f-statistics for the considered categorical variables normalized to the maximum

The change from a rural to a suburban/urban environment (α) is the feature with greater influence in the ACHs, closely followed by NF. The least impactful are RS, ES, and SR. Although the ANOVA test allows extracting relevant information, the main drawback is that it only captures linear relationships. As non-linear relationships are present in the dataset, other methods should complement the analysis.

A decision tree regression can inform on the feature importance of both continuous and categorical variables as it assigns scores to them depending on the total reduction of the criteria

attributed to each, usually the Mean Squared Error (MSE) (Figure 5.7) [378]. It refers to the total decrease in node impurity weighted by the probability to reach that node and generally informs on the ability of a specific variable to split the samples in the dataset as the tree develops from root to leaves. The node probability is the ratio between the number of events that reach the node and the total number of events. The feature is more important the higher the ratio.

There are two main advantages of this method compared to traditional panel data [379]: (i) it identifies non-linear relationships between the predictors; (ii) it is computationally less intensive, and so the whole dataset can be treated simultaneously.

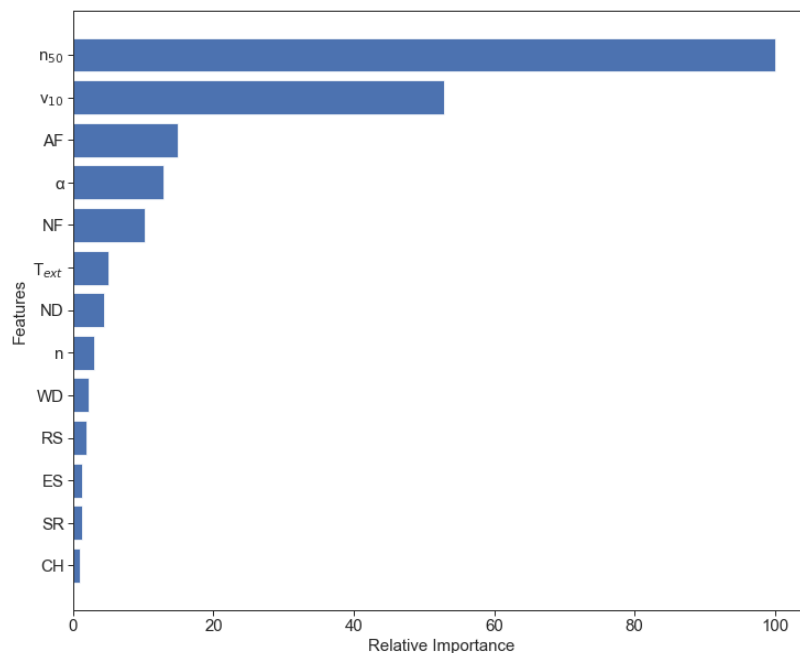


Figure 5.7. Feature importance by decision tree regression

The results point to n_{50} as the variable with the most impact in ACH variability. As expected, from the continuous meteorological variables, the wind speed (V_{10}) is the most impactful one, having over five times the impact of T_{ext} , while WD has residual importance. After n_{50} , AF is the second most important feature from the dwelling related continuous variables, followed by n. CH has residual importance.

Similarly to ANOVA results, the order of the most impactful categorical features remains the same in the decision tree regression results. The ES, SR, and RS have residual relative

importance compared to the other categorical variables, with only SR changing places with RS compared to the ANOVA results.

From the analysis of the results of the two methods, ES, RS, and SR categorical features are dropped from the dataset to evaluate dwellings performance. Therefore, only the combinations with a 2:1 SR, 4 ES, and a 20° RS will be considered for the rest of the Section, reducing the number of dwellings in the analysis to 3600 unique dwellings. Annex A5 details their characteristics.

5.2.2.3. Dwellings classified by the labelling strategy

To propose n_{50} performance ranges, one needs to detail the highest performing dwellings. Since α , NF, and ND, were the most impactful categorical features, only these will be addressed in this Subsection, comprising 12 total combinations.

The simulated dwellings are assessed by the time each is below, between, or above the limits defined in Subsection 5.2.1.4. By inspecting the ACH probabilities during the considered time scope, one can perceive the dwellings overall behavior. For each of the 3600 remaining dwellings, Figure 5.8 plots the ACHs probability being below 0.4 h^{-1} , between 0.4 and 0.7 h^{-1} , and above 0.7 h^{-1} plot against the ACH means. The results are divided between a rural and an urban terrain for further understanding. This categorical feature applies as it is the one identified as the most impactful in ACH variability.

Observing Figure 5.8, the higher the relative importance of wind, the less concentrated is the resulting ACH distributions. While the ACHs maintain a more compact configuration in urban terrain, the dispersion of ACHs intensifies as the terrain goes from urban to rural.

In a rural environment, the dwellings have an average ACH of 0.79 h^{-1} . It is 24.8% of the time below 0.4 h^{-1} , 31.3% between 0.4 and 0.7 h^{-1} , and 43.9% of the time above 0.7 h^{-1} . In this category, no dwelling performs over 63.9% of the time between 0.4 and 0.7 h^{-1} .

In an urban environment, the dwellings have an average ACH of 0.54 h^{-1} . It is 41.5% of the time below 0.4 h^{-1} , 35.4% between 0.4 and 0.7 h^{-1} , and 23.1% of the time above 0.7 h^{-1} . In this category, no dwelling performs over 83.3% of the time between 0.4 and 0.7 h^{-1} .

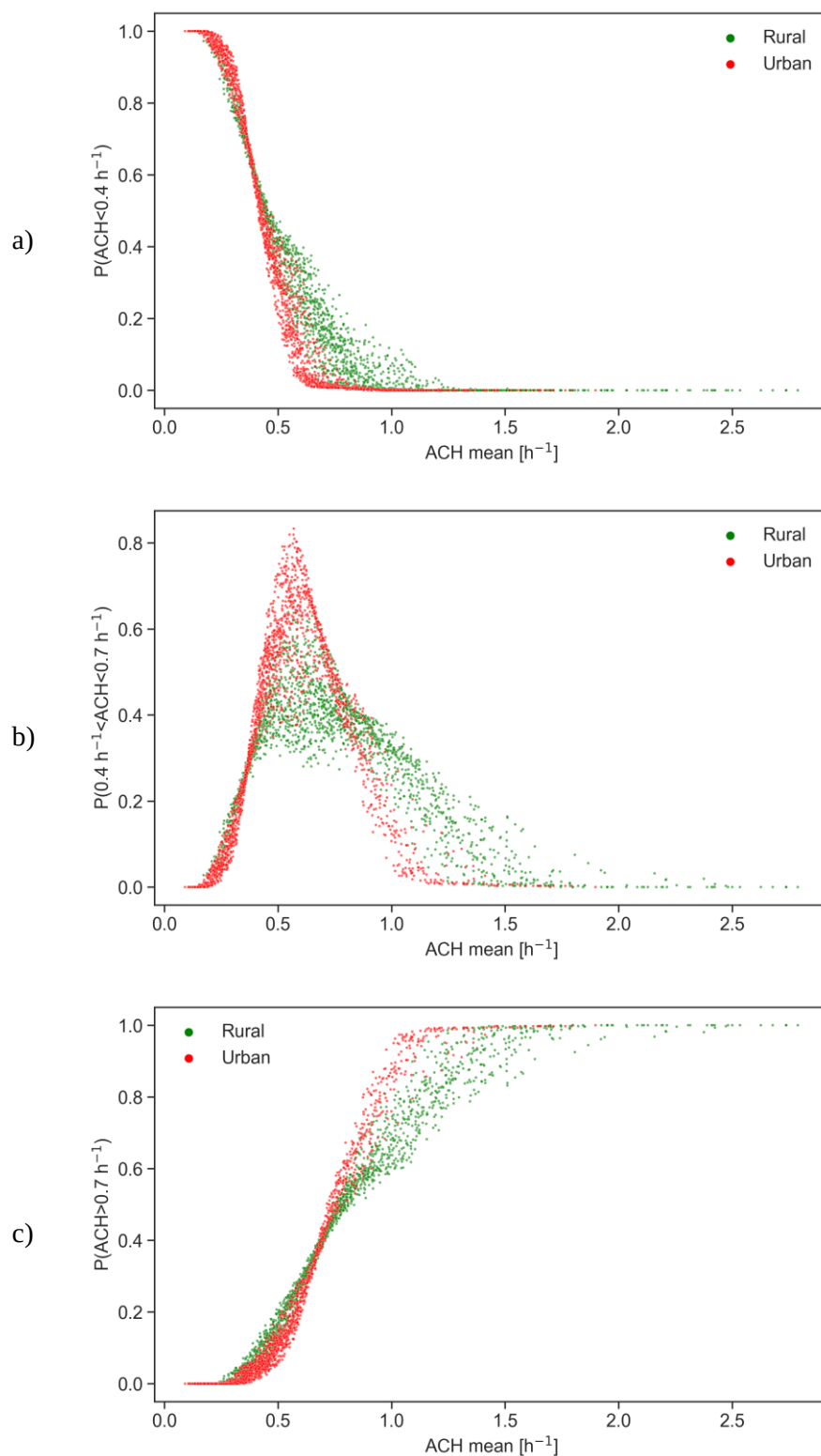


Figure 5.8. Mean ACH vs ACH probabilities for each dwelling after feature selection: a) $P(\text{ACH} < 0.4 \text{ h}^{-1})$; b) $P(0.4 \text{ h}^{-1} < \text{ACH} < 0.7 \text{ h}^{-1})$; c) $P(\text{ACH} > 0.7 \text{ h}^{-1})$

For the two considered terrains, the dwellings present suboptimal performance. As seen in Figure 5.8, if one intends to rely on natural ventilation in a terrain increasingly affected by wind speed, such as a rural environment, one needs to relax the expectations on the percentage of time a dwelling will surpass the ACH upper limit.

As such, and since one aims to use the highest performing dwellings to establish performance ranges, applying the methodology defined in subsection 5.2.1.4 results in the following lower and upper limits for the categories of the considered categorical variable (Table 5.8).

Table 5.8. Percentage of time the ACH of the compliant (Com) dwellings is below the lower and above the upper limits for each location after applying the labelling strategy. P(ACH condition) stands for the percentage of time the ACH complies with the stated condition

Time [%]	Rural ($\alpha = 0.14$)	Suburban and urban ($\alpha = 0.22$)
P(ACH < 0.4 h ⁻¹)	< 20	< 20
P(ACH > 0.7 h ⁻¹)	< 40	< 20

The sample in a rural environment has 96 dwellings, and the one in an urban environment has 100 dwellings, corresponding to 5.3% and 5.6% of the reduced dataset for each category (N=1800), respectively. Table 5.9 states descriptive statistics for these categories.

Table 5.9. Descriptive statistics of the groups of highest performing dwellings in a rural and an urban environment for the remaining dwellings dataset after feature selection. P(ACH condition) stands for the percentage of time the ACH complies with the stated condition

Feature	Metric	Rural ($\alpha=0.14$)	Suburban and urban ($\alpha=0.22$)
ACH [h^{-1}]	Mean	0.65	0.56
	Std. dev.	0.27	0.16
P(ACH < 0.4 h^{-1}) [%]	Mean	14.51	13.21
	Std. dev.	4.75	4.79
P(0.4 h^{-1} < ACH < 0.7 h^{-1}) [%]	Mean	52.14	72.32
	Std. dev.	6.02	5.11
P(ACH > 0.7 h^{-1}) [%]	Mean	33.35	14.47
	Std. dev.	5.38%	3.32%
n_{50} [h^{-1}]	Mean	4.89	5.75
	Std. dev.	0.75	1.03
N [-]	Mean	0.60	0.59
	Std. dev.	0.04	0.04
AF [m^2]	Mean	115.4	104.1
	Std. dev.	40.4	36.3
CH [m]	Mean	2.63	2.61
	Std. dev.	0.21	0.27
NF [-]	Mean	1.63	1.68
ND [-]	Mean	3.32	3.24

For the top 5% performing dwellings in a rural location, the average probability of the ACH being between 0.4 and 0.7 h^{-1} is 52.1%. For an urban environment, time averages of 13.2% under 0.4 h^{-1} and 14.5% above 0.7 h^{-1} showcase a more favorable performance regarding a natural ventilation strategy. Despite these performance disparities, averagely, the n_{50} offset is less than 1.0 h^{-1} , with 4.9 h^{-1} for the rural environment and 5.8 h^{-1} for the urban environment. As the NF and ND means show, frequency wise, dwellings with two floors tend to perform better than dwellings with one floor only. Additionally, a higher number of vertical ducts for extraction increase the dwelling ability to maintain proper ACHs.

5.2.2.4. Applicability of an airtightness based labelling strategy

Figure 5.9 plots the n_{50} values as a function of AF and compactness (CP) to perceive NF and ND impact in each of the locations and address the n_{50} range of the group and not only the means. Compactness represents the ratio between volume and envelope area, and it is a useful scale in regularizing dwelling characteristics for visualization and comparisons, as AF can point to misleading conclusions.

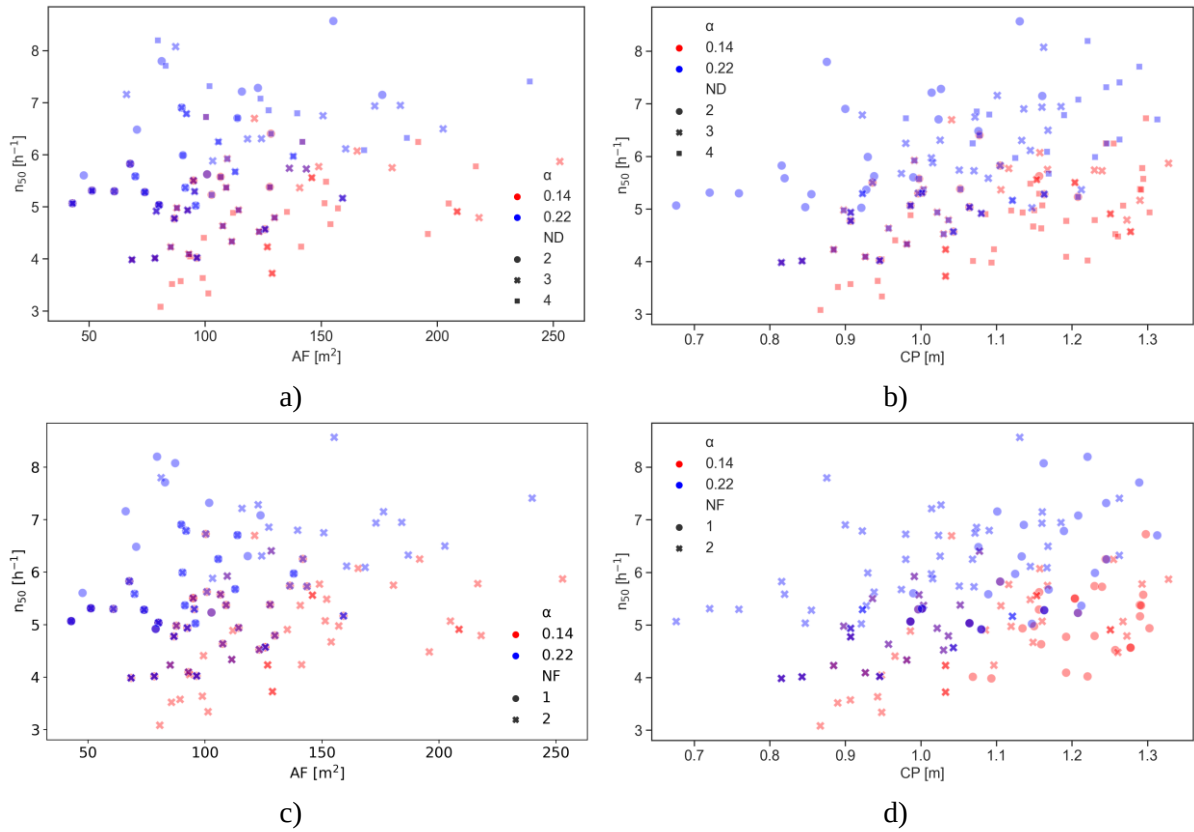


Figure 5.9. Airtightness vs geometry characteristics color split by environment: a) n_{50} vs AF detailed by number of ducts; b) n_{50} vs CP detailed by number of ducts; c) n_{50} vs AF detailed by number of floors; d) n_{50} vs CP detailed by number of floors

A positive trend is verified between the plotted features, as n_{50} increases when the floor area is larger or compactness grows, being the effect clearer in the latter. Generally, the increase in ND is associated with a rise in n_{50} . This effect is more pronounced in an urban environment.

A larger ND seems to be associated with maintaining adequate ACH rates in dwellings with larger AF or higher CP, as this extreme of the graph represents dwellings with three or four ducts only. In the other extreme, one perceives that a lower ND performs better in dwellings with lower CP and smaller AF. An NF of two is almost twice more prevalent than an NF of one, showing that the maintenance of the ACH between the pretended range accomplished with two floors more often.

Generally, one-floor dwellings need higher n_{50} than two-floor ones to maintain the same level of performance, again an effect noticeable to a greater extent in an urban environment. The lack of dwellings, after selection, in the lower range of the CP scale, in a rural environment, shows that a low CP leads to non-compliant dwellings in this location.

Overall, the graphs portray the environment as the feature that best splits the dataset. Additionally, the interpretation with CP values is clearer, as it represents more information about the dwelling than only AF. Still, even though the n_{50} ranges increase with CP growth, one does not expect this trend to continue for scenarios with less ES, i.e., less envelope area for the same volume resulting in a higher CP. Since ES identifies as a feature with residual relative importance, the expected result is a translation movement of the n_{50} range along the CP axis. Therefore, while obtaining a mathematical relationship between CP and n_{50} would be relevant, it loses significance for the reason stated. A rule of thumb for a particular CP ratio serves best practical applications.

For the particular scope of the used dwellings, meteorological data and the chosen labelling strategy in the performed research, the n_{50} should be between 3 and 5 h^{-1} for the CP lower half range in a rural environment. In the upper half range, the n_{50} should be between 4 and 6 h^{-1} . In an urban environment, the n_{50} should be between 4 and 7 h^{-1} , in the lower half of the CP range. It should be between 5 and 8 h^{-1} , in the upper half (Table 5.10).

Table 5.10. Dwelling n_{50} range in a rural and urban terrain as a function of its compactness, in the case of four vertical exposed walls

n_{50} [h^{-1}]	Terrain	Rural		Urban	
	Limits	Lower	Upper	Lower	Upper
CP [m]	<1.0	3	5	4	7
(ES=4)	>1.0	4	6	5	8

5.2.2.5. Restricted scope and generalization path

While the workflow presented can be generalized, the case study has restricted boundaries and acceptance criteria. It refers only to single-family houses of one or two floors in uniform rural and urban terrains, and therefore, the results relate solely to these typologies of dwellings.

Regarding the terrain, variation from uniform characteristics will most likely fall between fully rural and urban terrain performance ranges. For single-family dwellings with an increased number of floors, one expects the performance ranges to move to lower ranges of n_{50} . For multi-family homes, there is the effect of increased vertical lengths of stack ducts in lower floors compared to single-family houses, and higher wind impact in dwellings on upper floors.

For these, while the portrayed performance ranges are useful within the restricted scope of the used dataset, representing over 79% of the Portuguese residential built stock (see subsection

5.2.1.1), the remaining dwellings need additional research in establishing their airtightness performance ranges.

For reasons of computational cost, only one representative month of the heating season was considered for simulation. Using a larger time frame would output results increasingly accurate to the weather experienced at the chosen location.

To generalize the presented methodology, and as the produced outputs are dependent on a restricted scope, the three main stages alongside their aspects and respective constraints are shown in Figure 5.10. While these were the input variables in this Application, other input variables could lead to interesting findings, particularly related to dwelling characteristics.

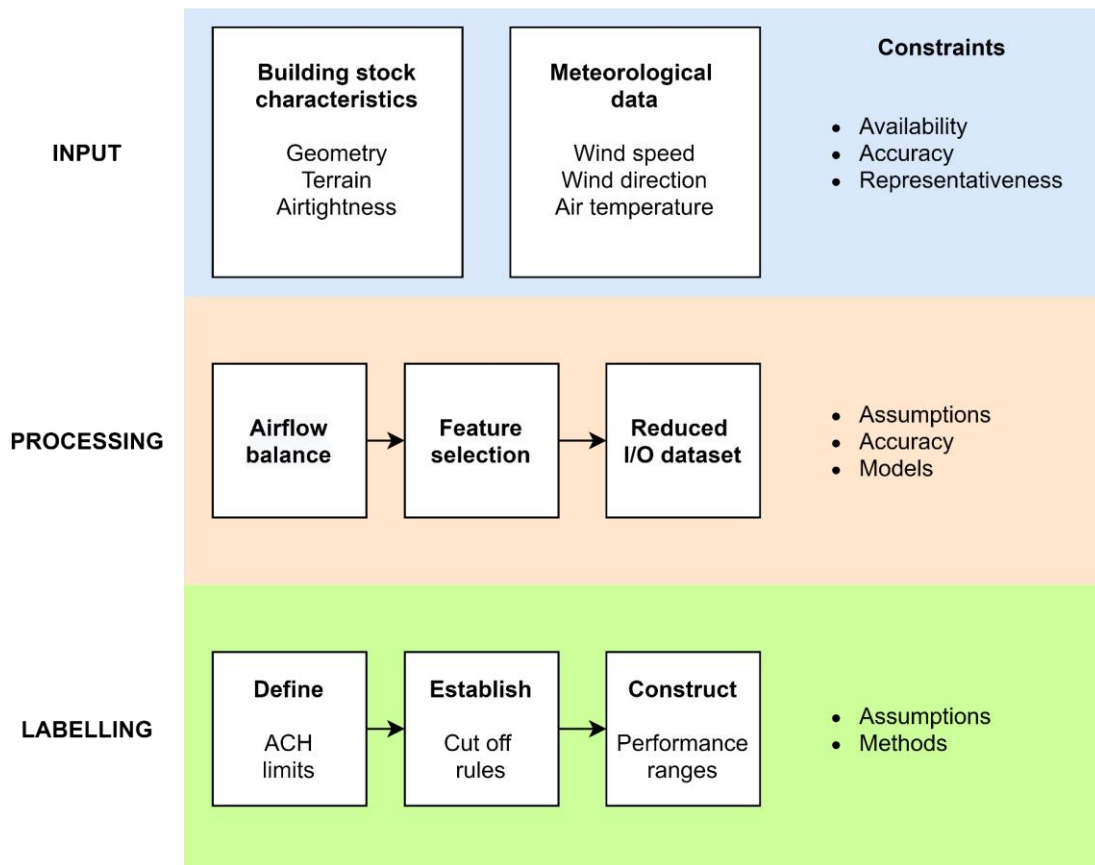


Figure 5.10. Setup for generalization of performance labelling strategies

Finally, these results are the product of the defined ACH lower and upper limits and cut off rules in establishing labels. A change to those would inherently alter the outputted airtightness performance ranges. Although one believes the proposed operating ACH limits to be an

adequate middle ground between health needs and energy conservation, their range is somewhat narrow. A wider one would make a natural ventilation strategy increasingly viable in dwellings with different sets of characteristics.

5.3. AIRTIGHTNESS COMPLIANCE TOOL FOR NATURALLY VENTILATED DWELLINGS (A6)

From Application A5, ordering the features by relative importance helps one better understand the relative impacts of meteorological, geometrical, airtightness, and terrain features. The proposed methodology provides visualization and definition of performance ranges and can bring additional disclosure on a generally taken-for-granted topic. Still, the combined use of a physical model and a probabilistic approach can be too complex for the practitioner's needs and general societal use.

The objective of Application A6 is to tackle this challenge by developing and applying a methodology based on trained predictive models of the airtightness performance of naturally ventilated dwellings. The trained models represent a tool that allows a practitioner to check the airtightness compliance of naturally ventilated single-family homes regarding health and energy efficiency issues. Application A6 aims to:

- Emulate the whole process of airflow balance for a specific meteorological dataset, reducing computational costs and time;
- Train classification models to predict the label of new dwellings, either non-compliant by default (NCd), compliant (Com), or non-compliant by excess (NCe);
- Train regression models to predict a dwelling average ACH and the percentage of time the ACHs are below, between, and above the lower and upper limits defined in Application A5;
- Provide the structure for a potential user-friendly airtightness performance compliance tool.

5.3.1. METHODOLOGY ON THE COMPLIANCE TOOL

5.3.1.1. Input dataset

The input dataset encompasses the terrain and dwellings characteristics, the resulting ACH times series, and the respective labels that resulted from the probabilistic approach developed in Application A5. Subsection 5.2.1.1 details dwellings, terrain and meteorological variables.

For a month representative of the average heating season of the southern Europe mild conditions, a total of 43200 unique dwellings regarding continuous and categorical variables were simulated regarding ACHs, using a single zone model based on method 1 of the standard EN 16798-7:2017 [195].

Feature importance and airtightness performance ranges for the particular case study are available in Application A5. To label the dwellings as compliant (Com), non-compliant by default (NCd), or non-compliant by excess (NCe), constraints on ACH time series globals, particularly ACH probabilities, regarding lower and upper limits were defined (Labelling block in Figure 5.4). This rationale resulted in the Com dwellings needing to comply with a percentage of time above the upper limit of 20% and 40% for rural and urban locations (α), respectively (Table 5.8). For more details on the rationale, refer to Subsection 5.2.1.4.

5.3.1.2. Metamodeling workflow

Figure 5.11 portrays a flowchart of obtaining the input datasets and workflow to get the regression and classification models trained and tuned.

For a comprehensive tool, and since surrogate models benefit from large datasets for training, one uses the whole dataset, 43200 dwellings. The same criteria and limits, presented in Subsection 5.2.1.4, apply to classify the dwellings.

As this hard labelling confers a significant loss of information on the amount of time the dwelling performs, in parallel, multi-output regression models predict the percentage of time the ACH of each dwelling is below 0.4 h^{-1} , between 0.4 and 0.7 h^{-1} , and above 0.7 h^{-1} and its respective mean ACH.

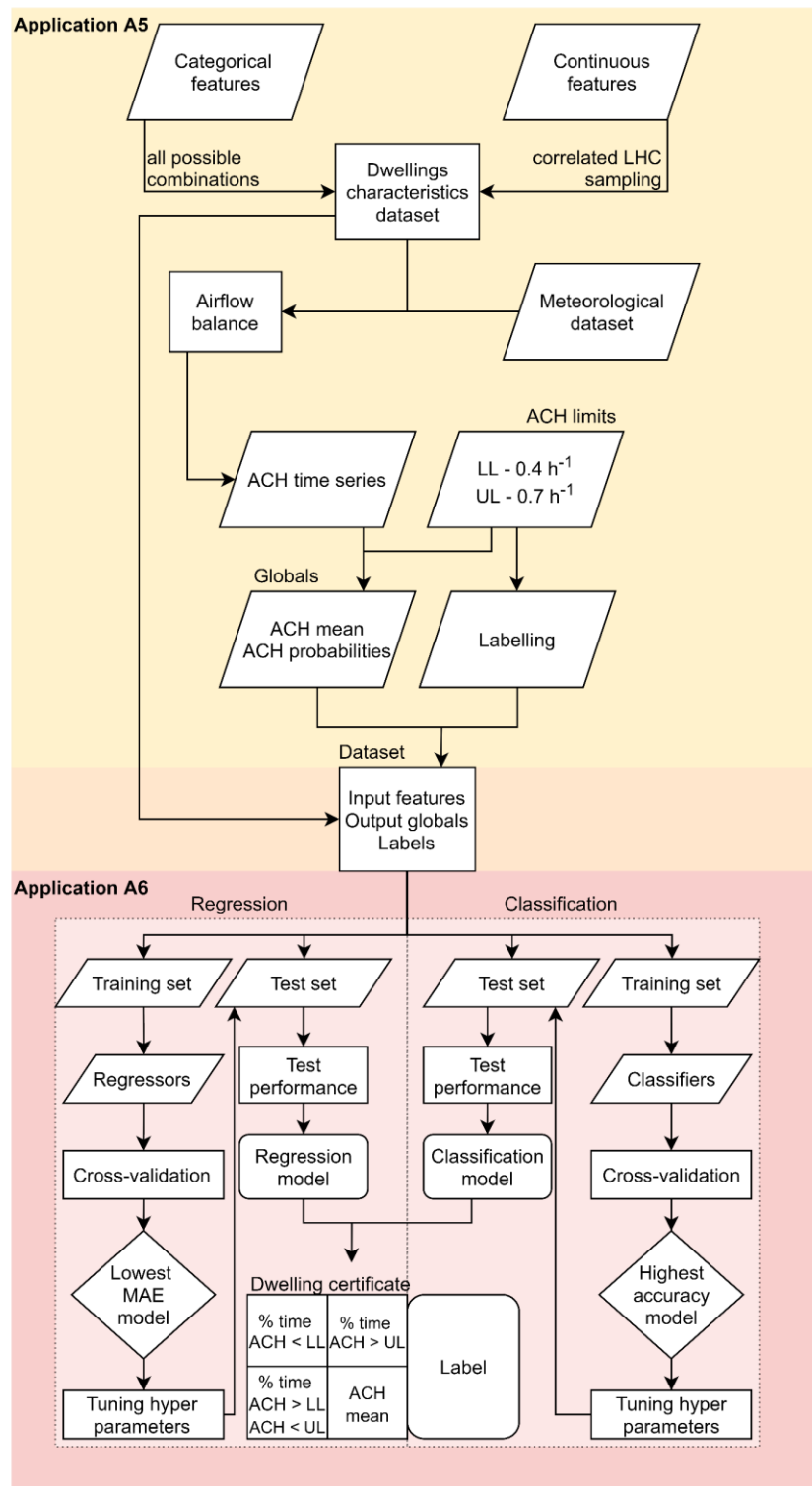


Figure 5.11. Flowchart on dataset input from Application A5 and the application of regression and classification models in the current Application A6

In the proposed workflow (Figure 5.11), the joint output of the best performing classifier, the one with the highest accuracy, and the best performing regressor, the one with the lowest mean

absolute error (MAE), will be a vector of five cells, with numerical information on the dwelling performance and a categorical label. The numerical output will be the three ACH percentages and the ACH mean. This approach fully characterizes the dwelling airtightness performance, including the respective performance class (the outputted label).

As seen in Subsection 2.4.2, single methods such as support vectors and decision trees and ensemble methods such as random forests and gradient boosted decision trees provide promising results in replacing complete simulation setups.

As so, five models were applied to the present research, two single models: support vector machines (SV) and decision tree (DT), and three ensemble models: random forest (RF), extreme gradient boosting (XGB) and categorical boosting (CB). All of them apply to both classification and regression problems.

SVs were first developed for classification purposes and rely on finding a hyperplane that best divides an input dataset, being the vectors the data points near the hyperplane, defining its position [380]. If there are only two input features, the hyperplane is just a line. The determination of the model parameters corresponds to a convex optimization problem. Although the classifier is a hyperplane in the transformed feature space, the boundary shape in the original input space may be nonlinear. The transformation is dependent on the used kernel function [381]. Extension to regression changes the error function.

DTs encompass two elements, nodes and branches [378]. The root node uses the variable that best splits the data. Intermediate nodes can use the same variable of the root node or others. As the variable importance in splitting observations increases, the higher its frequency in the tree [382]. Leaf nodes represent predictions, either a category in a classification setup or a numerical value in a regression one. Branches set true or false paths for the node conditions they depart. After the learning process, the resulting flowchart serves as a roadmap for predicting newly presented observations. In classification, the quality of splits is done by assessing the impurity at each node, commonly by Gini or entropy criteria. In regression, the mean squared error (MSE) or the mean absolute error (MAE) are usually applied.

While a DT method offers increased interpretability, compared to other single methods, such as SVs, it comes with several disadvantages that result in a trend of the developed model to overfit the training data. At this point, ensemble methods are of interest, such as the case of RF [383]. A RF is an ensemble method that performs predictions by weighting several decision

trees, commonly referred to as weak learners [384]. The weighting includes bootstrap resampling and random feature selection, among other methodologies. A randomly selected subsample from the training data trains each tree in bootstrap resampling. A reduced number of input variables are used at each node to split the observations in random feature selection. These processes mitigate the drawbacks of single DT models.

Proposed by Friedman [385], gradient boosted decision trees combine the advantages of RF, but instead of bagging homogeneous weak learners, they fit sequentially, adapting from the previous iterations. Each iteration focuses on the misclassified observations or those with the highest errors from the previous one. It can often lead to overfitting of the model to the training dataset. Furthermore, the sequential architecture increases computational costs compared to bagging methods. XGB [386] adds a regularization term to the objective function, improving model generalization and reducing the number of iterations on finding the loss function minimum by computing the second partial derivatives.

Although CB [387] introduces changes in leaf growth, feature importance, and the encoding of categorical features, the main difference to XGB comes from the split criteria. CB applies Minimal Variance Sampling [388], which is a weighted version of stochastic gradient boosting [389], that resulted in increased quality models compared to XGB implementations [390][391][392].

5.3.2. RESULTS AND DISCUSSION ON THE COMPLIANCE TOOL

5.3.2.1. Pre-processing

From the criteria and limits for labelling described in Subsection 5.2.1.4, the whole dataset resulted into 1257 dwellings labelled as Com, 10377 dwellings as NCd, and 9966 dwellings NCe, in a rural environment; while, in an urban environment, 847 dwellings as Com, 13482 as NCd, and 7271 as NCe. Descriptive statistics of the highest performing dwellings are available in Table 5.11.

Table 5.11. Descriptive statistics of the groups of highest performing dwellings, the compliant (Com) labelled, in a rural and an urban environment for the whole dataset

Feature	Metric	Rural ($\alpha=0.14$)	Suburban and urban ($\alpha=0.22$)
ACH [h^{-1}]	Mean	0.65	0.55
	Std. dev.	0.25	0.15
ACH < 0.4 h^{-1}	Mean	14.24%	13.27%
	Std. dev.	4.69%	4.82%
0.4 h^{-1} < ACH < 0.7 h^{-1}	Mean	52.08%	72.44%
	Std. dev.	6.43%	5.40%
ACH > 0.7 h^{-1}	Mean	33.68%	14.29%
	Std. dev.	5.25%	3.92%
n_{50} [h^{-1}]	Mean	5.36	5.86
	Std. dev.	1.21	1.35
N [-]	Mean	0.60	0.60
	Std. dev.	0.04	0.04
AF [m^2]	Mean	124.79	101.06
	Std. dev.	57.30	32.98
CH [m]	Mean	2.62	2.61
	Std. dev.	0.21	0.26
SR [-]	Mean	1.45	1.50
RS [$^{\circ}$]	Mean	10.64	12.04
ES [-]	Mean	3.15	3.12
NF [-]	Mean	1.61	1.54
ND [-]	Mean	3.19	3.33

Unbalanced groups populate the dataset, resulting in several drawbacks in applying classification models [393]. One needs to equalize the number of dwellings in each label to that with the most by oversampling minority classes, this way overcoming the overfitting problem of random oversampling when the classes have disparate representativeness. The process cannot add information or variability to the original dataset. Therefore, a Synthetic Minority Oversampling Technique for Nominal and Continuous features (SMOTE-NC) applies, which allows for the presence of continuous and categorical features [394]. SMOTE-NC is a data augmentation technique that synthetically samples the minority classes into the size of the majority class based on nearest neighbors judged by the Euclidean distance between data points in feature space. As so, being NCd the majority class with 23859 dwellings, the final input dataset is 71577 dwellings, three times the majority class size, and equally divided by the three classes.

The dataset divides randomly into training and test sets in a proportion of 80% and 20%, respectively. The training set features fit a scaler to center the data at mean 0 and standard deviation of 1. They are then transformed according to the fitted scaler, ensuring that the original magnitude of each variable does not affect its impact on the model. The dwelling

features in the test set transform according to the computed scaler. The test set is not included in fitting the scaler so that it does not introduce bias in the training set.

A five K fold cross-validation (CV) applies to the training set for each model to assess the average MAE in regression. A K fold cross-validation splits the dwellings into k equal-sized subsets, in other words, k consecutive folds, without shuffling. Each fold applies once as a validation set while the others form the training set.

In classification, a five stratified K fold cross-validation is applied to the training set to determine the average accuracy. The stratified K-fold differentiates from the standard version by ensuring that the folds preserve the same percentage of events for each class, an important procedure to avoid bias in classification.

A grid search with cross-validation applies to the regression model with the lowest average MAE and the classification model with the highest average accuracy. A grid search uses all the possible combinations of the provided ranges of hyperparameters to fit and score a training set to a certain model. The method keeps the hyperparameters that output the best score. In both regression and classification, the resulting models with the tuned hyperparameters are used to fit the test set.

5.3.2.2. Multi-output regression models

The scoring metric used in the regression models was the Mean Absolute Error (MAE). The average train MAE, CV mean MAE, and CV standard deviation MAE are displayed in Table 5.12. Only test set predictions portray the separate MAE for each output.

Table 5.12. Average train MAE, and CV average and standard deviation MAE for the considered regression models

MAE [-]	Average train MAE	CV average MAE	CV std. dev. MAE
SVR	0.0456	0.0466	0.0004
DTR	0.0000	0.0241	0.0005
XGBR	0.0177	0.0210	0.0003
RFR	0.0058	0.0173	0.0001
CBR	0.0140	0.0156	0.0002

The single models all performed worse than the ensembles. Nonetheless, the DT performed marginally worse than the XGB regressor. RFR and CBR performed similarly, with CBR

getting the lowest average CV MAE and showcasing less overfitting to the training data from the two. For this model, the number of trees, the maximum depth, and the learning rate tune separately to identify the ranges for grid search (Figure 5.12).

The number of trees identified was 2000 and 3000. The maximum depths identified were 10 and 12. The learning rates determined were 0.3 and 0.4. The grid search between the eight combinations, totaling 40 folds, resulted in the best parameters being 3000 trees, with a maximum depth of 10 and a learning rate of 0.3. The corresponding average CV MAE was 0.79 %, with a standard deviation of 0.007 %. It represents 50% of the MAE before tuning the hyperparameters. As a final evaluation, one looks into the MAEs of the final model in predicting: the ACH mean, the percentage of time below 0.4 h^{-1} , between 0.4 and 0.7 h^{-1} , and above 0.7 h^{-1} , with the test set. Table 5.13 presents the MAEs. Figure 5.13 plots the predicted versus the actual outputs from the model application to the test set.

As the ACH between 0.4 and 0.7 h^{-1} has two boundaries compared to the other two with only one each, the MAE is higher in the first. Still, overall, the tuning of the best performing model results in a robust regressor with the MAE never exceeding 1.02% in the percentage of time the ACH of a dwelling is within a certain range. Regarding the ACH mean, the MAE is residual.

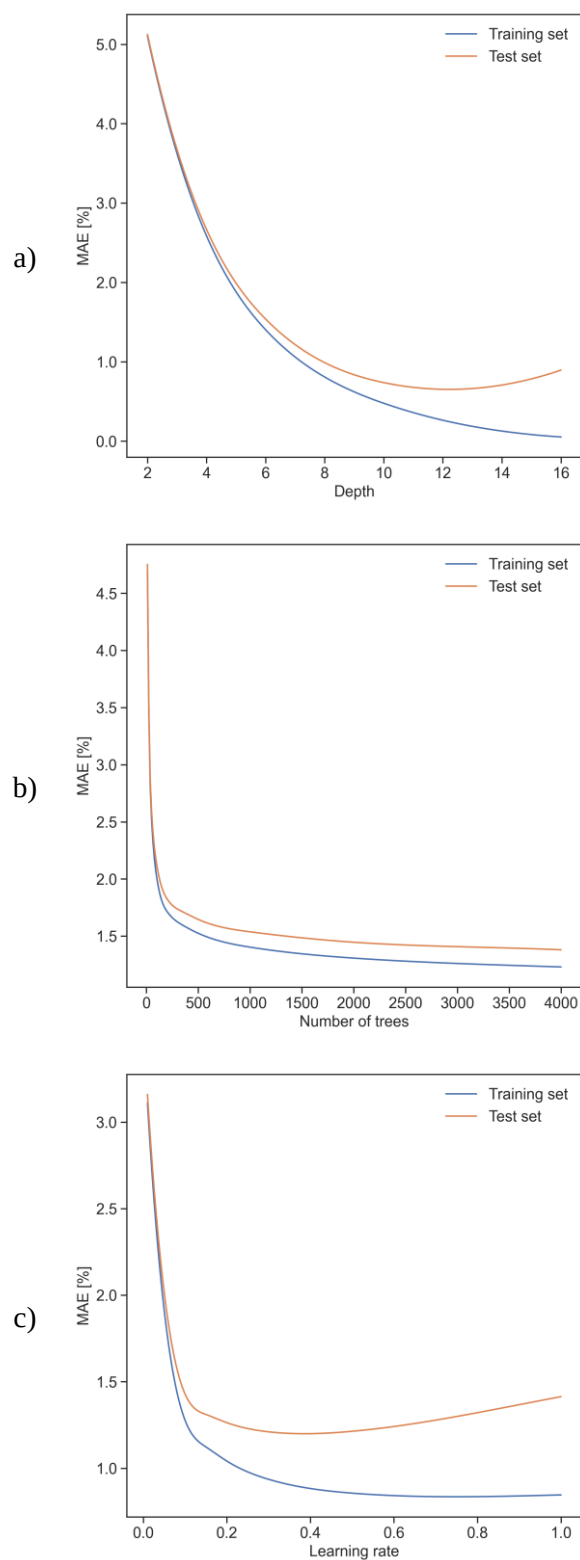


Figure 5.12. Standalone CB regressor hyperparameters tuning using CV: a) the number of trees; b) maximum depth of trees; c) learning rate.

Table 5.13. MAEs resulting from the prediction of test set outputs with the best performing hyper tuned regression model

Output	MAE
ACH mean	0.003 h ⁻¹
ACH < 0.4 h ⁻¹	0.82%
0.4 h ⁻¹ < ACH < 0.7 h ⁻¹	1.02%
ACH > 0.7 h ⁻¹	0.63%

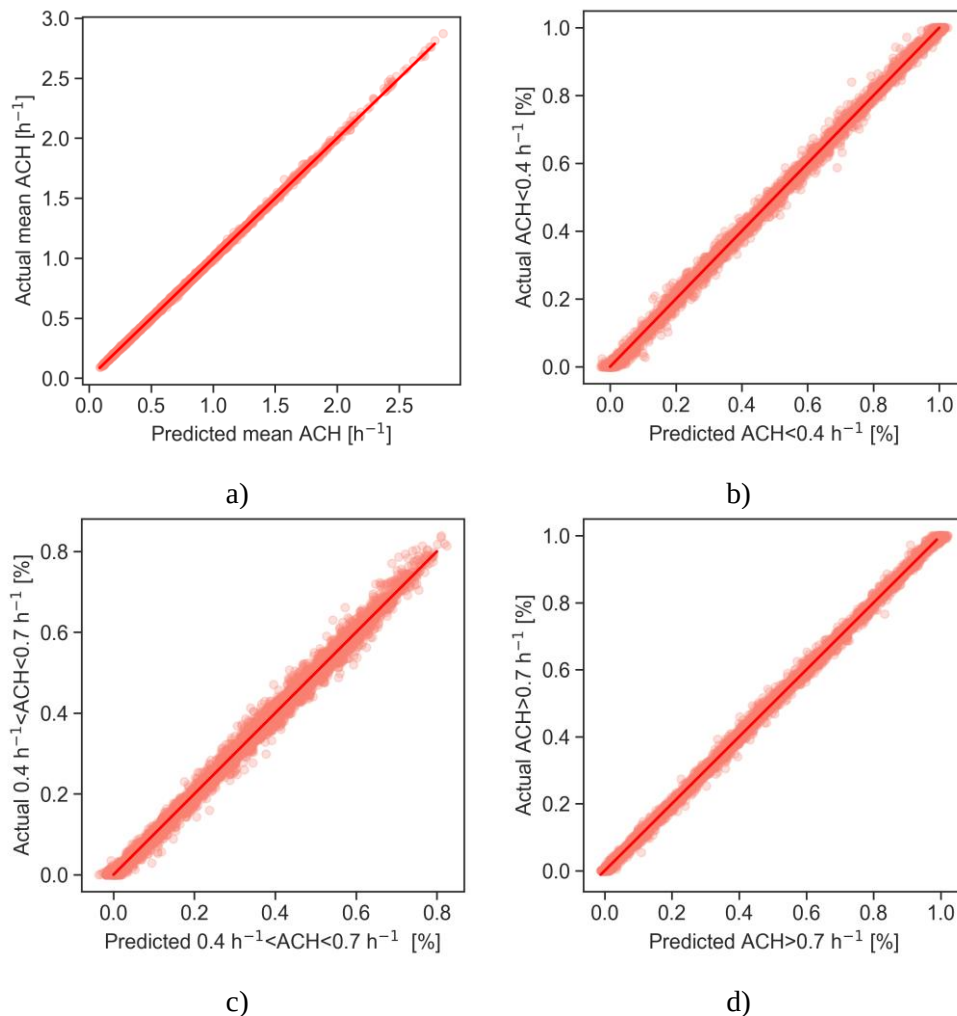


Figure 5.13. Predicted versus actual outputs with the test set

5.3.2.3. Multi-output classification models

Table 5.14 displays the training accuracy, CV mean accuracy, and CV standard deviation accuracy. Again, the single models all performed worse than the ensembles. Nevertheless, DT performed marginally worse than the RF classifier. The ensemble methods performed similarly,

with XGBC getting the highest average CV accuracy and the lowest standard deviation between fold scores.

Table 5.14. Average train accuracy and CV average accuracy and standard deviation scores for the considered classification models

Accuracy [%]	Average train accuracy	CV average accuracy	CV std. dev. accuracy
SVC	85.43	84.98	0.43
DTC	99.89	94.99	0.15
RFC	99.89	96.19	0.17
CBC	98.03	96.72	0.12
XGBC	98.60	96.78	0.18

For this model, tuning of the number of trees, the maximum depth of each, and the learning rate occurred separately to identify the ranges for grid search (Figure 5.14).

The number of trees identified was 150 and 200. The maximum depths determined were 7 and 8. The learning rates were 0.4 and 0.5. The results of the grid search in the eight combinations, totaling 40 folds, resulted in the best parameters being 150 trees, with a maximum depth of 7 and a learning rate of 0.4. This best estimator's average CV accuracy was 97.27%, with a standard deviation of 0.08%.

The final evaluation concerns its application to the test set. The classification metrics (Table 5.15) and the confusion matrix (Figure 5.15) for these predictions portray the model performance on the test set.

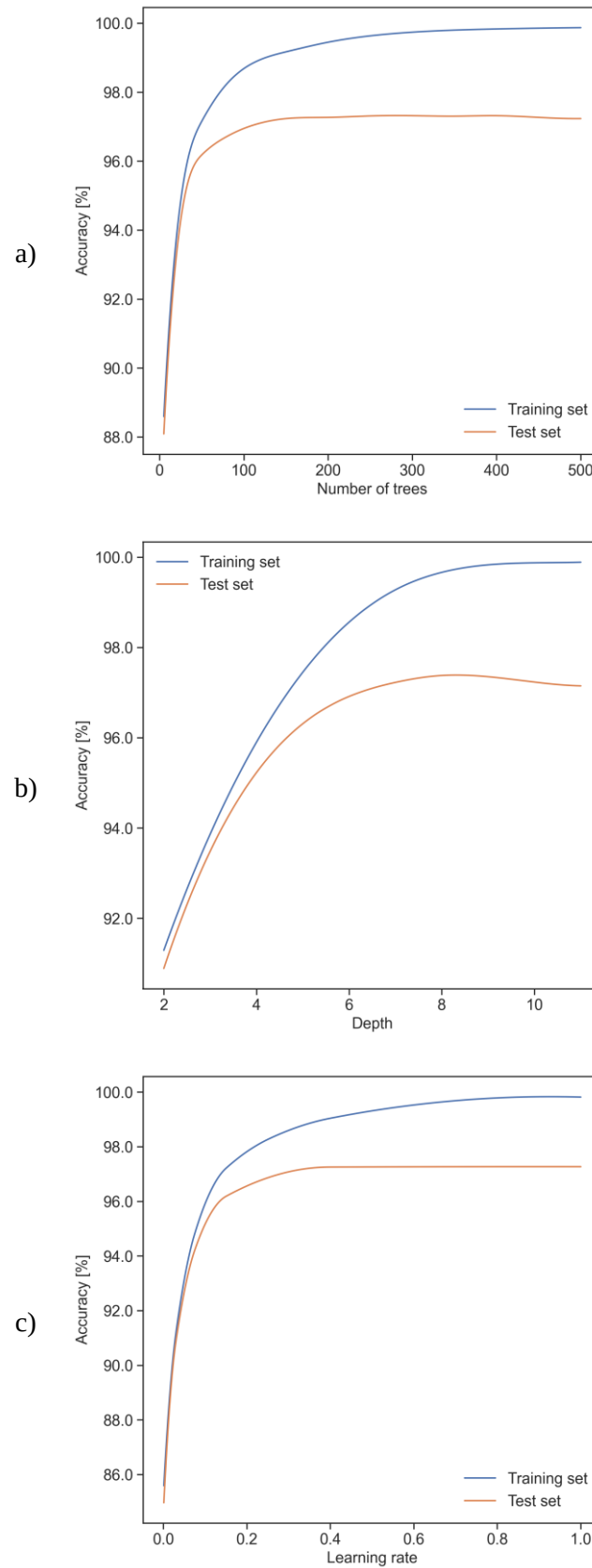


Figure 5.14. Standalone XGB classifier hyperparameters tuning using CV: a) the number of trees; b) maximum depth of trees; c) learning rate.

Table 5.15. Classification metrics resulting from the prediction of the test set classes with the best-performing hyper tuned classification model

Labels	Precision	Recall	F-score	Support
NCd	98.04 %	97.12 %	97.58 %	4695
Com	95.89 %	97.67 %	96.77 %	4725
NCE	98.06 %	97.18 %	97.62 %	4896
Average	97.33 %	97.33 %	97.32 %	14316

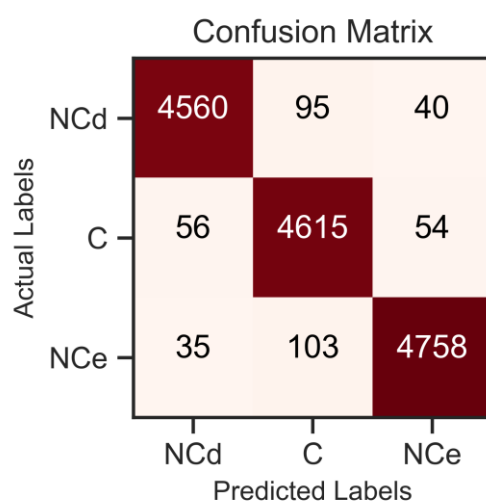


Figure 5.15. Confusion matrix of the test set

As classes NCd and NCE share the least similarity, the risk of misclassification is lower. More false positives are present in class Com, as precision scores are lower than the other classes. Still, this class scores the highest recall, the ratio of correctly predicted observations to all the true observations in the same class. It is the preferable outcome since one prefers to label dwellings as compliant if they are close to the boundaries of compliance in a non-compliant group. The alternative is to label the dwelling as non-compliant when it is compliant. Overall, the achieved accuracy of 97.32% in test set predictions supports the robustness of the classification model.

5.4. LIFE CYCLE ASSESSMENT OF WHOLE ENVELOPE AIRTIGHTNESS SOLUTIONS (A7)

Application A6 showed that a compliance tool is possible, has potential, and may be practical in evaluating a current dwelling airtightness performance. Still, it does not provide any further

information or recommendation for non-compliance. While for dwellings with low air change rates over time, the opening of windows may partially mitigate the issue, for homes with excessive air change rates, energy and comfort issues are at stake, which often no immediate actions can minimize.

The objective of Application A7 is to propose an assessment of the life cycle impacts of applying full envelope airtightness solutions and using it in the subset of naturally ventilated dwellings labelled as having excessive heat losses due to ventilation and infiltration in Application A5. It aims to:

- Evaluate the energy performance variation from a default scenario to one with the implementation of whole envelope airtightness solutions;
- Assess the environmental performance of several improved scenarios, including the combinations of two whole envelope airtightness solutions and five heating systems;
- Quantify the Life Cycle Costs of adopting these airtightness solutions for dwellings equipped with each of the five considered heating systems.

5.4.1. LIFE CYCLE ASSESSMENT METHODOLOGY

5.4.1.1. Scope of airtightness solutions and dwellings type

The present research applied an LCA methodology to provide insights into the dwellings labelled as NCE, in Application A5, regarding their energy performance assessment, environmental impacts, and life cycle costs of applying envelope airtightness solutions [395].

In line with the identified disregard for the topic, Environmental Product Declarations (EPDs) related to complete airtightness solutions and individual elements are scarce [329]. One understands from Subsection 2.5.2 that assessing singular elements that constitute the air barrier is quite unfeasible in an LCA approach. The available ones often do not comprise the same modules in the system boundary list of environmental impacts, creating difficulties in correctly summing their impacts.

Furthermore, quantifying singular elements such as point envelope penetrations or envelope elements perimeters is increasingly prone to misjudgment and bias compared to evaluating surface elements such as the envelope area. Therefore, considering whole envelope airtightness solutions seems to be a more plausible path. While research reports significant disparities in materials airtightness performance in a controlled environment [103], one must assume that

commercial products and systems are completely airtight when properly applied. Therefore, the main goal is not to compare solutions by their ability to perform in conferring airtightness but to assess airtightness solutions' environmental and cost performance as a function of a dwelling airtightness level and installed heating system. With this rationale, two external whole envelope airtightness systems, with their own EPDs, were chosen for analysis: a mechanically fastened (MECH) [396] and fluid applied (FLUID) [397] one.

These solutions already account for the estimated number of separate elements needed to perform and the detailing between the system and other components, such as windows, and technical penetrations, such as electrical and plumbing systems, since they include self-adhered flashings and tapes. They share system boundary modules, production and installation phases, and end-of-life transport. Their impacts are reported in the functional unit of one square meter (m^2), leading to a straightforward comparison of environmental performance [398]. A functional unit is a quantified description of a product that serves as the basis of reference for the subsequent impact assessment calculations [399].

The scope of the airtightness solutions is closely associated with dwelling construction types. Dwellings of traditional construction are mostly susceptible to point penetrations, such as pipes and cables, and elements perimeters, such as windows and doors. The opaque envelope is mostly homogeneous in these, providing one or more highly airtight layers by default.

By comparison, most lightweight dwelling construction types experience an increase in the contribution of the opaque envelope to the whole envelope leakage. It is mostly justified by the higher partitioning of envelope elements, e.g., SIPs or wood frames, to comply with geometry requirements. Because of it, most of the buildings of this last construction type require purpose provided air barriers as a necessary component of an airtight envelope solution.

Thus, while the chosen whole envelope airtightness solutions provide detailing of the opaque envelope with point penetrations and elements perimeters, meaning that there is a benefit for traditional constructions as well, they are more suitable to lightweight constructions which experience the higher payoff. Additionally, the potentially occurring moisture condensation in envelope inner layers has far less serious consequences in traditional compared to lightweight constructions. Hence, the present Application focuses mainly on and is most appropriate to this latter construction type.

5.4.1.2. Considered environmental indicators

Environmental indicators were extracted from the two used EPDs [396][397] (Table 5.16). They include: abiotic depletion potential for both fossil (ADPF) and non-fossil resources (ADPE), global warming potential (GWP), depletion potential of the stratospheric ozone layer (ODP), formation potential of tropospheric ozone photochemical oxidants (POCP), acidification potential of land and water (AP), and eutrophication potential (EP). These indicators are assessed using the characterization factors of CML [400]. Two additional indicators related to energy consumption were extracted from the EPDs: non-renewable primary energy (NRPE) and total primary energy (TPE), obtained through the Cumulative Energy Demand (CED) single-issue method [401].

Table 5.16. Life cycle assessment indicators considered for the comparison of whole envelope airtightness solutions in the form of air barriers by the functional unit (m^2)

Parameter	Unit	Mechanically fastened (MECH) [396]	Fluid applied (FLUID) [397]
ADPE	[kg Sb eq.]	2.64E-07	1.61E-05
ADPF	[MJ]	1.17E+01	7.21E+01
GWP	[kg CO ₂ eq.]	5.38E-01	3.83E+00
ODP	[kg CFC-11 eq.]	1.24E-06	3.62E-07
POCP	[kg C ₂ H ₄ eq.]	2.90E-04	8.15E-03
AP	[kg SO ₂ eq.]	1.45E-03	1.07E-02
EP	[kg PO ₄ eq.]	1.44E-04	1.36E-03
NRPE	[MJ]	1.24E+01	7.60E+01
TPE	[MJ]	1.27E+01	8.00E+01

5.4.1.3. Life cycle cost methods and primary energy considerations

Life cycle cost (LCC) methods enable the effective evaluation of investment options, considering the impact of all costs instead of initial expenses alone, and planning the management of buildings and infrastructures during their lifetime [395].

As the EPDs of the solutions do not indicate a reference service life (RSL), their lifespan is treated as a cover material, similar to others applied in the exterior layers of the envelope, such as insulation materials. According to EN 15459-1:2017 [402] the lifespan for these is 40 years. There are no maintenance costs to be included in the calculation of global costs, as they are elements of the envelope non-accessible after installation. Therefore, a dwelling RSL savings are simply the subtraction of the difference in operational costs from two scenarios, the

application or absence of one of the proposed airtightness solutions, through its RSL, from their initial costs (Eqs. (5.1) and (5.2)). For each year after, the annual savings in operational costs adjust to a discount factor (Eq. (5.3)). A discount factor is a weighting term to convert future values into net present values (NPV) [305].

The CYPE software can be applied to generate construction prices and quantify the initial investment by using similar solutions to the ones considered in the present Application [403]. The MECH solution was considered a vapor barrier with an air permeability of $0.03 \text{ m}^3/(\text{h}\cdot\text{m}^2)$ at 50 Pa, at 7.68 €/m^2 (VAT included). For the FLUID solution was adopted the compound price of a spray-applied liquid polyurethane-based waterproofing coating at the cost of 20.51 €/m^2 (VAT included). Eq. (5.4) displays the formula for the payback period (PP). The PP is the time, in years, that the financial savings from a certain improvement scenario equals its initial investment [404]. A positive PP indicates that the financial savings exceed the initial cost before the end of the RSL.

$$RSL_{savings} = \sum_{i=1}^{RSL} \Delta C_{a,i} \cdot R_{d,i} - C_0 \quad (5.1)$$

$$\Delta C_{a,i} = \frac{\Delta Q_{v,i}}{\eta_k} \cdot P_s \quad (5.2)$$

$$R_{d,i} = \left(\frac{1}{1 + \frac{r}{100}} \right)^i \quad (5.3)$$

$$PP = j \text{ for } C_0 \leq \sum_{i=1}^j \Delta C_{a,i} \cdot R_{d,i} \quad (5.4)$$

$RSL_{savings}$	reference service life savings (€)
$\Delta C_{a,i}$	the difference in operational costs between a scenario of absence or application in the year i (€)
$R_{d,i}$	discount factor in the year i (-)
C_0	initial investment on applying the airtightness solution (€)
$\Delta Q_{v,i}$	the difference in heat losses between a scenario of absence or application in the year i (kWh)
η_k	nominal efficiency of the heating system k (-)
P_s	energy price by source s (€/kWh)
r	discount rate in year i (%)
PP	payback period (year)

Table 5.17 compiles the considered heating systems, their efficiencies, and respective energy sources, their prices and conversion factors from final energy to primary energy.

Table 5.17. Considered heating systems and efficiencies, their energy sources and respective prices

Heating system	Heating system efficiency (η)	Energy source	Energy price [€/kWh]	F _{PE} [kWh _{PE} /kWh]
Electric radiator	1.0	Electricity	0.2133 [405]	2.5
Natural gas boiler	0.90 [406]	Natural gas	0.0783 [405]	1.0
Pellet heat recovery	0.75 [406]	Biomass	0.0516 [407]	1.0
Heat pump (min. efficiency)	3.00 [406]	Electricity	0.2133 [405]	2.5
Heat pump (high efficiency)	5.00	Electricity	0.2133 [405]	2.5

The selected four types of heating systems are the most common in the Portuguese built stock [408]. The efficiencies (η) of the natural gas boiler, pellet heat recovery, and heat pump for residential buildings were obtained from national technical documents [406]. A heating system efficiency translates the ratio between the total energy output and the total energy input. The minimum requirements were chosen for all the heating systems, and an additional heat pump with a higher efficiency was considered as an example of a top-performing one.

Energy costs on electricity and natural gas refer to Portuguese energy prices (VAT included) for household consumers available at Eurostat [405] in the second half of 2020. For biomass as pellets, the used value refers to the value in Bioenergy Europe [407] for 2018, at 0.27 €/kg. As the Low Heating Value (LHV) of pellets is 18.84 MJ/kg [409], which equals 5.23 kWh/kg, the pellets price can be converted to 0.0516 €/kWh. The discount rate (r) in energy prices is 3%, in line with European Commission directives [410].

The heating system efficiencies (η) and the primary energy factors (F_{PE}) from final energy to primary energy apply in calculating the primary energy needs (Eq. (5.5)). These factors account for energy used for transportation, processing, losses, etc. They are sourced from additional Portuguese legislation [411] and are in fair agreement with the factors obtained using the CED v1.09 method [401] in SimaPro with data from the Ecoinvent database [412]. The latter sum up to 2.72 kWh_{PE}/kWh for 1 kWh of electricity, 1.21 kWh_{PE}/kWh for 1 m³ of natural gas, and 0.96 kWh_{PE}/kWh for 1 kg of wood chips that make up pellets.

Eq. (5.6) gives the energy payback period (EPP). Similar to PP, the EPP is the time, in years, that the primary energy savings from a before to after intervention scenario equals or overcomes the embodied energy of that same intervention.

$$\Delta PE_a = \frac{\Delta Q_v}{\eta_k} \cdot F_s \quad (5.5)$$

$$EPP = \frac{EE_0}{\Delta PE_a} \quad (5.6)$$

F_s	conversion factor between final energy and primary energy for energy source s (kWh _{PE} /kWh)
ΔPE_a	annual difference in primary energy needs between a scenario of absence or application (kWh _{PE})
EPP	energy payback period (year)
EE_0	embodied energy of applying an airtightness solution (kWh _{PE})

5.4.1.4. Heating loads and assumptions

Being heat transfers by air change rates the scope of this research, and windows opening a prevalent strategy in the cooling season [82], one considers only heat transfers through air exchanges in the heating season. Since the meteorological dataset used is from the Porto metropolitan area, one uses the region's heating degree-days (HDD) which amount to 1250 °C [371]. Eqs. (5.7) to (5.9) show the calculations required to obtain the heat losses through air change rates during the heating season. They correspond to the adaptation to the Portuguese legislation [413] of the quasi-steady state method of ISO 13790 [414].

$$\Delta Q_v = 0.024 \cdot HDD \cdot (H_{v,before} - H_{v,after}) \quad (5.7)$$

$$H_{v,before} = 0.34 \cdot ACH_{before} \cdot A_f \cdot C_h \quad (5.8)$$

$$H_{v,after} = 0.34 \cdot ACH_{after} \cdot A_f \cdot C_h \quad (5.9)$$

HDD	heating degree days (°C)
$H_{v,before}$	coefficient of heat transfer during the heating season in the absence scenario (W/°C)
$H_{v,after}$	coefficient for heat transfer during the heating season in the application scenario (W/°C)
ACH	air change rate (h ⁻¹)
A_f	floor area (m ²)
C_h	ceiling height (m)

One assumes the treatment of the whole opaque envelope area. Self-regulating vents integrate the windows frames of the main housing divisions to offset the reduction in ACH from the absence of air infiltration through the building envelope. Since the vents are self-regulating, one will assume that, with the proper dimensioning, average ACHs values will become similar to those of the Com labelled dwellings, 0.55 h⁻¹ and 0.65 h⁻¹ for urban and rural locations, respectively. This assumption applies in assessing energy performance.

As these elements often integrate across window frames depth, and their composition is similar to the frame itself for functional and aesthetic reasons, the potential environmental impact of these vents, the embodied energy, and the initial investment is assumed to be residual compared to a window without the vents. This hypothesis is true in design scenarios, as windows installation takes place anyway, and retrofit scenarios where windows replacement often occurs without airtightness being the main focus. The glazed area is considered to average 20% of the envelope area, according to the results of a study of reference buildings in the Portuguese built stock [364].

5.4.2. RESULTS AND DISCUSSION ON LIFE CYCLE IMPACTS

5.4.2.1. Energy performance

As revealed in Subsection 5.2.2.2 of Application A5, RS, SR and ES all have residual relative importance in explaining the variability of ACHs. The terrain (α) is the categorical feature with the most relative importance. For these reasons, only the dwellings with a 20° RS, a 2:1 SR, 4 ES, 2 NF, and 3 ND undergo evaluation. The subset further splits between rural and urban terrains for visualization and interpretation. This subset totals 298 unique dwellings: 171 in a rural environment and 127 in an urban environment. Table 5.18 informs on the centrality and variability of these dwellings' features. Annex A7 details their features.

Table 5.18. Descriptive statistics of the NCe labelled dwellings for a 2:1 SR, 4 ES, 20° RS, 2 NF, and 3 ND

Feature	Metric	Rural ($\alpha=0.14$)	Urban ($\alpha=0.22$)
ACH [h^{-1}]	Mean	1.11	0.85
	Std. dev.	0.39	0.25
ACH < 0.4 h^{-1} [%]	Mean	2.61	1.76
	Std. dev.	4.64	2.88
0.4 h^{-1} < ACH < 0.7 h^{-1} [%]	Mean	25.60	38.78
	Std. dev.	16.21	25.19
ACH > 0.7 h^{-1} [%]	Mean	71.79	59.45
	Std. dev.	19.05	26.97
n_{50} [h^{-1}]	Mean	9.08	9.96
	Std. dev.	3.64	3.82
n [-]	Mean	0.59	0.59
	Std. dev.	0.04	0.04
AF [m^2]	Mean	129.18	116.46
	Std. dev.	62.87	59.80
CH [m]	Mean	2.63	2.62
	Std. dev.	0.28	0.25

In Subsection 5.4.1.3, one admitted that the maintenance cost of an air barrier implementation would be null since there is no access to it after installation. Therefore, only the expenditure with energy consumption applies for annual costs. Table 5.19 presents descriptive statistics of the savings in energy consumption between the scenarios of absence and application of an airtightness solution. The median in an urban environment is around two-thirds of that in a rural environment. The mean in an urban environment is slightly below 40% of that in a rural environment. Overall, as the distributions approach higher quantiles, the differences are emphasized.

Table 5.19. Annual savings in energy consumptions between the absence and application scenarios for the NCe labelled dwellings with a 2:1 SR, 4 ES, 20° RS, 2 NF, and 3 ND

ΔQ_v [kWh]	Rural	Urban
Mean	1460	867
Std. Dev.	1401	810
Minimum	143	111
1%	169	111
5%	260	125
25%	570	315
Median	947	645
75%	1870	1201
95%	4189	2544
99%	8193	4905
Maximum	9111	5080

While these reductions in energy consumption are a positive outcome, a comprehensive outlook on the economic viability of these applications is only achieved by identifying which dwellings, with which heating systems, have positive PP. When so, one quantifies the savings through the RSL, a positive RSL. On the contrary, one quantifies the cost of obtaining an improved indoor environmental quality (IEQ) cost, a negative RSL.

Additionally, one must assess the energy payback period (EPP). It allows identifying if the saved primary energy in heating the indoor environment compensates for the embodied energy of each air barrier solution by the end of the reference service life.

5.4.2.2. Environmental performance

From the analysis of Table 5.16, only ODP presents lower impacts by square meter with the application of FLUID instead of MECH. For all the other environmental indicators, the FLUID impacts significantly exceed MECH's.

The number of years the reduced primary energy from heating the dwellings take to equalize the embodied energy of the application, the EPP, present very different outcomes depending on the airtightness of the dwelling, the heating system, and the solution applied to the envelope (Figure 5.16).

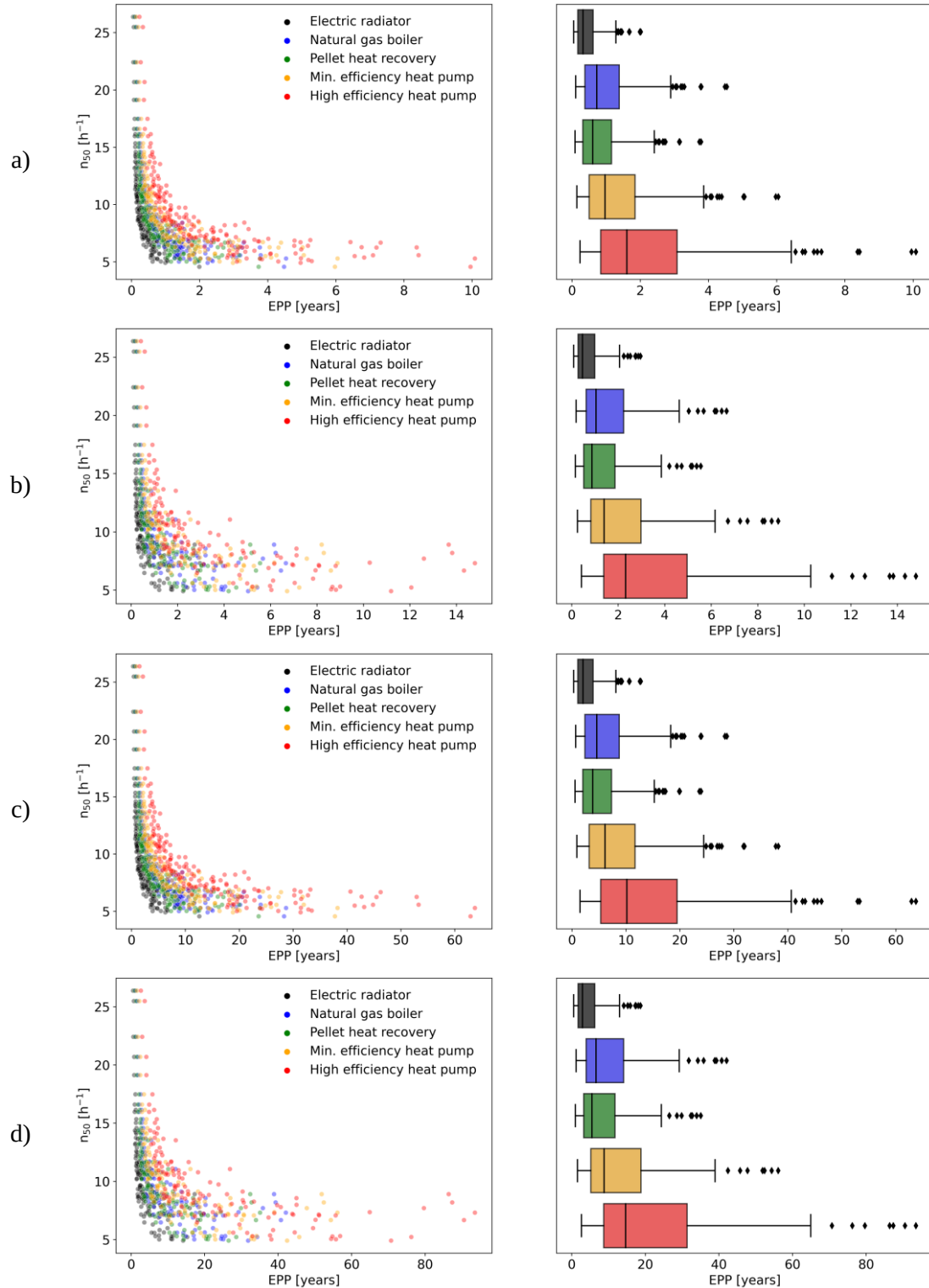


Figure 5.16. Energy payback period (EPP) as a function of the airtightness performance (n_{50}) of the considered dwellings, by terrain, air barrier solution, and heating system in both scatter plots (left column) and boxplots (right column): a) rural terrain – MECH solution; b) urban terrain – MECH solution; c) rural terrain – FLUID solution; d) urban terrain – FLUID solution.

The EPPs of applying an air barrier are diminished as the dwelling has a higher n_{50} value. The dwellings equipped with electric radiators have the lowest EPP, followed by pellet heat recovery, natural gas boiler, minimum efficiency heat pump, and the high efficiency heat pump. Table 5.20 further informs on EPP's means and standard deviations for the considered air barrier solutions, terrains, and heating systems.

Table 5.20. EPP mean and standard deviation by air barrier solution, terrain, and heating system

EPP [years]			Electric radiator	Natural gas boiler	Pellet heat recovery	Min. efficiency heat pump	High efficiency heat pump
Air barrier solution	Terrain						
MECH	Rural	Mean	0.46	1.03	0.86	1.37	2.29
		Std. dev.	0.39	0.88	0.73	1.17	1.95
	Urban	Mean	0.75	1.68	1.40	2.24	3.73
		Std. dev.	0.66	1.48	1.23	1.97	3.29
FLUID	Rural	Mean	2.89	6.50	5.42	8.67	14.45
		Std. dev.	2.46	5.53	4.61	7.38	12.29
	Urban	Mean	4.71	10.61	8.84	14.14	23.57
		Std. dev.	4.16	9.35	7.79	12.47	20.79

Treating a dwelling envelope with a FLUID solution confers an EPP 6.32 higher than that of a MECH solution, independently of the terrain and heating system. On average, independently from the heating system and air barrier solution, the EPP of a dwelling in an urban location is 1.63 higher than the EPP of a dwelling in a rural location.

For a MECH solution, independently of the heating system and terrain, all the dwellings justify its implementation regarding primary energy as the EPP never surpasses the respective RSL. For a FLUID air barrier, in rural terrain, only a portion of the dwellings equipped with a high efficiency heat pump does not have a positive EPP, being it 6.4%. In urban terrain, this percentage increases and is joined by a small percentage of dwellings equipped with minimum efficiency heat pumps and natural gas boiler, 18.1%, 5.5%, and 1.6%, respectively.

5.4.2.3. Life cycle costs results

Addressing the embodied energy payback does not provide the complete picture. One needs to appraise each dwelling savings through the RSL to assess the economic viability. Examining the dwellings with a positive and negative PP through their RSL savings as a function of heating

system, airtightness solution, and airtightness performance (n_{50}) provides further understanding. Table 5.21 presents this data.

While 80.2% of the dwellings with electric radiators experience a positive PP, in a MECH solution, this percentage drops to 19.1% in the ones equipped with high efficiency heat pumps. The natural gas boiler, the minimum efficiency heat pump, and the pellet heat recovery place in between, by descending PP. The mean PPs range from 11.0 and 23.2 years but experience substantial variability, with standard deviations between 8.3 and 9.4 years.

The order of PP by heating system is unchanged in a FLUID solution, but the percentages drop drastically, ranging from 45.3% to 1.0% of dwellings with a positive PP. The mean PPs range from 18.2 and 27.7 years and experience standard deviations between 7.6 and 9.1 years.

With MECH, in the groups with positive PP, the RSL savings are more pronounced in dwellings equipped with electric radiators, averaging 5438 €, and less in dwellings with a high efficiency heat pump, with 1123 €. The averages of negative PP groups range from -569 € to -1076 €. With FLUID, for the negative PP groups, the RSL savings range from -2437 € to -3853 €, showing the greater financial burden of this airtightness solution than MECH.

Table 5.21. Mean and standard deviations for the variables of interest of the dwellings with positive and negative PP, by heating system and airtightness solution

	Pos. PP [%]		n_{50} [h ⁻¹]	PP [years]	RSL savings [€]	Neg. PP [%]		n_{50} [h ⁻¹]	RSL savings [€]
Electrical radiator	80.2	Mean	10.2	11.0	5438	19.8	Mean	6.5	-569
MECH		Std. dev.	3.8	8.3	6192		Std. dev.	1.2	400
FLUID	45.3	Mean	12.0	18.2	5385	54.7	Mean	7.3	-2437
		Std. dev.	3.9	9.1	6327		std	1.6	1449
Natural gas boiler	49.7	Mean	11.8	17.9	2161	50.3	Mean	7.2	-902
MECH		Std. dev.	3.9	9.4	2567		Std. dev.	1.6	526
FLUID	11.1	Mean	16.4	25.8	2301	88.9	Mean	8.6	-3124
		Std. dev.	4.8	8.2	2856		Std. dev.	2.5	1592
Pellet heat recovery	39.3	Mean	12.5	19.5	1730	60.7	Mean	7.5	-960
MECH		Std. dev.	4.0	9.0	2048		Std. dev.	1.7	552
FLUID	5.0	Mean	18.7	26.1	2242	95.0	Mean	9.0	-3326
		Std. dev.	5.0	8.7	2468		Std. dev.	3.0	1592
Min. eff. heat pump	40.9	Mean	12.3	19.4	1775	59.1	Mean	7.5	-955
MECH		Std. dev.	4.0	9.2	2112		Std. dev.	1.7	546
FLUID	5.7	Mean	18.3	26.2	2228	94.3	Mean	8.9	-3295
		Std. dev.	4.8	8.5	2521		Std. dev.	2.9	1594
High eff. heat pump	19.1	Mean	14.5	23.2	1123	80.9	Mean	8.3	-1076
MECH		std	4.5	8.2	1335		Std. dev.	2.3	600
FLUID	1.0	Mean	24.8	27.7	1670	99.0	Mean	9.3	-3853
		Std. dev.	2.1	7.6	1446		Std. dev.	3.4	1482

The lowest average n_{50} in the dwellings with positive PP is 10.2 h⁻¹, in a MECH solution and 12.0 h⁻¹, in a FLUID solution. Still, they experience substantial variability, as the standard deviation ranges from 3.8 to 4.5 h⁻¹ in MECH and from 2.1 to 5.0 h⁻¹ in FLUID, respectively.

To assess this relationship, one addresses the annualized savings through the RSL as a function of the airtightness performance (n_{50}). Since natural gas boiler, pellet heat recovery, and minimum efficiency heat pump have similar performances, as their percentages of dwellings with positive PP are close to each other, only the minimum efficiency heat pump is assessed. Figure 5.17 shows this data, by terrain, for the two considered air barrier solutions.

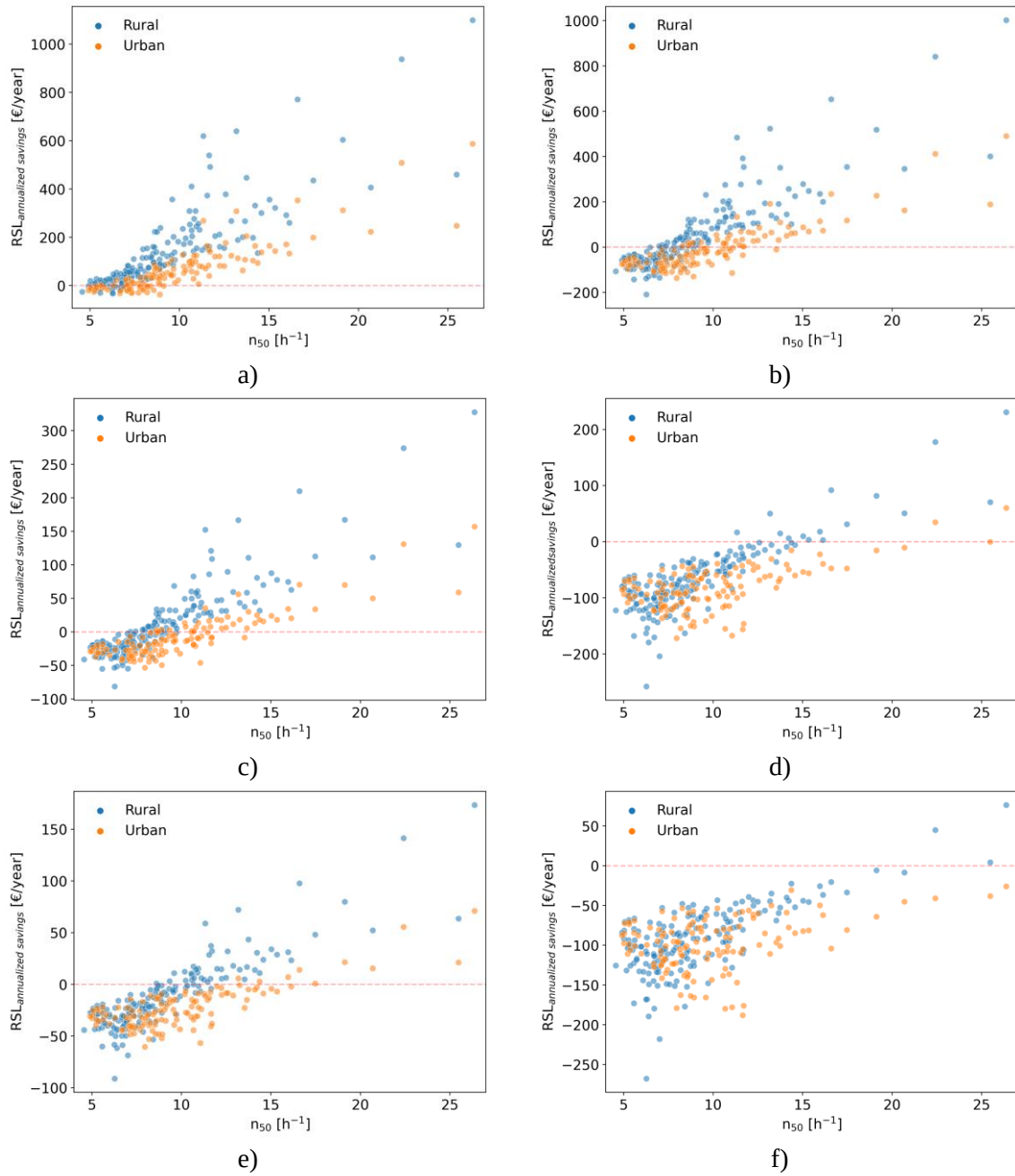


Figure 5.17. RSL annualized savings, by terrain, as a function of airtightness performance (n_{50}): a) electric radiator – MECH; b) electric radiator – FLUID; c) min. efficiency heat pump – MECH; d) min. efficiency heat pump – FLUID; e) high efficiency heat pump – MECH; f) high efficiency heat pump – FLUID;

These results portray the information with a higher degree of interpretability. For MECH, in a rural location, all dwellings have positive RSL annualized savings with an n_{50} over 6.9 h^{-1} when equipped with electric radiators, over 9.7 h^{-1} with minimum efficiency heat pump, and over 11.7

h^{-1} with high efficiency heat pump. With a FLUID solution, these n_{50} need to be over 8.9 h^{-1} , 14.6 h^{-1} , and 20.7 h^{-1} , respectively.

The lower bound n_{50} values increase in an urban location. For MECH, they are of 9.1 h^{-1} , 13.5 h^{-1} , and 16.1 h^{-1} , and for FLUID, they reach 13.5 h^{-1} , 25.5 h^{-1} , and 26.4 h^{-1} , for the same order of heating systems.

Overall, for the research case study's scope, for dwellings equipped with electric radiators, adopting a MECH solution almost always justifies the financial investment, especially in rural locations, as even for those with negative RSL savings, they are quite low. The opposite occurs with a high efficiency heat pump, especially in urban locations. For all the other dwellings, the relationship between airtightness performance and the heating system will condition the RSL savings to be positive or negative. As a more expensive solution, FLUID experiences even greater costs. The greater majority of the dwellings compute negative RSL savings. The exception is on dwellings equipped with electric radiators as a heating system where the results are quite mixed.

Table 5.22 indicates the heating systems ranked by EPP and RSL savings from applying an airtightness solution. The first ranked has the shortest average EPP and the highest average RSL savings. While scoring second in average EPP, the pellet heat recovery scores fourth in RSL savings, meaning that despite being environmentally superior, it comes with an aggravated financial burden, compared to the natural gas boiler and the minimum efficiency heat pump.

Table 5.22. Ranked heating systems by shortest average EPP and highest average RSL

Rank	EPP [years]	RSL savings [€]
1	Electric radiator	Electric radiator
2	Pellet heat recovery	Natural gas boiler
3	Natural gas boiler	Min. efficiency heat pump
4	Min. efficiency heat pump	Pellet heat recovery
5	High efficiency heat pump	High efficiency heat pump

5.5. AIRTIGHTNESS PERFORMANCE AND SUSTAINABILITY FINAL REMARKS

The Applications of the present Chapter pursued a further understanding of how the Portuguese residential building stock, existing and new single-family buildings alike, typical of the southern European context, can be increasingly sustainable regarding airtightness performance.

The research presented in Application A5 intended to identify the impacts of dwelling characteristics and portray airtightness performance ranges by establishing a reproducible methodology. The results depended on calculating the ACHs of a dataset of dwellings with a wide scope of features for a representative month of the heating season in a southern European context and applying a rationale on air change rate limits. Four main points are taken:

- The rationale allowed one to label the dwellings as non-compliant by default (NCd), non-compliant by excess (NCe), and compliant (Com). NCd when the dwellings had ACHs inadequate for health purposes by being too low too often. NCe when the dwellings had ACHs inadequate for energy efficiency issues by being too high too often. Com, when the dwellings had limited time, ranges below and above the defined lower and upper ACH limits.
- Regarding the characteristics of dwellings, airtightness (n_{50}) was the most influential continuous feature, followed by the floor area (AF). The terrain (α) was the most influential categorical feature, followed by the number of floors (NF).
- The characteristics of the dwellings influence their permissiveness in surpassing the defined ACH upper limit (0.7 h^{-1}). The dataset splits best by using categorical features. Thus, the terrain was the feature best splitting the data. In rural terrain, the highest performing dwellings needed relaxation of the percentage of time over the upper limit twice that in urban terrain. The thresholds found were less than 40% and 20% of the time, respectively, in rural and urban terrain.
- In a rural terrain, the n_{50} of the highest performing dwellings ranged between 3 and 6 h^{-1} . The n_{50} of the highest performing dwellings in urban terrain ranged between 4 and 8 h^{-1} . Although these ranges are wide, they are mainly dependent on the compactness of the dwelling (ratio of volume to floor area), the number of floors, and the number of stack ducts. By assessing these properties, one narrowed the resulting airtightness performance ranges. The overall average n_{50} of the compliant dwellings was 5.3 h^{-1} , with 4.9 and 5.8 h^{-1} in rural and urban locations.

Most of the implemented airtightness limits across the EU country members align within the lower bound and average values of this research's achieved airtightness performance ranges. While this accordance partially validates the empirical limits in force in central and northern European countries, the forced hard limits and the often consideration of only one feature seems

reductive and potentially counterproductive to the primary objectives of proper envelope airtightness, particularly regarding minimum ACHs for the health and comfort of the occupants. Considering several impacting features would be a better approach in defining airtightness requirements in general, and in the particular scope of this research, for the southern European context.

The research developed in Application A6 intended to create a tool to check airtightness compliance in naturally ventilated dwellings by training predictive models with the dataset used in Application A5, adding the outputted ACHs time series and the dwellings' respective labels in the same Application.

From the existing Machine Learning methods identified as promising in the literature, Application A6 applied a total of five. These models focused on regression capabilities of predicting mean ACH, percentage of time below the defined lower ACH limit, between the lower and the upper limits, and above the upper ACH limit. Regarding classification, the models focused on labelling the dwellings as non-compliant by default (NCd), non-compliant by excess (NCe), and compliant (Com).

- The developed pipeline produced robust predictions. The regression model identified as the best predictor was the Categorical Boosting Regressor (CBR). The test set MAEs on the percentages of time, predicted with this model, was 0.82% for the ACH below 0.4 h^{-1} , 1.02% for the ACH between 0.4 and 0.7 h^{-1} , and 0.63% for the ACH above 0.7 h^{-1} . Regarding the mean ACH, the MAE was 0.003 h^{-1} .
- The categorical model identified as the best predictor was the eXtreme Gradient Boosting Classifier (XGBC). The average accuracy of the test set, predicted with this model, was 97.33%, with an F-score of 97.58%, 96.77%, and 97.62%, for dwellings non-compliant by default (NCd), compliant dwellings (Com), and for dwellings non-compliant by excess (NCe), respectively.

The results of both regression and classification methods demonstrate robustness by having low mispredictions. The used case study showcased the potential of applying the developed methodology, encouraging future works towards its application to different case studies.

Application A7 explored the life cycle impacts of applying whole envelope airtightness solutions in a subset of naturally ventilated dwellings, labelled as having excessive heat losses

by air change rates in Application A5. The life cycle assessment contributed to picturing and contextualizing the impacts of including air barrier solutions in the design of new dwellings and the retrofit of existing ones.

Performing LCA on the airtightness performance of dwellings can be tricky. Considering whole building air barrier solutions seemed to be the most robust research path, but still, several assumptions are needed. Four points are made:

- For a MECH solution, independently of the heating system and terrain, all the dwellings justify its implementation regarding primary energy as the EPP never surpasses the respective RSL. For a FLUID air barrier, in rural terrain, only a portion of the dwellings equipped with a high efficiency heat pump does not have a positive EPP,
- A FLUID solution conferred an EPP 6.32 higher than that of a MECH solution, independently of the terrain and heating system. On average, independently from the heating system and air barrier solution, the EPP of a dwelling in an urban location was 1.63 higher than the EPP of a dwelling in a rural location.
- The dwellings with positive PP range from 80.2% to 19.1% if they are equipped with electric radiators or high efficiency heat pumps. The mean PPs range from 11.0 and 23.2 years. The natural gas boiler, the minimum efficiency heat pump, and the pellet heat recovery place in between, by descending PP. The order of PP by heating system is unchanged in a FLUID solution, but the percentages drop drastically.
- In the same order of heating systems, with MECH, in the groups with positive PP, the average range from 5438 € to 1123 €. The averages of negative PP groups range from -569 € to -1076 €. With FLUID, for the negative PP groups, the average RSL savings range from -2437 € to -3853 €.

With the current analysis, and for the restricted scope and acceptance criteria of the used case study and assumptions, the adoption of mechanically fastened air barrier solutions is recommended in the context of southern Europe with its mild heating season, especially in dwellings equipped with electric radiators.

Still, a FLUID solution has several technical advantages compared to a MECH one. It more easily adapts to complex envelope geometries and provides more efficient adhesion and detailing in connections between envelope components and respective penetrations.

Finally, it is relevant to highlight that the outputted results from the Applications of the present Chapter refer solely to single-family houses of one or two floors in uniform rural and urban terrains. Still, these typologies represent over 79% of the Portuguese residential building stock. While variations from uniform will likely result in intermediate performance ranges from the ones achieved, research in buildings with a greater number of floors and multi-family dwellings would output different airtightness performance ranges.

Although one believes the proposed operating ACH limits to address both health needs and energy efficiency issues, they confer a rather narrow range of operating ACHs. A wider one would make a natural ventilation strategy viable in a wider range of dwellings characteristics and their respective combinations.

For reasons of computational cost, one considered a representative month of the heating season only for ACH simulation. Using a larger time frame would output results increasingly accurate to the weather experienced at the chosen location.

Despite the identified constraints, the methodologies presented in this Chapter can be generalized to setups that fully map the meteorological conditions of several locations and typify the diversity of dwellings and terrain characteristics.

6

CONCLUSIONS AND FUTURE WORKS

6.1. RESEARCH CONTRIBUTIONS

The present thesis successfully developed and applied a methodology for classifying and defining the adequate air permeability of naturally ventilated dwellings, which may support the recommendation of optimal airtightness performance ranges in the future.

As is the case of southern Europe, where natural ventilation dominates the residential building stock, mild climate regions have the most to gain from the produced research. The established framework addresses the long-lasting challenge of balancing conflicting energy consumption and health-related issues in the air change rate strategy in buildings with passive ventilation. The developed work intends to promote a healthier, decarbonized, more efficient and less energy-intensive building stock. By providing a clear path to attain these, the author believes that the contributions of this research will bring a significant boost in chartering these improvements to both current regulations and AEC practices soon.

Most of the methodology in achieving the proposed objective targeted technical aspects, including economic and environmental issues. Their definition was the product of a reviewing process mainly on: practices and procedures in measurement protocols; boundaries and constraints in airflow modelling frameworks; and airtightness requirements and performance characterization in regulations. This way, both the experimental and simulation fields were tackled while addressing the definition of what an adequate airtightness performance should be.

Starting from broader scopes, identifying features embedded in current practices that hinder a correct adaptation to the mild climates of southern Europe allowed focusing on more concise subtopics within these aspects. These guided the definition of the secondary objectives that influence the applicability of the whole methodology by providing assurance and additional

support to its implementation. Throughout the advancement and application of the hypotheses to case studies, the research delivered several contributions to the state of the art and society. Some of the most relevant are as follows:

- *Guidelines for selecting envelope solutions and their performance assessment during the construction process* – as the results from laboratory tests deviate from actual in-situ performance, the construction process must undergo measurements at critical phases. Prescriptive actions such as incorporating a purpose provided air barrier solution could mitigate the lack of agreement;
- *A comprehensive procedure to experimentally characterize air leakage paths quantitatively and qualitatively* – results imply that proper planning regarding the order of sealing steps benefits the quality of the results. They also point to the latest applied regression model providing more reliable input data for risk analysis and confidence intervals on air change rate performance. The procedure allows straightforward decisions for interventions in existing buildings;
- *Guidelines to simulate different combinations of airtightness levels and air leakage paths configurations* – coupled with the in-situ characterization serves to corroborate the findings on air leakage paths distributions and perform risk analysis. The adequate design of ventilation strategies depends on the prior knowledge of the airtightness level, as the whole system performance depends on it;
- *A single zone airflow model that incorporates intra hour meteorological variability, including changing atmospheric stability* – results indicate that dealing with these aspects adds detail that has potential benefits to indoor air quality and the optimization of passive ventilation strategies. The use of hourly distributions and stochastic sampling provides a more exhaustive approximation of the actual conditions;
- *A dataset on the airtightness and geometric characteristics of a single family residential built stock* – the engineered procedure successfully created a dataset representative of a building stock. This dataset was created by statistically treating the outputs of a major measurement campaign, and it is representative of a large portion of the Iberian built stock. It was used as input to the developed single-zone airflow model, referred to in the last contribution, to generate air change rate time series, and together with these, applied in the subsequent research;

- *A template on defining an airtightness performance labeling strategy* – a rationale in defining lower and upper air change rate limits and applying it to the outputted time series of running the generated dataset through the single-zone model allows classifying dwellings according to their compliance status. By identifying the top-performing dwellings, the path is set for obtaining adequate airtightness performance ranges;
- *A methodology to evaluate the adequate airtightness performance ranges of naturally ventilated dwellings* – together with the last contribution, they convey the core of the developed research in adapting airtightness performance ranges to the context of southern Europe. The obtained results partially support the empirical limits in force in other countries while pointing that considering several impacting features would be a better approach in defining airtightness requirements;
- *A Machine Learning framework for assessing airtightness performance and compliance* – intending to fulfil the general societal use, this framework communicates the air change rates due to airtightness performance and classifies a dwelling according to a labelling strategy, requiring only geometric features and the results of an airtightness test of a dwelling. It needs buildings characteristics and meteorological datasets, and the time series from the resulting airflows for training. Results show that a tool like this would provide low errors and high accuracies;
- *Guidelines for an LCA and LCC assessment of envelope airtightness solutions* – assessing the feasibility of these solutions can point to the potential environmental and economic net positive paths, increasing awareness and encouraging adherence by the AEC industry. Results show a mixed outcome depending mainly on the existing heating system and its energy source, while pointing to the easier accomplishment of environmental net gains than economical.

The above contributions are the outputs of completing the secondary objectives, which the author believes done fruitfully. The application to case studies and their conclusions show that the generalization of most methodologies is possible. The results, in themselves, are the product of restricted scopes and thus have narrower acceptance criteria. Therefore, while they may not provide a comprehensive outlook on all possible aspects of airtightness research, they provide valuable insights and encourage future investigations.

6.2. FUTURE RESEARCH PATHS

The work in the current thesis, mainly the developed methodologies, are structured to ease their dissemination either by publishing, either for applying them to other datasets and case studies, as each complementary objective delineates a well-defined sub scope.

Only the generalization of one of its methodologies lacks literature availability for support. It relates to the application of changing atmospheric stability. The category boundaries of the σ_A method require adjustments according to the site roughness, and the roughness length is typically not uniform in all directions at the measuring site. While CpCalc+ provides an interesting tool to obtain the wind pressure coefficients with changing wind shear coefficient, its use is limited to some predefined standard geometries and specific ranges of wind shear coefficients, particularly the upper limit cap. These are two primary examples of future research paths.

The test of additional dwellings and their envelopes using the comprehensive procedure to characterize air leakage paths quantitatively and qualitatively could support and complement the achieved results. It would potentially refine the procedure and encourage its application in deciding which air leaks to intervene in leaky envelopes.

Applying test results treated using the preferred regression method in modelling setups to assess the confidence intervals of the outputs of simulations needs research. It would be relevant in the risk analysis of accomplishing minimum air change rate requirements and providing a significant warranty of the adequate performance of the envelope system.

The identification and sealing of air leakage paths and further testing in case studies would provide additional knowledge for the guidelines on simulating different combinations of airtightness levels and air leakage paths configurations by providing additional data for input and comparison with simulation results. It would be relevant to perform this in future case studies, together with uncertainty consideration, in the case of sensitivity analysis.

Additional future works regarding the developed single-zone airflow modelling should include assessing the impact of using alternative formulations, such as the quadratic equation in modelling airflow paths and the logarithmic law in vertically extrapolating wind speeds. Moreover, analyzing the correlation between meteorological variables and pressure distribution along the building facade could bring additional insights.

Regarding the labelling strategy and the study of adequate airtightness performance ranges, future research should address: different and broader datasets on building characteristics and meteorological data as inputs; test combinations of ACH limits and cut-off rules in the labelling strategy, and therefore, construct complementary airtightness performance ranges. The future research outputs would complementarily allow testing the robustness of the Machine Learning framework.

Future works in LCA and LCC scopes should favor: the use of different envelope airtightness solutions; the tackling of assumptions regarding the air change rate performance of applying self-regulating vents; the adaptation from a methodology predominantly focused on lightweight to traditional construction. This last is quite challenging because of the difficulty in objectively or even statistically quantifying airtightness solutions in the heavy construction types.

Finally, in the long run, the methodologies presented can be applied to setups that fully map the meteorological conditions of several locations and typify the diversity of dwellings and terrain characteristics. It would form the groundwork for a possible airtightness performance and sustainability tool, with potential for application at regional, national, and EU levels. It could be a complementary asset to energy certification programs of either public or private initiatives.

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ANNEX A2

This Annex refers to Application A2. The equations presented here are used to determine the regression parameters of the linearized power law (a and b) of $y = a \cdot x + b$. The corresponding uncertainties and correlations coefficients are detailed for the two regression methods: Ordinary Least Squares (OLS) and Weighted Line of Organic Correlation (WLOC).

The value of s^2 refers to the variance of the airflow component. OLSy assumes the sum of squares of the distances between the regression line and the initial airflow coordinates in y. In OLSu, it takes the form of the inverse of the square of the uncertainty in the airflow component $-1/u^2(\ln(qi))$.

Ordinary Least Squares

$$a = \frac{N \sum x_i y_i - \sum x_i \sum y_i}{N \sum x_i^2 - (\sum x_i)^2} \quad (A2.1)$$

$$b = \frac{\sum x_i^2 \sum y_i - \sum x_i \sum x_i y_i}{N \sum x_i^2 - (\sum x_i)^2} \quad (A2.2)$$

$$u(a) = \sqrt{\frac{N \cdot s^2}{N \sum x_i^2 - (\sum x_i)^2}} \quad (A2.3)$$

$$u(b) = \sqrt{\frac{s^2 \sum x_i^2}{N \sum x_i^2 - (\sum x_i)^2}} \quad (A2.4)$$

$$r(a, b) = \frac{-\sum x_i}{\sqrt{N \sum x_i^2}} \quad (A2.5)$$

Weighted Line of Organic Correlation

$$v_i = \frac{1}{u(x_i)} \quad (A2.6)$$

$$w_i = \frac{1}{u(y_i)} \quad (A2.7)$$

$$a = \frac{\sqrt{\sum v_i w_i \sum v_i w_i y_i^2 - (\sum v_i w_i y_i)^2}}{\sqrt{\sum v_i w_i \sum v_i w_i x_i^2 - (\sum v_i w_i x_i)^2}} \quad (A2.8)$$

$$b = \frac{\sum v_i w_i y_i - a \sum v_i w_i x_i}{\sum v_i w_i} \quad (\text{A2.9})$$

$$u(a) = \sqrt{\sum \left(\frac{\partial a}{\partial x_i} \right)^2 \frac{1}{v_i^2} + \left(\frac{\partial a}{\partial x_i} \right)^2 \frac{1}{w_i^2}} \quad (\text{A2.10})$$

$$\frac{\partial a}{\partial x_i} = \sqrt{\frac{\Delta y}{\Delta x} \frac{(\sum v_j w_j x_j) v_i w_i - (\sum v_j w_j) v_i w_i x_i}{\Delta x}} \quad (\text{A2.11})$$

$$\frac{\partial a}{\partial y_i} = \sqrt{\frac{\Delta y}{\Delta x} \frac{(\sum v_j w_j) v_i w_i y_i - (\sum v_j w_j y_j) v_i w_i}{\Delta y}} \quad (\text{A2.12})$$

$$u(b) = \sqrt{\sum \left(\frac{\partial b}{\partial x_i} \right)^2 \frac{1}{v_i^2} + \left(\frac{\partial b}{\partial x_i} \right)^2 \frac{1}{w_i^2}} \quad (\text{A2.13})$$

$$\frac{\partial b}{\partial x_i} = a \left(\frac{-v_i w_i}{\sum v_j w_j} - \frac{(\sum v_j w_j x_j)^2 v_i w_i}{\Delta x \sum v_j w_j} + \frac{(\sum v_j w_j x_j) v_i w_i x_i}{\Delta x} \right) \quad (\text{A2.14})$$

$$\frac{\partial b}{\partial y_i} = \frac{v_i w_i}{\sum v_j w_j} - \frac{(\sum v_j w_j x_j) v_i w_i y_i}{\sqrt{\Delta x} \sqrt{\Delta y}} + \frac{(\sum v_j w_j x_j) (\sum v_j w_j y_j) v_i w_i}{\sqrt{\Delta x} \sqrt{\Delta y} \sum v_j w_j} \quad (\text{A2.15})$$

$$\Delta x = \sum v_i w_i \sum v_i w_i x_i^2 - \left(\sum v_i w_i x_i \right)^2 \quad (\text{A2.16})$$

$$\Delta y = \sum v_i w_i \sum v_i w_i y_i^2 - \left(\sum v_i w_i y_i \right)^2 \quad (\text{A2.17})$$

$$r(a, b) = \frac{u^2(a + b) - u^2(a) - u^2(b)}{2u(a)u(b)} \quad (\text{A2.18})$$

$$u^2(a + b) = \sum \left(\frac{\partial a}{\partial x_i} + \frac{\partial b}{\partial x_i} \right)^2 \frac{1}{v_i^2} + \left(\frac{\partial a}{\partial y_i} + \frac{\partial b}{\partial y_i} \right)^2 \frac{1}{w_i^2} \quad (\text{A2.19})$$

Table A 4.1. Airflow rate – pressure difference pairs for the different sealing steps during depressurization (D) and pressurization (P) tests.

DEF	Q _{env}	Δ _p	MEV	Q _{env}	Δ _p
D	924.10	64.71	D	779.21	64.96
	894.99	60.29		735.81	58.69
	837.81	54.01		708.71	55.01
	774.15	47.54		654.06	47.63
	735.26	42.69		608.18	42.02
	677.59	37.15		563.45	36.50
	615.24	30.98		515.47	31.82
	555.40	25.87		466.45	26.68
	487.62	20.63		394.59	19.68
	404.80	15.21		329.62	15.78
P	927.73	66.77	P	812.77	70.03
	881.29	60.72		754.39	61.36
	831.83	55.57		706.65	55.37
	773.38	48.80		661.66	48.28

	690.60	39.64		613.72	42.16
	670.66	37.86		571.57	38.20
	605.75	31.93		525.67	34.60
	547.27	26.82		468.42	27.36
	470.67	21.12		394.59	20.42
	396.72	15.53		341.26	15.96
HAC	Q _{env}	Δ _p	ELE	Q _{env}	Δ _p
D	630.65	64.33	D	555.40	64.96
	594.97	58.00		522.20	59.45
	563.93	52.74		499.03	55.04
	536.52	48.35		464.41	49.89
	494.66	42.33		418.02	42.48
	459.95	37.05		409.22	40.44
	419.13	31.37		359.17	33.15
	354.91	23.69		314.00	26.74
	319.91	20.30		276.31	21.90
	268.41	15.04		217.21	15.08
P	629.56	65.87	P	569.22	64.72
	594.62	60.71		546.15	60.72
	553.01	54.97		513.08	54.51
	525.77	49.85		460.40	46.70
	497.30	44.68		447.37	43.61
	445.79	38.26		398.08	36.59
	417.80	33.87		357.09	30.77
	356.16	26.33		319.05	26.47
	322.42	22.81		276.79	20.16
	257.52	15.87		215.33	14.12
LIG	Q _{env}	Δ _p	PLU	Q _{env}	Δ _p
D	522.77	69.84	D	509.45	66.47
	473.03	59.67		483.96	60.38
	448.71	55.81		451.00	55.62
	414.24	48.62		422.30	49.92
	385.06	43.53		393.07	44.34
	352.76	37.39		358.84	38.43
	323.08	32.82		325.36	32.54
	290.74	27.73		287.72	27.85
	239.49	19.83		278.51	24.84
	198.94	15.59		211.85	17.23
P	494.68	62.91	P	479.08	61.81
	463.45	53.83		450.33	56.36
	437.48	49.99		423.08	50.36
	410.63	45.10		403.64	48.01
	379.87	40.46		365.94	40.79
	352.48	35.48		345.76	38.32
	314.79	29.02		311.73	30.74
	280.65	24.26		275.90	25.64

	235.82	18.19		237.08	20.66
	176.19	12.37		186.57	14.84
WWJ	Q_{env}	Δ_p	WFJ	Q_{env}	Δ_p
D	426.46	65.16	D	352.48	64.78
	418.51	63.06		336.50	58.99
	375.88	53.69		313.01	53.26
	360.42	50.32		297.75	49.11
	329.20	43.67		270.60	42.72
	298.02	37.75		247.47	37.84
	269.22	32.33		223.34	32.65
	244.74	27.36		198.36	26.77
	208.30	21.65		179.51	21.90
	165.55	15.98		146.83	15.69
P	432.61	64.95	P	374.73	67.28
	399.31	58.14		356.10	59.18
	379.94	54.49		316.39	51.23
	350.07	47.13		309.28	49.00
	318.22	41.78		292.84	45.06
	295.54	37.11		266.08	38.27
	265.92	30.84		240.71	32.85
	238.99	26.68		209.06	26.09
	204.19	21.86		191.62	22.54
	140.36	12.42		151.38	15.22
WRJ	Q_{env}	Δ_p	WOJ	Q_{env}	Δ_p
D	341.10	65.99	D	328.01	68.67
	314.07	59.32		304.36	60.52
	295.90	54.41		287.37	55.57
	283.00	49.75		266.57	49.03
	244.54	41.22		248.38	43.80
	229.71	38.22		229.25	38.32
	195.50	29.37		210.47	32.90
	192.20	27.68		189.24	28.00
	158.55	21.46		154.64	20.98
	144.63	18.01		128.35	15.74
P	341.50	66.62	P	296.58	64.87
	317.90	58.19		289.04	58.82
	297.80	53.57		262.80	52.71
	278.20	47.67		246.24	47.80
	257.69	41.68		232.58	43.04
	241.74	37.24		214.01	37.42
	219.91	32.22		193.26	31.05
	202.51	27.66		166.43	24.51
	165.39	20.58		144.43	19.01
	139.34	14.81		122.12	13.80
OPE	Q_{env}	Δ_p	ENT	Q_{env}	Δ_p
D	182.09	65.30	D	67.71	64.26

	170.04	59.47		64.73	59.86
	168.18	53.70		59.24	54.46
	162.32	50.26		54.43	47.96
	143.77	42.41		50.86	43.66
	128.06	35.67		45.79	37.16
	116.39	30.44		41.27	31.96
	112.27	27.99		37.42	26.76
	93.94	20.66		31.71	21.06
	80.95	15.83		24.33	14.76
P	150.50	66.34	P	54.11	65.63
	141.95	60.41		51.98	61.78
	134.52	55.38		44.86	53.34
	121.55	49.84		44.93	51.25
	112.46	42.98		39.96	44.43
	102.80	37.21		35.80	37.06
	89.93	30.25		32.24	31.89
	84.05	27.13		27.80	26.22
	76.48	22.33		22.11	19.36
	59.29	16.16		19.25	15.95

ANNEX A4

Table A 4.2. Outputted WPCs from the CpCalc+ software for the different WSCs (α) on the envelope of the considered case study of Application A4.

$\alpha = 0.104$										
Envelope Surface										
Angle (deg)	1L	1U	2L	2U	3L	3U	4L	4U	5	6
0	0.655	0.755	-0.345	-0.386	-0.761	-0.832	-0.761	-0.832	-0.589	-0.504
45	0.215	0.243	-0.365	-0.385	0.215	0.243	-0.365	-0.385	-0.527	-0.942
90	-0.761	-0.832	-0.761	-0.832	0.655	0.755	-0.345	-0.386	-1.242	-1.260
135	-0.365	-0.385	0.215	0.243	0.215	0.243	-0.365	-0.385	-0.897	-0.533
180	-0.345	-0.386	0.655	0.755	-0.761	-0.832	-0.761	-0.832	-0.504	-0.589
225	-0.365	-0.385	0.215	0.243	-0.365	-0.385	0.215	0.243	-0.942	-0.527
270	-0.761	-0.832	-0.761	-0.832	-0.345	-0.386	0.655	0.755	-1.260	-1.242
315	0.215	0.243	-0.365	-0.385	-0.365	-0.385	0.215	0.243	-0.533	-0.897

$\alpha = 0.112$										
Envelope Surface										
Angle (deg)	1L	1U	2L	2U	3L	3U	4L	4U	5	6
0	0.653	0.746	-0.347	-0.380	-0.766	-0.819	-0.766	-0.819	-0.582	-0.484
45	0.214	0.240	-0.368	-0.379	0.214	0.240	-0.368	-0.379	-0.510	-0.892
90	-0.766	-0.819	-0.766	-0.819	0.653	0.746	-0.347	-0.380	-1.164	-1.181
135	-0.368	-0.379	0.214	0.240	0.214	0.240	-0.368	-0.379	-0.851	-0.518
180	-0.347	-0.380	0.653	0.746	-0.766	-0.819	-0.766	-0.819	-0.484	-0.582
225	-0.368	-0.379	0.214	0.240	-0.368	-0.379	0.214	0.240	-0.892	-0.510
270	-0.766	-0.819	-0.766	-0.819	-0.347	-0.380	0.653	0.746	-1.181	-1.164
315	0.214	0.240	-0.368	-0.379	-0.368	-0.379	0.214	0.240	-0.518	-0.851

$\alpha = 0.131$										
Envelope Surface										
Angle (deg)	1L	1U	2L	2U	3L	3U	4L	4U	5	6
0	0.643	0.723	-0.351	-0.365	-0.775	-0.787	-0.775	-0.787	-0.564	-0.437
45	0.211	0.232	-0.372	-0.364	0.211	0.232	-0.372	-0.364	-0.472	-0.775
90	-0.775	-0.787	-0.775	-0.787	0.643	0.723	-0.351	-0.365	-0.982	-0.996
135	-0.372	-0.364	0.211	0.232	0.211	0.232	-0.372	-0.364	-0.743	-0.482
180	-0.351	-0.365	0.643	0.723	-0.775	-0.787	-0.775	-0.787	-0.437	-0.564
225	-0.372	-0.364	0.211	0.232	-0.372	-0.364	0.211	0.232	-0.775	-0.472
270	-0.775	-0.787	-0.775	-0.787	-0.351	-0.365	0.643	0.723	-0.996	-0.982
315	0.211	0.232	-0.372	-0.364	-0.372	-0.364	0.211	0.232	-0.482	-0.743

$\alpha = 0.185$		Envelope Surface								
Angle (deg)	1L	1U	2L	2U	3L	3U	4L	4U	5	6
0	0.594	0.661	-0.344	-0.320	-0.760	-0.690	-0.760	-0.690	-0.520	-0.330
45	0.195	0.212	-0.365	-0.319	0.195	0.212	-0.365	-0.319	-0.384	-0.518
90	-0.760	-0.690	-0.760	-0.690	0.594	0.661	-0.344	-0.320	-0.577	-0.585
135	-0.365	-0.319	0.195	0.212	0.195	0.212	-0.365	-0.319	-0.507	-0.399
180	-0.344	-0.320	0.594	0.661	-0.760	-0.690	-0.760	-0.690	-0.330	-0.520
225	-0.365	-0.319	0.195	0.212	-0.365	-0.319	0.195	0.212	-0.518	-0.384
270	-0.760	-0.690	-0.760	-0.690	-0.344	-0.320	0.594	0.661	-0.585	-0.577
315	0.195	0.212	-0.365	-0.319	-0.365	-0.319	0.195	0.212	-0.399	-0.507
$\alpha = 0.344$		Envelope Surface								
Angle (deg)	1L	1U	2L	2U	3L	3U	4L	4U	5	6
0	0.261	0.473	-0.176	-0.157	-0.388	-0.339	-0.388	-0.339	-0.432	-0.195
45	0.086	0.152	-0.186	-0.157	0.086	0.152	-0.186	-0.157	-0.268	-0.288
90	-0.388	-0.339	-0.388	-0.339	0.261	0.473	-0.176	-0.157	-0.175	-0.178
135	-0.186	-0.157	0.086	0.152	0.086	0.152	-0.186	-0.157	-0.297	-0.284
180	-0.176	-0.157	0.261	0.473	-0.388	-0.339	-0.388	-0.339	-0.195	-0.432
225	-0.186	-0.157	0.086	0.152	-0.186	-0.157	0.086	0.152	-0.288	-0.268
270	-0.388	-0.339	-0.388	-0.339	-0.176	-0.157	0.261	0.473	-0.178	-0.175
315	0.086	0.152	-0.186	-0.157	-0.186	-0.157	0.086	0.152	-0.284	-0.297
$\alpha = 0.591$		Envelope Surface								
Angle (deg)	1L	1U	2L	2U	3L	3U	4L	4U	5	6
0	0.078	0.403	-0.064	-0.090	-0.142	-0.195	-0.142	-0.195	-0.432	-0.195
45	0.026	0.129	-0.068	-0.090	0.026	0.129	-0.068	-0.090	-0.268	-0.288
90	-0.142	-0.195	-0.142	-0.195	0.078	0.403	-0.064	-0.090	-0.175	-0.178
135	-0.068	-0.090	0.026	0.129	0.026	0.129	-0.068	-0.090	-0.297	-0.284
180	-0.064	-0.090	0.078	0.403	-0.142	-0.195	-0.142	-0.195	-0.195	-0.432
225	-0.068	-0.090	0.026	0.129	-0.068	-0.090	0.026	0.129	-0.288	-0.268
270	-0.142	-0.195	-0.142	-0.195	-0.064	-0.090	0.078	0.403	-0.178	-0.175
315	0.026	0.129	-0.068	-0.090	-0.068	-0.090	0.026	0.129	-0.284	-0.297

ANNEX A5

Table A 4.3. Input characteristics and ACHs globals of the top-performing dwellings, labelled as Com, compliant, in Application A5, with a 2:1 SR, 4 ES, and a 20° RS.

AF [m ²]	CH [m]	n ₅₀ [h ⁻¹]	n [-]	ND [-]	NF [-]	α [-]	P(ACH < 0.4 h ⁻¹) [%]	P(0.4 h ⁻¹ < ACH < 0.7 h ⁻¹) [%]	P(ACH > 0.7 h ⁻¹) [%]	ACH mean [h ⁻¹]
100.87	2.41	5.62	0.55	2	1	0.14	16.53%	43.75%	39.72%	0.68
80.14	2.29	5.03	0.58	2	1	0.14	18.47%	49.72%	31.81%	0.63
67.71	2.73	5.82	0.59	2	1	0.14	15.00%	46.39%	38.61%	0.69
51.26	2.62	5.31	0.66	2	1	0.14	18.61%	51.25%	30.14%	0.63
102.81	2.60	5.23	0.54	2	1	0.14	19.86%	45.28%	34.86%	0.65
60.89	2.31	5.30	0.60	2	1	0.14	10.28%	52.36%	37.36%	0.68
42.86	2.91	5.07	0.64	2	1	0.14	15.56%	54.44%	30.00%	0.63
74.02	2.90	5.28	0.56	2	1	0.14	17.22%	47.08%	35.69%	0.66
128.36	2.97	6.40	0.62	2	2	0.14	19.03%	41.53%	39.44%	0.69
106.66	2.94	5.57	0.60	2	2	0.14	18.47%	45.83%	35.69%	0.67
96.46	2.75	4.02	0.53	2	2	0.14	19.03%	53.47%	27.50%	0.60
86.78	2.78	4.77	0.60	2	2	0.14	20.00%	50.14%	29.86%	0.62
127.85	2.66	5.38	0.57	2	2	0.14	17.64%	45.69%	36.67%	0.67
125.80	2.63	4.57	0.53	2	2	0.14	16.53%	49.58%	33.89%	0.64
94.98	2.69	5.50	0.61	2	2	0.14	17.08%	46.67%	36.25%	0.67
80.14	2.29	5.03	0.58	3	1	0.14	4.86%	55.28%	39.86%	0.70
51.26	2.62	5.31	0.66	3	1	0.14	5.83%	55.69%	38.47%	0.69
136.32	2.37	5.74	0.59	3	1	0.14	18.06%	45.83%	36.11%	0.67
159.23	2.42	5.16	0.53	3	1	0.14	18.19%	44.86%	36.94%	0.66
125.80	2.63	4.57	0.53	3	1	0.14	19.03%	50.00%	30.97%	0.62
78.97	2.37	4.92	0.58	3	1	0.14	6.39%	55.28%	38.33%	0.68
42.86	2.91	5.07	0.64	3	1	0.14	4.58%	57.22%	38.19%	0.70
94.98	2.69	5.50	0.61	3	1	0.14	18.47%	47.64%	33.89%	0.65
143.63	2.35	5.73	0.57	3	1	0.14	16.53%	43.61%	39.86%	0.68
218.06	2.52	4.79	0.53	3	2	0.14	16.39%	48.06%	35.56%	0.66
165.54	2.60	6.07	0.63	3	2	0.14	17.64%	43.61%	38.75%	0.69
96.46	2.75	4.02	0.53	3	2	0.14	6.53%	57.50%	35.97%	0.67
126.82	2.48	4.23	0.57	3	2	0.14	17.22%	53.47%	29.31%	0.62
86.78	2.78	4.77	0.60	3	2	0.14	6.67%	54.17%	39.17%	0.69
85.17	2.52	4.23	0.63	3	2	0.14	14.58%	57.64%	27.78%	0.62
78.38	2.33	4.01	0.62	3	2	0.14	9.03%	61.53%	29.44%	0.64
114.39	2.87	4.94	0.58	3	2	0.14	13.47%	50.28%	36.25%	0.67
68.47	2.65	3.98	0.60	3	2	0.14	6.25%	63.06%	30.69%	0.65
123.27	2.58	4.52	0.56	3	2	0.14	13.06%	52.08%	34.86%	0.66

252.89	2.42	5.87	0.59	3	2	0.14	19.17%	41.94%	38.89%	0.68
180.59	2.36	5.75	0.63	3	2	0.14	19.72%	44.31%	35.97%	0.66
87.84	2.55	4.98	0.64	3	2	0.14	9.58%	53.61%	36.81%	0.68
140.77	2.81	5.36	0.59	3	2	0.14	15.83%	46.39%	37.78%	0.68
128.88	2.41	3.72	0.55	3	2	0.14	19.31%	56.53%	24.17%	0.59
121.27	2.79	6.70	0.70	3	2	0.14	18.75%	43.61%	37.64%	0.69
129.92	2.41	4.79	0.58	3	2	0.14	13.33%	51.11%	35.56%	0.67
109.56	2.69	5.92	0.67	3	2	0.14	15.56%	46.81%	37.64%	0.69
107.63	2.35	4.63	0.59	3	2	0.14	7.92%	53.89%	38.19%	0.68
145.97	3.23	5.56	0.60	3	2	0.14	20.00%	44.86%	35.14%	0.66
109.07	2.89	5.37	0.61	3	2	0.14	12.64%	48.19%	39.17%	0.69
111.49	2.47	4.33	0.60	3	2	0.14	16.53%	54.03%	29.44%	0.63
92.97	2.67	4.09	0.59	3	2	0.14	15.00%	56.81%	28.19%	0.62
148.98	2.65	5.77	0.63	3	2	0.14	18.89%	45.42%	35.69%	0.67
208.63	2.51	4.91	0.56	3	2	0.14	19.58%	47.22%	33.19%	0.64
92.47	2.42	4.94	0.62	3	2	0.14	5.97%	54.58%	39.44%	0.70
106.66	2.94	5.57	0.60	4	1	0.14	13.89%	47.36%	38.75%	0.69
96.46	2.75	4.02	0.53	4	1	0.14	9.58%	60.56%	29.86%	0.63
86.78	2.78	4.77	0.60	4	1	0.14	10.14%	56.94%	32.92%	0.65
100.38	3.07	6.73	0.67	4	1	0.14	17.50%	44.44%	38.06%	0.69
95.47	2.47	5.29	0.64	4	1	0.14	11.11%	54.58%	34.31%	0.66
78.38	2.33	4.01	0.62	4	1	0.14	16.53%	61.39%	22.08%	0.59
114.39	2.87	4.94	0.58	4	1	0.14	18.33%	50.83%	30.83%	0.63
68.47	2.65	3.98	0.60	4	1	0.14	12.92%	62.92%	24.17%	0.60
123.27	2.58	4.52	0.56	4	1	0.14	18.06%	52.22%	29.72%	0.62
87.84	2.55	4.98	0.64	4	1	0.14	13.89%	56.11%	30.00%	0.63
127.85	2.66	5.38	0.57	4	1	0.14	14.03%	47.36%	38.61%	0.68
129.92	2.41	4.79	0.58	4	1	0.14	18.47%	51.67%	29.86%	0.63
107.63	2.35	4.63	0.59	4	1	0.14	11.67%	56.25%	32.08%	0.64
109.07	2.89	5.37	0.61	4	1	0.14	17.92%	47.78%	34.31%	0.65
92.97	2.67	4.09	0.59	4	1	0.14	19.03%	57.92%	23.06%	0.58
125.80	2.63	4.57	0.53	4	1	0.14	12.08%	51.39%	36.53%	0.66
94.98	2.69	5.50	0.61	4	1	0.14	7.92%	53.06%	39.03%	0.70
141.90	2.38	6.25	0.64	4	1	0.14	18.47%	45.14%	36.39%	0.67
92.47	2.42	4.94	0.62	4	1	0.14	10.69%	55.97%	33.33%	0.65
111.97	2.51	4.88	0.68	4	2	0.14	15.42%	53.89%	30.69%	0.64
89.40	2.59	3.57	0.63	4	2	0.14	18.06%	62.08%	19.86%	0.57
153.97	2.85	4.67	0.59	4	2	0.14	18.47%	50.83%	30.69%	0.63
126.82	2.48	4.23	0.57	4	2	0.14	8.47%	57.36%	34.17%	0.66
93.48	3.00	4.05	0.60	4	2	0.14	12.50%	59.44%	28.06%	0.62
85.17	2.52	4.23	0.63	4	2	0.14	6.53%	60.42%	33.06%	0.66
151.44	3.09	5.07	0.60	4	2	0.14	17.64%	48.33%	34.03%	0.65
157.23	2.46	4.97	0.62	4	2	0.14	15.56%	50.00%	34.44%	0.66
80.72	2.54	3.08	0.61	4	2	0.14	19.86%	63.89%	16.25%	0.54
78.38	2.33	4.01	0.62	4	2	0.14	3.19%	61.81%	35.00%	0.68
68.47	2.65	3.98	0.60	4	2	0.14	2.22%	60.00%	37.78%	0.69

141.33	2.69	4.23	0.59	4	2	0.14	18.33%	53.61%	28.06%	0.61
195.92	2.85	4.48	0.55	4	2	0.14	18.75%	50.28%	30.97%	0.63
85.71	2.57	3.52	0.64	4	2	0.14	19.31%	61.94%	18.75%	0.57
216.64	2.70	5.78	0.61	4	2	0.14	18.33%	43.75%	37.92%	0.68
128.88	2.41	3.72	0.55	4	2	0.14	10.00%	61.81%	28.19%	0.63
191.79	2.89	6.25	0.64	4	2	0.14	17.64%	42.92%	39.44%	0.70
145.97	3.23	5.56	0.60	4	2	0.14	14.17%	45.97%	39.86%	0.70
111.49	2.47	4.33	0.60	4	2	0.14	6.25%	58.06%	35.69%	0.67
92.97	2.67	4.09	0.59	4	2	0.14	4.03%	61.39%	34.58%	0.67
135.23	2.78	4.90	0.63	4	2	0.14	17.78%	51.25%	30.97%	0.64
204.94	2.71	5.06	0.58	4	2	0.14	17.92%	47.08%	35.00%	0.65
98.92	2.56	3.63	0.62	4	2	0.14	17.64%	61.53%	20.83%	0.58
152.07	2.87	5.48	0.62	4	2	0.14	15.14%	46.94%	37.92%	0.68
99.41	2.89	4.41	0.65	4	2	0.14	15.97%	56.39%	27.64%	0.62
208.63	2.51	4.91	0.56	4	2	0.14	14.31%	47.92%	37.78%	0.67
101.35	2.51	3.34	0.59	4	2	0.14	17.08%	63.75%	19.17%	0.57
70.64	2.51	6.48	0.55	2	1	0.22	14.58%	66.67%	18.75%	0.57
47.71	2.69	5.60	0.61	2	1	0.22	15.42%	74.31%	10.28%	0.53
81.29	2.65	7.80	0.67	2	2	0.22	19.03%	65.28%	15.69%	0.55
100.87	2.41	5.62	0.55	2	2	0.22	15.42%	70.14%	14.44%	0.55
69.93	2.59	5.58	0.57	2	2	0.22	6.81%	75.97%	17.22%	0.58
80.14	2.29	5.03	0.58	2	2	0.22	15.97%	72.92%	11.11%	0.53
67.71	2.73	5.82	0.59	2	2	0.22	12.64%	72.08%	15.28%	0.56
51.26	2.62	5.31	0.66	2	2	0.22	12.50%	76.53%	10.97%	0.54
176.35	2.39	7.15	0.56	2	2	0.22	16.67%	65.14%	18.19%	0.56
122.77	2.56	7.28	0.59	2	2	0.22	15.97%	65.97%	18.06%	0.57
89.92	2.46	6.90	0.62	2	2	0.22	15.56%	68.06%	16.39%	0.56
60.89	2.31	5.30	0.60	2	2	0.22	5.00%	78.33%	16.67%	0.59
95.97	2.43	5.02	0.51	2	2	0.22	10.69%	73.75%	15.56%	0.56
90.43	2.90	5.99	0.56	2	2	0.22	16.94%	69.31%	13.75%	0.55
113.91	2.92	6.70	0.56	2	2	0.22	17.64%	66.53%	15.83%	0.55
42.86	2.91	5.07	0.64	2	2	0.22	9.17%	79.44%	11.39%	0.55
74.02	2.90	5.28	0.56	2	2	0.22	16.94%	70.83%	12.22%	0.54
155.26	2.62	8.57	0.62	2	2	0.22	20.00%	61.25%	18.75%	0.56
91.45	2.79	5.37	0.51	2	2	0.22	9.58%	74.72%	15.69%	0.57
115.85	2.69	7.21	0.59	2	2	0.22	17.64%	65.69%	16.67%	0.56
66.15	2.75	7.16	0.69	3	1	0.22	17.92%	71.11%	10.97%	0.53
87.31	2.62	8.07	0.63	3	1	0.22	16.53%	63.75%	19.72%	0.58
69.93	2.59	5.58	0.57	3	1	0.22	4.86%	77.92%	17.22%	0.58
80.14	2.29	5.03	0.58	3	1	0.22	14.86%	74.72%	10.42%	0.53
67.71	2.73	5.82	0.59	3	1	0.22	9.17%	76.67%	14.17%	0.56
51.26	2.62	5.31	0.66	3	1	0.22	12.36%	77.36%	10.28%	0.54
89.92	2.46	6.90	0.62	3	1	0.22	18.75%	66.53%	14.72%	0.55
60.89	2.31	5.30	0.60	3	1	0.22	4.72%	78.75%	16.53%	0.59
95.97	2.43	5.02	0.51	3	1	0.22	14.86%	70.69%	14.44%	0.55
118.30	2.16	6.30	0.55	3	1	0.22	19.44%	63.06%	17.50%	0.56

78.97	2.37	4.92	0.58	3	1	0.22	17.36%	73.47%	9.17%	0.52
42.86	2.91	5.07	0.64	3	1	0.22	9.72%	79.17%	11.11%	0.55
74.02	2.90	5.28	0.56	3	1	0.22	16.11%	72.78%	11.11%	0.53
91.45	2.79	5.37	0.51	3	1	0.22	17.64%	67.36%	15.00%	0.55
96.46	2.75	4.02	0.53	3	2	0.22	18.33%	74.17%	7.50%	0.51
202.58	2.05	6.50	0.56	3	2	0.22	13.89%	66.53%	19.58%	0.58
105.70	2.73	6.25	0.59	3	2	0.22	9.03%	71.94%	19.03%	0.59
86.78	2.78	4.77	0.60	3	2	0.22	17.22%	72.92%	9.86%	0.52
150.82	2.20	6.75	0.62	3	2	0.22	17.22%	66.39%	16.39%	0.56
184.15	2.44	6.95	0.58	3	2	0.22	17.36%	64.86%	17.78%	0.56
95.47	2.47	5.29	0.64	3	2	0.22	18.89%	70.69%	10.42%	0.52
78.38	2.33	4.01	0.62	3	2	0.22	18.75%	75.14%	6.11%	0.51
124.28	2.49	6.31	0.60	3	2	0.22	13.06%	69.58%	17.36%	0.57
68.47	2.65	3.98	0.60	3	2	0.22	14.17%	79.17%	6.67%	0.52
137.97	2.02	5.97	0.59	3	2	0.22	10.83%	71.39%	17.78%	0.58
112.94	2.33	5.67	0.59	3	2	0.22	9.58%	73.61%	16.81%	0.58
173.12	2.45	6.94	0.58	3	2	0.22	16.25%	65.14%	18.61%	0.57
136.32	2.37	5.74	0.59	3	2	0.22	18.06%	68.61%	13.33%	0.54
103.29	3.56	5.88	0.54	3	2	0.22	10.28%	72.50%	17.22%	0.58
159.23	2.42	5.16	0.53	3	2	0.22	18.19%	68.75%	13.06%	0.54
160.60	2.61	6.11	0.55	3	2	0.22	15.69%	67.50%	16.81%	0.56
125.80	2.63	4.57	0.53	3	2	0.22	19.44%	70.42%	10.14%	0.52
94.98	2.69	5.50	0.61	3	2	0.22	15.42%	72.36%	12.22%	0.54
143.63	2.35	5.73	0.57	3	2	0.22	16.11%	68.61%	15.28%	0.55
91.96	2.67	6.79	0.66	3	2	0.22	12.22%	71.39%	16.39%	0.57
92.47	2.42	4.94	0.62	3	2	0.22	15.56%	74.44%	10.00%	0.53
123.78	2.38	7.08	0.61	4	1	0.22	16.11%	66.39%	17.50%	0.56
79.56	3.10	8.20	0.69	4	1	0.22	14.17%	70.83%	15.00%	0.56
105.70	2.73	6.25	0.59	4	1	0.22	15.97%	69.58%	14.44%	0.55
80.14	2.29	5.03	0.58	4	1	0.22	3.47%	78.47%	18.06%	0.59
51.26	2.62	5.31	0.66	4	1	0.22	5.69%	76.53%	17.78%	0.58
137.97	2.02	5.97	0.59	4	1	0.22	19.31%	67.50%	13.19%	0.54
102.81	2.60	5.23	0.54	4	1	0.22	10.28%	75.14%	14.58%	0.56
112.94	2.33	5.67	0.59	4	1	0.22	15.00%	72.22%	12.78%	0.54
82.98	3.43	7.71	0.64	4	1	0.22	17.64%	66.25%	16.11%	0.56
90.43	2.90	5.99	0.56	4	1	0.22	5.97%	75.14%	18.89%	0.59
113.91	2.92	6.70	0.56	4	1	0.22	18.47%	62.78%	18.75%	0.57
101.84	2.78	7.32	0.64	4	1	0.22	18.06%	67.22%	14.72%	0.55
78.97	2.37	4.92	0.58	4	1	0.22	4.72%	80.28%	15.00%	0.58
42.86	2.91	5.07	0.64	4	1	0.22	4.86%	75.97%	19.17%	0.59
74.02	2.90	5.28	0.56	4	1	0.22	2.78%	78.19%	19.03%	0.60
91.96	2.67	6.79	0.66	4	1	0.22	16.67%	71.39%	11.94%	0.54
128.36	2.97	6.40	0.62	4	2	0.22	15.14%	69.44%	15.42%	0.56
106.66	2.94	5.57	0.60	4	2	0.22	10.14%	74.31%	15.56%	0.57
239.88	2.18	7.41	0.61	4	2	0.22	18.75%	62.22%	19.03%	0.57
96.46	2.75	4.02	0.53	4	2	0.22	4.17%	83.33%	12.50%	0.57

86.78	2.78	4.77	0.60	4	2	0.22	3.89%	80.28%	15.83%	0.58
85.17	2.52	4.23	0.63	4	2	0.22	14.03%	78.33%	7.64%	0.53
100.38	3.07	6.73	0.67	4	2	0.22	14.17%	71.25%	14.58%	0.56
95.47	2.47	5.29	0.64	4	2	0.22	5.00%	77.92%	17.08%	0.58
78.38	2.33	4.01	0.62	4	2	0.22	7.92%	81.94%	10.14%	0.55
114.39	2.87	4.94	0.58	4	2	0.22	15.28%	73.61%	11.11%	0.54
68.47	2.65	3.98	0.60	4	2	0.22	5.69%	81.94%	12.36%	0.57
186.92	3.11	6.32	0.55	4	2	0.22	14.86%	67.92%	17.22%	0.57
123.27	2.58	4.52	0.56	4	2	0.22	13.61%	75.69%	10.69%	0.54
139.64	2.67	6.80	0.62	4	2	0.22	11.53%	69.17%	19.31%	0.58
87.84	2.55	4.98	0.64	4	2	0.22	7.64%	79.86%	12.50%	0.57
127.85	2.66	5.38	0.57	4	2	0.22	9.86%	74.58%	15.56%	0.57
129.92	2.41	4.79	0.58	4	2	0.22	14.58%	74.58%	10.83%	0.54
109.56	2.69	5.92	0.67	4	2	0.22	16.81%	71.53%	11.67%	0.54
107.63	2.35	4.63	0.59	4	2	0.22	5.14%	80.97%	13.89%	0.57
109.07	2.89	5.37	0.61	4	2	0.22	13.75%	74.03%	12.22%	0.55
111.49	2.47	4.33	0.60	4	2	0.22	15.83%	76.39%	7.78%	0.52
92.97	2.67	4.09	0.59	4	2	0.22	12.50%	79.17%	8.33%	0.53
159.23	2.42	5.16	0.53	4	2	0.22	6.25%	75.56%	18.19%	0.59
125.80	2.63	4.57	0.53	4	2	0.22	6.25%	78.89%	14.86%	0.57
127.33	2.97	6.85	0.64	4	2	0.22	16.81%	67.78%	15.42%	0.56
168.49	2.62	6.09	0.58	4	2	0.22	16.94%	67.50%	15.56%	0.55
141.90	2.38	6.25	0.64	4	2	0.22	16.94%	69.03%	14.03%	0.55
92.47	2.42	4.94	0.62	4	2	0.22	4.17%	78.75%	17.08%	0.59

ANNEX A7

Table A 4.4. Input characteristics and ACHs globals of the dwellings with high ACHs, labelled as NCe, non-compliant by excess, in Application A7, with a 20° RS, a 2:1 SR, 4 ES, 2 NF, and 3 ND.

AF [m ²]	CH [m]	n ₅₀ [h ⁻¹]	n [-]	α [-]	P(ACH < 0.4 h ⁻¹) [%]	P(0.4 h ⁻¹ < ACH < 0.7 h ⁻¹) [%]	P(ACH > 0.7 h ⁻¹) [%]	ACH mean [h ⁻¹]
88.88	2.95	10.19	0.50	0.14	0.00%	0.69%	99.31%	1.47
75.31	2.47	9.16	0.63	0.14	0.00%	16.67%	83.33%	1.15
72.70	2.66	25.48	0.62	0.14	0.00%	0.00%	100.00%	2.63
72.03	2.71	7.23	0.58	0.14	0.00%	21.81%	78.19%	1.03
81.29	2.65	7.80	0.67	0.14	0.69%	35.83%	63.47%	0.92
65.34	2.79	12.23	0.54	0.14	0.00%	0.28%	99.72%	1.69
49.59	2.35	7.15	0.59	0.14	0.00%	4.58%	95.42%	1.16
128.36	2.97	6.40	0.62	0.14	12.22%	41.25%	46.53%	0.75
66.15	2.75	7.16	0.69	0.14	0.97%	38.33%	60.69%	0.87
149.59	2.39	11.12	0.59	0.14	0.00%	15.83%	84.17%	1.26
106.66	2.94	5.57	0.60	0.14	8.47%	46.94%	44.58%	0.73
209.90	2.85	9.72	0.65	0.14	7.64%	35.56%	56.81%	0.92
239.88	2.18	7.41	0.61	0.14	11.25%	37.36%	51.39%	0.81
39.28	3.08	8.63	0.55	0.14	0.00%	0.69%	99.31%	1.38
183.24	2.38	6.68	0.65	0.14	17.22%	41.11%	41.67%	0.71
100.87	2.41	5.62	0.55	0.14	0.28%	39.17%	60.56%	0.85
123.78	2.38	7.08	0.61	0.14	1.25%	39.86%	58.89%	0.88
79.56	3.10	8.20	0.69	0.14	2.36%	39.86%	57.78%	0.88
166.27	2.21	7.93	0.56	0.14	0.28%	31.67%	68.06%	1.00
104.74	2.71	14.22	0.57	0.14	0.00%	0.69%	99.31%	1.67
315.22	2.16	9.60	0.54	0.14	0.00%	22.92%	77.08%	1.14
143.05	2.59	10.58	0.56	0.14	0.00%	13.06%	86.94%	1.29
336.36	2.54	11.66	0.59	0.14	0.00%	22.92%	77.08%	1.22
202.58	2.05	6.50	0.56	0.14	3.89%	40.56%	55.56%	0.83
129.40	2.14	10.94	0.53	0.14	0.00%	2.22%	97.78%	1.45
134.16	3.07	8.53	0.55	0.14	0.00%	26.25%	73.75%	1.06
86.25	3.17	14.58	0.60	0.14	0.00%	1.81%	98.19%	1.63
131.50	2.43	10.25	0.60	0.14	0.00%	18.89%	81.11%	1.18
185.06	2.56	6.90	0.64	0.14	15.56%	39.86%	44.58%	0.74
144.80	2.91	13.75	0.56	0.14	0.00%	3.61%	96.39%	1.57
105.70	2.73	6.25	0.59	0.14	1.94%	42.08%	55.97%	0.82
83.53	3.12	7.08	0.56	0.14	0.28%	28.61%	71.11%	0.97
87.31	2.62	8.07	0.63	0.14	0.28%	30.69%	69.03%	0.98
192.80	2.22	8.91	0.65	0.14	5.42%	36.94%	57.64%	0.91

150.82	2.20	6.75	0.62	0.14	5.14%	41.25%	53.61%	0.81
69.93	2.59	5.58	0.57	0.14	0.28%	30.69%	69.03%	0.89
73.37	2.25	11.26	0.59	0.14	0.00%	1.25%	98.75%	1.48
90.94	2.51	8.61	0.50	0.14	0.00%	3.06%	96.94%	1.32
148.37	2.36	6.93	0.63	0.14	7.92%	40.97%	51.11%	0.79
97.94	2.15	9.32	0.58	0.14	0.00%	12.50%	87.50%	1.22
80.14	2.29	5.03	0.58	0.14	0.69%	42.22%	57.08%	0.80
184.15	2.44	6.95	0.58	0.14	5.42%	39.72%	54.86%	0.83
146.57	2.92	26.38	0.58	0.14	0.00%	0.00%	100.00%	2.74
100.38	3.07	6.73	0.67	0.14	12.64%	43.33%	44.03%	0.74
93.98	2.76	9.06	0.57	0.14	0.00%	15.97%	84.03%	1.17
95.47	2.47	5.29	0.64	0.14	7.50%	52.08%	40.42%	0.71
142.48	2.71	7.45	0.54	0.14	0.28%	31.81%	67.92%	0.98
118.80	2.65	6.68	0.60	0.14	2.36%	40.83%	56.81%	0.84
133.62	2.68	8.20	0.68	0.14	10.83%	37.22%	51.94%	0.82
120.28	2.52	10.79	0.65	0.14	0.28%	25.00%	74.72%	1.13
211.20	2.43	6.42	0.56	0.14	6.25%	41.67%	52.08%	0.80
71.34	2.73	16.14	0.61	0.14	0.00%	0.28%	99.72%	1.82
57.79	3.00	7.68	0.64	0.14	0.28%	24.72%	75.00%	1.01
227.29	2.74	6.71	0.60	0.14	15.97%	39.86%	44.17%	0.73
67.71	2.73	5.82	0.59	0.14	0.28%	34.31%	65.42%	0.87
62.76	2.80	15.97	0.55	0.14	0.00%	0.00%	100.00%	2.08
290.26	2.65	11.71	0.59	0.14	0.00%	21.67%	78.33%	1.23
124.28	2.49	6.31	0.60	0.14	3.47%	42.22%	54.31%	0.81
51.26	2.62	5.31	0.66	0.14	0.97%	43.61%	55.42%	0.80
55.44	2.64	11.63	0.58	0.14	0.00%	0.28%	99.72%	1.59
137.97	2.02	5.97	0.59	0.14	2.50%	43.19%	54.31%	0.80
170.00	3.03	7.57	0.60	0.14	6.81%	38.89%	54.31%	0.84
59.90	2.82	12.25	0.60	0.14	0.00%	0.97%	99.03%	1.54
186.92	3.11	6.32	0.55	0.14	7.78%	41.11%	51.11%	0.79
275.37	2.21	8.94	0.56	0.14	0.00%	32.22%	67.78%	1.04
176.35	2.39	7.15	0.56	0.14	0.97%	39.03%	60.00%	0.90
97.45	2.55	9.35	0.52	0.14	0.00%	4.86%	95.14%	1.33
76.56	2.55	8.84	0.65	0.14	0.28%	24.31%	75.42%	1.05
102.81	2.60	5.23	0.54	0.14	1.11%	43.33%	55.56%	0.80
139.64	2.67	6.80	0.62	0.14	8.47%	41.25%	50.28%	0.79
122.77	2.56	7.28	0.59	0.14	0.69%	37.08%	62.22%	0.92
81.86	2.54	11.46	0.61	0.14	0.00%	6.39%	93.61%	1.38
89.92	2.46	6.90	0.62	0.14	0.42%	35.42%	64.17%	0.90
61.84	2.87	6.99	0.56	0.14	0.00%	17.22%	82.78%	1.07
215.24	2.42	10.56	0.57	0.14	0.00%	18.89%	81.11%	1.20
294.56	2.55	10.68	0.58	0.14	0.00%	25.00%	75.00%	1.16
243.95	2.59	11.06	0.64	0.14	1.67%	34.72%	63.61%	1.05
52.77	2.57	8.89	0.53	0.14	0.00%	0.28%	99.72%	1.43
112.94	2.33	5.67	0.59	0.14	2.08%	45.14%	52.78%	0.79
234.20	2.52	8.54	0.63	0.14	9.31%	36.25%	54.44%	0.86

266.04	2.58	6.40	0.58	0.14	15.56%	39.72%	44.72%	0.73
155.91	2.73	10.68	0.60	0.14	0.00%	22.92%	77.08%	1.17
82.98	3.43	7.71	0.64	0.14	2.22%	39.72%	58.06%	0.88
173.12	2.45	6.94	0.58	0.14	4.72%	40.00%	55.28%	0.84
173.92	2.73	8.62	0.53	0.14	0.00%	21.25%	78.75%	1.11
127.85	2.66	5.38	0.57	0.14	8.19%	46.67%	45.14%	0.73
60.89	2.31	5.30	0.60	0.14	0.42%	31.25%	68.33%	0.86
137.42	2.69	7.36	0.59	0.14	2.08%	39.58%	58.33%	0.88
250.54	3.34	7.01	0.60	0.14	17.08%	37.22%	45.69%	0.75
95.97	2.43	5.02	0.51	0.14	0.28%	36.67%	63.06%	0.84
116.83	2.54	8.27	0.62	0.14	0.56%	35.28%	64.17%	0.96
90.43	2.90	5.99	0.56	0.14	0.56%	39.44%	60.00%	0.86
136.32	2.37	5.74	0.59	0.14	5.69%	45.56%	48.75%	0.76
56.65	2.46	9.64	0.63	0.14	0.00%	4.86%	95.14%	1.29
225.67	2.59	8.75	0.55	0.14	0.00%	32.08%	67.92%	1.04
199.17	2.25	11.55	0.55	0.14	0.00%	7.64%	92.36%	1.39
69.21	2.33	12.50	0.61	0.14	0.00%	0.97%	99.03%	1.54
125.29	2.10	10.96	0.63	0.14	0.00%	17.08%	82.92%	1.22
54.15	2.61	13.26	0.56	0.14	0.00%	0.00%	100.00%	1.84
70.64	2.51	6.48	0.55	0.14	0.00%	18.61%	81.39%	1.03
103.29	3.56	5.88	0.54	0.14	2.08%	42.64%	55.28%	0.81
119.78	2.90	19.13	0.57	0.14	0.00%	0.00%	100.00%	2.10
118.30	2.16	6.30	0.55	0.14	0.28%	33.75%	65.97%	0.91
82.42	2.50	20.69	0.59	0.14	0.00%	0.00%	100.00%	2.31
96.96	2.43	10.60	0.57	0.14	0.00%	6.39%	93.61%	1.36
113.91	2.92	6.70	0.56	0.14	0.83%	39.44%	59.72%	0.88
107.15	2.62	13.53	0.67	0.14	0.00%	16.25%	83.75%	1.32
167.74	2.50	8.39	0.59	0.14	0.56%	35.42%	64.03%	0.97
224.08	2.64	13.18	0.53	0.14	0.00%	2.22%	97.78%	1.58
175.53	2.83	10.90	0.57	0.14	0.00%	17.36%	82.64%	1.23
101.84	2.78	7.32	0.64	0.14	2.50%	40.56%	56.94%	0.85
111.00	2.96	7.81	0.58	0.14	0.28%	34.31%	65.42%	0.96
145.38	2.37	7.09	0.58	0.14	1.11%	39.44%	59.44%	0.88
130.97	2.95	12.58	0.55	0.14	0.00%	3.61%	96.39%	1.52
106.18	2.76	11.66	0.65	0.14	0.00%	20.42%	79.58%	1.20
58.87	2.33	10.24	0.55	0.14	0.00%	0.28%	99.72%	1.54
99.89	2.51	9.56	0.60	0.14	0.00%	17.64%	82.36%	1.16
121.77	2.70	17.48	0.62	0.14	0.00%	0.97%	99.03%	1.79
144.21	3.07	9.93	0.61	0.14	0.28%	30.69%	69.03%	1.07
159.23	2.42	5.16	0.53	0.14	5.83%	45.97%	48.19%	0.74
47.71	2.69	5.60	0.61	0.14	0.28%	27.64%	72.08%	0.91
160.60	2.61	6.11	0.55	0.14	4.58%	41.25%	54.17%	0.80
125.80	2.63	4.57	0.53	0.14	6.25%	51.53%	42.22%	0.70
98.43	2.82	12.90	0.58	0.14	0.00%	3.06%	96.94%	1.52
122.27	2.35	9.13	0.65	0.14	0.56%	34.03%	65.42%	0.99
66.94	2.39	8.89	0.64	0.14	0.00%	15.69%	84.31%	1.14

113.42	2.54	8.52	0.55	0.14	0.00%	18.06%	81.94%	1.12
114.88	3.13	9.67	0.55	0.14	0.00%	16.39%	83.61%	1.20
78.97	2.37	4.92	0.58	0.14	0.83%	45.97%	53.19%	0.78
45.53	2.47	8.28	0.57	0.14	0.00%	0.97%	99.03%	1.34
179.72	2.55	7.65	0.61	0.14	6.39%	39.03%	54.58%	0.84
127.33	2.97	6.85	0.64	0.14	12.64%	40.83%	46.53%	0.76
117.32	2.91	10.34	0.58	0.14	0.00%	17.50%	82.50%	1.21
170.77	3.04	6.26	0.61	0.14	17.08%	42.36%	40.56%	0.70
74.67	2.32	14.11	0.61	0.14	0.00%	0.28%	99.72%	1.68
84.08	2.58	7.99	0.68	0.14	0.97%	37.36%	61.67%	0.91
168.49	2.62	6.09	0.58	0.14	11.67%	41.67%	46.67%	0.74
108.59	2.61	8.43	0.57	0.14	0.00%	21.53%	78.47%	1.09
132.55	2.68	10.82	0.54	0.14	0.00%	7.22%	92.78%	1.36
119.29	2.53	13.66	0.62	0.14	0.00%	8.61%	91.39%	1.45
33.07	2.31	14.37	0.58	0.14	0.00%	0.00%	100.00%	2.21
42.86	2.91	5.07	0.64	0.14	0.83%	42.92%	56.25%	0.80
74.02	2.90	5.28	0.56	0.14	0.56%	41.11%	58.33%	0.82
94.98	2.69	5.50	0.61	0.14	5.42%	48.47%	46.11%	0.74
112.45	2.49	10.71	0.56	0.14	0.00%	8.33%	91.67%	1.33
75.93	2.32	11.99	0.54	0.14	0.00%	0.28%	99.72%	1.69
230.66	2.63	7.96	0.56	0.14	1.53%	38.75%	59.72%	0.93
139.08	3.02	22.41	0.56	0.14	0.00%	0.00%	100.00%	2.48
185.99	2.69	7.86	0.66	0.14	14.72%	36.81%	48.47%	0.78
155.26	2.62	8.57	0.62	0.14	1.81%	38.06%	60.14%	0.94
269.01	2.77	11.34	0.52	0.14	0.00%	9.72%	90.28%	1.38
105.22	2.76	9.74	0.64	0.14	0.28%	29.86%	69.86%	1.05
64.50	2.31	7.83	0.59	0.14	0.00%	8.89%	91.11%	1.16
141.90	2.38	6.25	0.64	0.14	13.89%	42.92%	43.19%	0.72
77.17	2.61	8.71	0.52	0.14	0.00%	2.78%	97.22%	1.32
120.78	2.85	7.11	0.55	0.14	0.28%	33.19%	66.53%	0.95
212.52	2.99	8.42	0.67	0.14	17.08%	35.83%	47.08%	0.78
63.64	2.51	9.52	0.61	0.14	0.00%	6.67%	93.33%	1.27
159.91	3.31	5.58	0.56	0.14	15.00%	43.47%	41.53%	0.70
236.05	2.32	8.19	0.57	0.14	0.69%	37.50%	61.81%	0.96
400.08	2.80	6.28	0.57	0.14	19.86%	39.17%	40.97%	0.70
88.36	2.84	7.36	0.57	0.14	0.28%	25.83%	73.89%	1.01
126.31	2.48	15.03	0.60	0.14	0.00%	1.67%	98.33%	1.64
143.63	2.35	5.73	0.57	0.14	4.44%	43.89%	51.67%	0.78
91.96	2.67	6.79	0.66	0.14	3.06%	44.03%	52.92%	0.81
110.04	2.57	8.90	0.63	0.14	0.28%	31.94%	67.78%	1.01
124.79	2.36	15.34	0.62	0.14	0.00%	3.47%	96.53%	1.61
91.45	2.79	5.37	0.51	0.14	0.28%	35.83%	63.89%	0.86
102.32	2.80	8.14	0.55	0.14	0.00%	20.83%	79.17%	1.08
203.75	2.91	16.60	0.58	0.14	0.00%	1.25%	98.75%	1.75
115.85	2.69	7.21	0.59	0.14	0.83%	38.75%	60.42%	0.90
88.88	2.95	10.19	0.50	0.22	0.00%	4.17%	95.83%	1.05

75.31	2.47	9.16	0.63	0.22	0.69%	35.42%	63.89%	0.82
72.70	2.66	25.48	0.62	0.22	0.00%	0.28%	99.72%	1.68
72.03	2.71	7.23	0.58	0.22	0.69%	43.19%	56.11%	0.76
81.29	2.65	7.80	0.67	0.22	2.92%	65.14%	31.94%	0.65
65.34	2.79	12.23	0.54	0.22	0.00%	0.83%	99.17%	1.21
49.59	2.35	7.15	0.59	0.22	0.28%	12.78%	86.94%	0.92
66.15	2.75	7.16	0.69	0.22	2.78%	68.75%	28.47%	0.63
149.59	2.39	11.12	0.59	0.22	0.69%	35.00%	64.31%	0.83
39.28	3.08	8.63	0.55	0.22	0.00%	2.50%	97.50%	1.07
100.87	2.41	5.62	0.55	0.22	1.81%	69.31%	28.89%	0.63
123.78	2.38	7.08	0.61	0.22	6.39%	68.47%	25.14%	0.61
79.56	3.10	8.20	0.69	0.22	10.97%	67.78%	21.25%	0.59
166.27	2.21	7.93	0.56	0.22	1.67%	59.86%	38.47%	0.69
104.74	2.71	14.22	0.57	0.22	0.00%	3.89%	96.11%	1.12
315.22	2.16	9.60	0.54	0.22	0.69%	47.36%	51.94%	0.76
143.05	2.59	10.58	0.56	0.22	0.28%	31.11%	68.61%	0.87
336.36	2.54	11.66	0.59	0.22	0.97%	48.06%	50.97%	0.77
129.40	2.14	10.94	0.53	0.22	0.00%	10.42%	89.58%	1.02
134.16	3.07	8.53	0.55	0.22	0.83%	54.03%	45.14%	0.72
86.25	3.17	14.58	0.60	0.22	0.00%	9.72%	90.28%	1.07
131.50	2.43	10.25	0.60	0.22	0.69%	41.53%	57.78%	0.79
144.80	2.91	13.75	0.56	0.22	0.00%	12.08%	87.92%	1.03
83.53	3.12	7.08	0.56	0.22	0.83%	57.36%	41.81%	0.70
87.31	2.62	8.07	0.63	0.22	1.25%	58.33%	40.42%	0.69
192.80	2.22	8.91	0.65	0.22	17.50%	60.00%	22.50%	0.58
69.93	2.59	5.58	0.57	0.22	0.83%	57.22%	41.94%	0.68
73.37	2.25	11.26	0.59	0.22	0.00%	4.44%	95.56%	1.06
90.94	2.51	8.61	0.50	0.22	0.00%	12.22%	87.78%	0.97
97.94	2.15	9.32	0.58	0.22	0.28%	28.33%	71.39%	0.87
80.14	2.29	5.03	0.58	0.22	1.67%	73.75%	24.58%	0.62
146.57	2.92	26.38	0.58	0.22	0.00%	0.28%	99.72%	1.71
93.98	2.76	9.06	0.57	0.22	0.56%	34.72%	64.72%	0.82
142.48	2.71	7.45	0.54	0.22	1.53%	61.53%	36.94%	0.68
118.80	2.65	6.68	0.60	0.22	10.28%	69.72%	20.00%	0.59
120.28	2.52	10.79	0.65	0.22	1.25%	49.86%	48.89%	0.74
71.34	2.73	16.14	0.61	0.22	0.00%	1.67%	98.33%	1.22
57.79	3.00	7.68	0.64	0.22	0.83%	47.22%	51.94%	0.74
67.71	2.73	5.82	0.59	0.22	1.11%	63.47%	35.42%	0.66
62.76	2.80	15.97	0.55	0.22	0.00%	0.42%	99.58%	1.45
290.26	2.65	11.71	0.59	0.22	0.69%	46.67%	52.64%	0.77
51.26	2.62	5.31	0.66	0.22	1.67%	69.31%	29.03%	0.64
55.44	2.64	11.63	0.58	0.22	0.00%	1.67%	98.33%	1.15
59.90	2.82	12.25	0.60	0.22	0.00%	4.31%	95.69%	1.08
275.37	2.21	8.94	0.56	0.22	2.36%	59.86%	37.78%	0.69
176.35	2.39	7.15	0.56	0.22	5.69%	68.19%	26.11%	0.62
97.45	2.55	9.35	0.52	0.22	0.00%	15.83%	84.17%	0.95

76.56	2.55	8.84	0.65	0.22	0.83%	47.08%	52.08%	0.74
102.81	2.60	5.23	0.54	0.22	4.03%	75.83%	20.14%	0.60
122.77	2.56	7.28	0.59	0.22	3.47%	66.81%	29.72%	0.64
81.86	2.54	11.46	0.61	0.22	0.28%	19.44%	80.28%	0.95
89.92	2.46	6.90	0.62	0.22	2.22%	64.86%	32.92%	0.65
61.84	2.87	6.99	0.56	0.22	0.28%	35.69%	64.03%	0.80
215.24	2.42	10.56	0.57	0.22	0.69%	42.64%	56.67%	0.79
294.56	2.55	10.68	0.58	0.22	0.97%	52.22%	46.81%	0.74
243.95	2.59	11.06	0.64	0.22	9.44%	59.86%	30.69%	0.65
52.77	2.57	8.89	0.53	0.22	0.00%	1.81%	98.19%	1.09
155.91	2.73	10.68	0.60	0.22	0.69%	47.22%	52.08%	0.76
82.98	3.43	7.71	0.64	0.22	10.14%	68.47%	21.39%	0.60
173.92	2.73	8.62	0.53	0.22	0.69%	45.56%	53.75%	0.76
60.89	2.31	5.30	0.60	0.22	0.83%	55.97%	43.19%	0.69
137.42	2.69	7.36	0.59	0.22	10.14%	66.94%	22.92%	0.60
95.97	2.43	5.02	0.51	0.22	1.11%	67.08%	31.81%	0.65
116.83	2.54	8.27	0.62	0.22	3.33%	63.89%	32.78%	0.65
90.43	2.90	5.99	0.56	0.22	2.92%	70.00%	27.08%	0.63
56.65	2.46	9.64	0.63	0.22	0.28%	14.17%	85.56%	0.95
225.67	2.59	8.75	0.55	0.22	2.08%	60.97%	36.94%	0.69
199.17	2.25	11.55	0.55	0.22	0.28%	23.61%	76.11%	0.93
69.21	2.33	12.50	0.61	0.22	0.00%	3.75%	96.25%	1.08
125.29	2.10	10.96	0.63	0.22	0.69%	36.39%	62.92%	0.82
54.15	2.61	13.26	0.56	0.22	0.00%	0.69%	99.31%	1.33
70.64	2.51	6.48	0.55	0.22	0.56%	37.78%	61.67%	0.79
119.78	2.90	19.13	0.57	0.22	0.00%	0.69%	99.31%	1.36
118.30	2.16	6.30	0.55	0.22	1.25%	62.50%	36.25%	0.67
82.42	2.50	20.69	0.59	0.22	0.00%	0.56%	99.44%	1.52
96.96	2.43	10.60	0.57	0.22	0.28%	18.47%	81.25%	0.95
113.91	2.92	6.70	0.56	0.22	4.03%	69.86%	26.11%	0.62
107.15	2.62	13.53	0.67	0.22	0.69%	35.00%	64.31%	0.84
167.74	2.50	8.39	0.59	0.22	3.75%	65.56%	30.69%	0.65
224.08	2.64	13.18	0.53	0.22	0.00%	10.00%	90.00%	1.04
175.53	2.83	10.90	0.57	0.22	0.69%	40.56%	58.75%	0.80
101.84	2.78	7.32	0.64	0.22	11.11%	68.61%	20.28%	0.59
111.00	2.96	7.81	0.58	0.22	2.78%	64.31%	32.92%	0.66
145.38	2.37	7.09	0.58	0.22	5.97%	68.61%	25.42%	0.61
130.97	2.95	12.58	0.55	0.22	0.00%	13.06%	86.94%	1.01
106.18	2.76	11.66	0.65	0.22	0.69%	43.06%	56.25%	0.78
58.87	2.33	10.24	0.55	0.22	0.00%	1.11%	98.89%	1.15
99.89	2.51	9.56	0.60	0.22	0.69%	37.92%	61.39%	0.80
121.77	2.70	17.48	0.62	0.22	0.00%	5.83%	94.17%	1.13
144.21	3.07	9.93	0.61	0.22	2.64%	59.03%	38.33%	0.69
47.71	2.69	5.60	0.61	0.22	0.83%	46.94%	52.22%	0.73
98.43	2.82	12.90	0.58	0.22	0.00%	12.64%	87.36%	1.02
122.27	2.35	9.13	0.65	0.22	3.47%	62.78%	33.75%	0.66

66.94	2.39	8.89	0.64	0.22	0.69%	32.22%	67.08%	0.83
113.42	2.54	8.52	0.55	0.22	0.69%	39.03%	60.28%	0.79
114.88	3.13	9.67	0.55	0.22	0.69%	37.08%	62.22%	0.81
78.97	2.37	4.92	0.58	0.22	2.36%	77.08%	20.56%	0.61
45.53	2.47	8.28	0.57	0.22	0.00%	2.64%	97.36%	1.05
117.32	2.91	10.34	0.58	0.22	0.69%	38.33%	60.97%	0.81
74.67	2.32	14.11	0.61	0.22	0.00%	2.92%	97.08%	1.15
84.08	2.58	7.99	0.68	0.22	3.19%	66.67%	30.14%	0.64
108.59	2.61	8.43	0.57	0.22	0.69%	43.61%	55.69%	0.76
132.55	2.68	10.82	0.54	0.22	0.28%	21.53%	78.19%	0.93
119.29	2.53	13.66	0.62	0.22	0.28%	25.00%	74.72%	0.94
33.07	2.31	14.37	0.58	0.22	0.00%	0.00%	100.00%	1.70
42.86	2.91	5.07	0.64	0.22	1.25%	67.64%	31.11%	0.64
74.02	2.90	5.28	0.56	0.22	2.22%	72.64%	25.14%	0.62
112.45	2.49	10.71	0.56	0.22	0.28%	24.58%	75.14%	0.92
75.93	2.32	11.99	0.54	0.22	0.00%	0.69%	99.31%	1.22
230.66	2.63	7.96	0.56	0.22	7.50%	66.94%	25.56%	0.62
139.08	3.02	22.41	0.56	0.22	0.00%	0.28%	99.72%	1.59
155.26	2.62	8.57	0.62	0.22	9.44%	64.31%	26.25%	0.62
269.01	2.77	11.34	0.52	0.22	0.28%	26.81%	72.92%	0.91
105.22	2.76	9.74	0.64	0.22	1.94%	57.36%	40.69%	0.70
64.50	2.31	7.83	0.59	0.22	0.28%	23.89%	75.83%	0.88
77.17	2.61	8.71	0.52	0.22	0.00%	12.08%	87.92%	0.97
120.78	2.85	7.11	0.55	0.22	1.81%	63.89%	34.31%	0.67
63.64	2.51	9.52	0.61	0.22	0.28%	18.06%	81.67%	0.92
236.05	2.32	8.19	0.57	0.22	4.72%	66.11%	29.17%	0.64
88.36	2.84	7.36	0.57	0.22	0.69%	51.67%	47.64%	0.72
126.31	2.48	15.03	0.60	0.22	0.00%	9.72%	90.28%	1.07
110.04	2.57	8.90	0.63	0.22	1.94%	59.44%	38.61%	0.69
124.79	2.36	15.34	0.62	0.22	0.28%	13.19%	86.53%	1.04
91.45	2.79	5.37	0.51	0.22	1.25%	66.53%	32.22%	0.65
102.32	2.80	8.14	0.55	0.22	0.69%	42.78%	56.53%	0.76
203.75	2.91	16.60	0.58	0.22	0.00%	8.75%	91.25%	1.10
115.85	2.69	7.21	0.59	0.22	3.61%	68.33%	28.06%	0.63