Indoor Air Quality in a Residential Building – A Health Issue

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Abstract. This study addresses the often-overlooked issue of indoor air quality, emphasizing its significance for the health and well-being of individuals spending a majority of their time indoors. Factors such as building occupancy, construction materials, and ventilation systems contribute to indoor air quality. Recognizing it as a critical environmental risk factor, this research focuses on assessing air quality in The Castle House, Lamego, through the measurement of PM10 and PM2.5 particles, temperature, barometric pressure, relative humidity, and carbon dioxide. The paper provides context, presents the study case, analyzes results, and concludes with implications for future research.

Keywords: indoor air quality · health and well-being · automatic monitoring

1 Introduction

When we talk about air quality, concerns usually refer to atmospheric pollution just outside buildings. However, people currently spend most of their time indoors, whether in their homes, workplaces or commercial and leisure areas, so ensuring good indoor air quality is essential for the health and well-being of these spaces' users. Indoor air quality is influenced by several factors, such as the occupancy of the building, the construction materials, the purpose for which it is intended, the activities carried out there, the building maintenance actions, and the type of ventilation and cleaning ventilation systems. Indoor air quality is an environmental risk factor of particular interest, as it can affect human health and cognitive functions and the productivity of those who spend a large part of their time in closed spaces.

The main objective of this work is to analyse the air quality in a column built to ventilate and illuminate the south facade of Casa do Castelo, which is partially buried. The Castle House is a small building located in the historic area of Lamego Castle, which was completely rebuilt to function as local accommodation. This reconstruction was carried out in accordance with the specific regulations of this historic area, in order to fully preserve the visual aspect of the heritage built inside the walls. It is a simple and poor building, with no relevant architectural value, but which is part of the set of buildings that

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identify this classified historic area. In this building, as in most of the others that belong this complex, due to the topography and also for economic reasons, one of the facades is the wall itself or the rocky mass of the area, with the houses being partially buried, with lighting problems, ventilation and humidity. In this context, and taking into account the fact that the exterior appearance of the building had to be maintained (architecture and materials), an architectural solution was studied which consisted of maintaining the existing façades but moving the house away from the rock mass on the inside, creating a column that goes from the ground floor to the 2nd floor for ventilation and lighting through a skylight placed on the roof, but away from it to allow air circulation. After the building started operating, especially in the summer, it was found that the ground floor smelled of mould, which indicated that there was no air circulation. Thus, we analyzed the air quality in The Castle House in Lamego by measuring PM10 and PM2.5 particles, temperature, barometric pressure, relative humidity and carbon dioxide. These parameters, especially the thermal gradient, also allow us to infer whether or not there is air circulation in that column.

This paper is structured as follows. After this introduction, the main topics considered in this paper are put into context. Then, the study case is presented, and the results are analysed. Finally, the main conclusions and future works are offered.

2 Indoor Air Quality

The quality of the indoor environment is a concern that has been with man for many centuries. It is always desirable that the air is fresh and pleasant. That is, it does not harm health. There is increasing evidence that the indoor environment's quality can profoundly affect home occupants' health [1, 2]. The concept of indoor environmental quality is quite complex and comprehensive, depending on many factors, such as temperature, relative humidity, air speed, the existence of odours, the concentration of microorganisms or dust in air suspension, noise level, and lighting, among others. These factors can be grouped into four major areas: air quality, hygrothermal quality, acoustic quality and lighting quality [3]. Good air quality is of paramount importance. A high degree of air purity, large air flows and efficient air filtration are necessary to obtain a good indoor environment. Air quality depends on the degree to which the air is free of pollutants that may irritate or harm occupants. The interior environment of buildings is contaminated by various substances that result from the current use of spaces and materials used in construction. These substances can have effects on the well-being of the occupants. The design and implementation of ventilation systems must consider the sources of pollution to evacuate these polluting substances to the outside, thus avoiding contamination of the indoor air. One of the methods used to assess the quality of indoor air in buildings, to reduce the risk to the health of occupants consists of determining the production rate of existing pollutants. It is not known how all polluting substances affect indoor air quality, so they are generally considered separately. Air quality also depends directly on the volume of the compartments. For this reason, in addition to ergonomic reasons, it is recommended that no ceiling heights be lower than the minimum recommended values. Some health problems caused by poor air quality are similar to the symptoms that affect us when we have the flu, so they are difficult to associate with the workplace. The indoor environment is rarely suspected of being the cause of symptoms.

Contaminants can also originate outside the building and pass through external air inlets or, in cases where the air extracted from the building by the air conditioning system is greater than the amount of air introduced, flowing inside the building through any crack available.

2.1 Indoor Air Quality in Residential Buildings

In residential buildings, indoor air quality is ensured by natural, mechanical or mixed ventilation systems. These systems are intended to supply fresh air to the occupants of these buildings, to the combustion appliances and to ensure the extraction of combustion products. This ventilation must be provided in comfortable and safe conditions, minimising energy consumption [4].

The high rate of pollutants inside buildings originates from occupancy density, equipment, and synthetic covering materials. Poor air quality can cause immediate, short-term, and even medium and long-term effects. It is essential to take care of indoor air quality, particularly in the building's design, installation and operation. Both the activities inside buildings and the materials integrated into the construction can produce or release undesirable substances into the indoor environment. Next, the pollutants described in Portuguese regulations in air quality are analysed.

The activities inside residential buildings and the materials integrated into the construction can produce or release undesirable substances into the indoor environment. The relative humidity of indoor air can directly and indirectly influence the occupants' activity. Low relative humidity values can cause sensations of dryness, skin and mucous membrane irritation, respiratory tract infections or discomfort in contact with some materials due to the generation of static electricity. High relative humidity values can also cause discomfort, inhibiting perspiration through the skin and the development of mould and mites that cause allergies, irritations and, in more severe cases, asthma. Relative humidity values, considered adequate, must be between 30 and 70%. The occupants' metabolism and activity produce carbon dioxide (CO2) and water vapour. Gas combustion also releases carbon dioxide and produces water vapour. Some consider that this gas is not toxic but a simple asphyxiant [5]. It is harmless at low concentrations of carbon dioxide, typically occurring inside buildings. But if the concentrations are high, it can cause drowsiness, breathing problems, headaches, fatigue, nausea, difficulty concentrating, etc.

Regarding limit values, the World Health Organization (WHO) [6] does not define a limit value for the concentration of this gas inside non-industrial buildings. However, prolonged exposure alters the body's acid-base balance, causing calcium loss in the bones. The main sources of CO2 production are human metabolism and all combustion sources in a home. Carbon monoxide (CO) is an odourless, tasteless and colourless gas resulting from combustion, especially in environments not rich in oxygen. At extremely low concentrations, carbon monoxide causes headaches and drowsiness. As the concentration increases, symptoms begin to include problems with concentration, vision and nausea and, in extreme cases, can lead to death as blood haemoglobin reduces oxygen to insufficient levels because it has a greater affinity for carbon monoxide. Very high concentrations of this gas can cause palpitations, vomiting, and cardiovascular problems, among others. All these pollutants mentioned above cause various anomalies in buildings, which in turn harm the quality of the indoor environment.

Various polluting substances can be released inside residential buildings by construction materials. The substances that have received the most attention are volatile organic components (VOCs) and formaldehyde (HCHO) [5] due to higher values inside than outside.

Pollutants that have a source mostly outside residential buildings must also be analysed, such as radon, particles, ozone and microorganisms.

Radon is a noble gas with no smell, colour or taste, radioactive of natural origin, and present in the soil. The concentration of radon inside houses depends on the concentrations of uranium and radium in the soil and subsoil under construction, as well as the infiltration routes of that gas and the ventilation of the house. Radon usually forms in the rocky materials beneath the building's settlement and diffuses and exhales from the rocks, entering buildings through cracks, cable passages and pipes. Radon concentrations are often higher inside basements and ground floor rooms than on upper floors. Air exchange with the outside depends on the occupants' ventilation habits and the houses' natural ventilation. Building materials, as they contain varying concentrations of uranium and radium, can also be a source of radon exhaled into buildings. However, as a general rule, the main source of radon is the soil under buildings [7]. Radon, when inhaled, is a carcinogen responsible for the increase in the incidence of lung cancer in exposed populations.

Measuring radon gas in indoor spaces is the only way to determine whether radon gas concentrations exceed the national reference level. The radon concentration inside buildings is not constant, showing daily variations (generally higher at night and lower during the day), seasonal (higher in winter and lower in summer), and annual.

Particles in indoor environments can have different diameters and types and carry living organisms such as viruses, fungi and bacteria. These particles may come from tobacco smoke, combustion products or outside air. Particles can be dust, fibres, pollens, etc. Dust is fine dust particles that generally originate from outdoor dust, and when inhaled, they deposit in the respiratory system and cause rhinitis, asthma, bronchitis and respiratory allergies. The fibres originate from glass and rock fibres found in various products and irritate the eyes, skin and respiratory tract. Pollens are produced by plants outdoors, but once indoors, they persist for a long time. Their chemical composition and geometric shape vary, meaning their effects on the human body vary. However, the smaller the particles, the more adverse the effects on health, which can be associated with respiratory problems, worsening symptoms in asthma patients, reduced lung function, etc. Prolonged exposure to this type of particle can also result in chronic bronchitis.

Ozone (O3) is a compound that produces adverse effects and can seriously affect human health and well-being. Inside buildings, ozone is released, particularly by photocopiers and laser printers. Ozone can be highly oxidising and reacts with various substances outside and inside, such as perfumes, furniture, carpets, paints, varnishes, and cleaning products, generating ultrafine toxic particles. Symptoms of exposure to ozone are related, in particular, to changes in lung functions, inflammation in the airways, and the worsening of asthma problems. Other symptoms are eye irritation, headaches and accelerated heart rate.

The four most significant categories of microorganisms that occur in indoor environments are bacteria, mites, microorganisms from pets and fungi. The variety and concentration of these microorganisms increase with the number of occupants. These microorganisms can cause allergies such as rhinitis (inflammation of the nose mucosa), asthma, sneezing, tears, colds, breathing difficulties, and digestive problems.

2.2 Ventilation

Ventilation in residential buildings must be general and permanent, as renewing indoor air ensures the healthiness of spaces, thus guaranteeing better air quality.

Indoor air quality can be controlled through a control strategy or by implementing appropriate ventilation strategies. Ventilation emerges as a fundamental strategy in managing indoor air quality, with localised extraction preferred in the presence of intense and punctual emission sources, as in the kitchen. Dilution and removal should be seen as mechanisms for eliminating pollutants generated in a dispersed manner. Ventilation systems supply new air to the occupants of the dwellings, to the combustion appliances, and to ensure the extraction of combustion products. Insufficient ventilation conditions have very negative impacts on indoor air quality. Relative humidity is often the determining factor in establishing extraction flow rates in service compartments. The admissions are located in the main compartments to provide metabolic oxygen and dilute pollutants and odours from the occupants. The climate naturally influences the choice of ventilation system, ranging from fully controllable systems with low air permeability to natural ventilation systems with high permeability of the surroundings. The sizing of ventilation systems must be careful. Mechanical ventilation systems activated according to pollutant removal needs require higher flow rates. In most residential buildings, the system installed is mixed. Ventilation systems must respect pre-existing evacuation location principles and take advantage of actions promoting evacuation to allow better ventilation of the entire fire. Air permeability and ventilation flow rates must be specified, which depend on the activities carried out inside the buildings and their occupancy.

Natural ventilation is the renewal of air promoted by natural actions (thermal and wind), which ensure controlled airflow between exterior air intake openings (windows and grilles) and air extraction openings (chimneys). In Portugal, natural ventilation in residential buildings must follow the specifications of standard NP 1037-1: 2002 (Ventilation and evacuation of combustion products from rooms with gas appliances. Part I: Residential buildings) [8]. The ventilation system is intended to ensure indoor air quality, supplying “new” air to the combustion appliances and ensuring the exhaustion of combustion products, which must be provided in comfortable and safe conditions. The ventilation rates of this system depend on the size and distribution of openings in the building envelope and wind pressure. Wind pressure depends on weather conditions, and openings in the building envelope must be controlled according to the weather. The World Health Organization states that very high ventilation rates should be avoided. Natural ventilation is carefully designed and constructed to ensure adequate ventilation rates, although occupants generally have to adjust openings when necessary. Like many other systems, natural ventilation has advantages and disadvantages [8].

Mechanical ventilation is the renewal of air promoted by mechanical fans, which ensures controlled and uninterrupted air flow between external air intake openings and air extraction openings connected to ducts. There are systems with mechanical inflation and extraction and systems with extraction fans only. Mechanical ventilation is a way of ventilating spaces that allows constant airflow to be imposed, regardless of external actions and users. It can include air supply and/or extraction and also heat recovery. It ensures the necessary flow to be inflated in spaces with an adequate interior temperature and allows humidity control, avoiding building pathologies. Collective systems installed in multi-family buildings must operate 24 h a day. Double-flow systems can be adopted to improve efficiency in colder areas, with heat recovery, which allows the new air to be pre-heated by crossing it with the extracted air. When a mechanical source provides ventilation, the building envelope can be closed. The air supplied for ventilation can be clean, that is, without pollutants from outside air. Furthermore, heating and cooling can be easily combined with mechanical ventilation systems. These systems can also control pressure differences over the building envelope and prevent damage, such as moisture, in the building structures.

Mixed ventilation occurs when there is natural and mechanical ventilation. New air enters through openings in the surroundings and is extracted through exhaust fans and extractors. It is possible to improve the resolution of the natural ventilation system by introducing mechanical support. Mixed ventilation often uses a low-energy auxiliary extraction fan in a natural ventilation duct. The fan is operated when forces are low or reverse flow is to be avoided. Its efficiency can be improved by zoning the building so that some parts operate under natural conditions while others are under mechanical ventilation. A mixed system may include a natural ventilation system combined with mechanical ventilation utterly independent of the system. Thus, natural ventilation is used for as long as possible, and the mechanical ventilation system takes over when this no longer occurs.

The following table presents a comparative analysis of the main advantages and disadvantages of natural, mechanical, and mixed ventilation systems.

3 Legislation

The national indoor air quality policy emerged following the transposition into domestic law of European Directive 2002/91/EC [10].

In existing buildings, the indoor air quality index for each pollutant was calculated based on the arithmetic mean of the maximum mean concentration values of the pollutant measured in each area of the home. The Indoor Air Quality Index (IQAI) of a building will be defined based on the pollutant with the worst classification [11].

With the publication of Directive 2010/31/EU [12], relating to the energy performance of buildings, the regime established by Directive 2002/91/EC was reformulated, reinforcing the promotion of energy performance in buildings and highlighting the goals and challenges agreed upon by the European Member States for 2020. This time, the new national regulations, Decree-Law 118/2013 [13], defined a non-mandatory indoor air quality certification, which constituted a setback. However, it considers the minimum values of fresh airflow per space and the protection thresholds for indoor air pollutant concentrations to safeguard health and well-being. It also highlights that adequate natural ventilation must be prioritised over forced ventilation from a perspective of optimising resources, energy efficiency and cost reduction. Indoor air quality audits are also eliminated. However, controlling pollution sources and adopting preventive measures are maintained, both in terms of the design of buildings and their operation, to comply with the legal requirements to reduce possible risks to public health.

In this context, to comply with the changes imposed by Decree-Law no. 118/2013, Ordinance 353-A/2013 of December 4 was published [14]. Table 1 presents the protection thresholds for radon, CO2, CH2O, CO, VOC and particulate matter (PM10 and PM2.5). Regarding indoor air quality in homes, it should be noted that there is no specific legislation, leaving it up to the occupants to ensure the air quality in their homes. However, in residential buildings, the only regulatory requirement related to indoor air quality refers to an air exchange rate of 0.6 h-1, as mentioned in the old decree-law. In the current legislation, the hourly calculation of the air exchange rate is based on the method that meets the requirements of standard EN 15242 [15] for commercial and service buildings.

Table 1. Protection threshold and tolerance margin for physical-chemical pollutants according to Ordinance No. 353-A/2013 [14]

Pollutants	Unit	Protection threshold	Tolerance margin [%]
Particulate matter (PM10 fraction)	$\mu g/m^3$	50	100
Particulate matter (PM2.5 fraction)	$\mu g/m^3$	25	100
Total Volatile Organic Compounds (VOCs)	$\mu g/m^3$	600	100
Carbon monoxide (CO)	mg/m^3	10	-
Formaldehyde (CH2O)	$\mu g/m^3$	100	-
Carbon dioxide (CO2)	mg/m^3	2250	30
Radon	Bq/m^3	400	-

– The concentrations in $\mu g/m^3$ and mg/m^3 refer to a temperature of 20 °C and a pressure of 1 atm (101.325 kPa);
– The protection thresholds indicated relate to an average of 8 h;
– The margins of tolerance shall apply to existing buildings and new buildings without mechanical ventilation systems;
– Radon analysis is mandatory in buildings built in granite areas, namely in the districts of Braga, Vila Real, Porto, Guarda, Viseu and Castelo Branco.

4 Case Study

4.1 The Castle House in Lamego

The Castle House in Lamego is a house intended for local accommodation, consisting of 3 floors and, as already stated, the south facade is partially buried. In this building, due to the topography and also for economic reasons, part of the south facades was the rocky mass of the area, causing lighting, ventilation and humidity problems. The house was completely rebuilt three years ago but taking into account the fact that the exterior appearance of the building had to be maintained (architecture and materials), an architectural solution was studied which consisted of maintaining the existing elevation but moving the house away from the rock mass on the inside, creating a column that goes from the ground floor to the 2nd floor for ventilation and lighting through a skylight placed on the roof, but away from it to allow air circulation (Fig. 1).

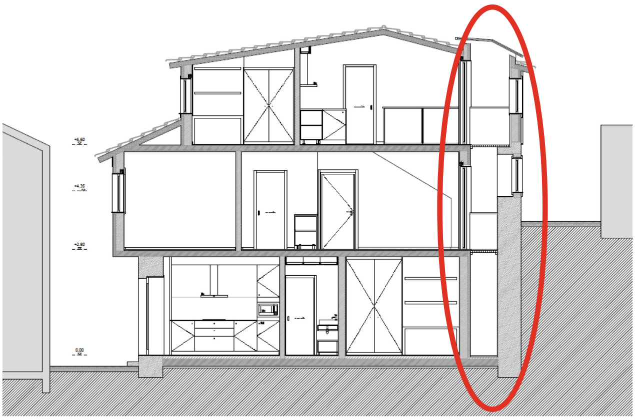


Fig. 1. Column for ventilation and lighting through a skylight placed on the roof

After it started operating, especially in the summer, it was found that the ground floor (Fig. 2) smelled of mould, which indicated that there was no air circulation and, probably poor air quality.

In this context as thought to analyse the air quality by measuring PM10 and PM2.5 particles, temperature, barometric pressure, relative humidity and carbon dioxide. The thermal gradient and the barometric pressure also allow us to infer whether or not there is air circulation in that column.

To this end, two devices, monitor AirAssure™ [16], Fig. 3, were placed inside the column, one on ground floor, “Walls”, and the other on floor 2, “Tower”, to collect data regarding air quality, Fig. 3 (Fig. 4).

Sixty-seven measurements were carried out on each AirAssure device/monitor between 3:27 pm on February 21, 2023, and 10:29 am on February 24 2023. The monitoring time was short because the main objective was to compare the air quality at the level of the ground floor, which is a non-ventilated area that, from time to time, smells mold, and the most ventilated area, which is the 2nd floor, next to the skylight. On the

Fig. 2. Ventilation column at the ground floor

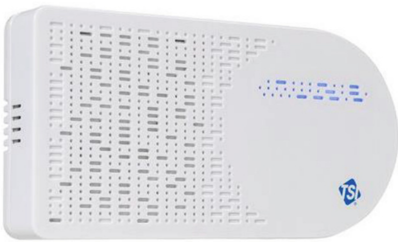


Fig. 3. Monitor AirAssure™ [16]

other hand, it was also intended to understand whether or not air was circulating in the ventilation column without mechanical ventilation.

In the Fig. 5, it can be observed all the data collected by the monitors placed, one on the "Wall" and on the "Tower" in the studied period.

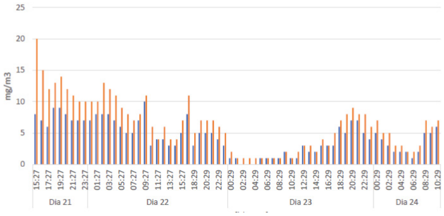
Analysis of Results

Regarding PM10 and PM2.5 particles, we found a greater concentration in the Tower, because the outside air contained more particles than the indoor air and since at the level of the "Tower" (2nd floor) the space is immediately connected to the outside by the skylight, the concentration of particles is higher at that level. Nevertheless, in both, they are lower than 50 mg/m^3, obtaining an AQI considered Good for health levels.

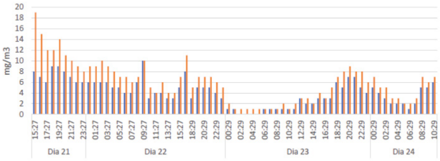
The carbon dioxide values are identical, as the average of the two measurements is very close, 421 ppm in the Wall and 416 ppm in the Tower.

Fig. 4. Ventilation devices and sensors. a) Walls, b) Tower

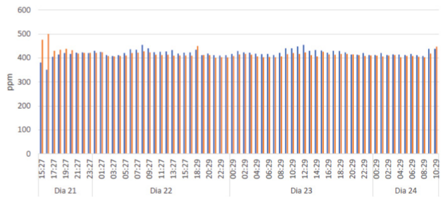
We found that the barometric pressure is lower in the Tower because it is a higher floor (2nd floor) in relation to the Wall which is the ground floor but the variation between the Wall and the Tower is more or even constant.



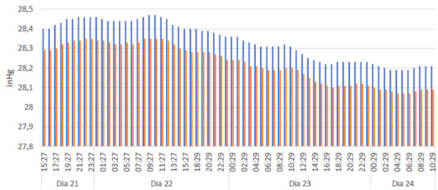
a) PM10



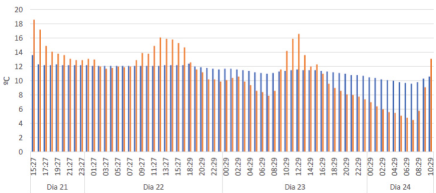
b) PM2.5



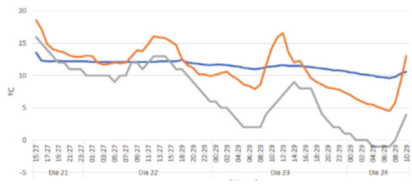
c) CO2



d) Barometric pressure



e) Interior temperature



f) Interiors and exterior (grey) temperatures.

Fig. 5. Datta collected by the monitors in the Wall (blue) and in the Tower (orange) between 21 and 24 of February 2023. a) PM10, b) PM2.5, c) CO2, d) Barometric pressure, e) Interior temperature, f) Interiors and exterior (grey) temperatures. (Color figure online)

The temperature in the Wall is constant because it is buried, and therefore very much protected from the action of the sun and other atmospheric agents. The same is not true in the Tower, as it is higher during the day than at night. If we compare it with the temperature outside, we see the same variation between the temperature of the Tower and outside. However, it should be noted that the outside temperature recorded was always lower than the temperature in the Tower. This finding allows us to infer that next to the skylight a "buffer" zone is created where a mass of air is hotter than outside and, as the area of connection to the outside is small, it is not enough to give the exit of this warmer air outside. The temperature in the Wall is generally lower than in the Tower and the pressure is higher, so it is difficult to circulate air from the Wall to the Tower, and it seems advisable to increase the ventilation area next to the skylight and use mechanical air circulation.

The relative humidity in the Wall is higher than in the Tower, reaching values of 80% humidity. The maximum value reaches 75% in the Tower, and the average during the period under analysis is 69% in the Wall and 63% in the Tower. We can conclude that the relative humidity in some measurements is above the recommended parameters. It is for this reason, and because there is no air circulation, that the mold smell appears.

Table 2 shows the mean values, mode and standard deviation of the readings recorded for the various parameters.

Table 2. Statistical analyses of the collected data.

Parameter		Device 1 – Walls			Device 2 - Tower		
		Mean	Mode	Standard deviation	Mean	Mode	Standard deviation
Temperature	ºC	11,506	12,10	0,805	11,196	12,00	3,341
Relative humidity	%	69,269	61,00	9,033	63,090	68,00	8,350
Barometric Pressure	mmHg	28,338	28,23	0,098	28,223	28,35	0,099
CO2	ppm	421	412,00	14,85	416	408,00	16,267
PM10	mg/m^3	4,343	5,00	2,609	6,358	7,00	4,166
PM2.5	mg/m^3	4,090	5,00	2,460	5,985	7,00	3,808

5 Conclusions and Future Work

The quality of the indoor environment is a very complex, comprehensive and highly important topic. However, it depends on several factors. For good air quality inside buildings, it is always desirable that the air that circulates is fresh and pleasant and does not negatively impact the health of the occupants. But today, there is increasing evidence that the indoor environment can profoundly affect the health of building occupants. The occupancy density of buildings and installed equipment are some factors that pollute the interior. Air pollutants can originate from human activity (for example, water vapour and relative humidity), construction materials (volatile organic compounds), and other types of pollutants, such as radon. All pollutants cause poor air quality that can affect human health. Indoor air quality is a parameter that affects all types of buildings, from residential buildings, offices, schools, day-care centres and kindergartens. In these locations, this parameter is ensured by ventilation systems intended to supply new air to the combustion appliances and provide the extraction of combustion products. It must be guaranteed to be in comfortable and safe conditions. For indoor air quality to be good, it is important that the two established criteria exist and are respected, which are the determination of limit values for polluting substances depending on the length of time occupants remain in the contaminated environment and the finding of criteria related to sensory effects caused by polluting substances in humans. However, the air quality in a building is assessed to satisfy the health and comfort criteria of the inhabitants/occupants. Ventilation is essential to control indoor air quality. The most used systems in Portugal are natural, mechanical and mixed ventilation. However, the most used system is the natural ventilation system, which ensures the desired ventilation rates and has greater efficiency in extracting pollutants. When sizing a system of this type, it is mandatory to be very careful. Thermal comfort essentially depends on the temperature and relative humidity of the air. Still, it also depends on the air velocity, the asymmetry of the radiant temperature, the floor temperature and the difference in air temperatures. If the occupants feel a simple draft or a very sharp temperature difference, they will feel very uncomfortable.

Regarding the case study, it should be noted that the quality of the outdoor air influences the quality of the indoor air and the ventilation, temperature, pressure and humidity are very important parameters in the circulation of air and therefore in its quality. As future work, it is very important to repeat this procedure in the summer, when the system works worst, due to the direct action of the sun on the skylight and accumulation of hot air next to the skylight.

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