Enhancing Natural Ventilation in Family House Buildings in Hungary by Integrating Passive Air Conduction Systems

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Modar Ali

Table of Contents

Nomenclature and abbreviations

GHG - Greenhouse gas

PACS - Passive air conduction systems

ACH - Air change rate

IAQ - Indoor air quality

CFD - Computational fluid dynamics

EU - European Union

HVAC - Heating, ventilation, and air conditioning

IPCC - Intergovernmental panel on climate change

BES - Building energy simulation

WOS - Web of science

DHW - Domestic hot water

AC - Air conditioning

EER - Energy efficiency ratio

AHU - Air handling unit

COP - Coefficient of performance

DF - Daylight factor

CIE - International commission on illumination

WWR - Window to wall ratio

PMV - Predicted mean vote

PV - Photovoltaic

RANS - Reynolds Average Navier Strokes Equation

GCI - Grid convergence index

List of Figures

List of Tables

Chapter 1. Introduction

1.1. Abstract

In the time of climate change, it is fairly argued that humankind is perhaps facing the most serious existential threat throughout its entire history on planet Earth. At the same time, there is an overwhelming body of evidence that proves the responsibility of humankind for triggering global warming and climate change, specifically after the industrial revolution that started in the middle of the 18th century. Since then, greenhouse gases (GHGs) have been rapidly emitted and have accumulated in the atmosphere causing the global greenhouse effect. Climate change has been threatening our way of living with the increasing extreme weather events and the degradation of ecosystems. The rapidly growing global population, on the other hand, is putting more pressure on our resources and involving more aspects into the climate challenge like the social, economic, and political aspects. Therefore, it is absolutely necessary to organize a global collective collaboration of governments, agencies, professional bodies, decision-makers, and experts to take actions that are based on scientific ground, in order to mitigate climate change and adapt to it. Since the topic of climate change is not exclusive to a certain field of science, researchers from multiple research areas are getting increasingly involved in sustainability-related research in their own fields to investigate and suggest considerable improvements that could be applied in our daily lives.

Architects and researchers in the field of architecture and building construction are not an exception from being involved in climate-related and sustainability-oriented studies and research activities. On the contrary, it is essential to further improve the built environment especially when we find that the building sector is affiliated with roughly a third of the global energy consumption and greenhouse gas emissions.

This research is specifically dealing with the family house buildings. The residential sector is responsible for a considerable share of energy consumption within the building sector, but it is mostly not in the research focus as other building types like industrial, commercial, and office buildings. Enhancing the energy performance of buildings incorporates many approaches

that include and are not limited to refurbishment and utilizing passive design principles. The refurbishment process provides an excellent opportunity for rethinking the building design and structure in a way that improves the building's energy performance and allows the incorporation of new passive approaches. The case studies of this research were either partially or totally subject to a refurbishment approach in their own context. As will be explained in later chapters, the refurbishment process made room for adjusting the building design and integrating architectural elements that utilize passive energy and passively use the forces of nature to reduce relying on mechanical equipment. The passive approach in this case is natural ventilation that was enhanced by integrating passive air conduction elements. Utilizing natural ventilation efficiently saves energy from mechanical cooling and mechanical ventilation. The research investigates the efficiency of different geometry and operation scenarios of such solutions in order to reveal their effectiveness and to provide recommendations for related future research and implementations. It investigates integrating passive air conduction systems (PACS) and their influence on airflow patterns, air change rate (ACH), and indoor temperature. The Venturi effect is tested as an important factor in magnifying the passive conduction and stimulating natural ventilation.

1.2. Research Questions

The findings of this research aim to answer the following questions:

1. How much is the residential sector highlighted in the literature regarding the topic of passive ventilation?
2. What is the current status of updraft passive ventilation in residential buildings in the literature?
3. What are the potential benefits of refurbishing typical Hungarian detached family houses, and how to optimize the process in terms of energy consumption and comfort in the indoor environment?
4. What is the influence of integrating a PACS that has a Venturi-shaped roof in the detached family house?

5. What is the influence of different wind directions on the aerodynamic performance of the detached family house, and how to optimize it?
6. What is the influence of integrating a PACS in a semi-attached family house building within a surrounding built environment?

1.3. Research Aim and Objectives

The research focuses on utilizing natural ventilation in the residential sector and more specifically, in family house buildings. Therefore, it aims to reveal efficient practices in this regard and to provide further recommendations for either practical implementation or future research and development. Through this process, the research objectives could be broken down into the following:

1. Scanning the literature regarding the investigated topic by conducting a literature review. The literature review provides the needed background and understanding of the topic in the context of energy and comfort, main physical principles, utilizing natural ventilation in vernacular architecture, evaluation of natural ventilation, and modeling airflow.
2. Conducting a bibliometric analysis to reveal and analyze the current status of literature regarding the topic of updraft passive ventilation. The analysis aims to provide metrics regarding publication trends, affiliated research areas, geographical distribution, and trends of keywords.
3. Developing a simulation-based refurbishment approach of typical Hungarian detached family houses.
4. Analyzing the impact of the proposed refurbishment in terms of energy demand, thermal comfort, visual comfort, and indoor air quality (IAQ).
5. Identifying the aerodynamic impact of Venturi-shaped roof and PCAS when integrating into a detached family house.
6. Analyzing the impact of all wind directions on the performance of an integrated PACS in a detached family house, and developing optimized operation scenarios.

7. Identifying the impact of integrating a PACS in an attached family house on the behavior of natural ventilation and thermal comfort.

1.4. Research Methodology

The research objectives were realized through several published studies [1–3] which are presented in the following chapters (3, 4, 5, and 6) where the methods of each study are explained and detailed. Figure 1.1 represents a conceptual framework for the research methodology in a simplified manner.

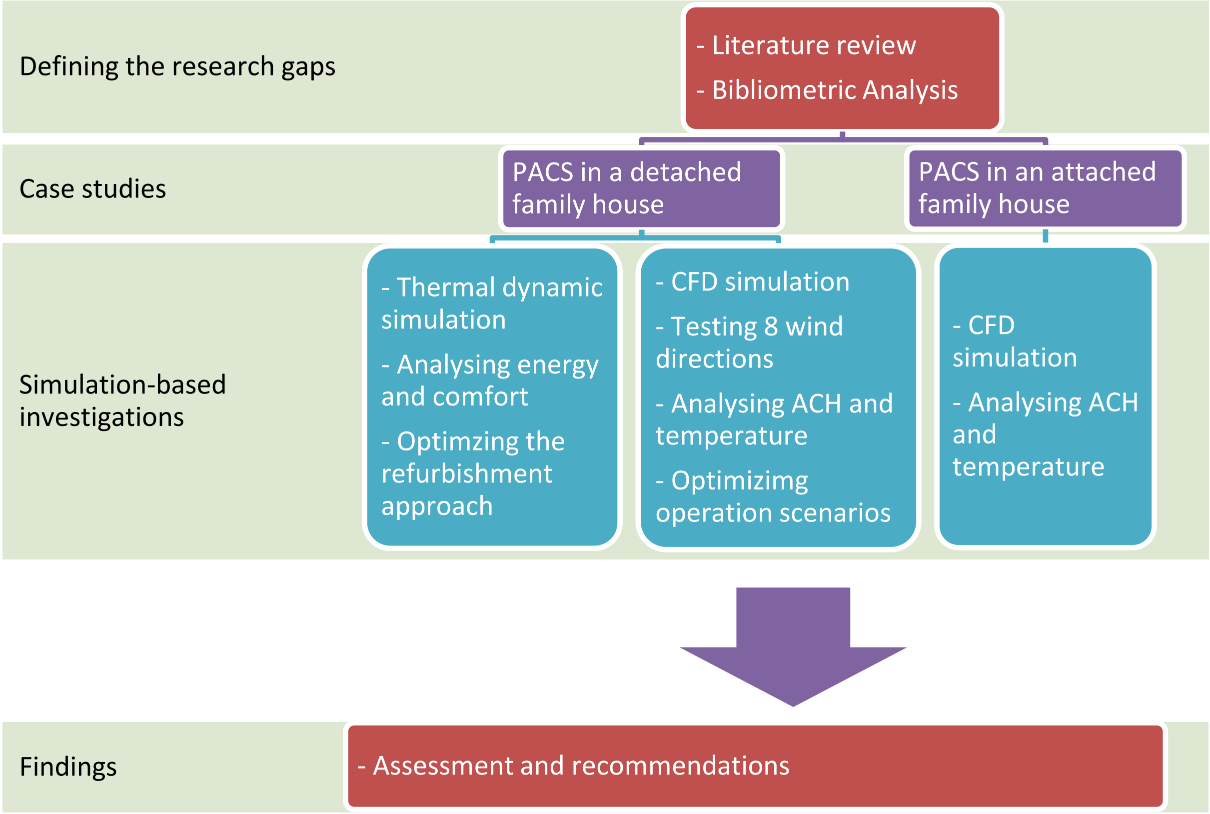


Figure 1.1. Conceptual framework for the research methodology

1.5. Research Structure

In addition to the introductory chapter, this research includes the following chapters:

Chapter 2 includes an extensive literature review that provides a general overview of the topic of natural ventilation in family house buildings while reviewing related topics like energy and comfort, climate change and the building sector, the residential sector, principles of natural ventilation and a brief background of its physics, natural ventilation implementations in vernacular architecture, and computational fluid dynamics (CFD).

Chapter 3 provides a bibliometric analysis with the purpose of mapping the current research trends on the topic of updraft natural ventilation in residential buildings. The search covers the two main data bases: Scopus and Web of Science. A selected combination of keywords is adopted for the search. This chapter analyses the growth of the research interest in the topic, the affiliated research areas, the geographical distribution, and the keyword clusters.

Chapter 4 investigates the refurbishment approach of a detached family house building in Hungary. It utilizes the thermal dynamic simulation tool to compare the old state of the house with the refurbished one. The comparison includes energy demands, energy consumption, and thermal comfort.

Chapter 5 deals with the same previous case study, but it analyses the role of the integrated PACS and the Venturi-shaped roof in enhancing natural ventilation. 8 wind directions and 3 operation scenarios are investigated through the CFD simulation tool. The performance is assessed by two main factors: ACH and indoor temperature for several operation scenarios. The potential energy savings of implementing the PACS is also investigated while considering indoor comfort.

Chapter 6 tests the integrated PACS in the second case study which is a semi-attached family house building. It utilizes the CFD tool to analyze the effectiveness of the ventilation method.

Chapter 7 contains the final conclusions of the research and recommendations for future research.

Chapter 2. Literature Review

2.1. Energy and Comfort

The European Union (EU) has issued the European Green Deal with the aim of reaching zero net emissions of greenhouse gases in Europe by the year 2050. Buildings are responsible for 40% of energy consumption [4]. Reduction of greenhouse emissions certainly requires improving the energy efficiency in the buildings sector and reducing energy demand [5]. The challenge of energy is global and it is becoming more serious every year. The effects of the energy crisis are heavily evident in the depletion of energy resources and the environmental effects [6]. In a big part, energy consumption is affiliated with buildings and the seeking to have a comfortable indoor environment for people to occupy [6].

Most of the energy consumption in buildings is linked to heating, ventilation, and air conditioning (HVAC) [7]. Therefore, it is highly recommended to reduce energy consumption in a way that prevents our resources from depletion and protects the environment. Utilizing renewable energy in buildings significantly limits the dependency on fossil fuels and enhances the preservation of ecosystems at both local and global levels [7].

Reduction of GHG emissions from buildings can be achieved by three main methods: reduction of energy consumption and buildings’ embodied energy, switching to renewable energy and using fuels with lower carbon footprint, and controlling the emissions of non-CO_2 GHGs [8].

Many efficient technologies can help, when applied, in reducing CO_2 emissions caused by energy use in buildings. However, these technologies are still far from being implemented widely enough to minimize the life-cycle cost, and this is because of many dominant market barriers [8]. Having that said, and since implementing the technologies that reduce CO_2 emissions in buildings depends on the occupant’s behavior and the consumer’s choices, non-technological methods can provide other solutions. These non-technological methods are considered as passive methods and they include highly efficient ventilation and cooling systems, passive solar design, highly efficient lighting, envelope insulation materials, solar water heaters, efficient building materials, and multiple glazing. Passive methods are able to reduce a great deal of GHGs but they are still limited in usage due to many reasons like the lack of awareness [8]. The shape of the building affects its energy cost and thermal performance. For instance, the compacted shape is recommended in cold climates while it is no longer recommended in mild climates [9]. However, a correlation was found between the building's relative compactness and the total energy requirement, especially for cooling [10].

Building refurbishment can offer a window to improve the building’s energy performance. When conducting a study on residential buildings in Switzerland and their refurbishment methods in light of the energy transition goals, Flourentzou concluded that deep energy refurbishment is required to reduce the performance gap [11].

Furthermore, the Intergovernmental Panel on Climate Change (IPCC) concludes in its report that “the human influence on the climate system is clear. This is evident in most regions of the globe” [12]. The impacts of climate change are difficult to predict, and they differ from one region to another. The solution policy involves reducing the dependence on fossil fuels and improving energy efficiency and sustainability [7].

2.2. Passive Design and Energy Efficiency

Energy efficiency has been the focus of immense efforts recently. Seeking energy efficiency means providing the desired environmental conditions while consuming the least amount of energy [7, 13].

Since the building sector is one of the biggest contributors to global energy consumption and thus one of the biggest sources of GHG emissions, a lot of efforts were made to promote the role of renewable energy in buildings [7]. Adapting renewable energy to buildings is achieved by two methods; the active method when utilizing renewable technology, and the passive method when utilizing the building morphology in a way that obtains the maximum energy savings from the renewables [7].

2.2.1. Active Design

The mechanical equipment of the building represents the active ventilation method. The HVAC systems are responsible for 60-70% of the total energy use in residential buildings. 30-50% of this portion is dedicated to ventilation. That is why the topic of developing efficient natural ventilation has a major role in cutting the energy impacts of the building sector [14].

2.2.2. Passive Design

The passive building design, which considers the local climate, is a very effective approach to adopt in the battle against global climate change by limiting the energy costs of the building. When the building adopts a climatic passive design, energy for mechanical heating and cooling is reduced, and natural energy is utilized to the maximum creating a comfortable indoor environment [15].

2.3. Natural Ventilation and Buildings

Natural ventilation is the oldest known method for ventilation buildings. In fact, it had been the only known method until the beginning of the 20th century when mechanical ventilation and air conditioning methods were developed and spread rapidly especially due to the cheap energy resources [16]. As a result, natural ventilation has been almost neglected in modern buildings since the 50s of the 20th century [17]. Only in recent years, concerns have been raised about climate change. This shifted the attention globally towards reducing energy consumption and GHGs and, therefore, the tendency to use mechanical cooling has considerably declined and is replaced with improving the role of natural ventilation in our buildings [16].

The main purpose of natural ventilation is not particularly providing oxygen since the air in most buildings contains sufficient concentrations of oxygen and the risk of completely losing oxygen can only happen in very tight-sealed places. The main benefits of natural ventilation are plenty and it contributes to human health, comfort, and well-being. When it is properly utilized, natural ventilation helps to remove heat from the air while refreshing it. It also removes humidity and other diluting particles while reducing the cost and occupied space of the mechanical equipment. Natural ventilation cools the building down during the night by extracting heat loads of the thermal mass leaving room for extra thermal storage during the day. Air velocity directly contributes to human comfort by cooling the human body through evaporation and it can make the person more tolerant of slightly warmer air temperatures when the air is moving faster [18].

It is argued that good IAQ increases the productivity of the building’s occupants when it is within accepted limits according to health standards. CO_2 concentration is one of the most important indicators of IAQ and it heavily depends on sufficient ventilation [19].

Ventilation in a building means changing the air of its enclosed spaces. Indoor Air Quality is concerned with keeping air free of contaminants in harmful concentrations. To keep a good state of IAQ, air should be constantly moved out and replaced with fresh clean air from external sources [14]. Insufficient ventilation could be responsible for excessive humidity, condensation, overheating, unwanted smells, and pollutants [20].

It was demonstrated in previous research that the implementation of passive cooling systems could lower the global energy demand by 2.35% [21]. The phrase "passive cooling" refers to the architectural design of buildings that respond to the conditions of the local climate, thereby promoting comfortable and sustainable indoor environments through natural methods [21]. The benefits of incorporating natural ventilation in buildings can be summarized as follows: lower operating costs, Improved thermal comfort levels, and enhanced air quality [21]. In Arid regions, indoor thermal comfort during the entire cooling season, or in part of it, can effectively be maintained by implementing wind towers in both conventional and modern ways of design [15].

Natural ventilation has been promoted as an effective strategy to limit energy consumption in buildings by providing high IAQ [22]. Natural ventilation can be helpful to fulfill the cooling need and limit the dependence on mechanical air conditioning systems. Successful natural ventilation also helps in meeting the required indoor thermal comfort which reduces the use of HVAC [23].

2.4. Principles of Natural Ventilation

Investigating natural ventilation and its passive behavior in buildings has been the topic of many research papers in the literature. However, it is important at the beginning to clarify the physical principles that create or stimulate natural ventilation and affect its patterns. Thus, we will have a better understanding when trying to answer ventilation questions or solve ventilation problems.

The literature shows that two main forces drive natural ventilation. These forces are caused by pressure differences: wind-driven ((hydrostatic pressure differences), buoyancy-driven (density pressure differences), and a combination of the two [14, 18, 24, 25].

2.5. Driven Forces of Natural Ventilation

2.5.1. Wind-driven

When the wind hits a building, it creates a zone of high pressure on the windward side and a zone of low pressure on the leeward side, which creates a pressure difference through the building section [18].

2.5.2. Buoyancy-driven

Thermal buoyancy is a force that is formed by differences in air density due to cooling, heating, and gravitational acceleration [16]. The physics background explains that when air warms up, it gets lighter and less dense, so it rises up. Temperature differences in the air cause pressure differences as well. Such difference is particularly noticed between indoor temperature and ambient temperature, and it stimulates the air flow movement when air escapes the building from higher-level openings [18, 26]. Natural ventilation has a big potential for energy efficiency because of its ability to utilize thermal buoyancy for guiding air and moving heat and pollutants through the building interior. The use of thermal buoyancy can be maximized in modern buildings because they have airtight envelopes and might contain many heat sources from the occupants and the electrical equipment. With the proper use of solar radiation, sufficient thermal buoyance force can be stimulated to provide acceptable thermal comfort and indoor air quality [16].

2.5.3. Mixed-forces Natural Ventilation

Wind and buoyance can operate simultaneously but usually one of them overcomes the other depending mainly on the availability of wind. However, the mix of these two forces can generate complex airflow [17, 25]. Figure 2.1 shows the basic physical principles of natural ventilation [27].

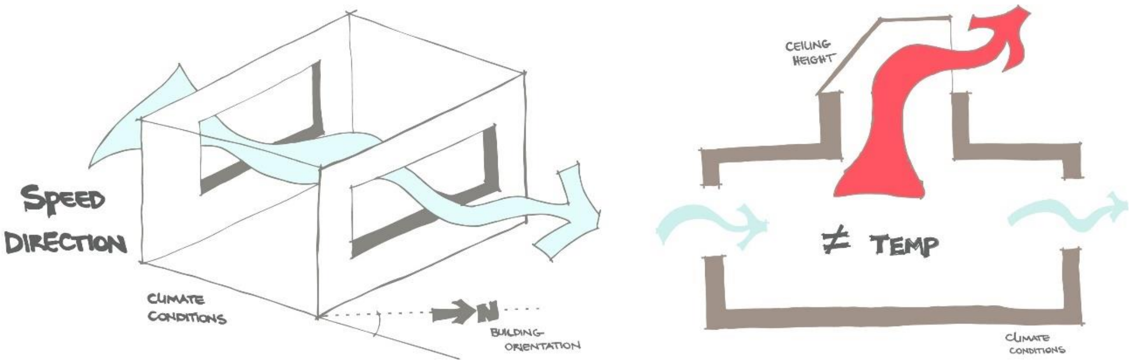


Figure 2.1. Basic physical principles of natural ventilation [27].

2.6. Architectural Strategies of Natural Ventilation

2.6.1. Single-sided Ventilation and Cross Ventilation

Stimulating natural ventilation through opening windows is considered the most typical way. There are three situations of this type of ventilation: 1) Single-sided ventilation, 2) Corner ventilation, and 3) Cross ventilation.

The cross ventilation is capable of achieving a high flow rate that has a considerable cooling effect but at the same time, it might cause draft-induced discomfort and it is only possible when the room has two free opposite sides to open windows. The characteristics of corner ventilation are similar to those of the cross ventilation but its influence is more limited in area. The single-sided ventilation is considered to be more controllable and capable of providing acceptable flow rates. There are two types of single-sided ventilation: the single-opening variation and the multiple-opening variation. The difference is that in the first type the same opening acts as inlet and outlet for the airflow, while in the latter type, inlets are usually differentiated from outlets. Figure 2.2 shows different compositions of natural ventilation [28].

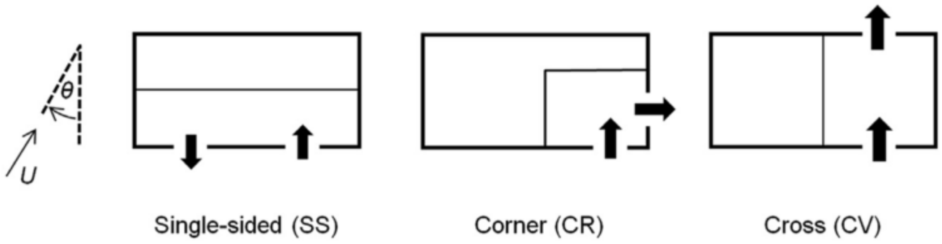


Figure 2.2. Compositions of natural ventilation in buildings [28].

Night cooling happens when the building is ventilated during the night so the structure is cooled and contributes to better thermal comfort during the day. To keep the cooling effect, ambient warm air should be blocked from entering the building during the day by closing the openings, and solar gain must be minimized by effective solar protection. Night cooling is optimized by using building materials with high thermal capacity and good thermal insulation [17, 29].

2.6.2. Wind-induced Ventilation

Some systems are implemented to achieve wind-induced ventilation like wind-towers and rotating ventilators [24]. Wind towers have been historically developed in multiple shapes and designs with the main function of cooling the building by stimulating natural ventilation. They have been mainly geographically located in regions with hot-dry or hot-humid climates [30].

The wind-driven ventilator is a low-cost passive technique that contributes to improving indoor air quality and comfort by limiting excessive humidity and accumulating odor smoke. The turbine is usually installed on the roof and has no operating cost [31–33].

2.6.3. Buoyancy Driven (Stack) Ventilation

The stack ventilation occurs due to temperature differences between the indoors and the outdoors which stimulates the warm air inside the building to flow up and escape, and therefore is replaced by fresh cooler air that has a higher density and inters the building from the bottom. Stack ventilation is best utilized when the wind speed is insufficient to cause cross ventilation. However, the stack ventilation is not ideal in the summertime because the temperature difference is not considerable [14].

2.7. Methods of Evaluating Natural Ventilation in Buildings

2.7.1. Research Methods Regarding Natural Ventilation

Computer simulation is commonly used as a primary tool for assessing building prototypes, despite the availability of imperial studies and real cases. The advancement in computational capabilities has made CFD more feasible as an assessment tool, although simulations can still be time-consuming. Co-simulation between CFD and Building Energy Simulation (BES) is expected in future studies. Meta-models and surrogate models can provide reliable results in sensitivity analysis and building performance evaluations while reducing simulation time and cost. Optimization methods can also be combined with these models to improve the building design by promoting natural ventilation. In addition, wind pressure coefficients and other parametric analyses are being used to assess building performance with natural ventilation. The numerical models can be validated with data obtained from experimental methods using small-scale or full-scale models, including wind tunnel investigation. The validation can also be achieved based on other empirical data from the literature [27].

2.7.2. Performance Assessment Indicators

2.7.2.1. Air Change Rate

The indoor environment is the microenvironment where people spend a large share of their time. Therefore, indoor air pollutants directly affect the occupants’ health. The indoor air content of pollutants, CO_2, and particulate matter is mainly affected by the air exchange rate between the indoor and outdoor environments [34]. ACH per hour is the measurable indicator to evaluate the IAQ and to design the building's ventilation system [35]. ACH refers to the number of times in an hour that the volume of air, equal to the volume of the ventilated space (room or building), is replaced by fresh outdoor air. Thus, it is strongly linked to the infiltration and ventilation rate [36]. ACH can be calculated through the equation (2.1) [37, 38].

$$ACH\ (h^{-1}) = \frac{Volumetric\ air\ flow\ rate}{Unit\ volume} = \frac{v\ (m^3\ h^{-1})}{V\ (m^3)} \tag{2.1}$$

2.7.2.2. *Temperature*

Utilizing natural ventilation within a structure enhances the quality of the indoor environment. In regions with advantageous weather patterns, this approach not only enhances the comfort of those inside but also serves as an efficient method for passive cooling. However, in climates characterized by significant daily temperature variations, a planned ventilation strategy is recommended. Specifically, nighttime ventilation effectively cools the building's thermal mass, leading to a reduction in both the peak and average indoor air temperatures on the subsequent day. This strategy proves especially effective in buildings with substantial thermal mass and effective insulation, thereby supporting scheduled natural ventilation [39]. Since utilizing natural ventilation contributes to maintaining indoor thermal comfort, the indoor temperature is an important factor in assessing the effectiveness of natural ventilation [40].

2.8. Historical Background from the Vernacular Architecture

Middle Eastern traditional architecture has adopted wind towers for centuries as elements of passive ventilation. Wind towers can utilize both wind-driven and buoyancy-driven airflow [14]. In these areas characterized by hot summers, buildings historically incorporated specific architectural elements and components designed to protect occupants from harsh outdoor conditions. Among these features, the Windcatcher served an essential role. Its primary function was to capture external airflow and guide it into the building and courtyard, with the goal of directly cooling occupants by enhancing convective and evaporative heat transfer from their bodies. Additionally, it played an indirect role by removing heat stored within the building's structure. When the wind passed over both the tower and the building, it generated a wind pressure that affected various openings. Air would enter through the windward openings, characterized by positive wind pressure while exiting through the leeward openings, associated with negative or lower pressure values. Figure 2.3 shows the typical operation of traditional windcatchers [41]. Windcatchers, however, are a type of wind tower that only operates wind-driven ventilation. Windcatchers are one of the effective methods for natural ventilation in buildings. However, it can be argued that windcatchers are not paying enough attention in the current construction sector [42].

The windcatcher is an architectural element installed on the top of the building with the purpose of allowing the ambient fresh air to enter the building [43]. Windcatchers can be categorized into three categories; vernacular windcatchers, modern windcatchers, and super-modern windcatchers. The formation of the windcatchers can vary in design factors like the tower height, the cross-section, and the openings [44]. External wind and the buoyancy effect are the main forces that stimulate natural ventilation through the windcatcher mechanism. Traditionally, The efficiency of the windcatcher is significantly influenced by the quantity of openings. A higher number of openings results in decreased efficiency [45].

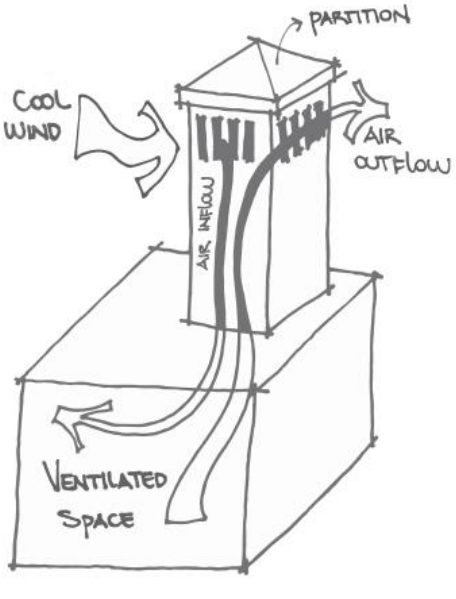


Figure 2.3. Operation of traditional windcatchers [27].

2.9. Computational Fluid Dynamics (CFD)

CFD simulations have been largely used when designing and analysing buildings due to their ability to provide a comprehensive overview of the building's thermal comfort, airflow velocity, air temperature, and many other indicators for indoor and outdoor environments [46]. In literature and the research community, CFD was the most prevalent tool to predict ventilation performance because of its reliability and good agreement with analytical models and experiments. In addition to its ability to be used with other simulation tools to reduce the needed computing power [47]. The CFD simulation model is capable of predicting natural ventilation with window operation and predicting pressure coefficients [48].

2.10. Summary

The embodied energy in the building sector is affiliated with a large share of GHG emissions and ongoing climate change. Enhancing energy efficiency in buildings during the operation phase has an essential role in reducing their carbon footprint while maintaining the level of indoor comfort.

Natural ventilation is a fundamental aspect of building design, with a significant impact on energy efficiency. It leverages the principles of fluid dynamics to provide a passive cooling and ventilation mechanism, reducing the reliance on mechanical HVAC systems. In the context of hot and dry regions, the historical utilization of wind catchers in vernacular architecture offers valuable insights into modern sustainable building practices.

The concept of natural ventilation is fundamentally related to the principles of fluid dynamics. It benefits from the movement of airflow driven by pressure differences, temperature gradients, and wind patterns to provide a comfortable indoor environment and an energy-efficient building performance.

One of the most important historical examples of natural ventilation is the wind catcher, a feature frequently employed in hot and dry regions to harness prevailing winds. The wind catcher functions as a passive cooling device by directing external air into the building, promoting convective heat exchange and evaporative cooling of occupants. Additionally, it facilitates the removal of heat stored in the building structure, further enhancing indoor comfort.

The significance of learning from vernacular architecture in these regions lies in the efficient adaptation of building design to local climate conditions. By integrating the accumulative experience of traditional practices, modern architects and engineers can utilize the potential of natural ventilation, reducing energy consumption, and promoting sustainability. The utilization of wind catchers and other time-tested solutions enhances the environmentally conscious approach to contemporary architectural design.

To conclude, natural ventilation is a crucial component of energy-efficient building design, regarding the principles of fluid dynamics. The historical use of wind catchers in vernacular architecture illustrates the effective harnessing of natural ventilation in hot and dry regions. By considering traditional practices and combining them with modern scientific knowledge, sustainable building designs can be developed that reduce energy consumption, promote indoor comfort, and contribute to a more environmentally conscious built environment.

Chapter 3. Updraft Natural Ventilation in Residential Buildings: A Bibliometric Analysis

3.1. Background

The last few decades have witnessed a profound improvement in the buildings' energy efficiency regulations and policies. However, most of these improvements targeted the industrial buildings where the residential buildings fell behind and their share of energy consumption rather increased due to the lack of knowledge of their behavior [49]. The residential sector is responsible for around 27% of the final energy consumption in the EU [50]. Energy consumption of residential buildings is widely affected by the climate zone, weather conditions, the urban context, and the lifestyle of the occupants [49].

The updraft airflow is a phenomenon that describes the vertical upward movement of the airflow influenced by a combination of the buoyancy effect and crosswind flow [51]. Even though the buoyance effect is the main driving force of the updraft airflow, the crosswind effect is a research subject of many research papers in order to reduce uncertainty about its exact role [51]. The updraft airflow is utilized as a passive ventilation method for buildings and other built environment situations where it is usually coupled with the solar effect to form the "solar chimney" [2, 52–56].

The solar chimney is an element that stimulates vertical air movement by using solar energy to heat the inner air, so it escapes from the top as a result of the created temperature difference which, consequently, creates a difference in air density and pressure. The pulled air is replaced by fresh cooler air that enters through lower openings [52]. Solar chimneys have been used in buildings as natural ventilation elements and many studies investigated the role of different factors influencing their performance [53].

Zhang et al. investigated the airflow characteristics of implementing a solar chimney into a multi-story building. They found that the chimney size has a greater influence on the airflow movement than the solar radiation intensity within the tested context [54]. Fine et al.

investigated the passive ventilation performance of a solar chimney in a high-rise residential building. Their research revealed that the airflow on every floor is affected by multiple factors including the width of the solar collector, solar flux, inlet temperature, and the number of floors [55].

Solar chimneys are sometimes equipped with a Venturi disc on the top to create the venturi suction effect and to increase passive ventilation even further [2, 56]. Katona et al. compared the updraft and the downdraft performance of a wind tower in a winery building. However, in both cases, an updraft wind tower that is topped by a Venturi-shaped roof exhausted the air from the building [56]. We have also performed a Computational Fluid Dynamics (CFD) simulation investigation on a passive ventilation system in a family house building. The systems included an inner chimney with a venturi plate on top. It proved to enhance natural ventilation throughout the building [2].

Most of the surveyed literature focuses on solar chimney utilization in non-residential buildings. This chapter aims to define the size of the research database that specifically deals with the updraft natural ventilation in residential buildings since their final energy consumption exceeds a quarter of the total consumption of the building sector.

3.2. Methodology

This research uses the bibliometric analysis method to explore the investigated field. The bibliometric analysis applies a statistical approach to track qualitative and quantitative changes in a given topic by creating a publication profile of the chosen topic and revealing its research trends year by year [57]. Therefore, this kind of research paves the way for other researchers to evaluate the research activity and conduct their own research on the given topic [58].

The investigation in this chapter uses two online research databases: the Web of Science (WOS) and Scopus, which are two of the biggest research engines for searching for academic literature [59]. These two databases provide good coverage of high-impact journals and research items in different disciplines. They also provide suitable outputs to conduct a bibliometric analysis [60]. This chapter surveys the literature using a combination of keywords that guarantees relevant results to the topic of updraft natural ventilation in the context of residential buildings. The keyword combination includes terms like "shaft", "atrium", "wind catcher", "badgir", "inner shaft", "venturi", and "solar chimney"; which are architectural elements of updraft ventilation. The chapter analyzes the research tendencies in terms of the number of publications, the geographical distribution, and the research fields, and finally analyzes the keywords by creating visualizations using VOSviewer software.

3.3. Results and Discussion

The search was conducted on the 21st of July 2023. The search results comprise 166 publications from Scopus and 150 publications from WOS. Exclusion criteria are applied by defining the time period starting from 1996 until the research date and by taking results in the English language only. After exclusion, the final dataset obtained 162 and 149 publications from Scopus and WOS respectively.

Figure 3.1 reveals the number of publications per year in both WOS and Scopus databases. The highest number of publications is between the years 2019 and 2021. This shows a growing interest in the research topic in recent years, which might be linked to two factors: 1) the Covid pandemic spread and the consequence importance of having healthy indoor spaces, 2) the recent energy crisis, and the urgent need for reducing energy consumption.

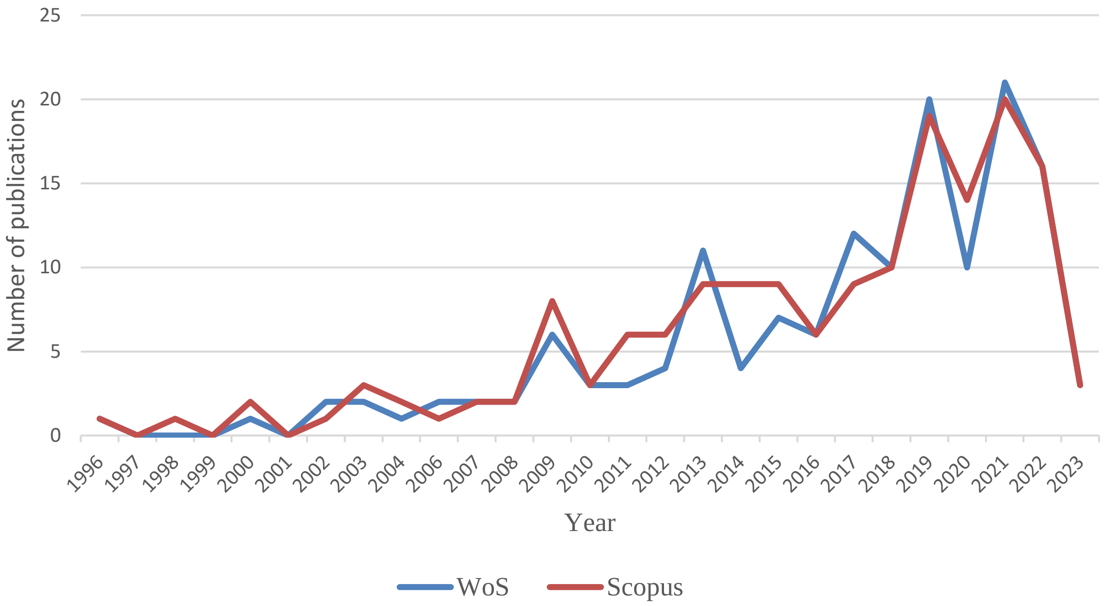


Figure 3.1. Number of publications per year in WOS and Scopus.

Regarding the research area where the extracted publications are published, the top three research fields according to Scopus are Engineering (34%), Energy (17%), and Environmental science (13%) (see Figure 3.2). On the other hand, the top three research fields according to WOS are Energy fuels (24%), Engineering (23%), and Construction building technology (21%) (see Figure 3.3). The geographic distribution of the results shows a high interest in the topic in China, Iran, Malaysia, the UK, Thailand, India, USA, Italy, and Mexico as Figure 3.4 shows. It is habitual for this topic to gain high interest in hot or hot dry climates since these regions of the world have historically developed such passive architectural solutions (for ex. The Middle East, Northern Africa, Southern Europe, and Eastern Asia). However, it is interesting to see that countries with tropical climates (Malaysia, Thailand, and India) are among the top producers of publications. This indicates that updraft ventilation is promising even in climate zones where it has not been historically developed.

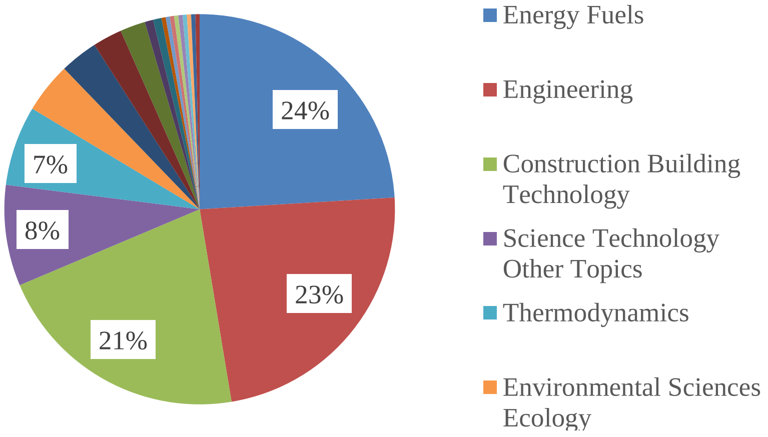


Figure 3.2. Distribution of publications to research areas in Scopus.

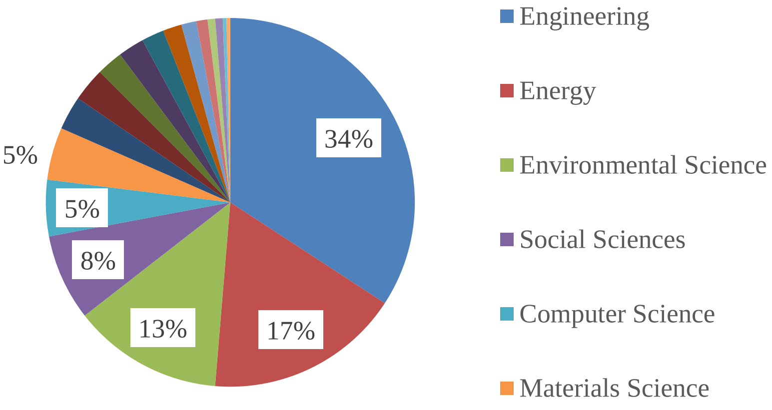


Figure 3.3. Distribution of publications to research areas in WOS.

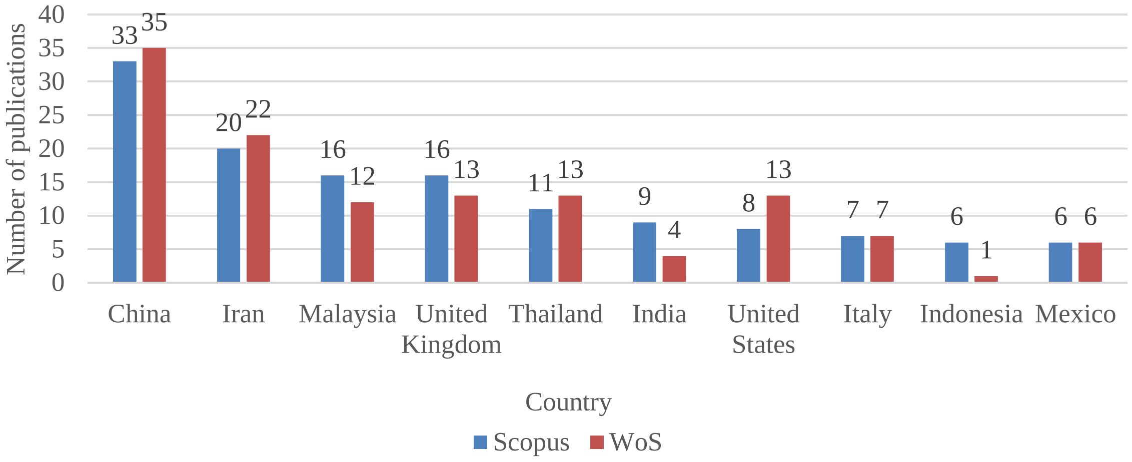


Figure 3.4. Geographic distribution of publications in both Scopus and WOS databases.

Visualizing the literature keywords of both WOS and Scopus using VOSviewer (Figure 3.5) shows the main discussed themes in the topic. Only keywords that appear at least 5 times are considered in this visualization. The keywords show that the concepts of comfort, energy efficiency, and thermal performance have a significant presence in the literature. CFD is also mentioned as a tool to simulate the buildings' behavior.

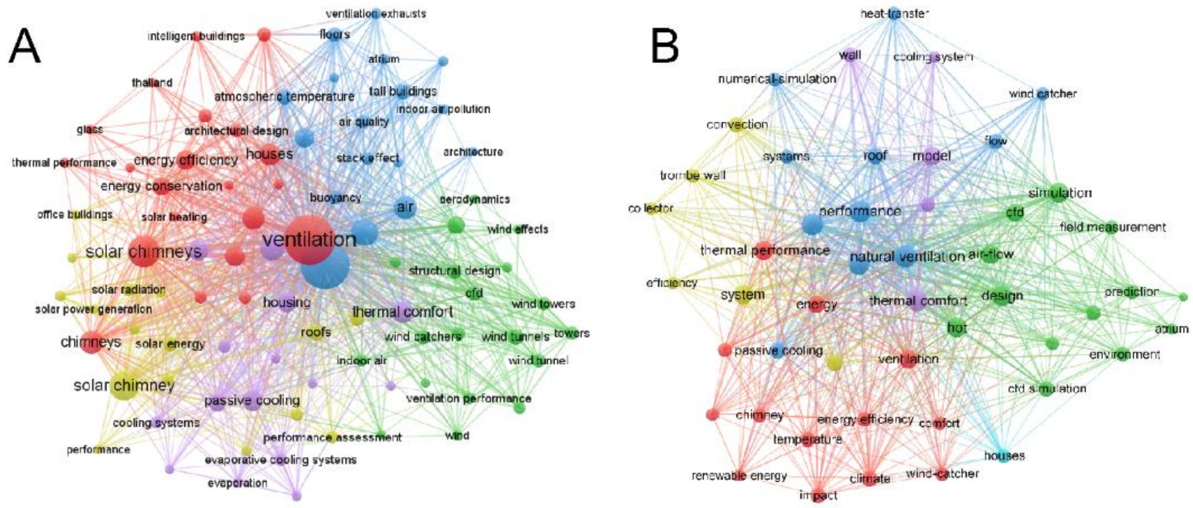


Figure 3.5. Clusters of related keywords in (A) Scopus and (B) WOS.

3.4. Conclusions

This chapter presents a bibliometric analysis of updraft natural ventilation in residential buildings to determine the research trends, publication growth, geographical area, and the research fields of this topic.

The bibliometric analysis is collected from Scopus (162 documents) and WOS (149 documents). The chapter finds that the research on this topic is relatively recent and continuously gaining a growing interest. It started in 1996 and has gradually grown until it peaked between 2019 and 2021. Therefore, it is a promising topic that is proven to be important by the researchers. The geographic distribution of the related research shows that it is conducted not only in regions where this ventilation method is traditionally known but also in regions where there is no previous experience with such a ventilation method like tropical climatic zones. This opens the door for researchers to experiment with the updraft ventilation method in different climate zones, like the continental or the temperate climate, within their distinctive context. Regarding the research field, engineering and energy host the biggest number of publications in both databases, followed by other engineering fields. The field of architecture has a certain importance in this research topic, however, it falls behind many positions in the number of documents. Therefore, this analysis suggests that more studies in the field of architecture to be conducted since the architectural elements and solutions could detect the full potential of the updraft natural ventilation in residential buildings especially in the new climate zones where experimenting with new customized geometries is likely to be needed. The literature extracted keywords provide extra guidance for future research.

Corresponding publications: accepted manuscript to be published by Springer.

Chapter 4. A Simulation-based Refurbishment Approach of a Typical Detached House in Hungary

4.1. Background

The energy performance of buildings has been one of the major issues that should be tackled to face climate change. In the EU, buildings are responsible for 40% of energy consumption [61]; whereas residential buildings alone were responsible for 27.2% of energy consumption in 2017 [62]. Moreover, the building sector is expanding and raising the threat of greenhouse gas emissions [61]. That is why the EU initiated the 2030 Climate Target Plan, which highlights the role of building renovation in improving energy efficiency and aims to raise the renovation rate, which is currently about 1%, given the fact that 75% of the EU building stock lacks energy efficiency today [63]. Due to the European Commission 2020 country report for Hungary [64], energy efficiency in the residential sector is still weak and the country was behind the EU 2020 target as the energy consumption per capita was still 12% higher than the EU average threshold. Strict regulations for energy efficiency of new buildings are being implemented from 2021 but refurbishment potentials are still not fully sustained [64]. ‘Cube houses’, (Figure 4.1) as called in Hungary, are detached houses with similar floor plans [65], which have been built in Hungary since the 1960s. It is a family house consisting of two bedrooms and is usually equipped with a gas boiler for heating and an electric boiler for Domestic Hot Water (DHW). More than 800,000 units were constructed, hence this type can be considered a typical family house in Hungary [66].

Figure 4.1. The refurbishment design project from SDE19 competition (left), a typical 'Cube house' in Pécs, Hungary (right)

Refurbishment brings more benefits than demolition and new construction; not only in terms of the environmental impact but also the social, while the economic benefits are not always guaranteed [67]. A. Power argues that refurbishment brings saving in time, cost, community impact, limiting building expansion, reuse of existing infrastructure, and protecting existing communities. It also brings a significant reduction in building energy consumption in both the short and long term [68].

In general, demolishing an existing building and the construction of a new one can take up to 80 years to recover the environmental impacts [69]. Moreover, Life Cycle Assessment (LCA) studies analyze the process of building refurbishment. They show a high reduction in CO_2 emissions if buildings are refurbished [70]. Therefore, renovation helps in achieving a clean energy transition. That was confirmed and highlighted by a European Commission report, which showed the importance of building energy renovation to make the shift to a low-carbon building stock [71].

The vast majority of the traditional 'Cube houses' share the same plan and structure, but they can still differ in some insignificant details [65]. The presented case study is a new structure that was designed with the imitation of the Cube house's most common geometry (single floor, non-extruding entrance door, pyramid-shaped roof, brick walls structure, and horizontally attached large symmetric pairs of windows) in an attempt to present new insights for how the refurbishment process can possibly be realized.

4.1.1. Energy Design Refurbishment

The new house is a timber lightweight structure that was built in the frame of the Solar Decathlon Europe 19 competition. The main external feature is the ‘Venturi’ disc that covers a small atrium as a ventilation chimney-tower in the center of the house (Figure 4.1). The aim is to stimulate natural ventilation through the house as the ‘Venturi’ disc accelerates the wind flow passing under it, causing a suction effect on exhaust ventilation [72]. In addition, traditional chimney ventilation in a well-sealed house has proven to be commonly effective, simple, and low-cost [73].

The living space (living room + kitchen) was oriented toward the south with a fully-glazed façade that leads to the partially shaded terrace. The glazed façade enhances solar gains and day-lighting in winter and the external shading protects from overheating in summer. The windows are equipped with sliding shading panels made of recycled aluminum while the terrace and the other facades are equipped with sliding shading panels made of wooden tree branches.

4.2. Methodology

The chapter proposes a comparative analysis between the old ‘Cube houses’ and the new suggested refurbishment design by applying a zonal thermal simulation method. The simulation is conducted with the aid of the IDA ICE 4.8 indoor climate and energy software tool using dynamic energy simulations for refurbishment is a well-known approach for assessing the set of variations. It aims to filter the variations based on improving energy efficiency and thermal comfort [74].

4.3. Boundary Conditions

4.3.1. Location and Climate

Hungary has a typical continental climate. The greater part of the country has a moderately warm and dry climate according to the Hungarian Meteorological Service. The annual mean temperature in most parts of Hungary is between 10 and 11 °C. The common wind direction is from the North with velocity varying between 2 and 4 m/s [75]. The weather station (Budapest-Pestszentlőrinc) was adopted for the weather data with a latitude of 47.433 N and a longitude of 19.183 E [76].

4.4. Model Description

The two cases were built in the climate and energy simulation modeling framework as shown in Figure 4.2.

The old ‘Cube house’ possesses a net floor area of 69.3 m^2. The house consists of a bedroom, a living room, a dining room, a kitchen, a bathroom, a toilet, and an entrance. The external wall is a 38 cm thick brick wall. Windows have double-pane glazing. The thermal bridges are set to ‘poor’ as is the case in this old building type. The house is traditionally equipped with a gas boiler for heating. Even though having a cooling system was not typical when they were built in the 1960s, more ‘Cube houses’ are recently being equipped with Air Conditioning (AC) due to climate change. Hence, an air conditioning system was implemented here for cooling in the modeled case.

The refurbishment design has a net floor space of 64.5 m^2. The house model consists of two main zones; the bedroom zone including a desk space, and the living zone including a kitchen and dining. The external wall is 38 cm in thickness. The thermal insulation includes cellulose fibers of 20 cm thickness and flexible wood of 5 cm thickness. The thermal bridges are set to the category ‘good’. The mechanical properties of the building elements in both houses are listed in Table 4.1, and the initial simulation settings are listed in Table 4.1.

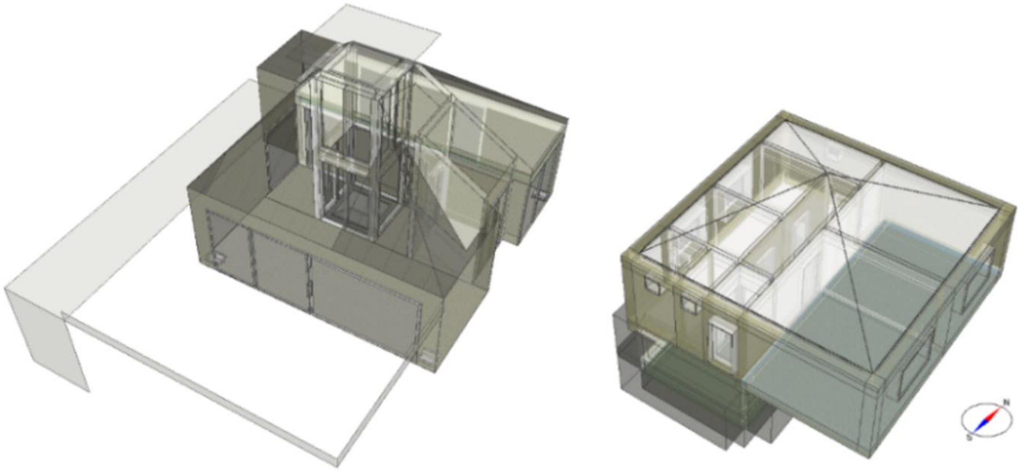


Figure 4.2. The simulation models of the refurbishment design (left) and the ‘Cube house’ (right).

Table 4.1. Mechanical properties of building elements.

	windows		walls	floor	roof
	U-value W/(m^{2}K)	T (solar transmittance)	U-value W/(m^{2}K)	U-value W/(m^{2}K)	U-value W/(m^{2}K)
‘Cube house’	3.35	0.7	1.127	1.203	5.106
Refurbishment design	0.92	0.21	0.12	0.11	0.606

Table 4.2. Initial settings for the simulation models.

	Infiltration		Lighting		Window/ Envelope ratio	Average U-value W/(m^{2}K)
	Air Change	Air tightness L/(s.m^2 ext. surf.)	Input per unit (W)	Luminous efficiency (l2/W)		
‘Cube house’	2	0.55252	18	72	3.20%	0.3793
Refurbishment design	6	1.7427	18	72	12.90%	1.906

4.4.1. Operation Settings

The old 'Cube house' typically has no mechanical ventilation. It depends on the window opening, which was scheduled to be opened during the night (from 22:00 to 8:00) in summer (from 1st of September to 31st of August) to enhance night cooling. During transition seasons (from the 15th of April to the 31st of May and from the 1st of September to the 15th of October), the windows are opened 3 times a day; 5 min each time. The bedroom, living room, dining room, and kitchen are equipped with an AC system that has a cooling power of 3.9 kW with an energy efficiency ratio (EER) of 2.5.

The modeling settings of the building services systems of the refurbishment design were identical to the executed situation in reality. The supply and exhaust ventilation is balanced at 360 m3/h. The air handling unit (AHU) operation schedule is set in accordance with the opening schedule in each season of the year. The AHU operates during the day (from 8:00 to 22:00) in summer (from the 1st of June to the 31st of August) where night cooling (passive ventilation) is being used. During the transition seasons (from the 15th of April to the 31st of May and from the 1st of September to the 15th of October), the AHU ensures air change during the nights (from 22:00 to 08:00), while in the daytime the natural ventilation is on. In the rest of the year (winter), the AHU is always on. The doors that open to the atrium (chimney) and the windows integrated into the glazed façade are opened during nights in summer and during the day (4 times; 4 min each) in transition seasons (from 15th of April to 31st of May and from 1st of September to 15th of October). The louvers at the top of the tower and the floor slots are opened during summer and transition seasons (from the 15th of April to the 15th of October).

Heating and cooling capacities were set identical to reality as well. The total heating capacity is set to 7.8 kW; its coefficient of performance (COP) is 4. The total cooling capacity is set to 8.8 kW, having an EER of 3.2. A floor heating system is applied with 70 W/m2 of power, coupled with a ceiling cooling system with 80 W/m2 capacity in the sleeping area and 60 W/m2 of power in the living area. The bathroom is equipped with a radiator of 76.65 W/m2 power. In both models, default schedules for occupancy and lighting were used.

4.5. Results and Discussion

4.5.1. Cooling and Heating Demand

The load calculations are designed with ideal heating and cooling systems without specifying the exact HVAC systems. It is the initial stage where the investment cost is estimated, conducted in the coldest two months (January and February) and in the hottest two months (July and August). The aim is to define the maximum required power capacity of the mechanical system for cooling and heating to fulfill the necessary indoor comfort. The results show that the refurbishment design achieves 44.1% savings in heating capacity and 7% savings in cooling power, (Figure 4.3).

Transmission heat loss through walls and roof is 21.6% of the one in the 'Cube house' and through thermal bridges is 51.1%, which is mainly responsible for the difference in heating load.

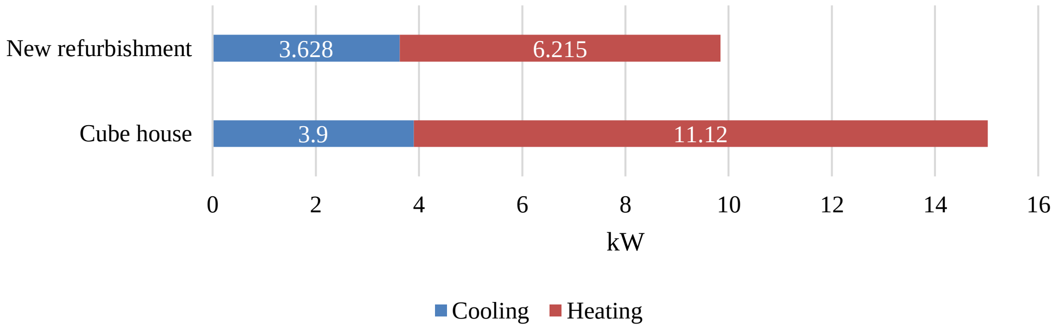


Figure 4.3. Heating and cooling load capacity [kW] in the two scenarios.

4.5.2. Visual Comfort

Artificial lighting is a major contributor to carbon emissions as it can occupy up to 40% of the building's energy consumption [77]. Natural light, on the other hand, has a positive effect on human well-being [78, 79]. Daylight Factor (DF) in definition is the ratio of the internal illuminance (E_i) at a point inside the building to the horizontal external illuminance (E_o) under an International Commission on Illumination (CIE) overcast sky [80]. The value of DF is related to the building type, window dimensions and positions, glazing properties, and room surface reflectance [79]. Due to the Active House specifications and EN17037 standard [81], when applying 300 lx as required E_i the DF threshold is 1.7% based on the equation (4.1):

$$DF = \frac{Ei}{Eo} 100\%. \qquad (4.1)$$

The refurbishment design showed a 36.1% advantage over the ‘Cube house’ regarding the percentage of floor area that fulfills 1.7% or more of DF, as Figure 4.4 shows.

On the other hand, the illumination was measured at a threshold level of 300 lx throughout the simulation at 4 time points (the solstices and equinoxes of the year); 12 p.m. on March, June, September, and December. Figure 4.5 shows the percentage of floor area that fulfills each level of illumination. The results prove that the refurbishment design is 18.725% better than the ‘Cube house’ in the average of the four seasons, especially in winter where the difference reaches 33.1% more floor area fulfilling 300 lx or more. The improvement in DF and illuminance is due to raising the Window-to-Wall Ratio (WWR) and redistribution of openings mainly to the South.

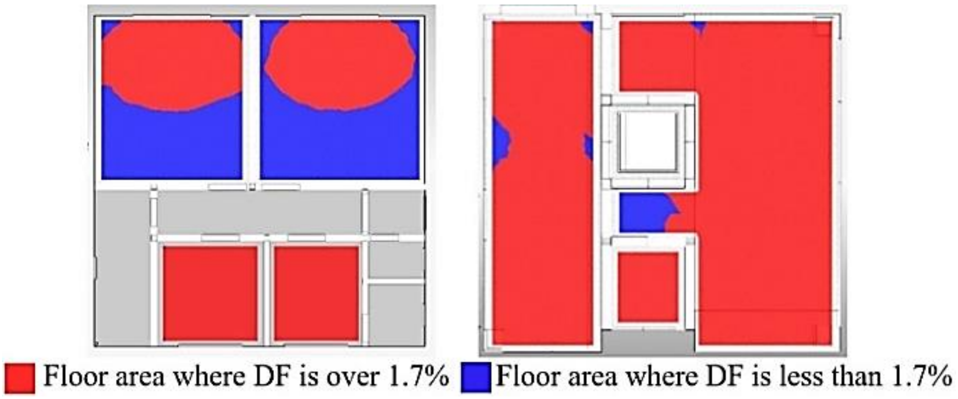


Figure 4.4. DF at the threshold of 1.7%; ‘Cube house’ (left); refurbishment design (right).

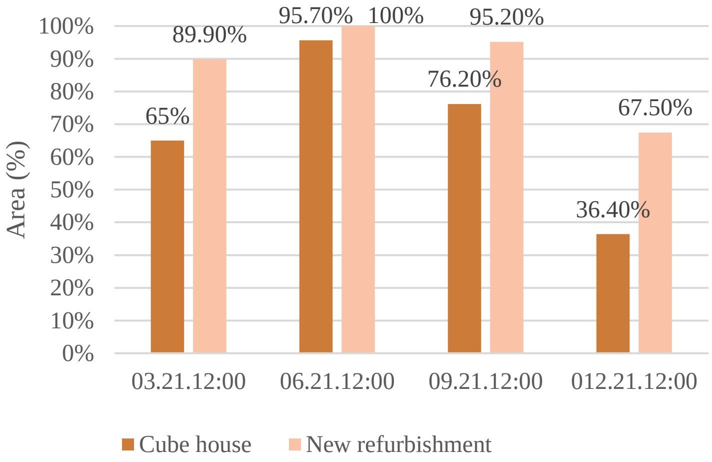


Figure 4.5. Illuminance comparison by coverage percentage of floor area at 300 lx.

4.5.3. Thermal Comfort

The main measured indicator for thermal comfort is the Predicted Mean Vote (PMV). The PMV is an index for thermal sensation on a 7-point scale based on the heat balance of the human body [82]. After running the whole year simulation, PMV was measured in accordance with category II from standard EN 15251 [83], which is represented on the PMV scale from -0.5 to +0.5 [84]. Figure 4.6 shows the mean number of hours that fulfill Category II in a year. The PMV results show that the refurbishment design performs 49% better in the sleeping area and 40.5% better in the living area. Overheating in summer was compensated by utilizing both night cooling and mechanical cooling since natural ventilation alone was not enough to avoid overheating.

One reason for the PMV results is the surface temperature. Figure 4.7 demonstrates a comparison of the surface temperature distribution of walls and windows during the heating season with higher values of the refurbished case, specifically in the coldest heating period.

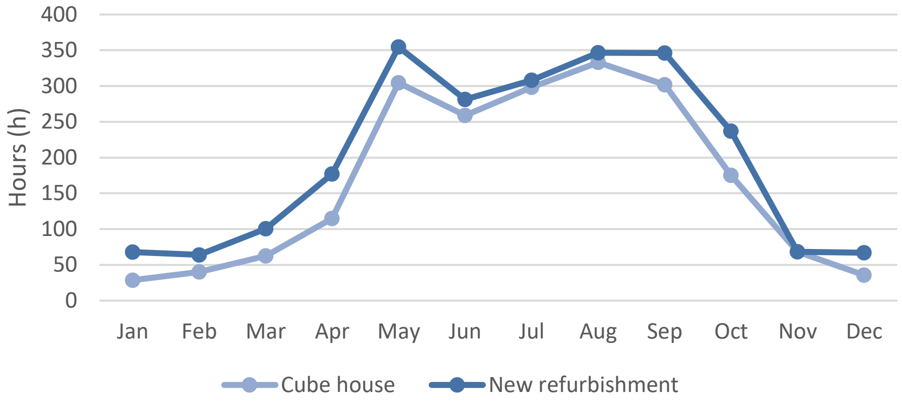


Figure 4.6. PMV ratio of the year [h].

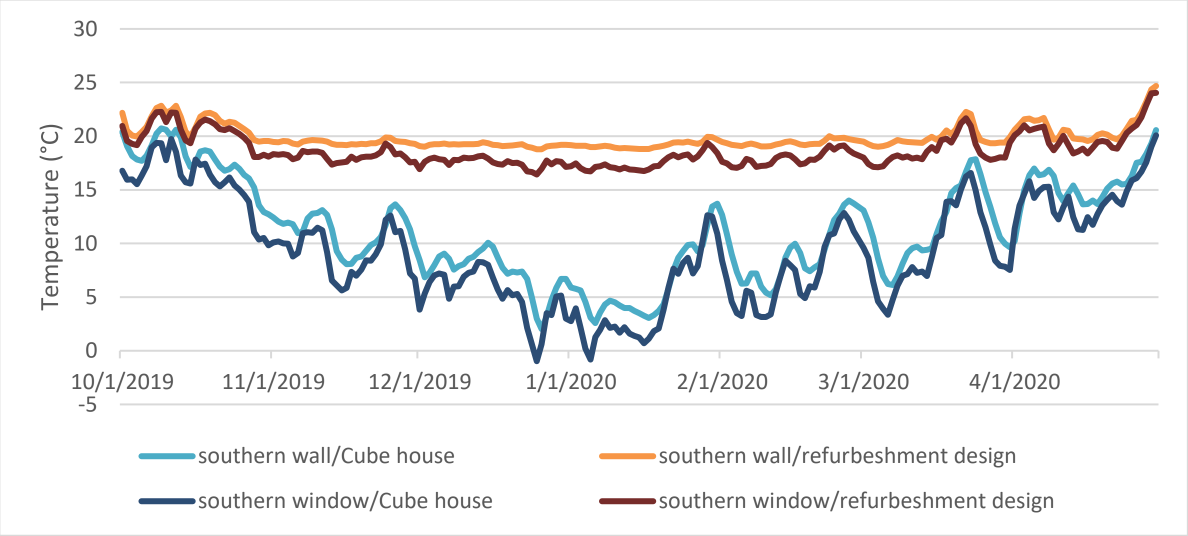


Figure 4.7. Surface temperature comparison from 1st October to 30th April, [°C].

4.5.4. Indoor Air Quality

IAQ is considered the final outcome of both air pollutants and existing ventilation that decreases them. CO_2 concentration level is the main indicator of IAQ and ventilation quality [85]. It was compared by measuring the number of hours when the CO_2 level does not exceed 800 ppm (the threshold of 'SDE19' competition standards), whereas the less ppm content the better air quality.

The simulation results show that the refurbishment design achieve 93% of accepted hours compared to 44.15% for the ‘Cube house’. Figure 4.8 shows the correlation between CO_2 concentration and air age, which are considerable indicators for IAQ. Air age refers to the time since fresh air entered the room, where the smaller the air age, the better the IAQ [86]. The improvement of IAQ is due to the air circulation stimulated by the Venturi disc, inducing natural ventilation through scheduled window openings, and the AHU operating when natural ventilation is not possible.

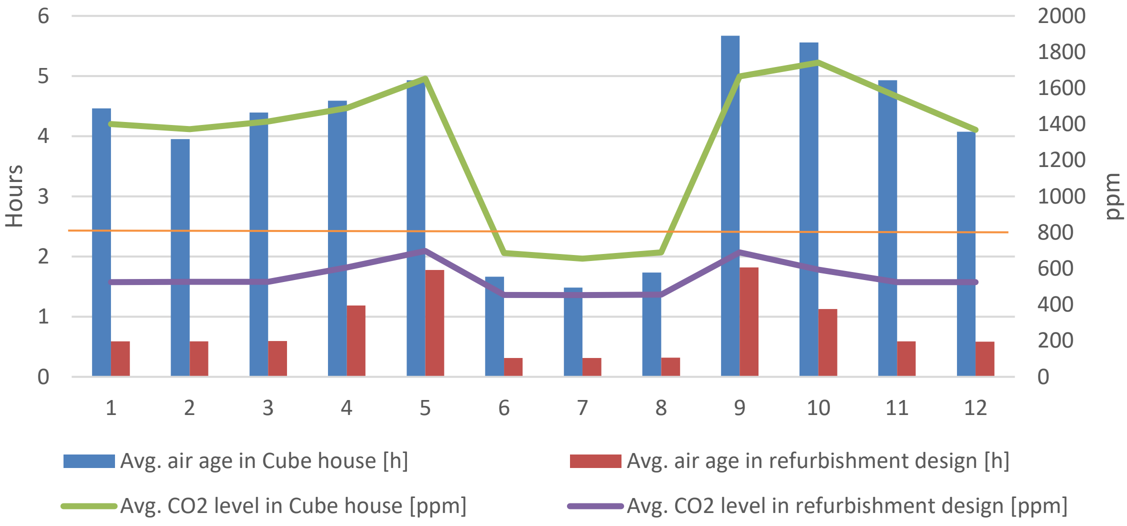


Figure 4.8. The average CO_2 concentration and air age in all rooms on a monthly basis.

4.5.5. Energy Consumption

Identical appliances, schedules, and occupants were applied to both models. Figure 4.9 illustrates the final energy consumption results of a whole-year simulation. The refurbishment design shows a 52.3% reduction in total delivered energy over the level of the ‘Cube house’. The reduction is especially significant in heating, where it reaches 80.04%. The total energy produced by the Photovoltaic (PV) panels is 17006 kWh, which equals 93.4% of the total delivered energy.

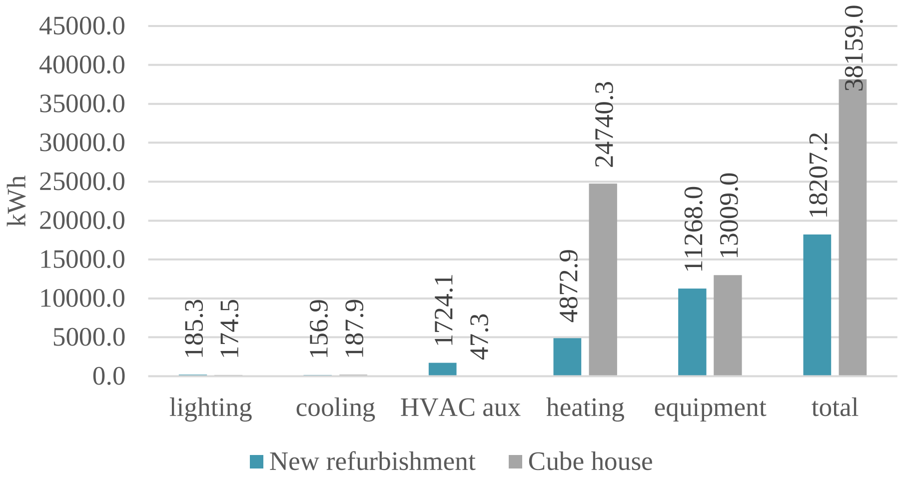


Figure 4.9. Comparison of delivered energy in a year, [kWh/year].

The main energy conservation is observed in the heating consumption. Based on the simulation results, envelope transmission during the heating season through walls and thermal bridges are 90.4% and 94.6% higher respectively in the ‘Cube house’, which is related to the improved thermal insulation and thermal bridges in the refurbishment design. Though the WWR in the refurbishment is 4 times bigger than in the ‘Cube house’ (12.9% to 3.2%), the transmission heat loss through the windows is almost the same during the heating season and the significantly higher window transmission loss in the refurbishment design during the cooling season supports the cooling and saves cooling energy. Infiltration heat losses in the refurbishment are reduced to half, due to tighter joints in the envelope and due to the AHU ventilation performance, including a heat recovery unit with an 80% efficiency rate. The ‘Cube house’s window ventilation in the complete year provided larger heating where the new refurbishment design depended on heat recovery and less dependency on the window opening. The mechanical ventilation resulted in 1020 kWh/year heat loss during heating, but it was compensated by the heat recovery and less needed window ventilation.

4.6. Conclusions

The chapter demonstrates a new approach to tackling an important housing problem within the Hungarian context since the issue of ‘Cube houses’ has not only an environmental perspective but also economic and social ones. The chapter shows the possible beneficial outcome of refurbishing 'Cube houses' and represents a vision of how the refurbishment process might take place. Although, the selected geometry attempted to combine the most common architectural characteristics of this type of house considering the fact that some varieties can be distinguished among them in this context.

Under continental climate conditions, the refurbished version of a typical family house proved superior in the PMV, daylight performance, IAQ, and energy balance. Based on the calculated results the following main insights can be concluded:

- The designed refurbishment brings up to 52.3% savings in energy consumption. The most crucial saving is provided in the heating system, dominating energy balance throughout the whole year. The main contributors to this improvement are the thermal properties of the opaque and transparent envelope structure;
- The role of cooling is not significant in the energy performance of family houses;
- The PMV of the refurbishment improves by 44.75% due to the higher thermal qualities, higher internal wall surface temperatures and operative temperatures;
- The IAQ improvement amounts up to 91.4% lower CO_2 -concentration, as the airflow rates increase due to the passive ventilation and the AHU ventilation;
- Daylight provision is 36.1% higher under mixed sky conditions, while by clear sky an average of 20% better illuminance intensity is provided since the refurbishment applies 4 times greater WWR.

The chapter proofed previous research regarding the utility of chimney ventilation in dwellings but it strongly recommends further research to realize the specific effect of the Venturi disc and the possible back drafting in the proposed method due to pressure changing. Computational Fluid Dynamics (CFD) simulations would be suitable for the recommended further investigation and validation of the proposed ventilation method.

Corresponding publications: [1].

Chapter 5. Ventilation Performance of an Updraft Passive Air Conduction System with Venturi-shaped Roof Structure in a Detached Family House

5.1. Background

Approximately 75% of buildings in the EU are estimated to lack energy efficiency, with the building sector accounting for 40% of final energy consumption and 36% of energy-related greenhouse gas emissions in the EU [87]. Hence, enhancing the building sector is crucial for conserving and utilizing energy efficiently. The European Commission has emphasized the significance of energy efficiency in realizing energy security by 2030 [88]. Residential energy consumption in Hungary exceeds the EU average by 12%. Therefore, there is a notable emphasis on enhancing the energy performance and efficiency of buildings, particularly given the considerable potential in Hungary. This entails implementing more stringent energy efficiency standards for both the construction of new buildings and the refurbishment of existing ones [89].

Mechanical systems are the main contributor to energy usage in buildings and they include HVAC systems [46]. The role of natural ventilation as a viable approach for reducing energy consumption in buildings and improving the IAQ has been emphasized [22]. Operating natural ventilation contributes to meeting the cooling demands and reducing the role of mechanical air conditioning systems. The effective implementation of natural ventilation also aids in attaining the required indoor thermal comfort, thereby reducing the dependency on HVAC systems [23].

When fluid flow (including airflow) passes through a space where the cross-section shrinks, the fluid flow accelerates due to the dropping pressure in a physical phenomenon called the Venturi effect [90, 91]. This effect is utilized not only in a building scale but also in an urban scale to improve pedestrians' comfort [92, 93]. This chapter focuses on translating the Venturi effect into an architectural element called 'Venturi disc' which is a disc-shaped roof topping the building at a specific height creating an air gap. The shrinking morphology of this gap causes the Venturi effect and generates a negative pressure zone in the narrowest section between the disc and the building. A suction effect is created due to the negative pressure which stimulates natural ventilation and pulls up the used air out of the building [94]. Operating this physical principle as a passive cooling system for buildings could be dated back to the windcatcher structures [95]. However, we can find in the literature many examples of implementing the windcatcher principle in modernized methods by utilizing the Venturi effect in architectural spaces and buildings [92, 95-99].

In a research conducted by Hooff et al. and Blocken et al., a Venturi-shaped roof was tested through Computational Fluid Dynamics (CFD) simulations and through a wind tunnel experiment. The main focus was to examine under-pressure in the narrowest section under the Venturi roof and the way it induces, or even creates, natural ventilation in the building. It was found that the Venturi effect was not the only factor influencing the passing airflow, but also the wind-blocking effect (resulting from the section contraction) which might guide the airflow to pass over or around the roof and not necessarily under it. Therefore, they found it was essential to balance these two governing factors. Their other focus point was experimenting with different morphological possibilities of the roof. Different variations were created by adding guiding vanes under the disc. The results revealed that adding the vans limited the passing airflow as they added extra resistance to the flow and reduced the under-pressure when compared to the free flow variant which showed optimal performance [94, 96].

Kistelegdi et al. quantified and validated the natural ventilation aerodynamics of an industrial building in southern Hungary through a wind tunnel experiment. The investigated zones were the atrium and the main production hall with its three passive ventilation towers covered with Venturi-shaped roofs. The experiment aimed to reveal the influence of wind induction and thermal buoyancy on the natural ventilation behavior which directly affected the indoor thermal comfort conditions and the building's energy efficiency. The test results proved the efficiency of the Venturi structure and could help to optimize it [97]. Katona et al. performed a CFD modelling and simulation of the same building where the Venturi-shaped roofs and solar chimneys were the focus of the study to quantify their role in inducing and accelerating airflow. Their results presented the updraft ventilation caused by the towers' structures and they proposed design guidelines to achieve reliable passive ventilation performance [98].

Farzan et al. were interested in investigating the influence of wind catchers on creating passive airflow in hot and humid climate where such a solution had not been seriously considered before. They tested a customized Venturi-shaped roof with CFD simulations. Even though the simulation was 2D, it was sufficient to show a promising potential of the Venturi structure in terms of ventilation and ACH for the specific investigated shape [99].

An investigation about the ventilation tower with a Venturi-shaped roof was conducted by Haw et al. in Malaysia where the climate is hot and humid. In such a climate, stack ventilation is not influential because of the insignificant temperature difference between indoors and outdoors. Therefore, their investigation focused on wind-induced ventilation and performed an empirical test coupled with CFD simulations. Their results showed that the Venturi-shaped roof was effective in stimulating wind-induced natural ventilation by creating enough pressure difference, even when the ambient wind velocity is below 0.5 m/s. The tower produced a sufficient extraction airflow rate and 57 ACH [100]. When testing the Venturi disc morphology in a wind tunnel experiment, Boroojerdian et al. compared the shallow ellipse, the ellipse, and the hemisphere in terms of inducing natural ventilation. The shallow ellipse form proved to perform the best [101].

Zhang et al. used CFD simulations to verify the influence of multiple geometry parameters on the natural ventilation performance of a Venturi-shaped roof in the Xichang region, China. The tested parameters included the size of the roof opening, the height of the Venturi deflector, the slope of the roof, and the geometry of the top opening louvers. It was found that the most significant influence was caused by the width of the roof opening, followed by the louvers' angle and the horizontal size of the Venturi deflector. Their research concluded that the tested structure is capable of fulfilling the comfort requirements of the building occupants when the natural ventilation method is optimized [102].

The Venturi effect was also investigated by Muhsin et al. for vertical ventilation shafts in multi-story residential buildings in Malaysia. They conducted both field measurements and CFD simulations. They explained the correlation between the sizes of the shaft, the openings, and the ventilated space. They concluded that by enlarging the shaft size, the ventilation rate was enhanced due to the Venturi effect [103].

Lim et al. also used the CFD method to investigate the natural ventilation performance of a wind-induced tower with a Venturi-shaped roof for an experimental building in Malaysia. They compared different varieties of roof formation based on the flow patterns and extraction rates. The formation parameters included the shape the height, and the tilting angle of the roof. They found that the ‘biconcave’ shape provided the best results [104].

The implication of the Venturi effect could also be realized on a smaller scale by Shukla et al. when they applied Venturi tubes to window surfaces in India. The aim is to enhance the airflow velocity passing through the window in a hot climate. With a CFD study, they were able to optimize the size and form of the Venturi tubes so they delivered better indoor comfort conditions by their ventilation performance compared to normal windows [105]. The Venturi effect could also be utilized on an industrial scale to develop ventilation devices when Kim et al. experimented with a totally passive Venturi-type ventilator. They evaluated the ventilation behavior in relation to the ambient wind velocity and the wall opening size. It was found that the ventilation rate linearly increased with the wind velocity and that the ventilation rate increased when applying wider wall openings for the wind intake [106].

The previous literature proved that the Venturi principle has a significant potential for comfort conditions and energy consumption when implemented either on the urban scale, the building scale, or even on the scale of smaller architectural elements. They showed that even in various climates, the Venturi effect could still be adjusted to suit the local weather conditions, at least partially. It was also demonstrated that CFD simulations have been a preferred tool to further develop ventilation solutions.

This chapter utilizes CFD simulations to investigate the role of a Venturi-shaped roof in inducing natural ventilation in a family house building. The passive ventilation approach has a special structure that is described later. The airflow patterns, indoor comfort conditions, and ACH are analyzed in different operation scenarios. The case is located in Hungary; therefore, this chapter aims to present valuable results regarding the performance of such roofs in the Central European climate context.

5.2. Methodology

Utilizing CFD technique is widely adopted by researchers to investigate airflow patterns and the efficiency of natural ventilation in buildings. Its results are considered reliable when it is well designed, especially with the increasing computing capabilities [46, 47, 107].

For the purpose of this study, the methodology includes two main steps. It starts with gathering data from the tested building like the location, the weather data, and the drawing layouts. This data is required for modeling the building. The building is modeled using ANSYS Fluent R.17.2 software. The created mesh is verified with a mesh independence analysis. The second step is simulating several operational scenarios and analyzing the results in order to describe the ventilation patterns and reveal the efficiency of the PACS and the Venturi-shaped roof in this context. The third step is verifying and estimating the energy and further thermal comfort performance of the proposed PACS by conducting thermal dynamic simulations.

5.3. The Case Study

5.3.1. Description of the Case Study

The case study represents a typical detached family house in Hungary that is called the ‘Cube house’. It is usually a single-story building whose construction process started in Hungary and other Eastern European countries after the Second World War, as previously described in (4.1) [65, 108].

The location of the case study is Szentendre, Hungary (latitude 47.66943 N, and 19.07561 E) on a flat terrain. The local climate conditions are described as “temperate oceanic” at a 1-km resolution according to the Köppen–Geiger classification [109]. The building is a one-story detached family house (Figure 5.1), as described in (4.1.1). It was designed with the passive ventilation concept of utilizing the Venturi effect. The house is characterized by a central chimney (its horizontal section measures 180*180 cm) that is covered with a Venturi-shaped roof. The Venturi disc has a 320 cm diameter and 15 cm maximum height at its center. At the same time, the house is elevated 21 cm above the ground to leave room for under-floor air inlets that are connected to shaded concrete channels which lead to four floor ventilation gaps distributed to the four corners of the house. The passive ventilation concept is that due to the Venturi effect, used air is sucked through the chimney upwards and it is replaced by cooler fresh air through the under-floor inlets and shaded channels.

5.3.2. Geometry and Modelling

SpaceClaim modeler is used to model the building after collecting the plans and needed data. The computational domain was created according to the best-recommended practice guidelines in a way that is suitable to test eight different wind directions [110]. The height of the building is h=7 m. Therefore, the size of the computational domain is 10*10*7 h (Figure 5.2). The building is modeled with the closest surrounding buildings since they have an impact on the airflow patterns around the building.

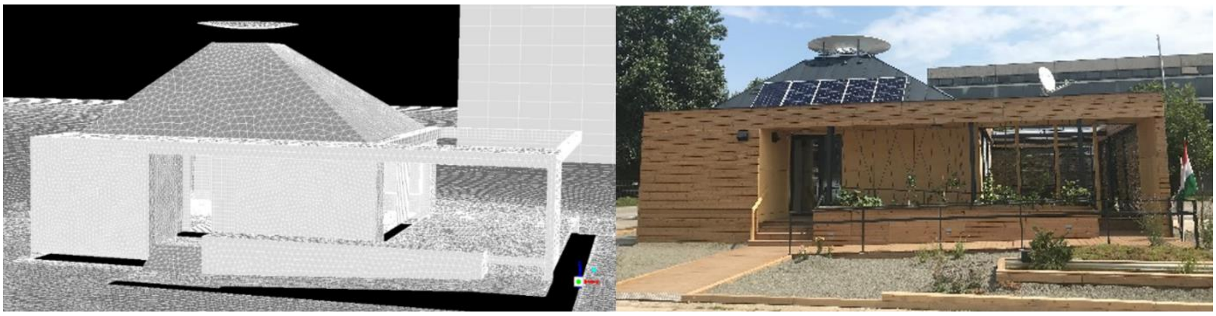


Figure 5.1. The generated medium mesh (left), and the reference house (right).

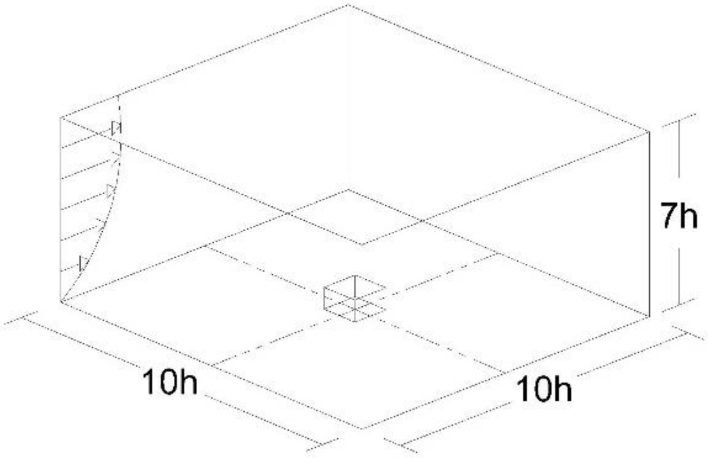


Figure 5.2. The size of the computational domain.

5.3.3. Boundary Conditions

The simulation is set based on the practice guidelines to mimic the real conditions of weather and airflow. “Compressed Ideal Gas” is chosen for the fluid material. The airflow turbulence is assigned with Reynolds Average Navier Strokes Equation (RANS) and standard k-ε. The used finite solver is Fluent. The discretization equation is assigned with the “SAMPLE” coupling algorithm-first order. The temperature of the fluid domain is fixed at 21°C as an average temperature of the 21st of September at 13:00. Weather data of temperature and wind velocity is derived from the Meteonorm database [111]. Figure 5.3 shows the wind conditions of Szentendre location and it shows that the prevailing wind direction ranges between north and west. The inlet of the computational domain is set to “velocity inlet”, where the outlet is set to “pressure outlet”. The other sides of the computational domain are assigned with “symmetry” as a boundary condition. The heat sources in the interior are set in the simulation representing two persons, kitchen appliances, and other electric devices.

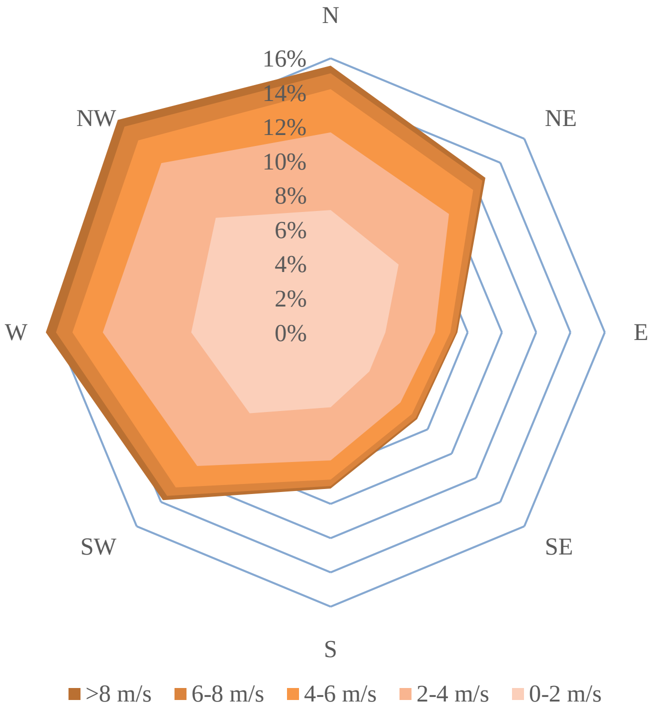


Figure 5.3. The wind conditions of Szentendre. Production of the Authors based on the Meteonorm database.

5.3.4. Grid Independence

An unstructured hybrid mesh was generated. It contained hexagonal, tetrahedral, prism, and wedge cells. Three mesh versions were created with different qualities: 1) the coarse mesh with 3,024,492 cells 2) the medium mesh with 5,307,557 cells 3) the fine mesh with 9,262,020 cells. The grid independence analysis was based on the guidelines by Celik et al. [112]. The reference parameter for validating the mesh was the airflow velocity passing through the top surface of the chimney. The Grid Convergence Index (GCI) of the fine mesh was 3.95%, whereas the GCI of the medium mesh was 2.37%. Figure 5.4 shows the accepted error range of the medium mesh, therefore, it was utilized further in the study. Figure 5.1 illustrates the medium mesh. Table 4.1 lists the metrics of the used mesh.

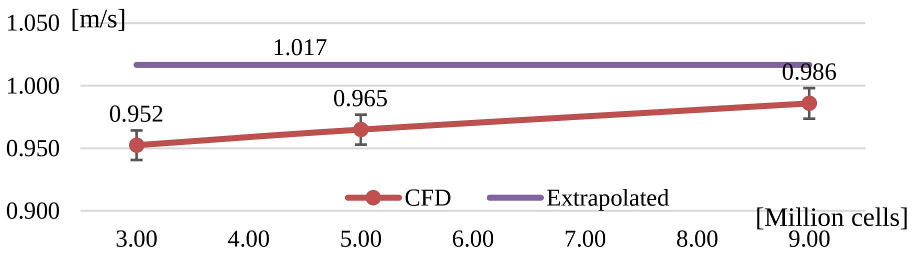


Figure 5.4. Airflow velocity as a parameter for refining the three grid versions.

Table 5.1. Metrics of the generated mesh.

Mesh metrics	Value
Number of elements	5307557
Number of nodes	1522892
Cell aspect ratio (max)	50.69
Ortho skewness (max)	0.882
Orthogonal quality (min)	0.1001

5.3.5. Scenarios

The investigated scenarios represent different conditions of operation. They mainly vary in closing or opening windows and ventilation openings in order to expose the potential of the PACS. Therefore, three main scenarios are realized; the reference scenario, the first scenario (Sc1), and the second scenario (Sc2). Figure 5.5 schematically shows the three scenarios and they are explained as follows:

- The reference case represents the conventional use of the house, whereby the windows are opened to ensure cross-ventilation, and the PACS is disabled by blocking the floor openings and the openings of the chimney that leads to the Venturi disc.
- In the first scenario, the windows are completely closed, and the proposed ventilation mechanism of the PACS is fully enabled, meaning the floor openings, the chimneys'

top (skylight opening of the chimney beneath the Venturi disc), and bottom openings are opened.

- The second scenario employs the floor openings, the façade windows, and the proposed PACS openings in a simultaneously opened state.

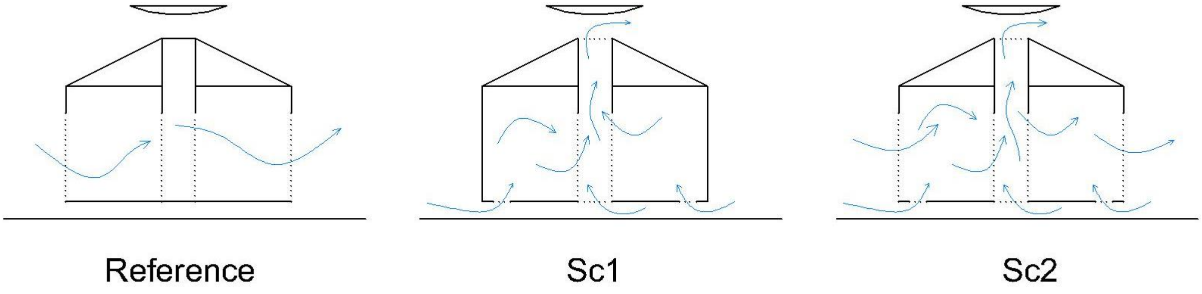


Figure 5.5. The reference case and the initial scenarios (illustrations).

5.4. Results and Discussion

5.4.1. Phase I

The three scenarios are simulated in a CFD environment at eight wind directions for each scenario. The investigated variables are ACH, temperature, and air velocity since they largely contribute to indoor comfort. The indoor thermal comfort is evaluated based on ASHRAE standards as a reference [113]. Figure 5.6 demonstrates patterns of airflow and average indoor temperature for the three scenarios in the case of the northern wind direction as it is one of the main local wind directions. All visual results of the three scenarios in 8 wind directions are displayed in Appendix A.

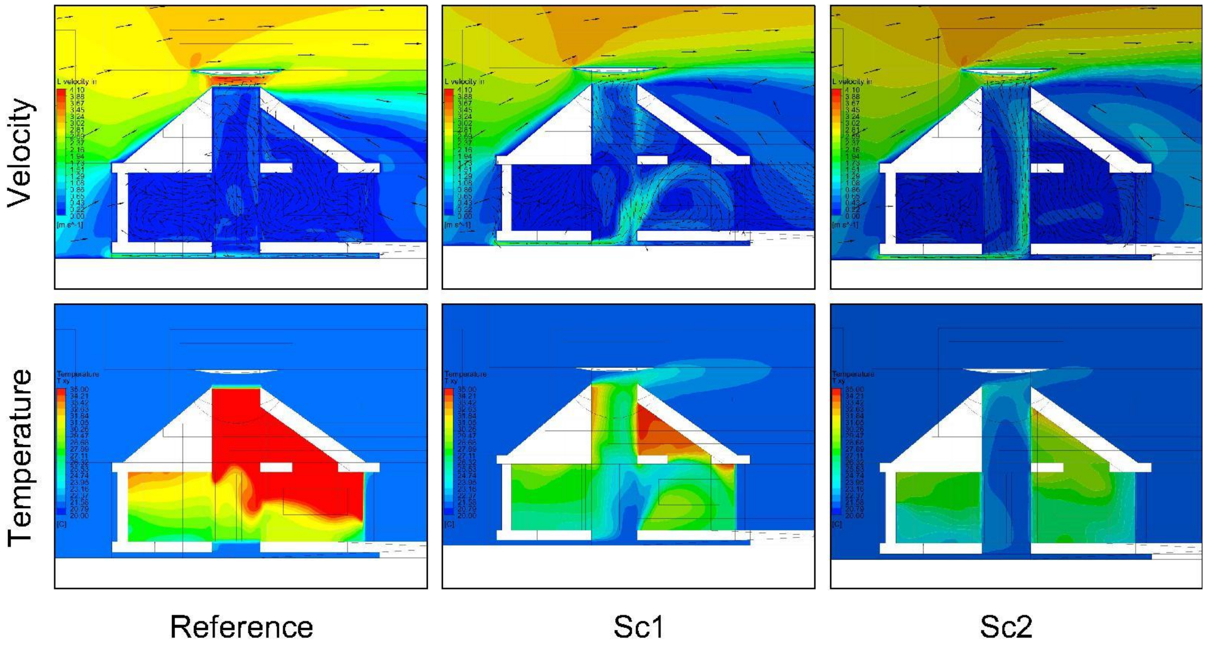


Figure 5.6. Air velocity and temperature profiles of the three scenarios at the northern wind condition.

The chimney is not taken as a part of the comfort zone in the analysis; however, it is included in the ACH calculations and the count of volume flow rate since it is a basic component of the ventilation mechanism, and its top opening acts as an outlet. This explains the ACH numbers that appear to be higher than average. Figure 5.7 and Figure 5.8 show the results of the simulated scenarios regarding average indoor temperature and ACH. Scenarios 1 and 2 show better performance than the reference case which illustrates the positive effect of the PACS in increasing indoor comfort and IAQ. On average of the eight wind directions, Sc1 and Sc2 provide almost 6 times ACH more than the reference scenario (21.53 to 3.7 ACH). On the other hand, scenario 1 shows a better performance in terms of indoor average temperature. When taking the average temperature of all wind directions, the temperature in Sc1 is approximately 4°C cooler than Sc2 (24.65°C to 28.77°C) and approximately 9.5°C cooler than the reference (24.65°C to 34.05°C). The reason for the cooler temperature in Sc1 might be explained that the inlet air flow is cooler as it is supplied through only the floor openings, so it benefits from crossing through the shaded space under the floor, whereas the inlet air flow the scenario 2 is supplied through a combination of the floor openings and the regular windows. In terms of ACH, both scenarios have similar performance.

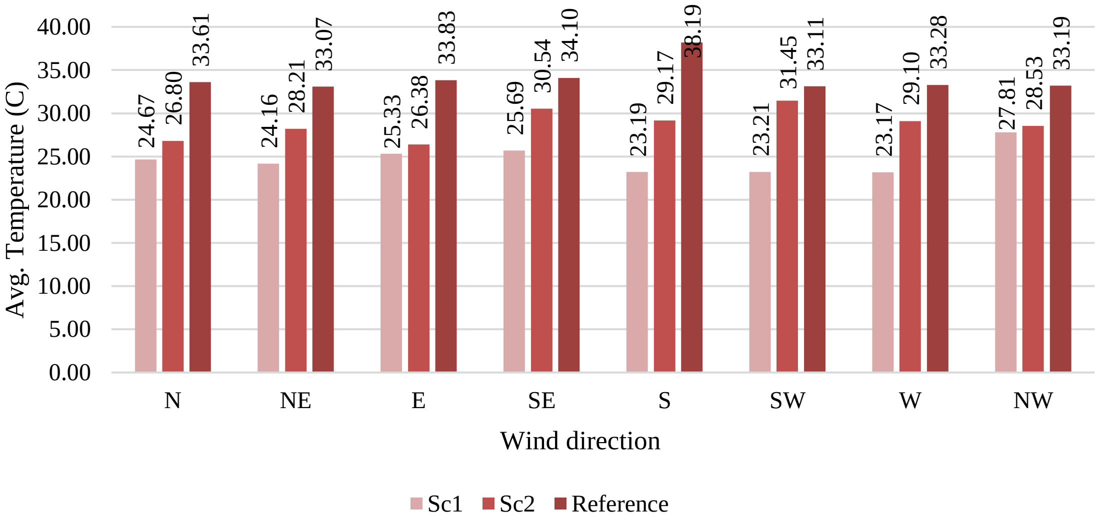


Figure 5.7. The average indoor temperature of the 3 scenarios in 8 wind directions.

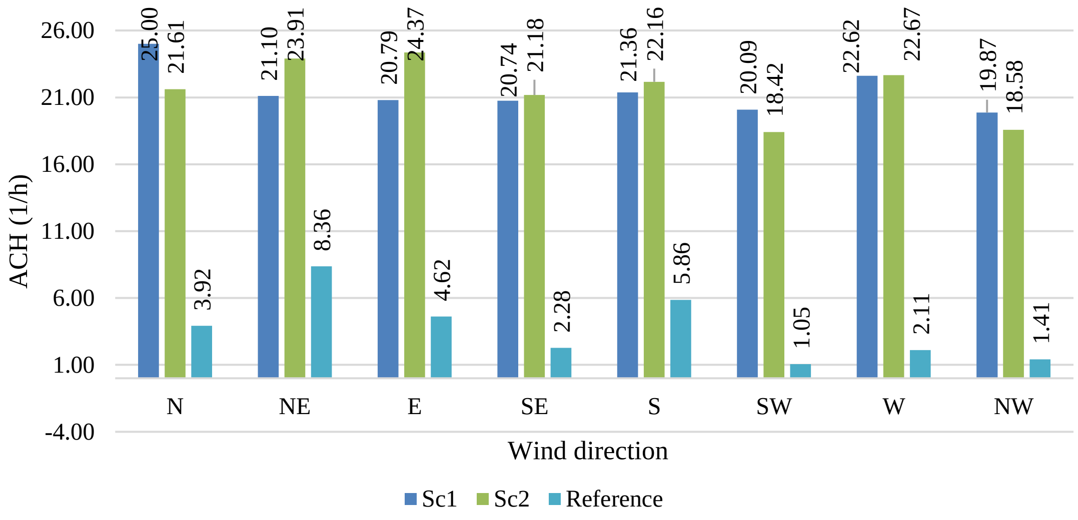
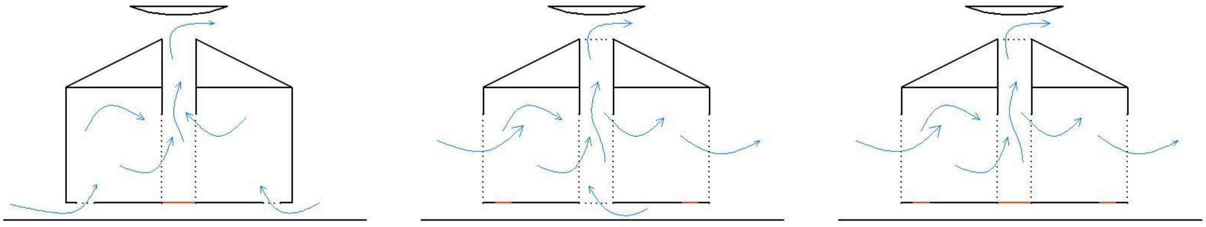


Figure 5.8. ACH of the 3 scenarios in 8 wind directions.

5.4.2. Phase II

The prior investigation was limited to scenarios 1 and 2 compared to the reference scenario. However, since the results of Sc1 and Sc2 did not significantly vary from each other, additional varieties were developed and created in order to deeply test the passive ventilation mechanism and to further explore its performance. One variety (Sc1.1) was developed from Sc1, and 2 varieties (Sc2.1 and Sc2.2) were developed from Sc2 (figure 9). The new varieties were not tested in all wind directions for the sake of time efficiency and computing power. Therefore, the southeastern (SE) wind direction was chosen since it showed the poorest performance in terms of indoor comfort in the prior investigation.

In the variety Sc1.1, the bottom of the chimney was closed and only the floor openings were left open as inlets. The purpose was to isolate the induction effect caused by the airflow from the bottom of the chimney to the top. In the variety Sc2.1, the floor openings were closed and only the chimney bottom and the windows were left open. The purpose was to isolate the effect of the floor openings and to investigate the ventilation behavior of the regular windows boosted by air conduction from the bottom of the chimney to the top. In the variety Sc2.2, the floor openings and the chimney bottom were closed and only the top of the chimney was left open, beside the windows. The purpose was to investigate the behavior of the regular house operation through window cross-ventilation boosted by the chimney and its Venturi-shaped roof only.



Sc1.1 Sc2.1 Sc2.2

Figure 5.9. The variations Sc1.1, Sc2.1, and Sc2.2 (changes are marked in orange).

The results of the variation Sc1.1 prove that the updraft air conduction through the chimney has a positive influence on the indoor climate. When comparing Sc1.1 (where the chimney air conduction is blocked) to Sc1, the average temperature gets approximately 1 degree warmer (26.49°C to 25.69°C) and ACH drops more than 50% (9.01 to 20.74) as shown in figures 10 and 11.

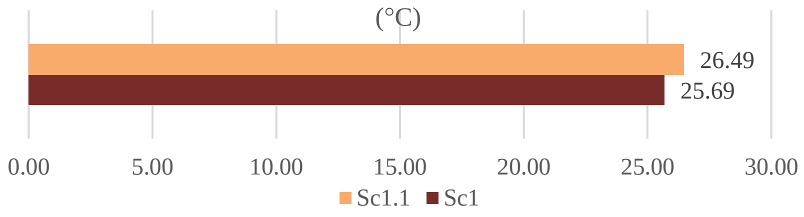


Figure 5.10. Average temperature of Sc1 and Sc1.1 in the southeastern wind direction.

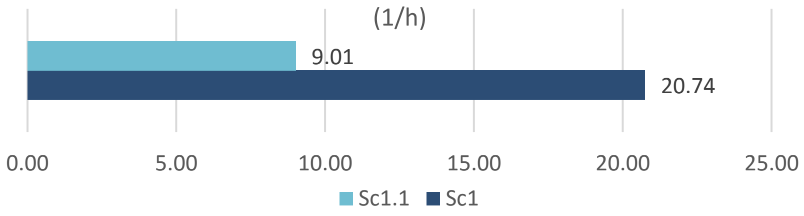


Figure 5.11. ACH of Sc1 and Sc1.1 in the southeastern wind direction.

When comparing the results of the variation Sc2.1 to scenario Sc2, the ACH is slightly lower (20.36 to 21.18) which is caused by blocking the role of the floor openings as inlets. However, The average indoor temperature is approximately 2 degrees cooler (28.3°C to 30.54°C). After investigating other parameters, we found that because of blocking the floor openings, the average velocity that passes through the chimney's bottom surface is 143% higher in Sc2.1 compared to Sc2 (0.33m/s to 0.23m/s). This could be responsible for the slight cooling effect as it causes a concentrated suction effect.

Scenario Sc2.2 assumes that the house operates with normal cross ventilation through windows in addition to the chimney as a wind tower. Therefore, it blocks any airflow intake through the under-floor embedded ventilation structure. Its results show that the ACH rate drops approximately 20% when compared to Sc2 (16.81 to 21.18) as Figure 5.12 displays. The average temperature, on the other hand, insignificantly drops around 0.2°C as demonstrated in figure 13. However, comparing Sc2.2 to the reference scenario of the same wind direction is relevant as the only changed parameter is opening or closing the top surface of the chimney. The compression shows that the performance of Sc2.2 clearly scores better results as the average temperature drops almost 4°C and the ACH rate is approximately 7.4 times higher. Hence, even though Sc2.2 has a lower ACH rate than Sc2 due to less updraft conduction through the chimney, it still overcomes the reference scenario by far, which proves the role of the chimney as an outlet for airflow that boosts passive ventilation in the building.

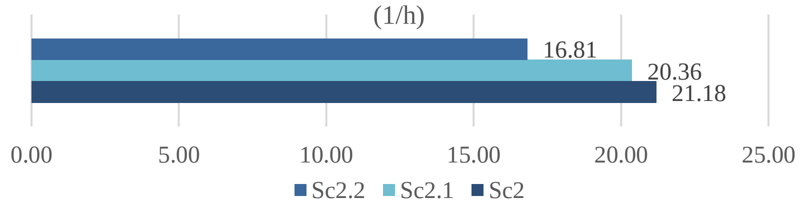


Figure 5.12. ACH of Sc2, Sc2.1, and Sc2.2 in the southeastern wind direction.

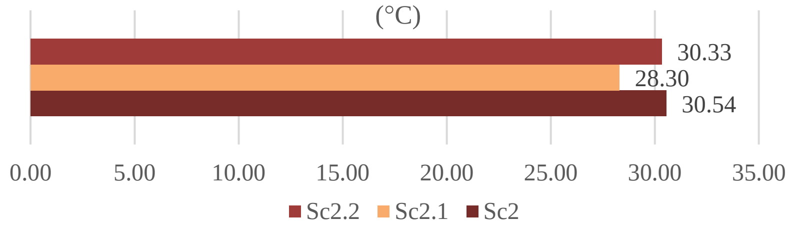


Figure 5.13. The average temperature of Sc2, Sc2.1, and Sc2.2 in the southeastern wind direction.

5.4.3. Energy Performance of the PACS

After quantifying the different cases in terms of ACH rates and indoor air temperature, it is crucial to estimate the energy savings of the PACS mechanism, compared to the building's mechanical cooling and ventilation during operation. To reflect the passive-ventilation results into operational values, we conducted a dynamic energy simulation using a multi-zonal thermal simulation method. IDA ICE 4.8 indoor climate and energy software environment was used for modeling and simulation. In order to link the CFD simulations to the dynamic energy simulations, Scenario S1.1 was chosen to represent the PACS operation since it forces the airflow to pass through the comfort zones and neglects the induction effect caused by the airflow from the bottom of the chimney to the top. This scenario the most suitable for comparison because it is applicable in the dynamic simulation method by representing the airflow through the comfort zones with an AHU that has the capacity to provide the same number of ACH (9 1/h).

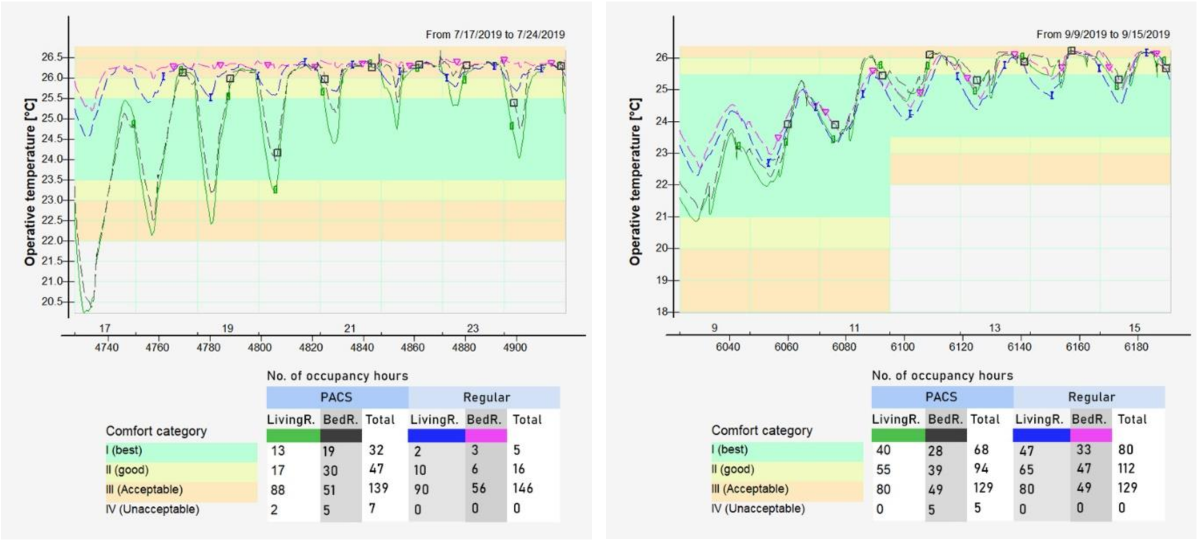
Two cases were modeled, 1) The reference case that assumes the regular mechanized operation of the house with an ACH of 2 1/h as a recommended value for regular residential use [114]. The rooms were equipped with ideal heaters and coolers. In the second case, 2) The PACS case was modeled and operated one week long in a hot summer period (17-24 July) and another week-long in a moderate transitional period (9-15 September). The operation of the PACS is allowed only during time intervals, when the ambient temperature ranges are between 20°C and 25°C to guarantee an acceptable level of indoor thermal comfort. These two weeks were chosen because of their stable and low-temperature fluctuations. The comfort level is measured in accordance with Category II (good) from standard EN 16798 [115]. Table 5.2 shows the operation schedule was applied to the full year as it consists of 3 different operating schedules: transition, summer, and winter schedules, to provide the desired entering ambient temperature (20°C - 25°C) as far as possible.

Table 5.2. Operation schedule of PACS.

Period	Opening times
Transition: 16 April to 31 May	10 - 19:30
Summer: 1 June to 31 August	23 - 8:30
Transition: 1 September to 15 October	10 - 19:30
Winter: 16 October to 15 April	closed

In the 2 week simulations, the comfort levels of the PACS model showed great potential in thermal comfort improvements during summertime (the hottest week of the year). Figure 5.14 demonstrates the simulation results regarding thermal comfort for both cases in the living room and the bedroom during the previously mentioned 2 weeks. When considering the number of occupancy hours when class II of thermal comfort is fulfilled, the case of PACS exceeds the regular case by 57% in the summer week. However, in the transition week, these values in the PACS model are slightly worse than in the regular AHU model by means of 15% less in Class II comfort hours. It is worth mentioning here that the comfort performance hours are the same in the Class III category that incorporates Class I, II, and the acceptable comfort hours (III), and that unacceptable hours are in fact periods with good operative temperatures.

Further influencing parameters for comparison were electric cooling and AHU fan electricity consumption since they represent the operation of the PACS mechanism and its role in cooling and ventilation. The simulation results show that PACS saves 97% of the energy in the July week (12.34 vs 408.26 kWh), and 39.6% of the energy in the September week (62.69 vs. 103.79 kWh) as illustrated in Figure 5.15.



No. of occupancy hours

Comfort category	PACS			Regular		
	LivingR. 🟩	BedR. ⬛	Total	LivingR. 🟦	BedR. 🟪	Total
I (best)	13	19	32	2	3	5
II (good)	17	30	47	10	6	16
III (Acceptable)	88	51	139	90	56	146
IV (Unacceptable)	2	5	7	0	0	0

No. of occupancy hours

Comfort category	PACS			Regular		
	LivingR. 🟩	BedR. ⬛	Total	LivingR. 🟦	BedR. 🟪	Total
I (best)	40	28	68	47	33	80
II (good)	55	39	94	65	47	112
III (Acceptable)	80	49	129	80	49	129
IV (Unacceptable)	0	5	5	0	0	0

(a) (b)

Figure 5.14. Thermal comfort simulation results of living room and bedroom in PACS case and the regular case, within a summer week;17-24 July (a), and a transition week; 9-15 September (b).

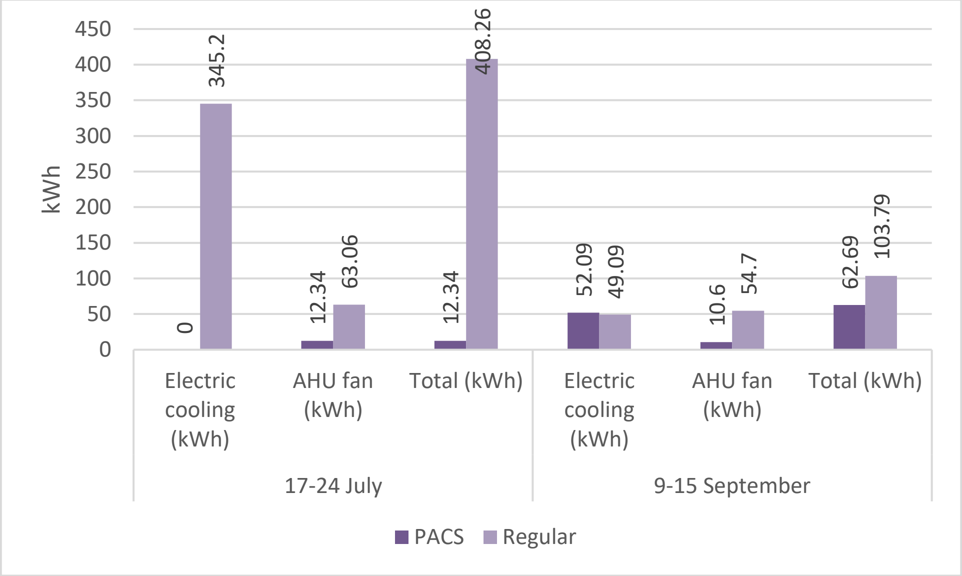
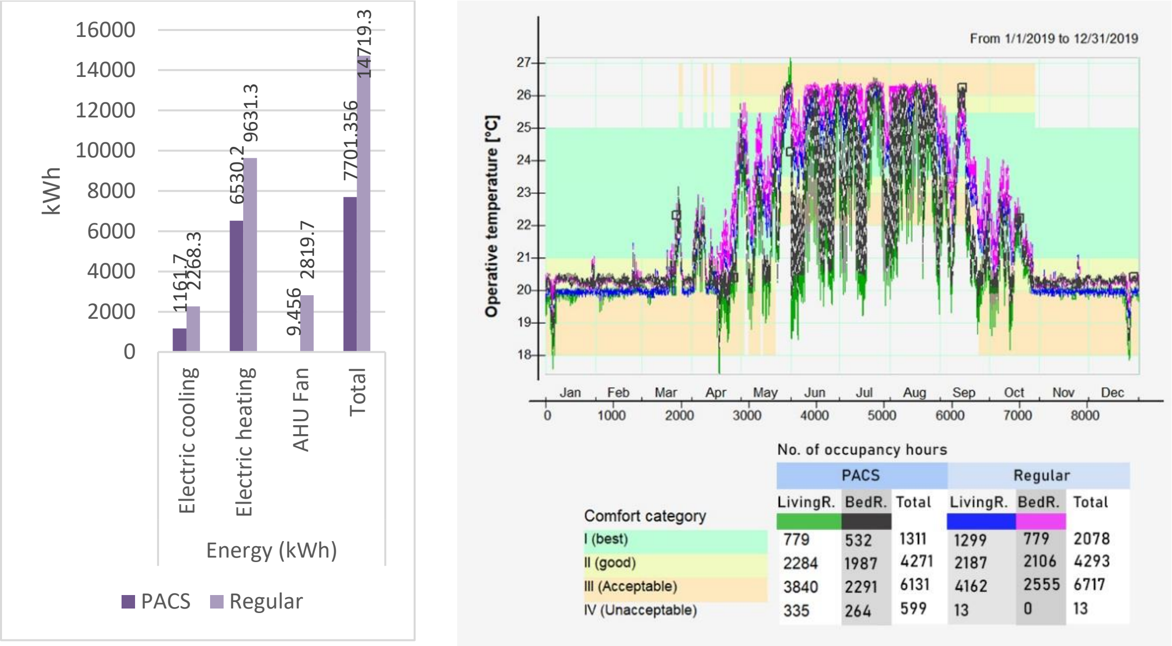


Figure 5.15. Energy savings of PACS compared to the regular operation in a July week and a September week.

The proposed PACS is operable during six months in the year. The ideal operation requires more sophisticated control, but the results show a large potential of utilizing it for a longer period, with stressing the need for further research and optimization. Because of the mentioned limitation, the amount of annual occupancy hours with Class II level of comfort in PACS case is around 90% of it in the regular case, but in Class III, the comfort performance is comparable where the difference is only 0.5% over the year as Figure 5.16 reveals. However, the yearly simulations also show significant energy savings in electric heating, electric cooling, and AHU fan. The PACS operation saves 47.7% of the regular operation energy (7701.3 vs 14719.3 kWh) as shown in Figure 5.16. The energy savings in the PACS case were possible by utilizing the night cooling in the hot season and the temperate day temperature of the transitional seasons to heat the interior.



	PACS			Regular		
Comfort category	LivingR.	BedR.	Total	LivingR.	BedR.	Total
	🟩	⬛		🟦	🟪	
I (best)	779	532	1311	1299	779	2078
II (good)	2284	1987	4271	2187	2106	4293
III (Acceptable)	3840	2291	6131	4162	2555	6717
IV (Unacceptable)	335	264	599	13	0	13

(a) (b)

Figure 5.16. The yearly simulation results comparison regarding energy (a) and comfort (b).

5.5. Conclusions

This chapter investigated the passive ventilation performance and indoor thermal comfort of a lightweight detached family house in Hungary. The study was carried out with regard to PACS, considering a central exhaust ventilation chimney that has a Venturi-shaped roof and is connected to an underfloor airflow inlet structure. In this context, the study investigates operation scenarios including opening characteristics and their ventilation efficiencies. Using the CFD simulation environment, the airflow pattern is calculated and modeled with a focus on air temperature, air velocity, and ACH rate as the main parameters to measure and compare the indoor thermal comfort and the passive ventilation behavior. The findings illustrate that the proposed PACS mechanism has a significant role in stimulating natural ventilation in family housings under temperate oceanic climate zone conditions.

The findings show that operating the proposed ventilation mechanism of the PACS (the Venturi roofed chimney that is connected to the under-floor ventilation inlet structure), whether with or without cross ventilation (via façade windows) provides 6 times higher ACH than operating cross ventilation (façade windows, reference case) alone. Regarding the average indoor temperatures, the proposed PACS generates a significant cooling effect by 9.5 K (in Sc1), compared to the reference cross-ventilation operation (24.65°C vs 34.05°C). When combining cross ventilation with the proposed passive ventilation mechanism, it still provides a cooler average indoor temperature of 5.28 K than operating cross ventilation alone (28.77°C vs 34.05°C).

Further operation scenarios in the southeast wind direction showed that activating air conduction through the chimney (opening its bottom surface) increases the ACH rate in the building by more than two times. This also cools the interior space by almost 1 K in the investigated context. Furthermore, the effect of the chimney with the Venturi-shaped roof alone was tested when it was combined with cross ventilation (Sc2.2). It was found that the exhaust chimney significantly enhances the ACH rate by 7.4 times its rate when operating conventional cross ventilation alone. It also helps in cooling the average indoor temperature by 4 K in the tested context.

Current findings demonstrate that PACS solutions deliver noteworthy importance not only in large-scale public buildings and industry halls but also in small-scale family house buildings. The results proved that only adding the chimney with the Venturi-shaped roof (regardless of the under-floor airflow inlet structure) has the ability to considerably improve the natural ventilation air flow rate and the average indoor temperature (cooling).

Regarding the energy calculations, the study was limited to selecting only one of the scenarios (S1.1) for its suitability to be tested in the dynamic energy simulation method, and it was compared to the regular operation of the mechanical AHU. The yearly simulation was also limited to the preliminary operation schedule of the PACS which did not provide the ideal indoor thermal comfort. However, PACS provided 90% of comfort hours in class II, and almost the same number of comfort hours in class III. The energy simulation results estimated around 50% of yearly savings in the cooling, heating, and ventilation demand, compared to the regular AHU-operated scenario.

The realized findings are promising because they could be applied to a larger share of already-built houses as a sustainable refurbishment solution. Future research should focus on investigating the geometry of the Venturi plate structure. This would help to optimize its performance regarding passive ventilation and indoor thermal comfort. It is also recommended that future research optimizes the operation algorithm of PACS in the thermal simulations.

Corresponding publications: [2] and a journal manuscript that is currently under review.

Chapter 6. CFD Investigation of Enhancing Natural Ventilation in Attached Family House Buildings in Hungary

6.1. Background

Since the building sector is responsible for around 30% of the global energy consumption [116] and around 40% of it in the EU [117], it is absolutely important to enhance the energy performance of the buildings. Integrating passive design techniques, especially natural ventilation, in the building is one of the most influential methods to reduce energy consumption and maintain an acceptable indoor comfort level [21].

Buildings' retrofitting has been highlighted as a key driver of achieving sustainability and energy efficiency in buildings [118, 119] since existing buildings are the main contributor to energy consumption in the building sector. Thus, many governments and international bodies generously invested in improving the energy efficiency of existing buildings by introducing policies and roadmap strategies [119]. The energy-retrofit process considers optimizing the energy efficiency and comfort level, and it is usually supported by simulation tools to help adopt the proper solutions [120]. The architecture practice, therefore, has significant importance in the buildings' retrofit as it combines the design approach with the technical inputs [121].

The majority of the European residential building stock does not meet the required level of energy efficiency due to the lack of awareness and relative regulations when the dwellings were originally built. Therefore, retrofitting the residential sector is a vital process to make it aligned with the recent energy criteria [122]. It was estimated that by 2020, 90% of the building stock in Hungary should be renovated and that 25% of the population live in dwellings that are in poor condition, even though 36% of the residential buildings were refurbished [123].

The indoor environment is the microenvironment where people spend a large share of their time. Therefore, indoor air pollutants directly affect the occupants' health. The indoor air content of pollutants and particulate matter is mainly affected by the air exchange rate between indoor and outdoor environments [34]. ACH is the measurable indicator to evaluate the IAQ and to design the building's ventilation system [35]. ACH refers to the number of times in an hour that the volume of air, equal to the volume of the ventilated space (room or building), is replaced by fresh outdoor air. Thus, it is strongly linked to the infiltration and ventilation rate [36].

Natural ventilation is mainly induced by the generated pressure difference around the building which is influenced by three factors: wind velocity, wind direction, and the difference in temperature. Therefore, any implemented natural ventilation mechanism is more effective when it takes advantage of the pressure difference. The wind tower operation is also induced by the pressure difference between the positive pressure on the windward side of the building and the negative pressure on the leeward side of the building. The pressure difference is created by the external wind around the building. Wind-driven ventilation usually operates parallelly with the buoyancy or stack effect which is induced by air temperature difference and becomes more effective in the absence of the wind [124].

Ray et al. investigated the buoyancy-driven natural ventilation for a 3-story office building through a shared ventilation shaft. They applied both a physical measuring experiment and CFD simulations. They found that a shaft with a smaller size caused higher flow rates in the upper floors due to the higher vertical momentum [125].

Ali et al. performed a CFD investigation on natural ventilation in a detached family house in Hungary. The house was equipped with under-floor ventilation inlets, an inner shaft, and a Venturi disc topping the shaft outlet to stimulate natural ventilation through the house. Indoor air velocity, ACH, and temperature were tested and it was proven that the studied ventilation mechanism is effective in enhancing natural ventilation [2]. Wagner et al. investigated and monitored natural ventilation and passive cooling of a low-rise office building in Germany. They found out that natural night ventilation could provide sufficient indoor thermal comfort even during the hot season by operating the opening of windows and skylights. The simulation results also revealed that different opening angles of the skylights affected the air change rates and their distribution over the different floors [126]. Kazemi Esfeh et al. conducted an experimental and numerical study on a typical room model to evaluate the wind-driven natural ventilation of a semi-cylindrical curved roof with a skylight. It was concluded that the curved roof behavior regarding natural ventilation was largely influenced by the wind direction and that the skylight operated as a suction element due to its lower pressure. They stated that the height of the curved roof has considerable importance in enhancing airflow circulation and that the effect of the curved roof was almost equal to that of the wind tower regarding natural ventilation [127].

Laurini et al. tested a ventilation chimney in a palace building in Italy. They concluded that maintaining a temperature difference between the top and the bottom guaranteed effective natural ventilation through the chimney [128].

Du et al. conducted a skylight ventilation design optimization of a low-rise office building through CFD simulations. They revealed the significant role of skylights in stimulating natural ventilation through an atrium. However, to prevent extra heat gain and energy consumption, skylights should be carefully designed by considering their positioning, arrangement, and height [129]. He et al. presented an experimental and CFD study of natural ventilation of a low-rise office building, whereas the natural ventilation was induced by a combination of mechanical equipment and roof windows. The roof window proved to be significantly more influential than the mechanical equipment and to be more effective when considering other wall openings [130]. Horan et al. investigated a naturally ventilated atrium space of a two-story office building. The atrium was equipped with roof vents and tested via CFD simulations. Their research revealed that ACH was considerably influenced by the wind direction in connection with the building’s form [131]. Wu et al. tested the natural ventilation through an integrated wind tower on the top of a low-rise house. They explored the influence of switching from single-sided natural ventilation to cross ventilation by changing the windows’ arrangement which led to enhancing ACH. They also found that the exhaust wind tower had a better performance when indoor temperature was higher than outdoor temperature due to the stack effect [132].

The case presented in this research is an attached family house. The house was originally built in the 70s as a typical family house. It was refurbished in 2015 based on the

Active House Standards. The house refurbishment won the Active House Award and the Energy Globe Hungary prize in 2017. In a previous study, the house was tested via dynamic thermal simulations. The refurbishment process considered rearranging the spaces and upgrading the building envelope. After refurbishing the house, the energy demand was considerably reduced and the final energy production was approximately two times larger than the final energy consumption [133]. This research is specifically testing the effectiveness of the skylight and the integrated solar chimney regarding natural ventilation.

6.2. Methodology

The methodology of this chapter could be divided into several steps. The first step is collecting the needed data for the tested building including plans, weather data, building operation data, etc., in order to model the building. The second step is modeling and simulating the reference case study in a 3D CFD environment using ANSYS Fluent R.17.2 software [134]. The third step is gathering and analyzing the results for the following parameters: air velocity, ACH, and air temperature. The final step is simulating the second scenario, comparing the results, and analyzing the natural ventilation performance of the house and its integrated solar chimney in connection to indoor thermal comfort.

6.3. Case Study

6.3.1. General Description

The case study is located in Pécs, Hungary, which has a latitude of 46.0833°N and a longitude of 18.2333°E. The location is demonstrated in Figure 6.1 Since the location is next to Mecsek hills, the terrain is sloped in a North-South direction.

The case study represents a family house building that was first built in 1974 as a typical attached house with 30 cm thick brick walls and concrete beams and slabs. After refurbishing the house in 2015, the design was modified. The house is directed East-West with a tilted axis. The concrete staircase in the middle divides the layout into two parts: the kitchen to the west and the living room to the east on the ground floor level, and the office room to the west and the bedroom-bath to the east on the first-floor level. The solar chimney gallery faces the staircase and is located on the south side of the house. The attic space is not divided from the solar chimney. On top of the solar chimney is an operable skylight. The roof was formed by a specific East-West axis, so it has a south-facing pitched half where the Photovoltaic panels are placed. The house is equipped with a Building Management System that monitors and controls the building's functioning and operation to ensure acceptable indoor comfort conditions. The system controls the operation of the windows and the solar chimney (natural ventilation), especially since the house was designed so that it could be naturally ventilated and night-cooled for seven months of the year [133].

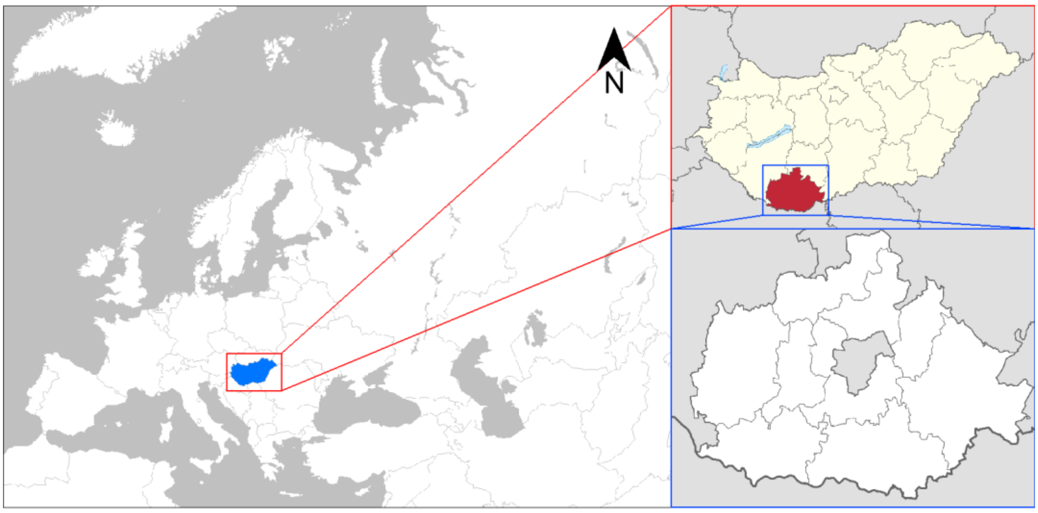


Figure 6.1. Location of the case study.

6.3.2. Geometry and Mesh Generation

The executive plans and details were collected and cleaned. The building and the terrain were modeled from scratch via SpaceClaim modeler software. The height of the building h=10 m. Therefore, the computational domain was created with a size of 20*20*5 h according to the recommended practice guidelines. The computational domain must consider the neighboring buildings and the sloped terrain since these factors could largely influence the airflow around the building. Figure 6.2 Shows the computational domain size.

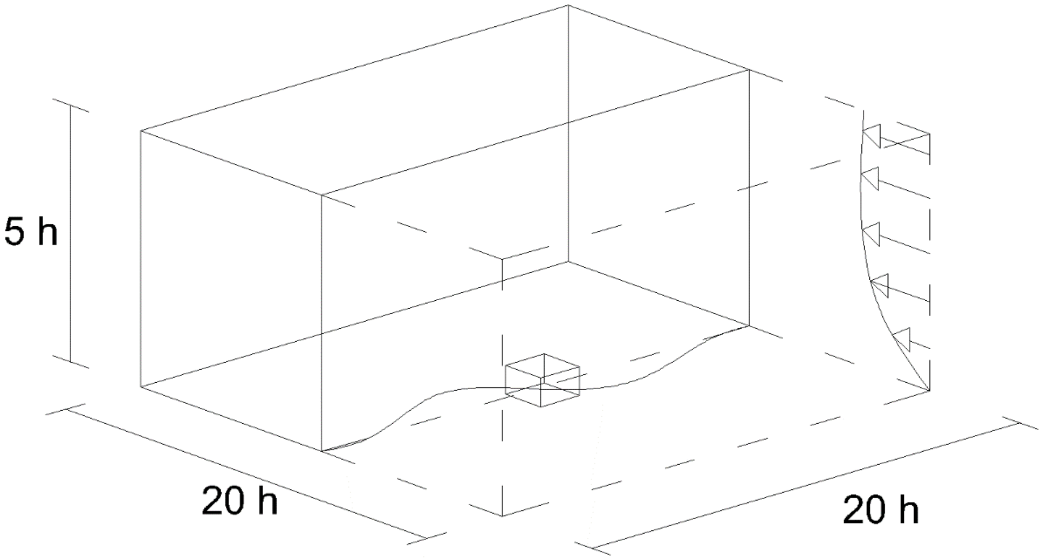


Figure 6.2. The size of the computational domain.

The following step is generating the mesh. The generated mesh is an unstructured hybrid mesh that combines hexagonal, tetrahedral, prism, and wedge cells. Figure 6.3 shows a section in the generated mesh. The mesh considered dividing up the geometry of the flow volume into zones so that the Navier-Stokes and turbulence equations can be solved. The mesh metrics are listed in

Table 6.1.

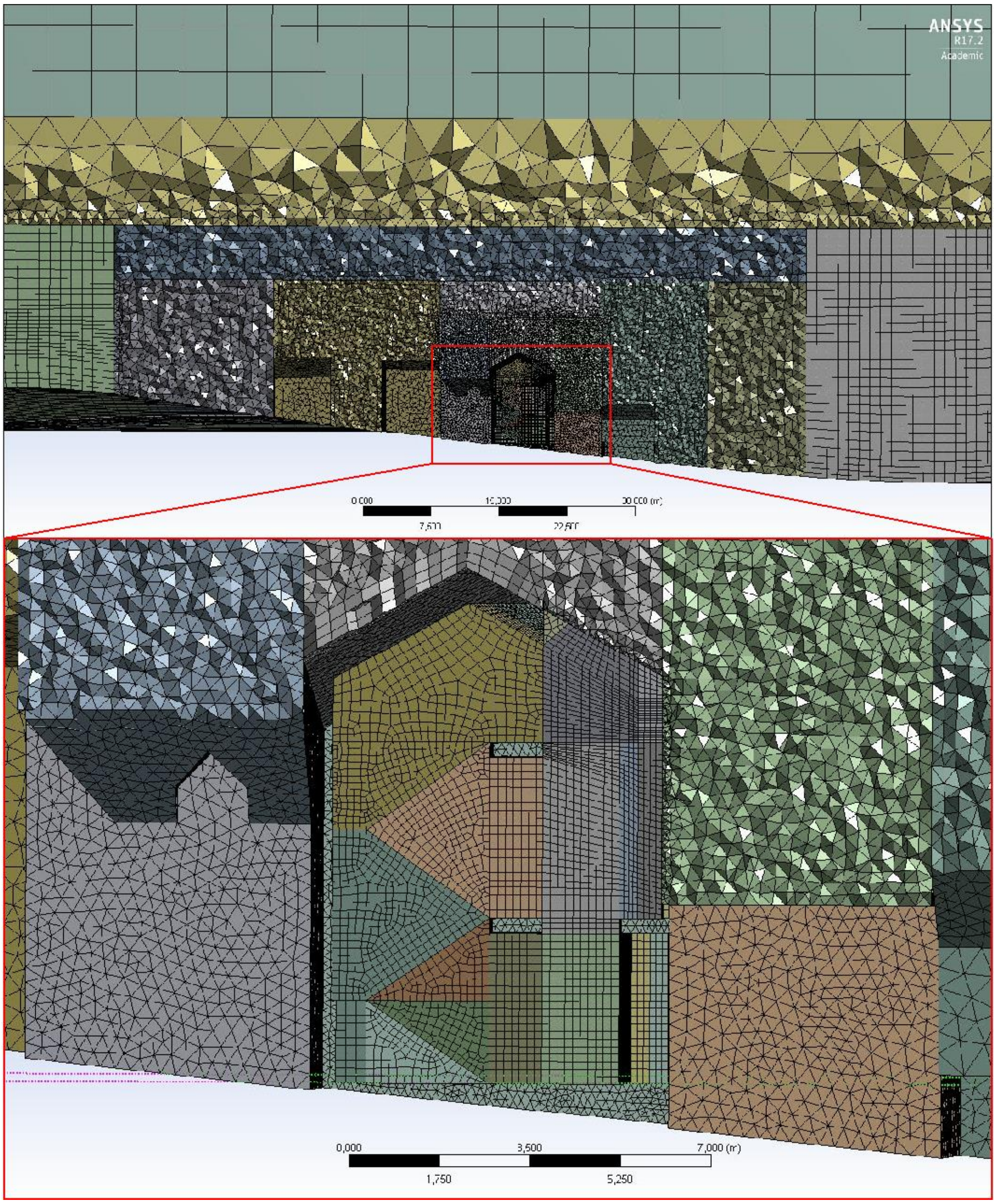


Figure 6.3. A section in the generated mesh.

Table 6.1. Metrics of the generated mesh.

Mesh metrics	**Value**
Element sizing of the interior	0.2 m
Number of elements	4905236
Number of nodes	1382904
Cell aspect ratio (max)	29.09
Ortho Skewness (max)	0.816
Orthogonal quality (min)	0.1001

6.3.3. Boundary Conditions

The fluid material is set as "Compressed Ideal Gas" and the Reynolds Average Navier Strokes Equation (RANS) and standard k-ε are chosen for the airflow turbulence simulation. Fluent finite volume is used as a solver. The "SIMPLE" coupling algorithm is chosen with the first-order scheme for equation discretization. A fixed temperature of 19.7°C is set for all parts of the fluid domain. The hourly-based Meteonorm database is used to acquire weather data (air temperature and wind speed and direction) for the local region [111]. Heat sources are considered for the simulation including persons and electrical appliances as shown in Table 6.2. The inlet of the computational domain is defined as velocity inlet, the outlet as pressure outlet, and the side and top boundaries as symmetry boundary condition.

The west wind direction is tested since it is the prevailing local wind direction with an annual wind average wind velocity of 2.73 m/s at a reference height of 10 m [56]. Figure 6.4 shows the local wind rose. 21st of September at 1 p.m. is the chosen simulation time for its suitability for utilizing natural ventilation.

Table 6.2. Indoor heat sources that are included in the simulation.

Location	**Heat source**	**Value (W)**
Kitchen	Cooking person	200
	Coffee machine	250
	Electric oven	800
	Dishwasher	400
	Microwave	400
	Fridge	60
Living room	TV	40

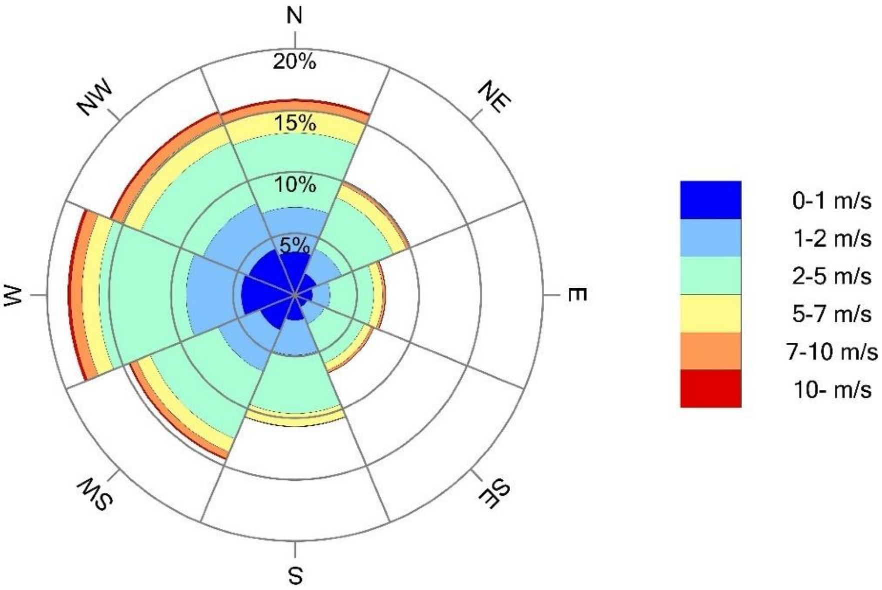
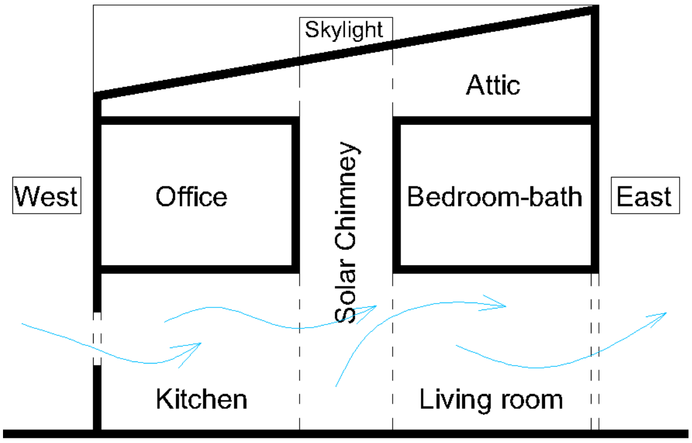


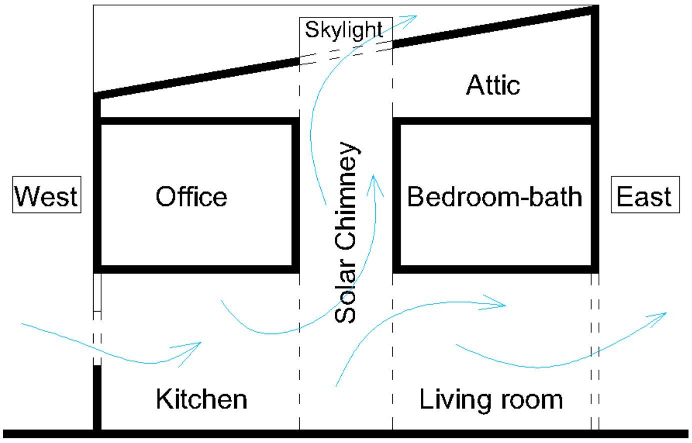
Figure 6.4. The local wind conditions [56].

6.4. Results and Discussion

The main purpose of this chapter is to detect the influence of the integrated solar chimney and the skylight operation regarding natural ventilation in the investigated house building. Therefore, two scenarios were tested. The reference scenario where the skylight is closed and only the western kitchen window and the eastern terrace door are opened to mimic the regular cross ventilation. In the second scenario (Skylight scenario) the only changing parameter is that the skylight is opened. In both scenarios, the western office room and the eastern bedroom-bath on the first floor are cut out from the investigated flow domain by closing their doors. Figure 6.5 shows schematic drawings of the two scenarios.



Reference scenario



Skylight scenario

Figure 6.5. Schematic drawings of the two investigated scenarios.

The simulation results show the effectivity of the integrated solar chimney when opening the skylight (Skylight scenario). Figure 6.6 shows the passive air conduction through the chimney. The most relevant indicator is the ACH which is 6.2 times higher in the Skylight scenario than it is in the reference scenario. Figure 6.7 shows the ACH comparison in both scenarios.

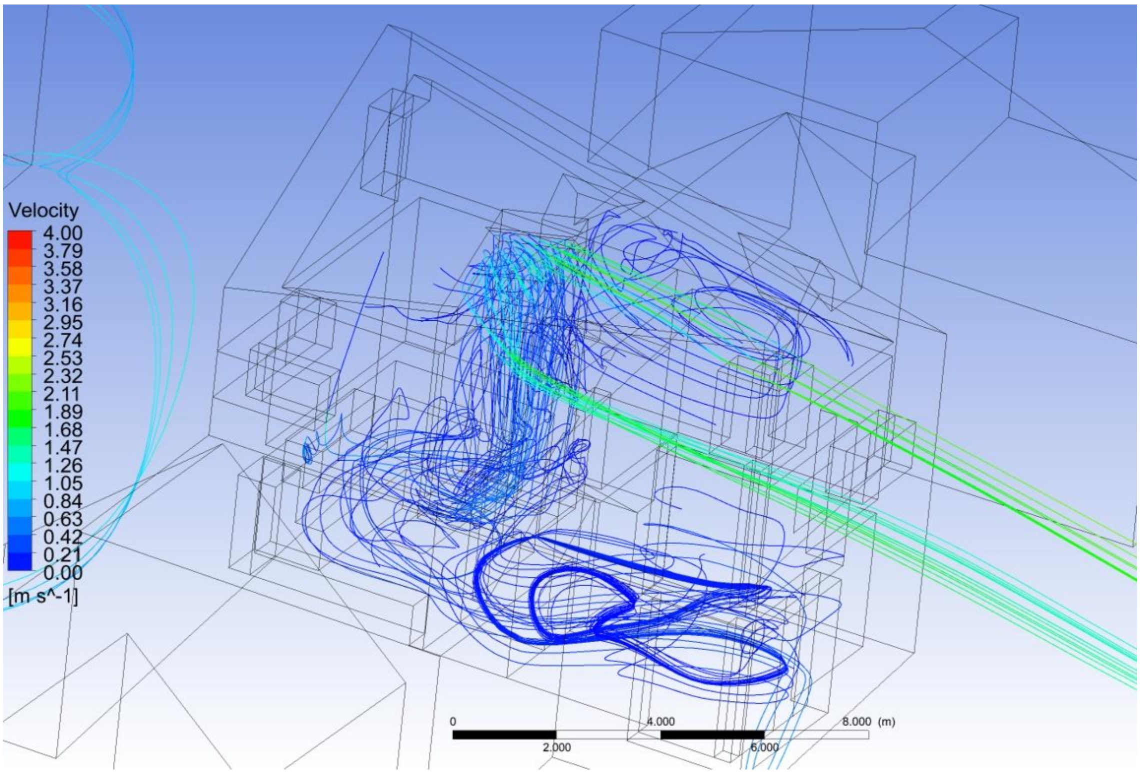


Figure 6.6. Passive air conduction through the chimney in 'skylight scenario'.

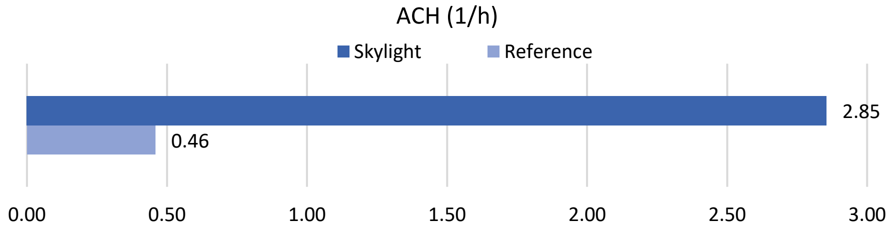
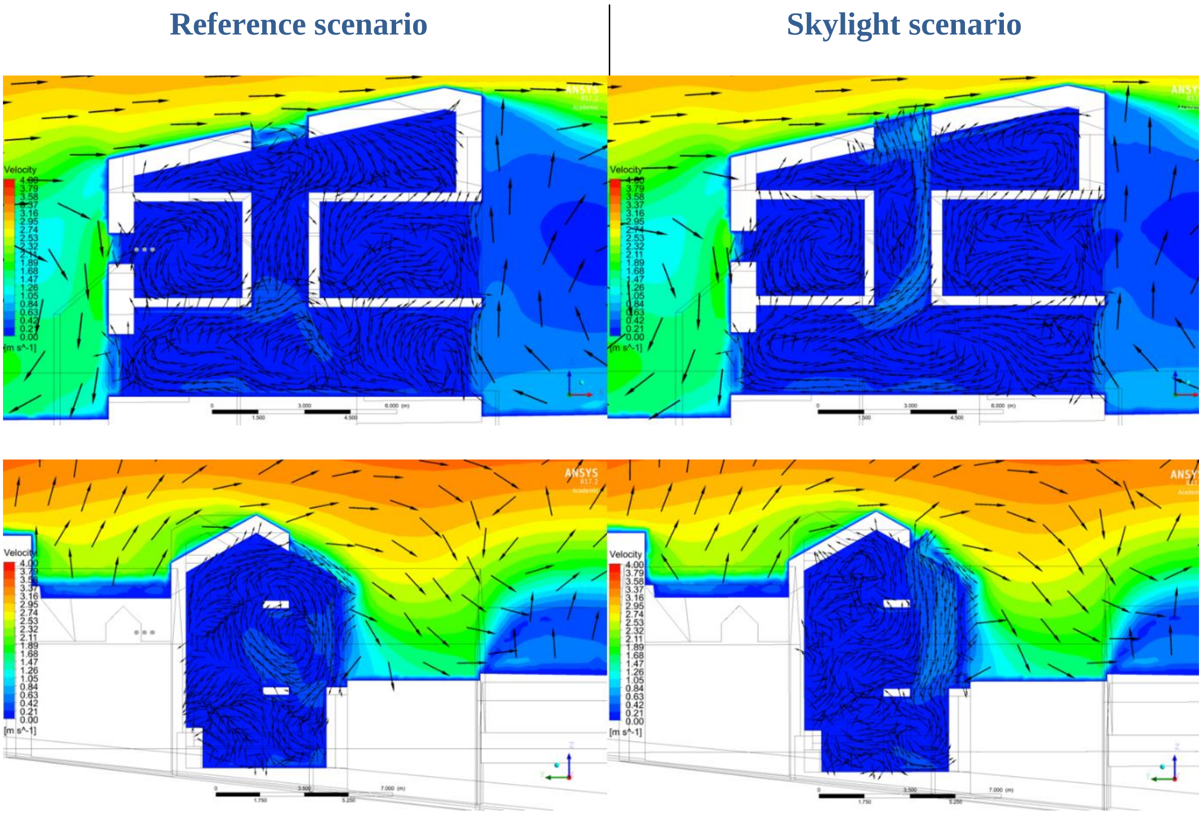


Figure 6.7. ACH comparison of the two scenarios.

The suction effect of the skylight converted both of the openings on the ground floor into inlets as shown in Figure 6.8. Because of the urban context, neighboring buildings are creating a buffer which causes vortexes next to the house.



Reference scenario

Skylight scenario

Figure 6.8. Air velocity in two perpendicular vertical sections of both scenarios.

Regarding other indoor comfort indicators, there is no significant difference in airflow velocity in the interior space and it is generally small in value (around 0.12 m/s). However, when we consider the chimney zone alone, air velocity in the Skylight scenario is 35% bigger than that in the reference scenario. That is understood because of the suction effect implied by the opened skylight.

Indoor temperature comparison perhaps clarifies the role of ACH in removing the interior heat loads. The average temperature in the Skylight scenario is around one degree cooler than that in the reference scenario, even though both cases are within the accepted comfort levels as shown in Figure 6.9. Airflow behavior is always linked to the indoor air temperature and the thermal comfort. Figure 6.10 clarifies how the ventilation through the chimney helps in removing the internal heat load together with the buoyancy effect when warmer air with less density floats upward.

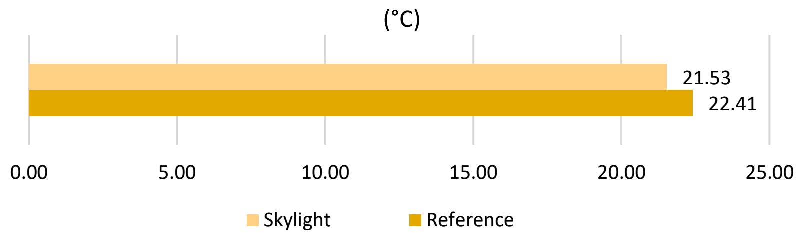


Figure 6.9. Avg. temperature comparison of the two scenarios.

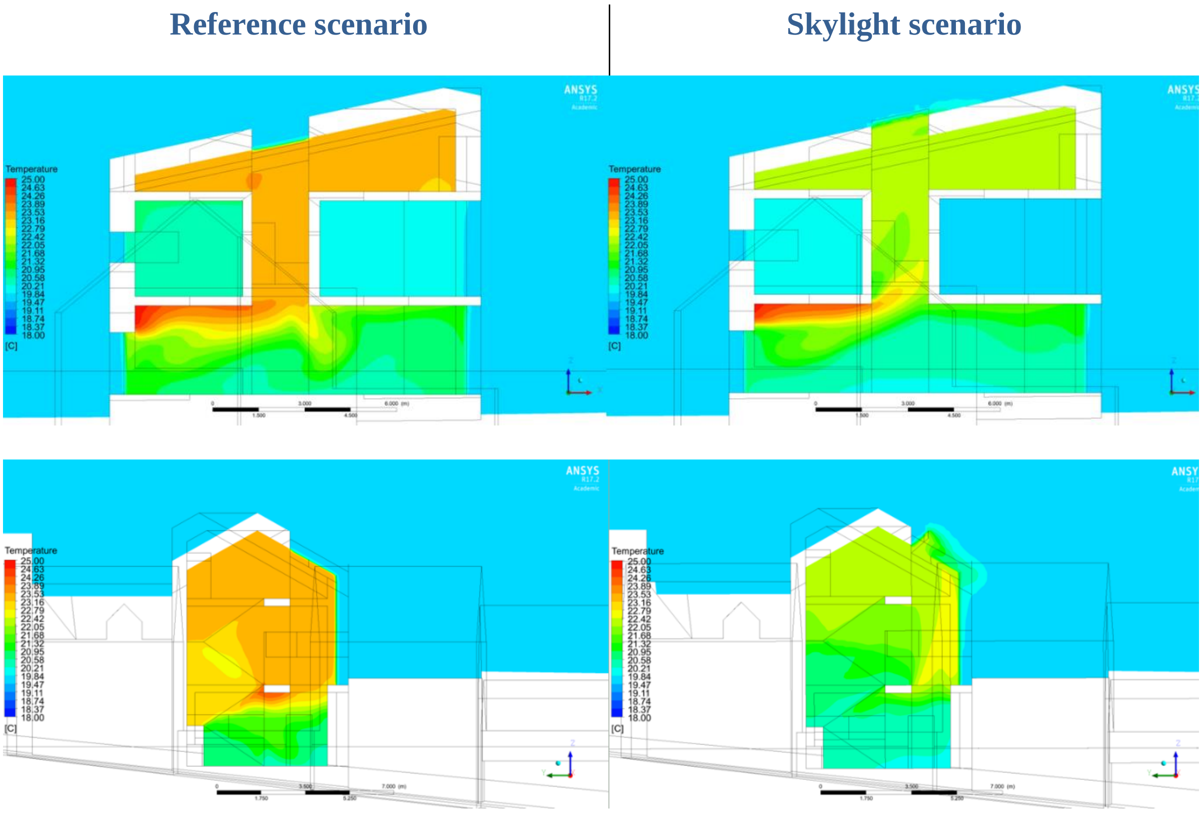


Figure 6.10. Air temperature in two perpendicular vertical sections of both scenarios.

6.5. Conclusions

This chapter conducted a CFD investigation of the role of an integrated solar chimney in enhancing natural ventilation in an attached family house building in Hungary. Two scenarios were tested and compared: the reference scenario (skylight closed) and the Skylight scenario (skylight opened). The solar chimney proved to provide 6.2 times more ACH and cooler indoor temperature.

For future research, it is recommended that field measurements to be taken, and to simulate further scenarios including more wind directions and investigating different geometries of the solar chimney that could enhance natural ventilation in the studied context even further.

Corresponding publications: [3].

Chapter 7. Final Conclusions and Recommendations

7.1. Main Scientific Findings

The research concludes with the following thesis statements:

7.1.1. Thesis 1

I investigated the potential benefits of refurbishing 'Cube houses' in a novel approach that combines the typical architectural characteristics of these houses. The proposed refurbishment is characterized by re-arranging orientation, Window-to-Wall Ratio (WWR), shading elements, improved building materials, energy-saving mechanical systems, and integrating a passive ventilation mechanism (PACS).

Under the specific climatic conditions of the continental region, the refurbished version of the typical family house demonstrates notable advantages in terms of Predicted Mean Vote (PMV), daylight performance, Indoor Air Quality (IAQ), and energy balance. The key conclusions drawn from the calculated results are as follows:

- The designed refurbishment offers substantial energy savings, with up to a 52.3% reduction in energy consumption, primarily attributable to enhanced thermal properties of the building envelope.
- Cooling plays a minor role in the energy performance of the family house in this context.
- The PMV significantly improves (by 44.75%) due to superior thermal qualities, higher wall surface temperatures, and operative temperature.
- IAQ experiences a substantial enhancement, with up to a 91.4% decrease in CO_2 concentration resulting from increased airflow rates due to passive and AHU ventilation.
- Daylight condition is significantly improved, with 36.1% higher illuminance intensity under mixed sky conditions and an average of 20% improvement under clear sky conditions, primarily due to a four times increase in WWR.

Corresponding publications: [1].

7.1.2. Thesis 2

I conducted an extensive exploration to assess the passive ventilation performance and indoor thermal comfort of a PACS in a lightweight detached family house located in Hungary. The investigation revolved around passive design strategies, with a specific focus on a central ventilation chimney featuring a Venturi-shaped roof and its connection to an underfloor airflow inlet structure. I considered various operational scenarios and opening characteristics. To analyze airflow patterns and their impact on indoor thermal comfort, CFD simulations were employed, with air temperature, velocity, and ACH serving as the main parameters for assessment and comparison. The findings underscore the substantial role played by the PACS in promoting natural ventilation whether used alone or in conjunction with cross ventilation. It was found that:

- When compared to cross ventilation alone, PACS provides a six-times increase in ACH and a reduction of average indoor temperatures by 9.5°.
- Activating air conduction through the chimney alone led to a more than twofold increase in ACH and a 1°C reduction in interior temperatures.
- The Venturi-shaped roof alone increased ACH by 7.4 times compared to cross ventilation alone.

Corresponding publications: [2], and a journal manuscript under review and to be published.

7.1.3. Thesis 3

Integrating the proposed PACS system into a detached family house has the potential to achieve enormous energy savings in heating, cooling, and mechanical ventilation. With taking into consideration that an acceptable level of indoor comfort is provided in 90% of the occupation hours throughout the year when applying only PACS and without operating any mechanical HVAC. The energy performance of the tested case achieved around 50% savings compared to a regular AHU-operated scenario. The in-depth investigation shows that operating the proposed

PACS has the potential to achieve energy savings that round up to 97% in summer (hot period) and 40% in autumn (transitional period) while maintaining a relatively acceptable level of comfort.

Corresponding publications: a manuscript is under review and to be published.

7.1.4. Thesis 4

I undertook a CFD investigation to examine the effectiveness of an integrated solar chimney with a skylight in enhancing natural ventilation within a semi-attached family house in a fairly dense urban fabric. The findings unveiled the substantial benefits of the solar chimney, which generated a remarkable 6.2-fold increase in ACH and a reduction in indoor temperature by 1 degree.

For prospective research endeavors, it is strongly recommended that field measurements be implemented to complement the CFD simulations. Such measurements would provide empirical validation and further insight into the actual performance of the solar chimney.

Corresponding publications: [3].

7.2. Further Work and Recommendations

This research was limited to the investigated case studies and their special context. Therefore, there is still room for further questions and research. It is highly recommended to conduct field measurements to provide better validation to the numerical results and, hence, proceed experimenting with further cases, geometries, and climatic contexts. The spectrum of future research might tackle different geometries of roofs, skylights, and Venturi covers of the tested buildings in order to optimize the natural ventilation performance. Taking the research to the generic level would enable larger potential implementation of the results.

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Appendix

This appendix shows the CFD simulation results of phase I of the investigated detached house. The listed pictures are visually showing the profiles of air velocity and temperature of the scenarios Sc1, Sc2, and the reference scenario in 8 wind directions, and in horizontal and vertical sections.

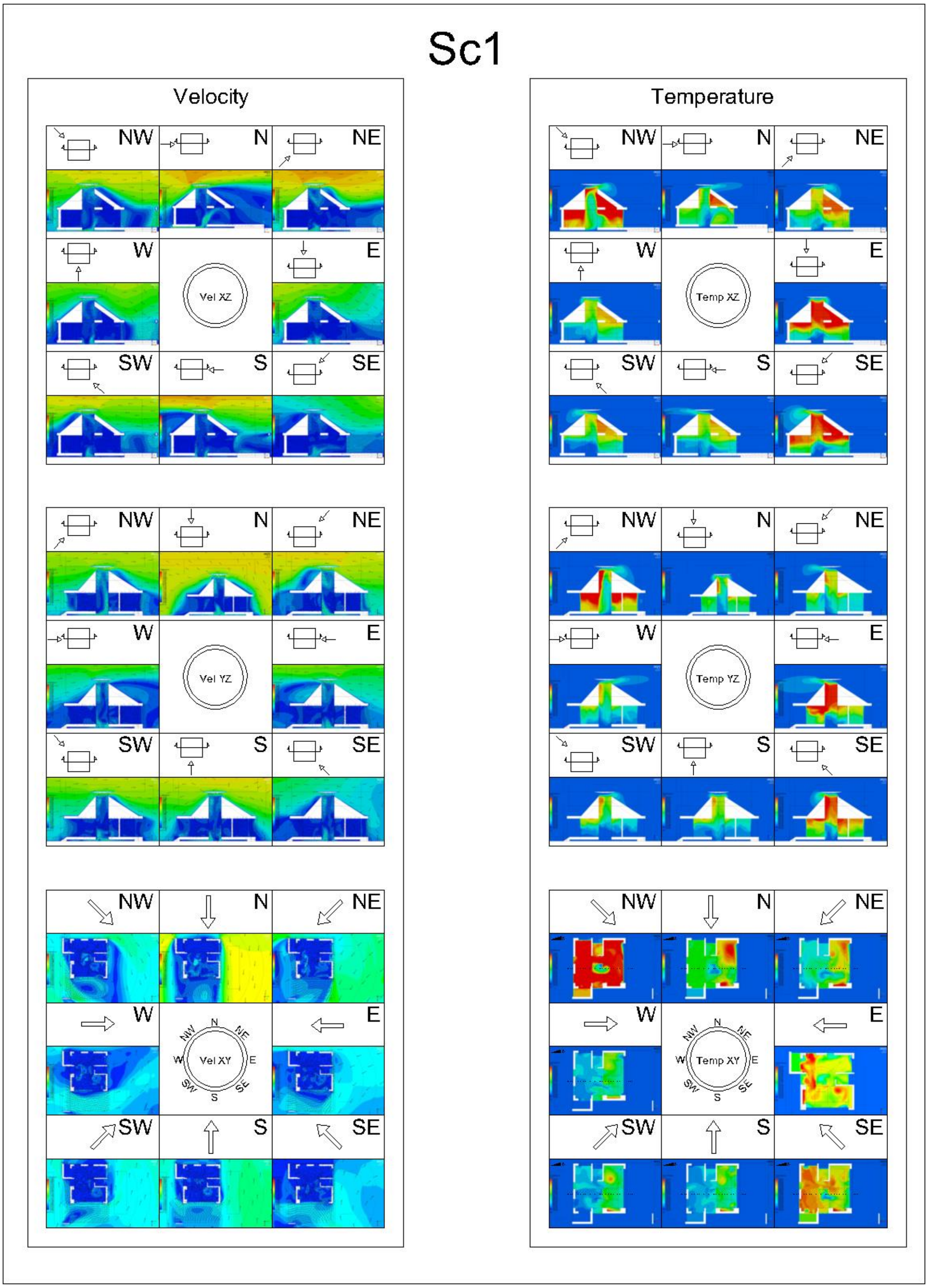

Figure A.1. Air velocity and temperature profiles of Sc1 for 8 wind directions.

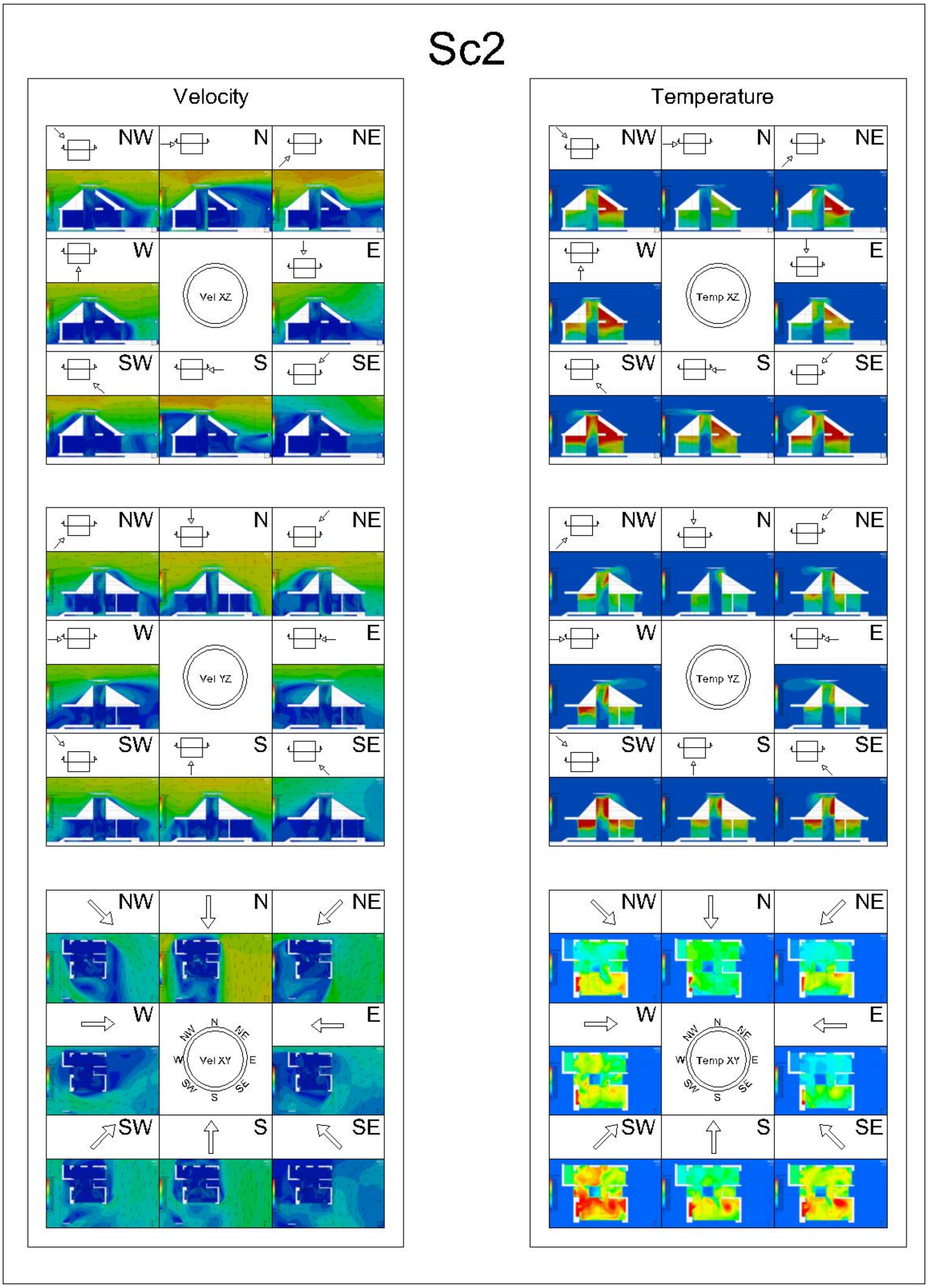

Figure A.2. Air velocity and temperature profiles of Sc2 for 8 wind directions.

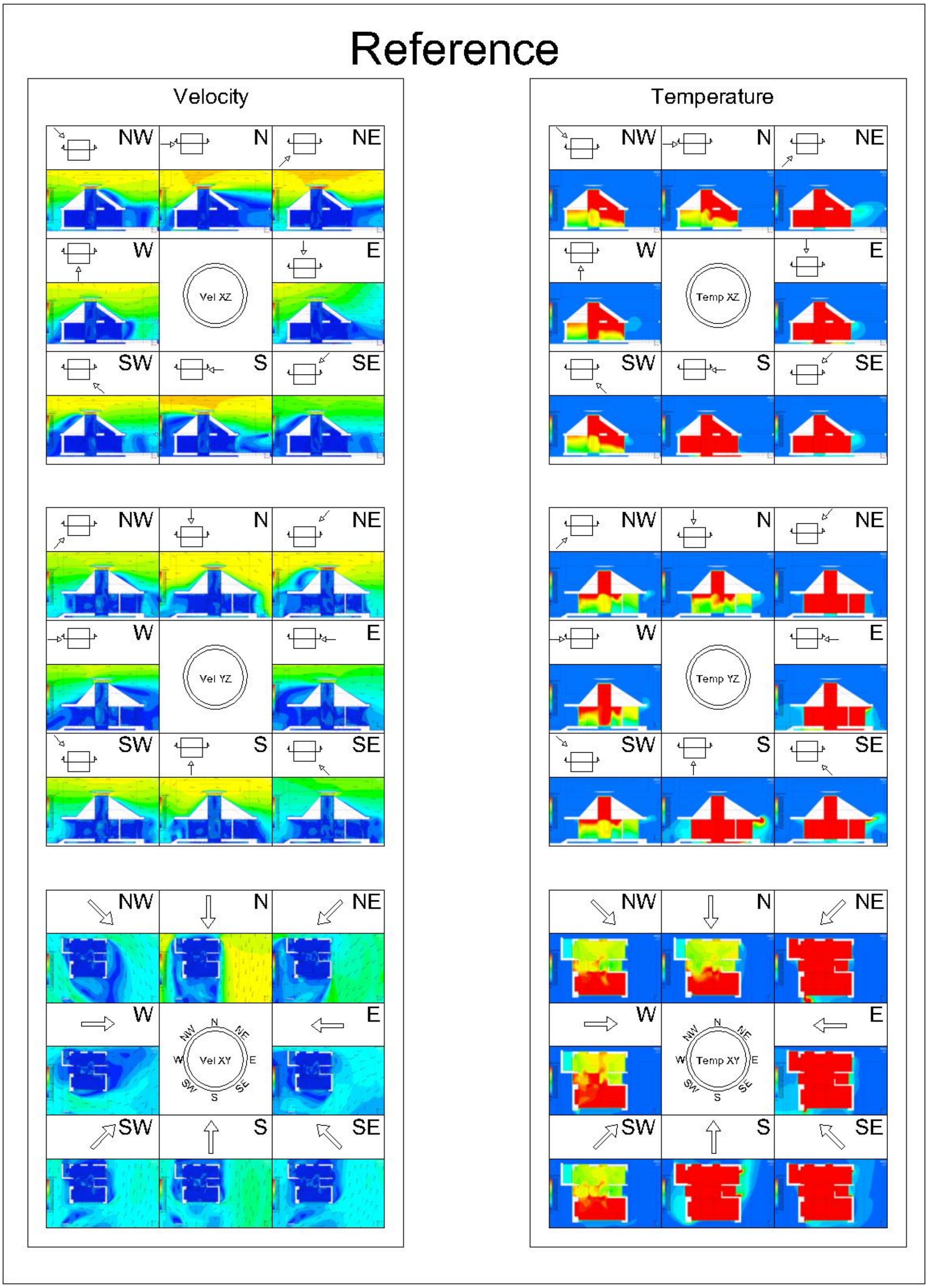

Figure A.3. Air velocity and temperature profiles of the reference scenario for 8 wind directions.