Performance-oriented design and assessment of naturally ventilated buildings

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Leistungsorientierte Gestaltung und Bewertung von natürlich belüfteten Gebäuden

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To my beloved son
Pedro Zen

Summary

A high-performance building must fulfill comfort and energy efficiency requirements. Possible solutions include passive strategies, such as improving the building envelope and taking advantage of natural light and ventilation. Natural ventilation (NV), for instance, can provide both thermal comfort and energy savings. However, its performance relies on building design and interaction with the local environmental characteristics. In this study, Natural Ventilation Potential (NVP) was analyzed under two approaches: a general evaluation using meteorological data and a specific investigation through building simulation, using an experimental house as a reference case located in a temperate climate with warm summer. Although there are many parameters and metrics applied in assessing NVP, predicting building air change rates (ACH) and airflows is a challenge for designers seeking to deal with this passive strategy. Among the methods available for this task, Computational Fluid Dynamics (CFD) appears as the most compelling, in ascending use. However, CFD simulations have high computational costs, besides requiring a range of settings and skills that inhibit its wide application. Therefore, a pragmatic CFD framework to promote wind-driven assessments through 3D parametric modeling platforms was proposed as an attractive alternative to enable the tool application. The approach addresses all simulation steps: geometry and weather definition, model set-up, control, results edition, and visualization. Besides, it explores alternatives to display and compute ACH and parametrically generates horizontal planes across the spaces to calculate surface average air velocities. Usually, network models throughout Building Energy Simulation (BES) are the most employed NV investigations approach, especially in annual analysis. Nevertheless, as the wind is a significant driving force for ventilation, wind pressure coefficients (Cp) represent a critical boundary condition when assessing building airflows, influencing BES models' results. The Cp values come from either a primary source that includes CFD simulations or a secondary one where the primary is considered the most reliable. In this sense, a performance metric was proposed, namely the Natural Ventilation Effectiveness (NVE). It verifies when outdoor airflows can maintain indoor temperatures within a comfortable range. The metric uses BES results, and within this context, the impact of five different Cp sources on its outputs was investigated. Three

secondary sources and surface-averaged Cp values calculated with CFD for both the whole façade and windows were considered. The differences between the CFD Cp values are minor when wind direction is normal to the surface, with more significant discrepancies for the openings close to roof eaves. Although there was considerable variance among the Cp sources, its effect on the NVE was relatively small. Additionally, when designing high-performance buildings for cold climates, efficient insulating systems are encouraged since they help reduce heat losses through the building envelope, thus promoting building energy savings. Still, climate exposure deteriorates material properties, compromising a building's energy performance over its lifetime. Therefore, this aging impact on the hygrothermal performance of an aerogel-based insulating system was investigated through a large-scale test, U-Value measurements, and heat and moisture transfer (HMT) models, calibrated with the experimental data. A low thermal conductivity degradation was measured after the tests, showing that its effectiveness is not harshly compromised throughout its life-cycle. Finally, this research performed parametric modeling and optimization to minimize annual building energy demand and maximize NVE. The workflow was divided into i) model setting, ii) sensitivity analyses (SA), and iii) multi-objective optimization (MOO), with a straightforward process implemented through a parametric platform. Input variables dimension was firstly reduced with SA, and the last step ran with a model-based optimization algorithm (RBFOpt). MOO results showed a remarkable potential for NV and heating energy savings. The design solutions could be employed in similar typologies and climates, and the adopted framework configures a practical and replicable approach for design approaches aiming to develop high-performance buildings through MOO.

Zusammenfassung

Ein Hochleistungsgebäude muss die Anforderungen an Komfort und Energieeffizienz erfüllen. Mögliche Lösungen umfassen passive Strategien, wie die Verbesserung der Gebäudehülle und die Nutzung von natürlichem Licht und Belüftung. Natürliche Lüftung (NL) zum Beispiel kann sowohl thermischen Komfort als auch Energieeinsparungen bieten. Die Leistung ist jedoch abhängig vom Gebäudedesign und der Interaktion mit den lokalen Umgebungsbedingungen. In dieser Studie wurde das natürliche Lüftungspotenzial (NLP) unter zwei Ansätzen analysiert: eine allgemeine Bewertung, die meteorologische Daten verwendet, und eine spezifische Untersuchung durch Gebäudesimulation, die ein experimentelles Haus in einem temperierten Klima mit warmem Sommer als Referenzfall verwendet. Obwohl es viele Parameter und Metriken gibt, die bei der Bewertung des NLPs angewendet werden, ist die Vorhersage der Luftwechselrate (LWR) und der Luftströme im Gebäude eine Herausforderung für Planer, die sich mit dieser passiven Strategie beschäftigen. Unter den Methoden, die für diese Aufgabe zur Verfügung stehen, scheint Computational Fluid Dynamics (CFD) mit zunehmender Beliebtheit am meisten zu überzeugen. CFD-Simulationen sind jedoch mit hohen Rechenkosten verbunden und erfordern zudem eine Reihe von Einstellungen und Fähigkeiten, die ihre breite Umsetzung erschweren. Daher wurde ein pragmatisches CFD-Framework zur Förderung windgetriebener Bewertungen durch parametrische 3D-Modellierungsplattformen als attraktive Alternative vorgeschlagen, um die Tool-Applikation zu ermöglichen. Der Ansatz umfasst alle Simulationsschritte: Geometrie- und Wetterdefinition, Modellaufbau, Steuerung, Ergebnisausgabe und Visualisierung. Außerdem werden Alternativen zur Anzeige und Berechnung von LWR untersucht und es werden parametrisch horizontale Ebenen über den Räumen erzeugt, um die oberflächlichen mittleren Luftgeschwindigkeiten zu berechnen. In der Regel sind Netzmodelle in der Gebäude-Energie-Simulation (GES) der am häufigsten verwendeten Ansatz für NB-Untersuchungen, insbesondere bei Jahresanalysen. Da der Wind jedoch eine bedeutende Antriebskraft für die Lüftung ist, stellen die Winddruckkoeffizienten (Cp-K) eine kritische Randbedingung bei der Beurteilung von Gebäudeluftströmen dar und

beeinflussen die Ergebnisse von GES-Modellen. Die Cp-K Werte stammen entweder aus einer primären Quelle, die CFD-Simulationen umfasst, oder aus einer sekundären Quelle, wobei die primäre als die zuverlässigste gilt. In diesem Sinne wurde eine Leistungsmessgröße vorgeschlagen, nämlich die Natürliche Lüftungseffektivität (NLE). Sie prüft, wann die Außenluftströme die Innentemperaturen in einem komfortablen Bereich halten können. Die Metrik verwendet GES-Ergebnisse und in diesem Zusammenhang wurde der Einfluss von fünf verschiedenen Cp-K Quellen auf ihre Ergebnisse untersucht. Es wurden drei Sekundärquellen und mit CFD berechnete oberflächengemittelte Cp-K Werte, sowohl für die gesamte Fassade als auch für die einzelnen Fenster, berücksichtigt. Die Unterschiede zwischen den CFD-Cp-K Werten sind gering, wenn die Windrichtung senkrecht zur Oberfläche verläuft, mit größeren Diskrepanzen für die Öffnungen in der Nähe der Dachtraufe. Obwohl es eine berücksichtigte Varianz unter den betrachteten Cp-K-Quellen gab, war ihr Einfluss auf den NLE gering. Weiterhin werden bei der Planung von Hochleistungsgebäuden für kalte Klimazonen effiziente Dämmsysteme gefördert, da sie Wärmeverluste durch die Gebäudehülle reduzieren und so die Energieeinsparung des Gebäudes begünstigen. Dennoch verschlechtert die Witterung die Materialeigenschaften und verringert so die Energiebilanz eines Gebäudes während seiner Lebensdauer. Daher wurde dieser Einfluss der Alterung auf die hygrothermische Leistung eines Aerogel-basierten Dämmsystems durch einen groß angelegten Test, U-Wert-Messungen und Wärme- und Feuchtetransfermodelle (WFT) untersucht, die mit den experimentellen Daten kalibriert wurden. Nach den Tests wurde eine geringere Verschlechterung der Wärmeleitfähigkeit gemessen, was zeigt, dass die Leistungsfähigkeit während des gesamten Lebenszyklus nicht stark beeinträchtigt wird. Schließlich führte diese Forschung eine parametrische Modellierung und Optimierung durch, um den jährlichen Energiebedarf des Gebäudes zu minimieren und den NLE zu maximieren. Die Arbeitsschritte wurden in i) Modellsetzung, ii) Sensitivitätsanalysen (SA) und iii) Mehrziel-Optimierung (MOO) unterteilt, wobei ein einfacher Prozess durch eine parametrische Plattform implementiert wurde. Die Eingangsgrößen-Dimension wurde zunächst mit SA reduziert und der letzte Schritt mit einem modellbasierten Optimierungsalgorithmus (RBFOpt) durchgeführt. Die

MOO-Ergebnisse zeigten ein bemerkenswertes Potenzial für NV- und Heizenergieeinsparungen. Design-Lösungen könnten in ähnlichen Typologien und Klimazonen eingesetzt werden und der beschlossene Rahmen konfiguriert einen praktischen und replizierbaren Weg für Designansätze, die darauf abzielen, Hochleistungsgebäude durch MOO zu entwickeln.

Contents

1. Introduction

The worldwide concern towards sustainable goals comprises promoting energy efficiency in buildings, which according to the European Union (EU) targets should advance by 27% until 2030 (European Commission, 2014). Such aims are justifiable as the edifices are responsible for a significant part of Greenhouse gas (GHG) emissions, being identified as having the greatest potential for climate change mitigation (Edenhofer et al., 2014). Consequently, performance-oriented design alternatives that can rely on passive strategies have been encouraged. The solutions include building envelope improvement using new insulating materials, besides taking advantage of solar heat, natural light, and ventilation (Gou et al., 2018).

In this context, naturally ventilated buildings have been welcomed as a feasible passive-cooling strategy. They are considered a suitable approach to obtain thermal comfort in mild climate regions (Aflaki et al., 2015), as well as a way to avoid overheating during the warmer seasons at subtropical (Fokaides et al., 2016) or even temperate/cold climates, where buildings are highly insulated (Brambilla et al., 2018; Oropeza-Perez and Østergaard, 2014). Moreover, for the climates where Natural Ventilation (NV) is restricted to a period of the year, implementing mixed-mode ventilation systems is an attractive solution (Huang and Hwang, 2016). Nevertheless, to be effective, the strategy must deliver the required airflow quantities to satisfy indoor air quality (IAQ) and thermal comfort using outside air (Chenari et al., 2016; Zhu et al., 2015). Thus, as Natural Ventilation Effectiveness (NVE) depends on local climate, quantitative data about its potential is fundamental in providing designers with accurate information to use wind and buoyancy's natural forces at the preliminary stage of building design. Different methods can be employed to verify if a specific place and period can provide the necessary air quantity in a building/room, namely standards (ASHRAE, 2019; EN, 2007), empirical calculations, direct and indirect measurements, and building simulations (Chen, 2009; Mateus et al., 2016; Shen et al., 2012). They can be either more straightforward or robust approaches, which subsequently vary in complexity and results' accuracy.

With computing technology advancement, the simulation-based design has been widely increased to predict several building performance aspects and apply parametric and optimization techniques. Given NV assessments, Computational Fluid Dynamic (CFD) is considered preferable to other methods due to its ability to address the NV phenomenon's complexity (Blocken, 2015; Ferrucci and Brocato, 2019). However, El Ahmar et al. (2019) highlight that CFD requires an extensive range of skills, being used primarily for research proposes, and not much in practical applications as a widespread resource among architects, who usually struggle to master it. Although one can find accessible airflow simulation resources and user-friendly approaches (Ferrucci et al., 2018; Kim et al., 2020), including parametric tolls (Utkucu and Sözer, 2020), there is still a gap regarding a framework to guide the process. For instance, when investigating Natural Ventilation Potential (NVP) to base either initial design or retrofit solutions, many variables are considered. Moreover, the NVP assessment can be generic or more specific, where the former contemplates climatic data and the latter aims at studying the characteristics of a particular building. Content to pave the way to such evaluations can assist CFD and other assessment tolls' use among non-experts, supporting passive strategy employment through the growing interaction between building design and simulation through 3D parametric modeling platforms.

In that sense, investigating ways to assess NV by combining representation and assessment tools, besides considering both the necessary data to carry out the analyses and the means to conduct them, is essential. As a result, establishing a holistic approach that involves performance-based design is an urgent demand, and how to develop practical strategies that support high-efficiency building development is the motivating question behind this research.

1.1. Objectives and scope

This thesis's primary goal is to investigate NVP and NVE assessment ways to promote practical and accurate performance-based design, focusing on naturally ventilated buildings. An experimental house is employed as a reference case. Moreover, existing software that combines building design simulation and optimization is explored, including customized functions from 3D parametric modeling platforms. The programs within this approach have transformed the project process and material valuations; thus, the need to master these tools and promote effective use in the practice and academic environment is becoming imperative.

From the aim, the following specific objectives were defined:

1. Review the state-of-art involving studies with naturally ventilated buildings, correlating re-searches associated to thermal comfort, energy efficiency, and indoor air quality;
2. Identify trends and movements to address the challenges that the naturally ventilated buildings' discipline faces in becoming a widespread, encouraged, and effective passive strategy;
3. Select a reference building to collect experimental data and, from there, develop and calibrate numerical models for subsequent investigations;
4. Explore the two NVP approaches, both of a given location and a building, to examine how either meteorological assessment or building measurements and simulations can identify NV feasibility;
5. Test different CFD modeling approaches regarding NV assessments to verify suitable forms to integrate the tool into the performance-based design process;
6. Propose a structured procedure to encourage CFD applications, guiding pre- to post-processing steps by managing the tool through a parametric design program;
7. Evaluate the hygrothermal behavior of a highly efficient insulation system developed for performance-oriented design applications;

8. Discover passive design optimal solutions with the multi-objective goal of improving NVE and minimizing building energy consumption.

This research's objectives and its respective steps compose six peer-reviewed scientific publications, giving more robustness and publicity to its results. Hence, the theme discussion is fomented, helping its academic and practical application. Figure 1 relates the study goals to their corresponding articles, summarizing the main aspects concerning each publication.

Finally, the research steps are presented with the following structure: Section 2 describes the experimental house used as the base case in the study and the measurement campaign conducted to validate the numerical models, as well as the weather characteristics. The research process and methods are presented in Section 3, subdivided into four sub-sections. Item 3.1 provides a general NVP evaluation based on weather data, while the NV assessment through numerical models is the focus in item 3.2. Additionally, a relationship between building energy efficiency and a material's thermal properties is the focus of item 3.3. In 3.4, an optimization process to improve the building NVE and minimize annual energy demand is summarized. A closing discussion is presented in Section 4, with a synthetic conclusion and ideas for feature research. Lastly, the original scripts implemented in this research are summarized in Section 5, while the detailed information regarding the publications and their status at the thesis submission time is listed in Section 6.

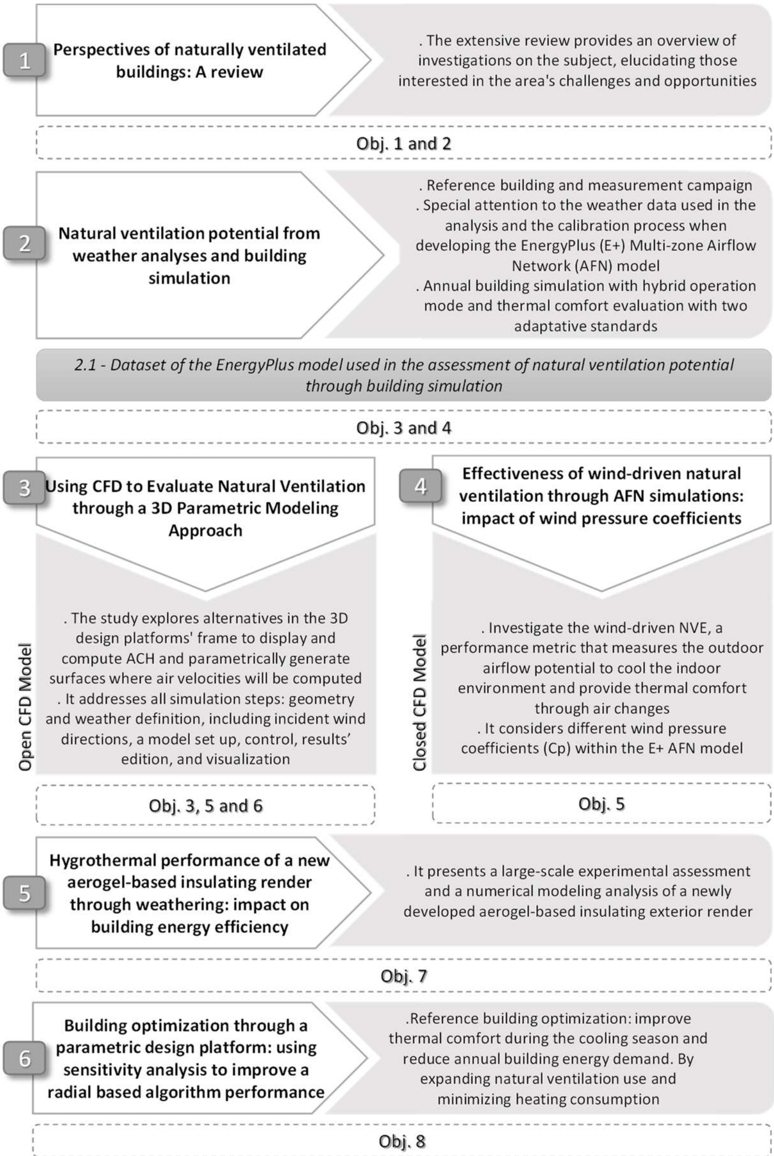


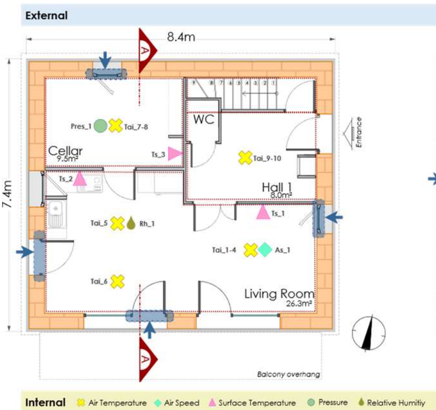
Figure 1. Research flowchart summarizing the literature production and research objectives

2. Reference Building

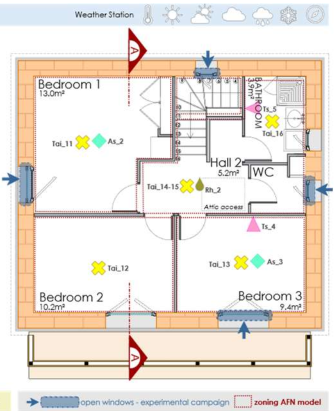
The base-case building concerns one of the four full-scale passive test houses from the INCAS experimental platform (Janssens, 2016; Spitz et al., 2012) at the French National Institute for Solar Energy - INES facility, located near Chambéry, in the French Alps (45° 38'38.5"N, 5°52'27.4"E, altitude 270m, +1h GMT - Figure 2). The 95 m² un-inhabited residence was the last one in the facility to be erected, built in 2013.

Figure 2. Map location of the INES facility, near Chambéry, France (iStock, 2021)

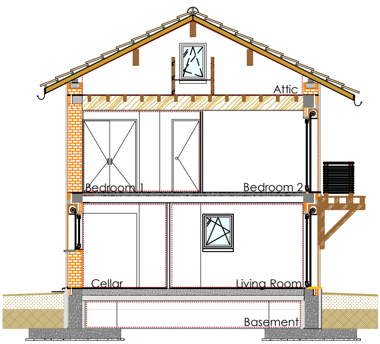
Figure 3 shows the INCAS MA house (I-MA), which is a rectangular low-energy building (7.5m x 8.5m) with most openings facing south (34% glazed). The opaque envelope construction is made of cavity bricks (42 cm), covered with 4 cm aerogel-based exterior rendering (λ= 0.11W/mK). Exterior windows are double glazed with their physical properties varying by each compass direction from 1.05 to 1.45 W/m²K.



(a) Ground-floor



(b) First-floor



(c) Section AA

Source: (Ibrahim et al., 2015)

(d) INES experimental platform: I-MA Overview

Figure 3. I-MA House: floor plans with internal sensors indication, section and outdoors overview

The experimental house is equipped with an extensive and continuous data acquisition (Agilent hardware) and storage system (every minute/24 h/day, 7 days/week). It includes 144 permanently installed sensors for wall and air temperature, humidity, flow meters, energy consumption, IAQ measurements, and illumination. Moreover, like the other INES platform edifices, the I-MA house has a design intended to simplify the numerical validation phase, which, associated with the experimental data availability, buoyed its choice as a reference building in this research.

2.1. Measurement campaign

Measurements on the experimental house took place for a week in August 2014 (19-25) under the following protocol:

- Night ventilation from 9:00 p.m. – 6:59 a.m: the internal doors were fully opened during the whole test, but only one window in each orientation per floor was tilt and turned opened, between 3° and 8° degrees (indicated by the blue arrow in Figure 3a and b). Moreover, despite the broad area of the south-oriented windows, just one third is operable, and the remaining part is fixed;
- External shutters remained open throughout the measurement;
- There were no interferences: the house had neither occupants, equipment, nor furniture;
- The underfloor heating system was off, and the building ventilation system (no-load supply airflow rate) was on for the whole period with approximately 135 m^3/h-0.5 vol/h.

Such protocol aimed to investigate the building thermal inertia, analyzing how the built environment responds to the external climate conditions' detriment. Additionally, it is essential to note that the measurements did not occur in this research context, and its results were made available due to cooperation between the institutes involved.

Figure 3a and b show where the sensors were placed in the I-MA house. Among the measured parameters, the indoor air temperature was recorded in all rooms with PT100 sensors placed in the room center at a

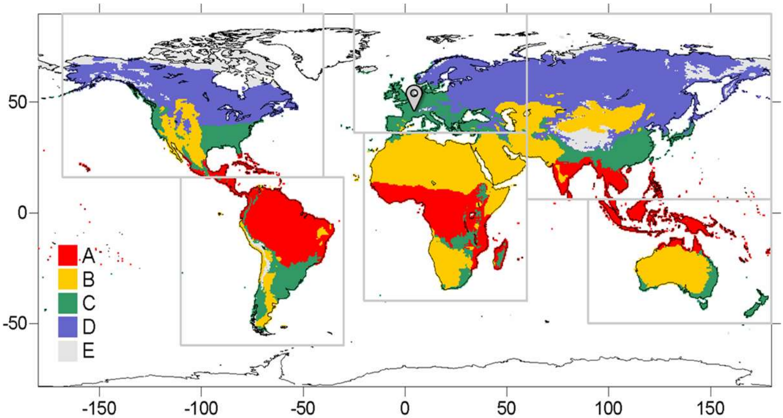
1.1m height, while internal air velocity was measured in three spaces with DeltaOhm anemometers also placed in the center of the room at a 1.1m height. These recorded data were used as a performance indicator during the calibration process of the numerical models. Thus, they were initially checked to meet the standard requirements for hourly calibration from ASHRAE Guideline 14 (ASHRAE, 2002) and the recommendations based on microclimate parameters proposed by Huerto-Cardenas et al. (Huerto-Cardenas et al., 2020).

A detailed description of the reference building construction and the main technical specifications, measurement equipment, and recorded data at the measurement campaigns are provided in this research second article: Natural ventilation potential from weather analyses and building simulation (Sakiyama, Mazzaferro et al., 2020).

2.2. Weather characteristics

According to the Köppen classification, Chambery - FR has a temperate climate with warm summer - Cfb (Peel et al., 2007), representing about 16.5% of the planet's climate. In Europe, it corresponds to almost 40% of the continental area, while it occupies about 20% of North and South America and 15% of Asia (Figure 4).

Local climate measurements are verified at INES's facilities with a Meteorological Weather Station located about 80 m to the platform where the reference house stands on a 12 m high mast. Figure 5 shows the hourly outdoor temperature and solar radiation measured in 2014. This on-site recorded data was used to create the weather file used at the energy simulations.



Source: Beck et al. (2005)

Figure 4. Spatial distribution of the five main Köppen climate types determined for the period 1951-2000. Rectangles indicate the continental sub-regions for which selected results are presented — marked region: Chambery, FR.

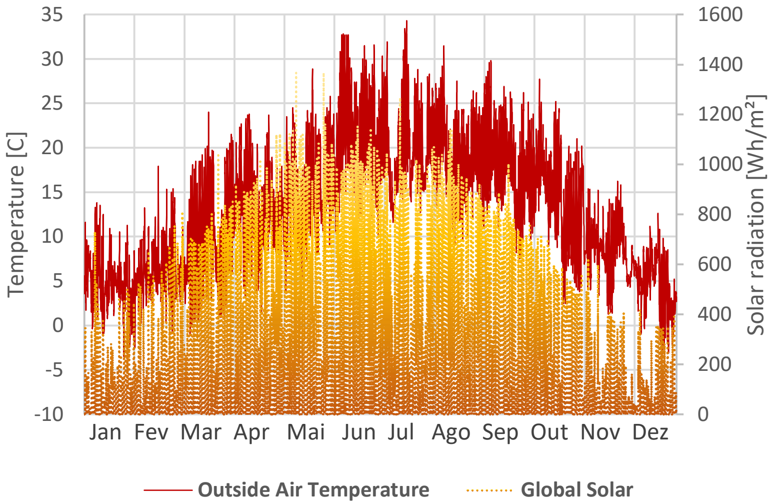


Figure 5. Outside air temperature and solar radiation measured in 2014

3. Research process and methods

Architectural design can be described as searching for the best solution among infinite possibilities, which must meet numerous stringent requirements. Designers need to consider several objectives and find a balance between them, especially when proposing performance-based solutions (Nguyen et al., 2014), adopting passive design, or climate response strategies (Chen et al., 2018). As a result, the range of computer simulation programs focused on building performance assessment has grown in the past decades. These tools are credited to assist the design and decision process, optimizing the final building performance with relatively low cost (Augenbroe, 2002).

Furthermore, algorithmic, computational, or parametric design has become a global trend by using new software tools developed to integrate building design simulation and optimization with digital representation programs. The platforms represent a new way of design thinking and decision-making that aids in developing high-efficient buildings (Touloupaki and Theodosiou, 2017b). According to Touloupaki and Theodosiou (2017a), software such as Rhinoceros or Rhino (Robert McNeel & Associates), Dynamo BIM (Autodesk), and GenerativeComponents (Bentley) have increased parametric 3D modeling application by nonprogrammers into design practice. The new generation of architects is becoming increasingly familiar with digital processes, so these integrated tools provide what is needed to create a performance-based design (Shi et al., 2016). Therefore, parametric 3D modeling and digital design and simulation-based process guided this research development. The choice to work primarily with such platforms relies on its aforementioned efficient design approach, which responds to the current challenges in designing high-performance buildings.

In this sense, the first investigation step was dedicated to a literature review on the research subject, namely performance-based design, but mainly focused on naturally ventilated buildings. The findings showed a crescent number of studies since 2015 on the topic, with a tendency to use numerical models to evaluate NV performance and parametrization and optimization. Two hundred seven publications were gathered, and their contributions compiled, showing challenges and opportunities regarding the state-of-art regarding NV use as a sustainable alternative.

The analysis results are detailed in this research's first publication: Perspectives of naturally ventilated buildings: A review (Sakiyama, Carlo et al., 2020). Moreover, the following aspects are highlighted:

- The NV basic physical principles and main assessment factors were illustrated;
- The required assessment factors for both NVP approaches were listed (from a place and a building), as well as the most used measures to quantify NV performance found in the literature review;
- The climates adopted in the investigated studies were identified and grouped to verify the most recurrent ones;
- Works on naturally ventilated buildings were collected and summarized according to the elements/features used to enhance the NV strategy evidencing its energy implications, and the most recurring parameters found in the reviewed literature were grouped in a graphical scheme;
- The share of literature number on IAQ evaluation metrics was demonstrated, as well as the simulation programs used in the collected articles;
- The methods used for validating numerical models were presented together with their related strengths and weaknesses, and studies involving the influence of input data on simulation outputs were identified;
- The literature on naturally ventilated buildings collected per year was summarized in a graph and the most recurrent countries and journals found in the reviewed articles.

Based on the bibliographic review, it was possible to confirm the themes with research potentials compatible with this thesis. Among the main gaps, the following are emphasized: use of CFD simulations in annual analyses, investigations on hybrid ventilation models to minimize the use of HAVC systems, and the development of optimization procedures to reduce time-cost simulation on performance-based naturally ventilated buildings.

3.1. Natural Ventilation Potential (NVP)

When investigating NVP, two approaches can be adopted: one that considers the ventilation potential from region/places, understood as a geographical or generic valuation; and other more specific, to study a particular building's characteristics. Table 1 presents the needed factors when using each approach, differing them in terms of its required input data. While the generic assessment is based on meteorological data (Causone, 2016), the specific evaluation studies a particular construction, configurations, or strategies (Li and Li, 2015). Both methods are important, as they provide valuable information for both first design or more advanced phases, where even a minimum air change rate in a room could be foreseen (Ben-David and Waring, 2016).

Simultaneously, the choice of one over the other depends on the data available for the analysis and the results accuracy desired. Each of the alternatives meets specific demands that determine which approach to use. The theme is profoundly discussed in the second paper published within this research: Natural ventilation potential from weather analyses and building simulation (Sakiyama, Mazzaferro et al., 2020). Moreover, a straightforward process to assess NVP from a specific location is proposed in the article based on the method described by Chen, Ton et al. (2017). Using the outdoor measurements available in a climatic file, one can quantify the number of hours in a typical year (8760h) when the outdoor conditions are suitable for NV.

Table 1. Assessment factors according to the NVP investigation approach (Sakiyama, Carlo et al., 2020)

NVP Generic assessment		NVP Specific assessment	
Weather data:	Air temperature, humidity, wind speed, wind direction, solar radiation	**Building characteristics**	Orientation, shape, façade pressure coeficients
Air quality data	Outside CO_2 concentration	**Opening characteristics**	Size, position, discharge coefficients, ventilation modus (cross and single-sided ventilation), opening schedule
Others	Noize	**Indoor aspects**	Air temperature, ACH/ ventilation rate, LMA, IAQ
		Others	User behavior, materials properties

The data required include air temperature, wind speed, and humidity values from the meteorological file. For the thresholds, the adaptative model was employed since it is used for naturally conditioned spaces and relates indoor acceptable temperature ranges based on the outdoors environment. A MatLab script was developed for the calculations, which uses a .csv file with the climatic data as input and returns the number of hours per year when the outdoor climate conditions corroborate for the passive strategy to ventilate an edifice.

Recorded data at the INES facilities were used to carry out the evaluation, where the base-case building stands. However, as the access to climate files at the project site does not represent a widespread practice, an easy-to-access weather file was also evaluated to portray a most realistic situation. The double analysis is justified because the local NVP assessments heavily depend on the meteorological database, and there is a risk it may not accurately represent the climatic conditions of the place under investigation. Therefore, special attention must be paid to the weather files used in NVP investigations and more specific examinations, usually carried out through simulations at the building level.

Further assessment of the reference building's NVP was also carried out within the framework of the second publication through Building Energy Simulation (BES), involving the following procedures:

- Determination of the total number of occupied hours (per month) in which the temperatures lie within the thermal comfort boundaries to make use of natural ventilation;
- Thermal comfort evaluation of occupied periods under natural ventilation, using two adaptive models: ASHRAE Standard 55 (ASHRAE, 2013) and the EN ISO 15251 (DIN EN, 2012). Both norms are employed in the analyses as their approaches are dedicated to buildings without mechanical cooling.

3.2. Natural ventilation assessment

The different procedures employed to assess NV can be classified as (i) simplified methods, including analytical and empirical models, (ii) computational simulation, and (iii) flow visualization/validation. Among the simulation options, which is the primary approach adopted in this study, there are multizone network models, zonal models, and CFD models. Within this research's scope, some numerical models were developed to study different ways to assess NV performance, using the experimental building (I-MA house) described in Chapter 2 as a reference case.

Table 2 lists these computational models, identifying the simulation engine, its function, and the publication in which it is used and, hence, described in detail. Additionally, these numerical models were made available in repositories with access links disclosed in their respective publications.

Table 2. Numerical models created to assess NV performance within this thesis

#	Numerical model	Function	Paper[1]	Simulation Engine
1	Initial Model	Calibration against the measured indoor air temperature during the experimental campaign – Multi-zone Airflow Network (AFN) model, following the experimental campaign protocol and configurations	2 (Sakiyama, Mazzaferro et al., 2020) (Sakiyama, Mazzaferro et al., 2021)	
2	Hybrid Model	Annual simulations to assess thermal comfort and heating thermal loads - From the calibrated AFN model, a hybrid behavior was included through the Energy Management System (EMS)		
3	Required Airflow	Required Airflow rate used in NVE assessment – From the calibrated model, it calculates the total cooling energy during the warm period as a reference to determine the amount of heat rate that the outdoor flow should be able to eliminate from spaces and thus achieve the target temperature during the cooling season	4 (Sakiyama et al.)	EnergyPlus version 9.1
4	C_p's Models	Available Airflow rate used in NVE assessment - From the calibrated AFN model, it investigates the impact of 5 C_p sources on NVE		

		during the cooling season		
5	Open CFD Experimental campaign	Model verification against the measured indoor air velocities during the experimental campaign – Steady airflow model that calculates the indoor air velocities in which the geometry follows the window configurations from the experimental campaign	3 (Sakiyama, Frick, Bejat et al., 2021)	OpenFOAM through Butterfly components in Grasshopper/Rhino
6	Open CFD Cooling Season	Indoor air velocities and air change rates –Same configurations from the verified model. All openings were left open, without frames, providing the maximum airflow rates in the spaces to assess if natural ventilation may be employed as a cooling strategy		
7	Closed CFD Façade patches	Surface-averaged C_p values over the building façade – The calculated values were used at the AFN E+ model that investigated the C_p impact on NVE	4 (Sakiyama et al.)	
8	Closed CFD Window patches	Surface-averaged C_p values over the windows – The calculated values were used at the AFN E+ model that investigated the C_p impact on NVE		

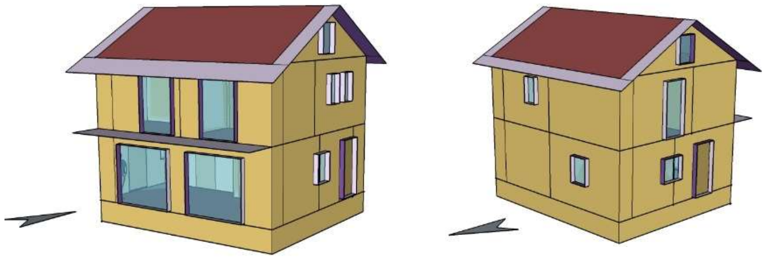
[1]Paper numbering follows the research flowchart presented in Figure 1.

Two numerical approaches were considered when modeling the I-MA house: BES and CFD. Although both models can calculate indoor air parameters, such as airflow rates, there are significant differences between them, for instance, computational cost and accuracy in predicting ventilation performance (Hensen and Lamberts, 2011). Due to the variances between the two simulation methods, both are considered in the research. The objective was to identify their capabilities about the NV evaluation and their relationship considering the parametric design process to develop high-performance buildings.

In this light, some aspects related to the numerical models, the performance metrics used at the NV assessments, and the theoretical background that supported the adopted approach are briefly addressed in the following items.

3.2.1. EnergyPlus models

The simulations ran with the EnergyPlus software (E+), version 9.1 (U.S. Department of Energy, 2019). The program is a validated physics-based BES program used worldwide for researchers, engineers, and architects developed by the US Department of Energy. The geometry is created with SketchUp Make 2017 using the OpenStudio Plugin for EnergyPlus (Figure 6). Ten thermal zones were modeled at the Airflow Network *(AFN) Multizone Object*: three on the ground, four on the first floor, and a staircase zone connecting both levels through a *horizontal opening* component, besides basement and attic. In Figure 3a-c, these thermal zones are marked with red dashed lines at the house floor-plans.



(a) (b)

Figure 6. EnergyPlus Model in SketchUp. a) South/East façades; b) North/West façades

An AFN model consists of nodes, for instance, rooms, connected by airflow elements that correspond to discrete airflow paths such as doorways, windows, and construction cracks (Walton, 1989). The pressure difference across these openings causes the wind-driven Airflow through the building zones, and the ventilation rate for each opening can be calculated by Equation 1 as:

$$AF = C_d A u_{wind} \sqrt{\Delta C_p}$$

Equation 1

Where AF is the airflow rate (m^3/s) across the opening between its associated nodes of the network, C_d is the discharge coefficient, A is the area of the opening (m^2), u_{wind} is the wind velocity (m/s), and ΔC_p is the difference in the surface-averaged wind pressure coefficient between windward and leeward walls. The literature suggests that C_d values range between 0.60-0.65 for sharp-edged openings (Chu et al., 2009; Chu and Wang, 2010; Flourentzou et al., 1998), although the coefficient might vary considerably depending on the opening porosity/configuration, wind angle, and Reynolds number (Costola and Etheridge, 2008; Karava et al., 2004). A deeper discussion on the subject is presented within the fourth paper of this thesis (Sakiyama et al.), and different C_d values were considered in the sixth

(Sakiyama, C. Carlo et al., 2021), when performing parametric simulations followed by a sensitivity analysis.

Moreover, as wind is a significant driving force for infiltration and ventilation, wind pressure and, therefore, wind pressure coefficient (C_p) is a critical boundary condition when predicting natural ventilation. The value expresses a coefficient that relates the velocity pressure on the building envelope to the velocity pressure derived from the mean wind velocity at a reference point (Liddament, 1986). Cóstola et al. (2009) analyzed the use of C_p in BES and AFN models, identifying that the coefficient is one of the main sources of uncertainty, influenced by wind speed and direction, building geometry, façade exposure, and opening position on the surface. The authors distinguish the ways to obtain the C_p values in either direct (primary) or indirect (secondary) sources. Field experiments, wind tunnel measurements and CFD simulations are considered primary, while databases, analytical/empirical models based on the compilation of wind tunnel studies, secondary.

Although data obtained by primary sources are considered the most reliable (Charisi et al., 2019), secondary data sources, especially databases, are the most often employed in BES-AFN analyses (Cóstola et al., 2009) since they are easier to obtain. Nevertheless, AFN models have proven to be reasonably reliable, practically accurate, and computationally effective (Axley, 2007). Therefore, they are extensively used in energy simulations of naturally ventilated buildings (Johnson et al., 2012), with some studies focusing on the effects of pressure coefficients on the outputs (Charisi et al., 2017; Ramponi et al., 2014).

A C_p discussion is the focus of the fourth article, entitled "Effectiveness of wind-driven natural ventilation through AFN simulations: impact of wind pressure coefficients" (Sakiyama et al.). Although other secondary sources are presented in the article, the following C_p sources were the ones considered within the numerical model:

1. C_p default values from AFN in EnergyPlus; at the field *Wind Pressure Coefficient Type,* "Average Surface Calculation" was

selected. For the calculations with low-rise buildings, which is the case of the reference edifice (I-MA), E+ uses the analytical model developed by Swami and Chandra (Swami and Chandra, 1987);

2. Database: Air Infiltration and Ventilation Centre (AIVC) (Liddament, 1986);
3. Tokyo Polytechnic Aerodynamic database of low-rise buildings (Tokyo Polytechnic University);
4. surface-averaged C_p values over the façade calculated with a CFD model (Section 3.2.2);
5. surface-averaged C_p values over the windows calculated with a CFD model (Section 3.2.2);

The values derived from each database, as well as those calculated by the CFD models, are presented in detail in the article. In addition, the impact of the different C_p sources used in the AFN model in NVE is also discussed in the paper.

AFN model calibration process

Calibration is understood as the process of determining whether a simulation model is an accurate representation of a particular objective of the study (Averill, 2008). As an initial synergy, the empirical whole model validation (Strachan, 1993) commends to statistically compare the model's measured and predicted data to quantify the degree of (dis) agreement and identify the sources of discrepancy between recorded data and model responses.

In this light, special attention was given to the weather data used to perform the simulations and the calibration process to create a reliable numerical model. Consequently, an evidence-based BES model development was implemented at the AFN model verification process, based on Coakley (2014). The procedure has a clear structure with a consolidated statistical method. A literature review on the subject is presented within the second article of this thesis (Sakiyama, Mazzaferro et al., 2020), also covering the entire calibration procedure.

Briefly, the process started from the E+ AFN model mentioned above and the internal temperatures measured during the experimental campaign, described in Section 2.1. A single performance indicator was considered sufficient due to the characteristics of the object of study: a full-scale facility test, with low uncertainty, bounded to its information source with well-known boundary conditions. Nevertheless, the model's input data were classified according to their source (e.g., sensor data, design documents), and their uncertainty ranges were assigned based on hierarchy, following the proposed in (Coakley et al., 2012). In a first overall model evaluation, time-series and scatter plots from measured versus predicted zone air temperature were plotted as a simple and effective way to find deficiencies in the model (Madsen et al., 2016). After a first trial and error approach, tuning individual zones input parameters, an analytical procedure took part with a reduced number of parameters. With this initial strategy, the model zones with the most significant discrepancies were identified, allowing minor one-off changes that minimized the uncertainties to be investigated in the automated step. Therefore, in this statistical calibration stage, denominated bounded grid search (Coakley, 2014), some variability ranges of continuous parameters were fixed to reduce the search space's dimensionality.

Correlation between predicted and measured data for each simulated zone involves the calculation of the dimensionless indices Normalized Mean Bias Error (%) – NMBE, and Coefficient of Variation of the Root Mean Square Error (%) – CV (RMSE), set out by ASHRAE Guideline 14 (ASHRAE, 2002). The simulation model is considered "calibrated" for NMBE values up to 5% and CV RMSE values up to 15%, for monthly measured data, or respectively 10% and 30%, for hourly measured data. After assigning the probabilistic density functions and determining the parameters range values, the parametric study was set up using the jEPlus software (Zhang, 2009; Zhang and Korolija, 2010), a Java shell for EnergyPlus. Finally, a Goodness-of-fit (GOF) analysis, a statistical criterion check, was applied to rank the solutions among the set of parametric simulations. The cases with the highest GOF are filtered out, and the ones with the lowest GOF value can be considered calibrated, as they provide closer outputs to the measured data.

Lastly, it is worth mentioning the central technical, and non-technical problems faced when calibrating the AFN model, including the simulation of the boundary conditions established in the experimental campaign. In this sense, a good understanding of the measurement protocol, e.g., window opening hours, opening degrees, is fundamental to translate it into the physical phenomena to be addressed in the model.

Hybrid behavior

Further investigations were conducted from the calibrated model, leading to newly developed models (Table 2), such as annual analyses under a hybrid behavior and calculation of cooling loads or airflows during the cooling season to assess NVE. The mixed behavior stands for the interaction with the windows for natural ventilation and the building's heat recovery system. Modeling these two systems' combinations was possible through the *Energy Management System* (EMS) object that allows specific criteria defined in E+ to be changed using a simplified programming language. Complete settings of the Initial and Hybrid EnergyPlus models used in the second article of this research (Sakiyama, Mazzaferro et al., 2020) were also published in data in brief (Sakiyama, Mazzaferro et al., 2021). The detailed data related to these E+ models guarantee a better and deeper understanding of the reference building addressed in the article, grounding the study and providing more information to aid in reading the paper.

3.2.2. CFD models

Most of the work was done within the commercial 3D modeler Rhino 5 through its widely adopted graphical algorithm editor, Grasshopper (Scott Davison), and its many plug-ins. Rhino 5 was used for the geometric model because Grasshopper is settled for parametrization, and Butterfly, a Ladybug Tool (Roudsari and Mackey), is used as an object-oriented python library that creates and runs the steady CFD simulations using the OpenFOAM software (OpenCFD Ltd., 2019), version 2006. Different wind directions (building rotation angles) and other geometric configurations such as wind tunnel dimensions and object functions can be parameterized to generate their respective CFD cases and post-processing surfaces automatically. Figure 8 shows a canvas overview with the scripts, exemplifying how the model is constructed through visual programing language.

A structured workflow showing the multiple software programs used for pre-processing, simulations, results' post-processing, and visualization is presented and detailed in the third article of this thesis (Sakiyama, Frick, Bejat et al., 2021), entitled: A 3D parametric modeling approach to assess wind-driven natural ventilation through CFD. Likewise, other aspects concerning the model description, such as the computational domain, solver settings, and mesh processing, are also covered in the publication. Its content should pave the way to promote CFD's application in wind-driven natural ventilation studies through tool integration in parametric design platforms. The approach can assist CFD's use among non-experts, facilitating case generation and providing new ways to visualize and compute the results.

As the study focus on wind-driven ventilation, the effects of buoyancy (thermal-driven ventilation) were not considered. The method procedure consists of two main activities. First, geometry and location under study are defined (Pre-processing), so the number of incident winds (angles and velocities) to be simulated is settled based on weather data analyses. Second, calculation and post-processing steps are repeated for each of the investigated wind angles.

In this context, the frequency distribution and wind speeds were initially extracted from the considered meteorological data to define the CFD boundary conditions, namely wind velocity, and direction. This examination runs through the Wind Rose component from the parametric environmental plug-in Ladybug (Roudsari et al., 2013) and native Rhino/Grasshopper elements. Each of the dominant incident wind directions defined after the analyses corresponds to a building rotation angle that configured a unique CFD model with its respective wind speed. Besides the wind data from the experimental campaign (19-25.08.14), the investigations also considered the cooling season, identified from April to

September (Sakiyama, Mazzaferro et al., 2020). While the former compares simulated to measured data, the latter aimed to consider the period in which natural ventilation could be used as a cooling strategy, thus configuring a more representative analysis.

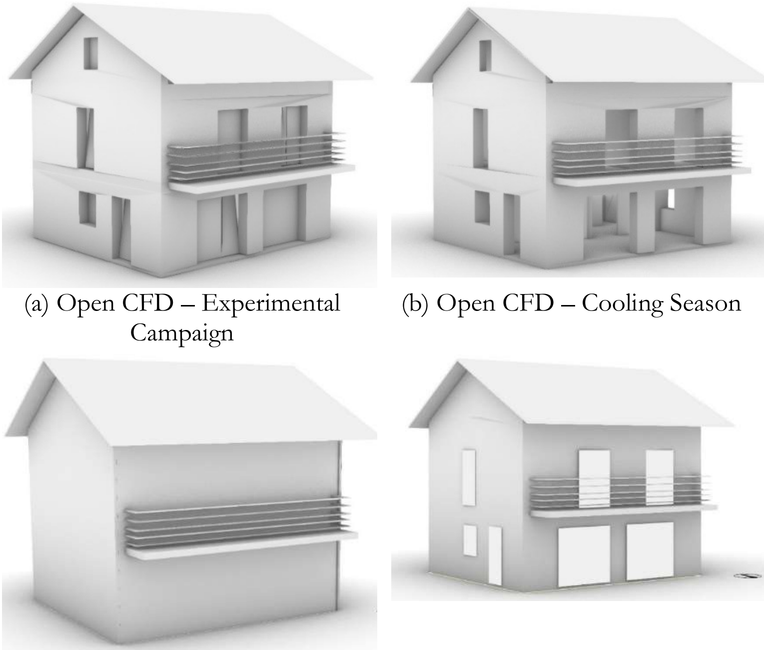
CFD model verification

The building configuration from the experimental campaign and its monitored data was set as a reference for analyzing the CFD outputs. Moreover, the indoor air velocities (m/s) recorded at a 1.2m height in the Living room were used as a performance indicator. Although the measurements are insufficient to carry out a rigorous numerical model validation, they provide proper orientation to guide analyses concerning natural ventilation performance.

Nevertheless, to demonstrate the accuracy of the numerical simulations, velocity components predicted within the CFD model were compared against the results from a wind tunnel experiment from Karava et al. (2011), which used particle image velocimetry (PIV) to measure the velocity field inside a single-zone. Comparing the numerical CFD results with the PIV measurements and the recorded indoor air velocities during the measurement week are presented in the third paper (Sakiyama, Frick, Bejat et al., 2021).

CFD models' outputs

Different geometries, CFD objective functions, outputs, and consequently post-processing alternatives were investigated within this research. In this sense, four geometries were created: two so-called "open," in which windows and the internal divisions of the reference house were modeled, and two "closed," where only the residence envelope was modeled (Figure 7).



(a) Open CFD – Experimental Campaign

(b) Open CFD – Cooling Season

(c) Closed CFD – Façade Patches

(d) Closed CFD – Window Patches

Figure 7. Investigated geometries within the CFD Models

At the two open models, one uses the window configurations from the experimental campaign to compare simulated and measured data, while the other is used for the cooling season assessments, and all openings were modeled unobstructed, without frames. This approach provides the maximum airflow rates to assess if natural ventilation may be employed as a cooling strategy. Different NV calculation methods can be applied within this modeling approach. In the context of the third article (Sakiyama, Frick, Bejat et al., 2021), both indoor air velocities and air change rates (ACH) were estimated and explores alternatives in the 3D design platforms' frame to display and compute ACH and parametrically generate surfaces where air velocities will be calculated.

As for the closed CFD models, in one of them, the windows and walls form a closed surface where the external building patches form a plane, corresponding to the area in which the C_p values can be calculated for the façades individually. In the other, each window was modeled as a single patch, so a C_p value was computed separately for each of the external openings. These results are presented and discussed under this thesis fourth article (Sakiyama et al.), which specially address the C_p subject.

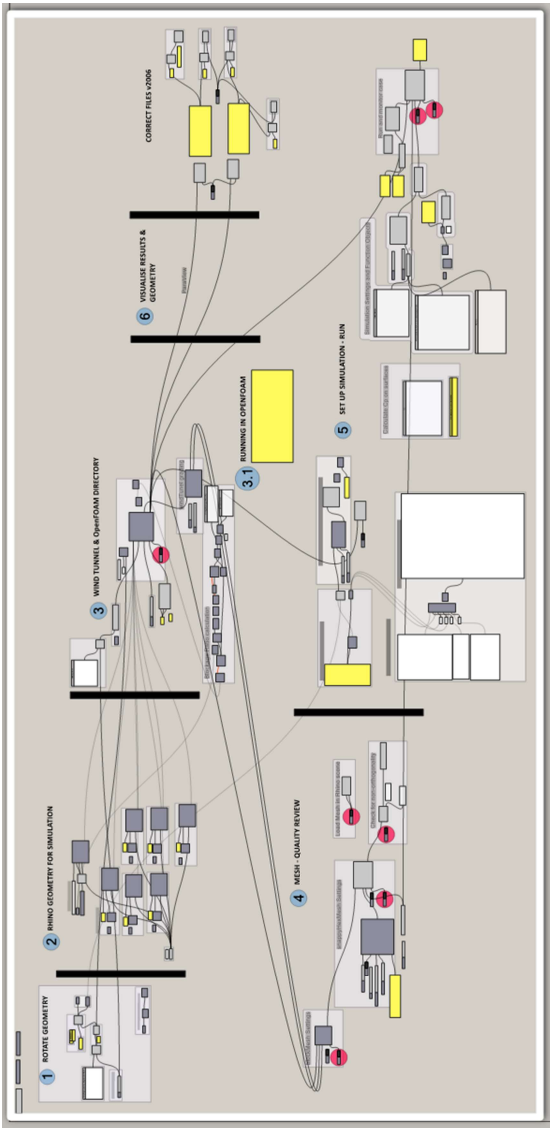


Figure 8. Grasshopper Canvas – CFD model script

3.2.3. Natural ventilation Effectiveness (NVE)

The theoretical framework for the performance metric Natural Ventilation Effectiveness (NVE) was extracted from the fourth article (Sakiyama et al.) and is presented in this item.

The metric verifies the number of hours the outdoor airflows can be used to cool a space, combining standard ventilation thresholds and AFN simulations, expressed in Equation 2. It calculates the weighted averaged of hourly ratios (α_i), between the available natural ventilation air changes per hour (ACH) - ACH_{avai} to the required ones (ACH_{req}) of zone i, where n is the total number of considered building zones, equal to 4.

$$NVE = {\sum_{i=1}^{n} V_i \alpha_i} \Big/ {\sum_{i=1}^{n} V_i} \qquad \begin{cases} \alpha = 1, if\ ACH_{avai} \geq ACH_{req} \\ \alpha = 1, if\ ACH_{req} = 0 \\ \alpha = 0, otherwise \end{cases}$$

Equation 2

ACH_{avai} corresponds to the hourly E+ output *AFN Zone Infiltration Air Change Rate* calculated for the Living room and Bedrooms 1-3, while the ACH_{req} is calculated through Equation 3 and Equation 4.

$$ACH_{req/min} = {3600 \cdot AF_{req/min}} \Big/ {V}$$

Equation 3

$$AF_{req} = {q} \Big/ {\rho\ c\ (T_{comf} - T_{out})}$$

Equation 4

Where AF_{req} is the required Airflow to offset cooling load, expressed in m³/s, which is converted to ACH considering the volume of the room (V), q is the heat rate (kj/s) calculated by the energy simulation (solar radiation, heat gains from people, equipment and light), ρ is the density of air (kg/m³), set as 1.27, and c is the specific heat capacity of the air (KJ/kgºC), equal to 1050. T_{comf} is used instead of T_{in} because it is assumed that when natural ventilation cannot provide sufficient comfort, occupants rely on mechanical systems. ASHRAE Standard 55 (ASHRAE, 2013) is used at the T_{comf} calculations.

Moreover, the minimum Airflow (AF_{min}) in m³/s, is calculated by Equation 5 and converted to ACH by Equation 3 following the design ventilation requirements for the breathing zone of occupiable spaces, according to ASHRAE 62.1 (ASHRAE, 2019).

$$AF_{min} = Q_p P + Q_a A$$

Equation 5

Where Q_p is the outdoor airflow rate required per person, set as 2.5 l/s.person; P is the zone population (largest number of people expected to occupy the zone during typical usage); Q_a is the outdoor airflow rate required per unit area, set as 0.3 l/s.m², and A is the zone floor area. Minimum and required Airflow are compared, so if ACH_{min} is greater, it is used as a reference, rather than ACH_{req}.

Finaly, as the NVE is evaluated in both the living room and bedrooms in the study, the performance metric was measured employing the weighted average among the considered spaces.

Metric usefulness

The Natural Ventilation Effectiveness (NVE) can be used as a performance indicator in naturally/hybrid buildings in temperate, colder climates, and tropical regions. The metric differs from other approaches such as heating and cooling degree days/hours, occupied hours in comfort, and ACH rates, providing an assessment focused on the outside air capacity to deliver the required airflow quantities to satisfy indoor air quality and thermal comfort. Therefore, when evaluating buildings that adopt natural ventilation as a cooling strategy, using the indicator would be more appropriated to investigate the airflow effects on building thermal comfort and performance.

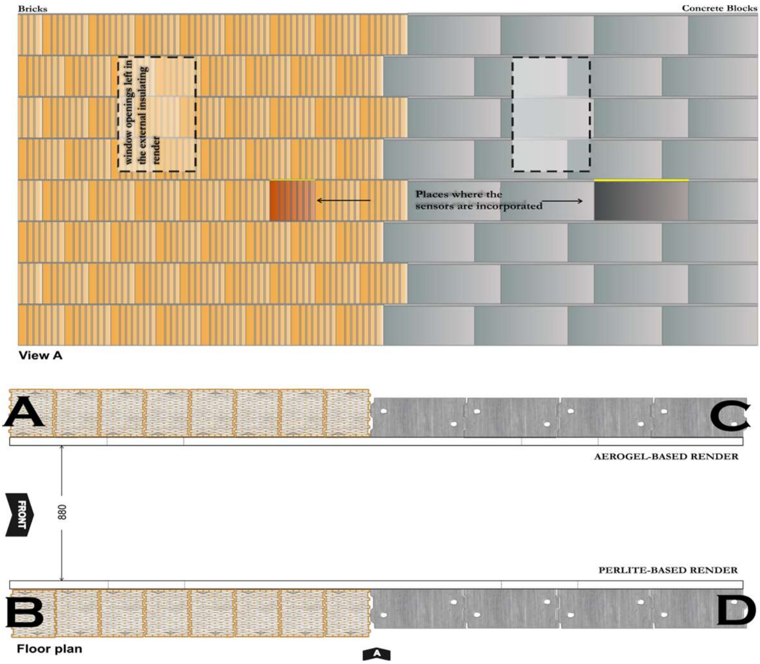
3.3. Hygrothermal performance of an Aerogel render

As energy consumption in buildings is directly related to the heat losses through its envelope, improving external walls' thermal resistance is an efficient way to enhance building thermal performance. In that light, an aerogel-based insulating external render was developed within the Wall-ACE project framework to reduce energy losses through a highly efficient insulation system (Wall-ACE Project, 2017-2019).

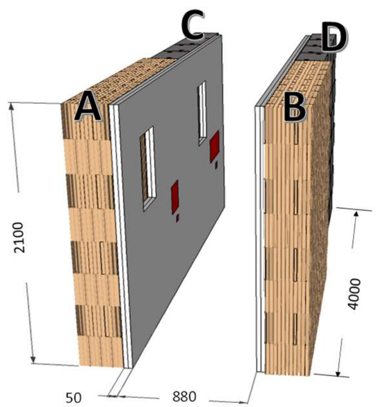
Besides complete material characterization, its structural and hygrothermal performance at the system level was tested through a large-scale monitored test, equipped with hygrothermal, impedance, and heat flux sensors. The test is usually used to assess external thermal insulation composite systems (ETICS) under harsh conditions, where the chamber is composed of two opposing walls of 4.0 x 2.1m (length x height) that stand 1 m apart. They are built in the lab and then enclosed by a sealing system (floor, ceiling, and two doors on the small dimensions); see Figure 9. Finally, verified materials are exposed to heat-rain, heat-cold, and rain-heat-cold cycles according to the DIN EN 16383 (DIN EN, 2016).

Following the average method regulated by ISO 9869-1 (ISO, 2014), U-value measurements were performed before and after submitting the material to weathering to verify the effects on the exterior render's performance. With these data, it was possible to estimate the thermal properties deterioration due to aging effects and evaluate how the material performance might decline over the years.

Moreover, based on these experimental data, a 2D heat and moisture transfer (HMT) model was developed and calibrated in Delphin 6 (B.C. Bauklimatik Dresden), allowing a direct comparison between the impedance measurements and the simulated water content. Finally, the impacts of the material thermal performance on energy consumption were verified through BES using the I-MA house as a reference.



(a) Floor plan of the tested walls and exterior view from the right side



(b) Perspective of the tested walls (c) Test rig

Figure 9. Large scale test rig

A detailed description of the large-scale test, including the main technical specifications, measurement equipment, recorded data, as well as the thermal conductivity and U-value determination and calibration of the HMT model, is provided in this research fifth article: Hygrothermal performance of a new aerogel-based insulating rendering through weathering: impact on building energy efficiency (Sakiyama, Frick, Stipetic et al., 2021).

3.4. Optimization

Building performance simulation using optimization methods or simply BSO is helpful since many variables that affect building performance are usually defined qualitatively and mainly considered in the conceptual design phase. Consequently, designers lack sufficient information to make effective and appropriate decisions to lead to high-performance buildings (Shi et al., 2016).

BSO has been explored to find optimal solutions among many potential combinations of several parameters involving passive design or responsive climate strategies. Tian et al. (2018) studied the integration of optimization algorithms into simulation-based design processes and summarized the different procedures applied within the technique. Table 3 outlines these multiple steps.

Table 3. Typical optimization methods applied in building performance simulation. Adapted from Tian et al. (2018)

Optimization procedures	Description
Three-phase optimization	The optimization process occurs in three phases: pre-processing, running the optimization, and post-processing
Multi-time design optimization	Building performance simulation with optimization methods is applied at each stage of building design
Sensitivity analyses and optimization	Sensitivity analyses are used to narrow the variables range, determine the significant ones, and filter those with little impact on the objectives. Optimization is then conducted with a narrow variable range.

In this context, the reference building went through parametrization, sensitivity analyses, and optimization to improve thermal comfort during the cooling period and reduce annual building energy demand. The focus relies on expanding natural ventilation use and minimizing heating and cooling consumption. Under a structured workflow, divided into i) model setting, ii) sensitivity analyses (SA), and iii) multi-objective optimization (MOO), the process is straightforwardly implemented through a parametric 3D modeling platform. Figure 10 presents the Grasshopper canvas, graphically summarizing the model scripts. Each of the steps is profoundly discussed in the context of this thesis' sixth article (Sakiyama, C. Carlo et al., 2021), entitled Residential building optimization through a parametric design platform: sensitivity analysis and radial based algorithm. Nevertheless, some methodological aspects are highlighted in the next items:

3.4.1. Model setting

Model creation within the optimization framework begins by importing the .idf file available in (Sakiyama, Mazzaferro et al., 2021) using Honeybee components. The base-case building geometry is translated into the 3D modeling parametric platform (Rhino + Grasshopper) through HB-Energy components. The numerical model follows the same configurations described in item 3.2.1 concerning zoning and the use of AFN objects. Similarly, openings operation regarding natural ventilation and building's heating/cooling system equals the annual analyses model, under a hybrid behavior. Ventilation control depends on occupancy and is based on a temperature setpoint, which was parametrized and varied from 20-22°C.

Optimization objectives and input variables

Three objectives, namely Natural Ventilation Effectiveness (NVE), Total Cooling Loads (TCL), and Total Heating Loads (THL), were defined as indicators to optimize indoor thermal comfort and building energy demand. The metrics were calculated for the living room and three bedrooms, being NVE measured through the weighted average among the four spaces, and the TCL and TCL added up.

Thirty-two input variables were initially determined involving six variables categories: building orientation, window-to-wall ratio (WWR), opaque and translucid envelope material properties, external window shading, natural ventilation, and HVAC system setpoints and AFN parameters (discharge coefficient and the fraction of operable glazed area).

3.4.2. Sensitivity analyses (SA)

Before the optimization, sensitivity analyses were performed to identify the influential variables among the vast input parameters to reduce optimization search space. The "sdo.analyze" function from Simulink® Design Optimization™ (MathWorks) was implemented in a Matlab script to analyze the relationship between the design (or input) parameters to the optimization objective (or output), using the Partial Ranked Correlation (PRC). First, a sample of 607 cases with raw values (0-1) was generated using the Sobol sampling method. The sample size was defined following the recommendation in (Cipriano et al., 2015), which states that the minimum sample size should de 15-19 times the variables number considered in the analysis. The 607 cases run using Colibri components, a tool that performs parametric simulations distributed with TT Toolbox (CORE studio at Thornton Tomasetti, 2017).

The calculated PRC of the 32 variables for the three objectives (NVE, TCL, THL) were plotted, sorting from the largest to the smallest absolute value. The higher the PRC absolute value, the more influential variable, and the PRC positive/negative value indicates the proportional/inverse relationship between an input parameter and the outputs. A final arrangement index was estimated with the PRC's sum for the three objectives, sorting the numbers according to their absolute value. Lastly, the 12 top influential variables regarding all objectives were screening out to be analyzed in the next optimization step, keeping the balance between the three considered objectives. Locally improved values were established for the less influential parameters.

3.4.3. Multi-objective optimization

Instead of using an evolutionary MOO algorithm, commonly employed in similar investigations (Hamdy et al., 2016; Konak et al., 2006), this research's last step uses a Radial Basis Function Multi-objective Optimization (RBFMOpt), also known as a model-based method.

The algorithm, available in Grasshopper via the plug-in Opossum (Wortmann, 2021), is considered an attractive alternative for performance-oriented design (Wortmann et al., 2015) because it is seen as particularly effective for optimizing problems with complex associations between variables and objectives and time-expensive simulations (Holmström, 2008). A benchmark study presented in (Wortmann, 2017; Wortmann and Natanian, 2020) showed its good performance compared to other algorithms, finding reasonable solutions with fewer simulations. In this step, the goal was to find the optimal values of the 12 selected influential passive design parameters for maximizing cooling ventilation (NVE) while minimizing the building energy demand (THL and TCL).

Among the outputted results is the hypervolume from each simulation, which measures the objective space's volume dominated by the set of points, e.g., design solutions (Wortmann and Natanian, 2020). Within MOO, the hypervolume must be maximized as all objectives are to be minimized. The goal is to dominate as much of the objective space as possible since, mathematically, if one set is better than the other, it spans a larger hypervolume (Zitzler et al., 2003). Therefore, the best solutions are based on this metric, which is comprehensively discussed in (Sakiyama, C. Carlo et al., 2021).

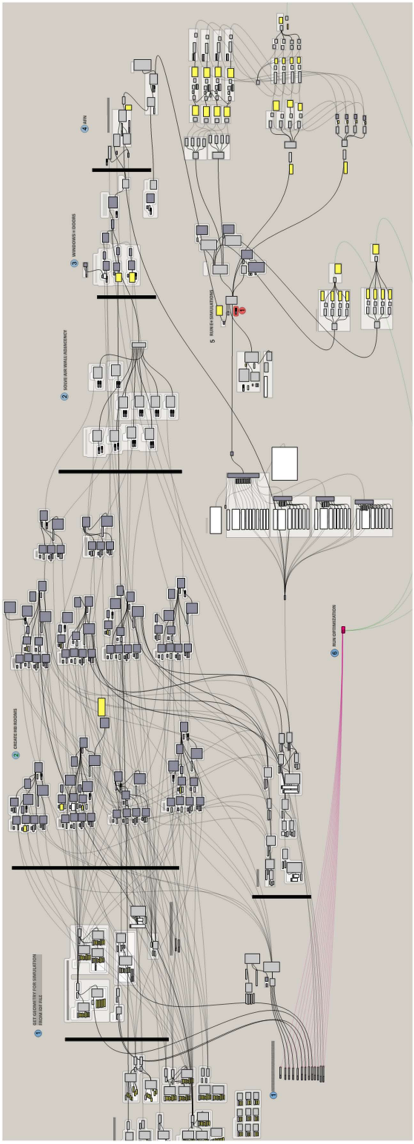


Figure 10. Grasshopper Canvas – MOO model script

4. Closing discussion

This research contributes to both academic and practical field, showing the added value of applying natural ventilation to buildings as a passive strategy or as a hybrid ventilation mode. It proposes different ways to predict and assess naturally ventilated buildings and demonstrates the importance of experimental data in the calibration process of complex BES, CFD and HMT numerical models, to assure they are as accurate as possible.

Furthermore, the study provides a pragmatic use of CFD for either building design or assessment, using the tool in stand-alone mode or coupled with BES. Moreover, the detailed information regarding wind data definition and numerical model settings can help future studies and applications willing to use CFD in natural ventilation assessments. Some practical applications also include the exhaustive data regarding numerical model calibration process, encouraging comprehensive building and material evaluations.

Additionally, the use of 3D modelling platform utilities automates pre- and pos-processing steps and accelerates the analysis. Moreover, when performing MOO, it is possible to manipulate multiple variables, specially geometric parameters. Considering this optimization procedure, the proposed methodology is both useful and replicable. The approach is suitable for project in early stages to provide sound and integrated solution for naturally ventilated buildings. Although the optimization step is restricted to the BSE model, using the NVE metric, Figure 11 illustrates a way to integrate CFD simulations to the process. In this case, the average air velocity inside the rooms would be investigated considering the geometry outputted as optimized solutions.

Finally, effective architectural solutions, that will meet the demands today´s world impose on us, depend on the availability of data and on the designer's ability to evaluate it. Therefore, this research sought to facilitate this process, focusing to use available tools and to propose methods that structure the development of high-performance projects. At the same time, there is still work to be done in this area and hopefully future studies will be able to carry this further, so this study achievements can influence many others.

Among some ideas for future research, the following are highlighted:

- Integration of the NVP Generic assessment in the 3D parametric platform as a component/evaluation tool that reads weather file and graphicaly outputs the monthly NVP hours;
- Transform the calculation of the NVE metric into a post-processing tool within the 3D platform, so the indicator will be an automatic output data;
- Incorporate into the process the investigation of options/alternatives to improve natural ventilation performance, e.g., non-active systems;
- Test the integration of CFD into the optimization process and compare the different performance indices used in each of the methods.

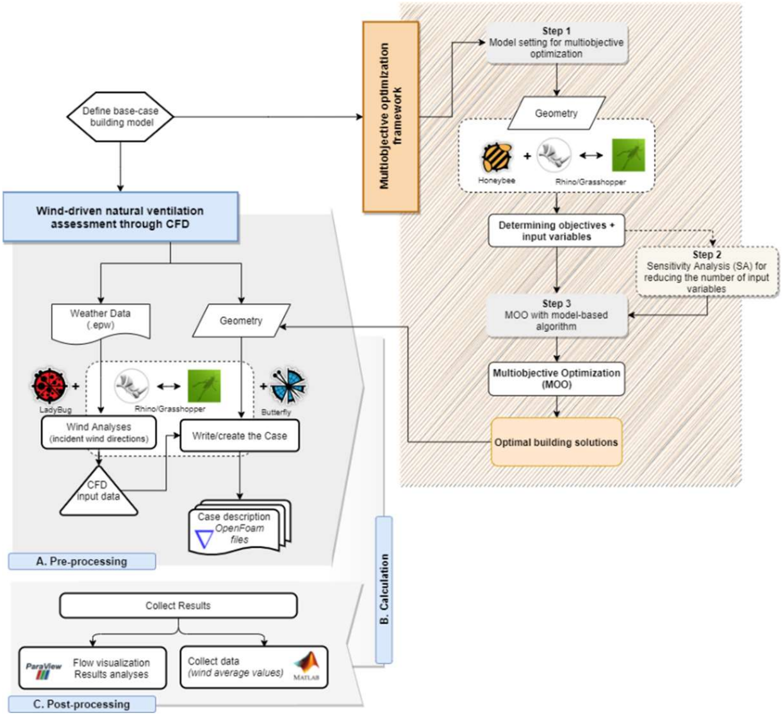


Figure 11. Flowchart combining multi-objective optimization and wind-driven natural ventilation assessment through CFD within parametric 3D modeling

5. Implemented scripts

This research's methodology used original scripts written by the author. Table 4 presents a summary of the developed scripts with a corresponding description, which were used during the research for analysis, result generation, and result representation. The original scripts were published in a data repository and are available at:

https://data.mendeley.com/datasets/wsx7h3h6r7/draft?a=17c206da-7daa-469b-a329-eba4f6278aaa

Table 4. Codes and description

Pos.	**Script name**	**Input argument**	**Output argument**	**Description**	**Nº code lines**
1	NVpotential	.epw/.csv file	. Image: NVP_Month . Image: NVP_threshold . Table: result for each year hour	Calculates the Natural Ventilation Potential (NVP) from an .epw /.csv file: number of hours/year when outside conditions are favorable to natural ventilation	43

2	calibration	.csv files with measurements and simulation results	Calibration results	Perform CV RMSE (Cumulative Variation of the Root Mean Squared Error) and NMBE (Normalised Mean Bias Error) analyses between numerous parametric simulations done with jPlus and measured data. Later on, the GOF (Goodness-of-Fit) is calculated, and the best CV RMSE and NMBE is weighted	97
3	Exceedance Hour Fraction	-	-	Calculates the fraction of occupied hours within the thermal zone, where the operative temperature is above the upper limit for 80% of acceptability (ASHRAE, 55).	219
4	AFrequired	.csv file with room volume	Table with the minimum required Airflow and air changes (ACH)-	Calculates the minimum Airflow required in each space- ASHRAE 62.1 (Breathing Zone - Outdoor Airflow).	676
5	NVrequired			Using E+ internal loads, the script estimates how much air change is needed to remove heat gains	61

6	NVavailable	-	-	Using the ACH calculated in AFN E+ the script get the mean values and also convert to Air flow.	389
7	getAll	-	CFD results (surface …)	CFD Postprocessing - Collects the result of the average speed calculated on the surface created in the Rhino (all subfolder's results)	313

6. List of publication

N.	Publication	
1	**Title**	
	Perspectives of naturally ventilated buildings: A review	
	Journal	**Publisher**
	Renewable and Sustainable Energy Reviews	Elsevier, Amsterdam, NL
	Status	**DOI**
	Published	https://doi.org/10.1016/j.rser.2020.109933
2	**Title**	
	Natural ventilation potential from weather analyses and building simulation	
	Journal	**Publisher**
	Energy and Buildings	Elsevier, Amsterdam, NL
	Status	**DOI**
	Published	https://doi.org/10.1016/j.enbuild.2020.110596
3	**Title**	
	Using CFD to Evaluate Natural Ventilation through a 3D Parametric Modeling Approach	
	Journal	**Publisher**
	Energies	MDPI, Basel, Switzerland
	Status	**DOI**
	Published	https://doi.org/10.3390/en14082197

4	**Title** Effectiveness of wind-driven natural ventilation through AFN simulations: impact of wind pressure coefficients **Journal**: Energy and Buildings **Publisher**: Elsevier, Amsterdam, NL **Status**: Under review **DOI**: N.A.	
5	**Title** Hygrothermal performance of a new aerogel-based insulating render through weathering: impact on building energy efficiency **Journal**: Building and Environmen t **Publisher**: Elsevier, United Kingdom, UK **Status**: Published **DOI**: https://doi.org/10.1016/j.buildenv.2021.108004	
6	**Title** Building optimization through a parametric design platform: using sensitivity analysis to improve a radial based algorithm performance **Journal**: Sustainability **Publisher**: MDPI, Basel, Switzerland **Status**: Published **DOI**: https://doi.org/10.3390/su13105739	

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