OPTIMAL VENTILATION STRATEGIES FOR BALANCING INDOOR AIR QUALITY, COMFORT AND ENERGY USE IN EDUCATIONAL BUILDINGS. THE IAQ4EDU PROJECT.

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Abstract

Currently, there is great concern about adequate indoor ventilation to prevent adverse effects on occupants' health, and, within educational buildings, to ensure students and professors' well-being and improve learning processes. This paper aims to present an innovative framework, developed within the IAQ4EDU project, to improve the effectiveness of the ventilation strategies in educational centres considering the indoor air quality, thermal comfort, energy consumption and global costs. This consists on characterise indoor air quality, simulate building ventilation strategies using reduced order models and develop multi criteria decision making method. 40 classrooms located in 20 Spanish educational buildings are used as case study.

Introduction

With the spread of the COVID-19 pandemic, indoor space ventilation has lately become a hot issue. Although the relationship between adequate ventilation of spaces and its impact on respiratory infections has already been studied. Some examples are the models created to estimate the risk of infection by tuberculosis, influenza, rhinovirus or SARS in indoor spaces developed by Riley et al. (1978) and updated by Gammaitoni and Nucci (1997). In this line, Du et al. (2019) concluded that the improvement of the ventilation rate by keeping carbon dioxide concentrations below 1000 ppm has an impact on a reduction in the incidence of infections. Adequate indoor ventilation is also necessary to guarantee the well-being of teachers and students and improve cognitive abilities (Yang et al., 2020).

The vast majority of Spanish academic buildings were built before 2007 without mechanical ventilation systems (RITE, 2007). Therefore, the IAQ (Indoor Air Quality) is subjective, depending on the perception of the inhabitants (Stabile et al., 2019) and their reactions. Natural ventilation solutions are considered the most effective and practical measures. Nevertheless, users may not always follow window opening recommendations due to poor thermal comfort, especially in cold seasons, thus compromising indoor air quality. On the contrary, when the occupants follow the recommendations, the energy consumption is increased to counteract the thermal discomfort.

The main objective of this paper is to introduce a novel methodological and technological framework for the optimization of ventilation strategies in scholarly buildings considering the indoor air quality, thermal comfort, energy use and global costs. Guaranteeing that indoor activities in educational facilities are conducted with adequate thermal comfort and indoor air quality by establishing proper ventilation strategies will increase the health and well-being of the occupants along with their performance and productivity. Following this section current trends in ventilation strategies, indoor air quality and thermal comfort in educational centres and decision making tools are presented. Then, an innovative approach for the optimization of ventilation strategies to offset indoor air quality, comfort and energy consumption in scholar centres is described. Finally, the case study is described and the expected results impact are presented.

Background

Ventilation strategies, indoor air quality and thermal comfort in educational centres

The most effective control strategy for respiratory diseases (i.e. tuberculosis, SARS-CoV-2 or COVID- 19) is ventilation (Du et al., 2019; Guo et al., 2021). According to this, HVAC operation guidelines developed in response to SARS-CoV-2 virus (i.e. REHVA, 2020; ASHRAE, 2020; CSIC, 2020; etc.) highlight the importance of indoor ventilation but they do not determine the specific ventilation rates (air changes/hour) required to eliminate the risk of transmission (Guo et al., 2021).

Natural ventilation depends on the temperature gradient between the indoor and the outdoor, the air velocity, the wind direction, the size and geometry of indoor spaces, the occupancy and the activities performed in there. Measuring ventilation air change rates is a difficult and expensive task and they are often assessed using CO_2 as a tracer. Several authors demonstrated that ventilation strategies based on CO_2 monitoring can also provide significant energy savings in front of constant air volume rates in educational contexts. In general, previous research initiatives have mainly focused on the students' exposure to air pollutants and its effects on brain development (i.e. the CleanAir@School project, 2020), but none of them have used indoor air quality results to identify proper air renovation strategies or have limited the scope to mechanical systems. Rufo et al. (2016) highlighted that despite the studies and European projects (SEARCH II Project, 2013; SINPHONIE, 2014) performed in the last decade on indoor air quality in school classrooms, the problem continues without satisfactory solutions.

CO_2 measurement practice generally relies on using deterministic approaches to determine air change rates. Nevertheless, previous studies reported successful implementations of stochastic approaches based on reduced order models and measured data for different purposes such as electrical heating load shifting (Robillart et al., 2019), to model the indoor CO_2 concentration (Macarulla et al., 2017), and to estimate buildings occupancy using CO_2 concentration measurements (Wolf et al., 2019) or ventilation rates (Macarulla et al., 2018). Reduced order models are seen as a good alternative to complex building models where small accuracy improvements require much more detailed information and increased computational efforts and, with that, its functional applicability gets reduced for business-oriented applications (Schubnel et al., 2020). The IAQ4EDU project aims to take advantage of relatively simple and solid reduced models to identify those ventilations rates that guarantee proper indoor air quality levels in educational centres, being able to address a high number of scenarios with reduced computational resources.

Within the thermal comfort area in educational centres, significant differences between the expected values of thermal comfort using models proposed by existing standards (ASHRAE 55, ISO 7730, EN 16798, etc.) and the values obtained in experimental campaigns have been identified by authors such as Haddad et al. (2016) and Wang et al. (2017). A review of previous thermal comfort field studies in school classrooms can be found in Aparicio-Ruiz et al. (2021). Few studies carried out a comparative analysis at different levels of education. In addition, and during the last decade, most of existing studies on thermal comfort in educational buildings were conducted in Asia and South-America, leaving European countries aside. This is important because both the main characteristics of the buildings and climate conditions have a huge impact on this kind of studies.

To the authors knowledge, no previous research initiatives simultaneously evaluate indoor air quality and thermal comfort in educational buildings to determine suitable ventilation strategies and corresponding ventilation rates. Only Franco and Shito (2020) have recently developed a multi-objective methodology to establish optimal mechanically assisted air exchange rate of indoor spaces based on the actual occupation's profile obtained by monitoring the increase of carbon dioxide concentration with time. The IAQ4EDU project will broaden the scope by assessing not only mechanical systems but also natural ventilation and hybrid (combination of both) approaches. In addition, this project adds other variables such as thermal losses and energy flexibility potential to maximize the accuracy and profit.

Decision making tools

In order to guarantee good and serviceable ventilation condition, the education community may need to invest in their HVAC infrastructure assets. However, such task is becoming more challenging than ever before due to the increase in demand and the reduction of human and financial resources (REHVA, 2020). Thus, it is utterly necessary to develop prioritization methodologies in order to assure rational and systematic investment choices based on economic, social and environmental grounds (Lazar et al., 2021).

In practice the most common way to prioritize investments is the cost effectiveness analysis, where the costs of different homogeneous alternatives are compared (Enthoven, 2019). Other monetary-based decision-support techniques are: financial analysis; life cycle cost analysis and cost-benefit analysis (Pujadas et al, 2017). However, prioritization decisions are often complex and multifaceted problems, which involve addressing and balancing a broad range of considerations, incorporating not only environmental information, but also economic and social aspects, technological and scientific data, ethical and political concerns, and stakeholder interests. All these considerations may make any decision process inherently multi-objective, limiting the individual or group capacity to decide. Consequently, decision-makers in the built environment demand systematic frameworks to integrate all this heterogeneous information facilitating a structured, understandable, and defensible decision (del Mar Casanovas-Rubio et al, 2019). A systematic methodology that is capable of synthesizing these heterogeneous considerations in order to evaluate and prioritize among different alternatives is multi-criteria decision analysis, so called MCDA (Pujadas et al, 2019).

A number of multi-criteria analysis' methodologies have been developed over time with the aim of providing a systematic framework that considers the multidimensional nature of real-world problem such as weighted sum model, weighted product model, compromise programming, analytical hierarchy process, ELECTRE, TOPSIS, PROMETHEE or VIKOR. Nowadays these methodologies are usually used introducing fuzzy modelling based on hesitant linguistic term to represent uncertainties on assessments. MCDA allows to break each problem into its constituent parts in order to understand evaluation (Jamwal et al., 2021). A complete review on the MCDA methodologies and its engineering applications for ranking homogeneous alternatives developed over the last twenty years can be found in Zavadskas et al. (2015a) and Zavadskas et al.(2015b).

Although project prioritization is a widely used tool to evaluate and rank projects or investments, all the existing research on this topic has been mainly focused on the evaluation and ranking of transportation infrastructure planning projects. However, little (or non) attention has been paid in the particular prioritization of investments in HVAC infrastructure based on a risk assessment.

Optimal ventilation strategies for balancing indoor air quality, comfort and energy use in educational buildings. The IAQ4EDU project

The IAQ4EDU project

The IAQ4EDU project, which aims to improve the effectiveness of ventilation strategies for the balance of indoor air quality, thermal comfort and energy consumption in educational buildings, is a project funded by the Spanish *Agencia Estatal de Investigación* within the funding program *Programa Estatal de I+D+I orientada a los retos de la sociedad*. The project has a duration of three years. It started in September 2021 and is scheduled to end in August 2024.

The IAQ4EDU project aims to optimize the ventilation strategies in educational buildings taking into account the indoor air quality, thermal comfort, energy use and global costs (encompassing operation and investment costs). Four specific objectives have been established to achieve the purpose of the project. In the first objective, the quality of indoor air and thermal comfort of Spanish educational centres (primary and secondary schools and universities) will be characterised. For this, a CO_2 monitoring protocol for classrooms and other teaching areas will be developed and current indoor air quality and thermal comfort in classrooms will be determined by building a controlled database. In the second objective, potential ventilation strategies that can be used in classrooms and teaching spaces will be identified and characterised in terms of investment and operating costs. In the third objective, potential ventilation strategies and their corresponding thermal performance, energy consumption and flexibility will be modelled using reduced order models. Within this objective reduced order models for air renovation strategies will be defined and validated. An energy optimizer based on reduced order models and a tool to estimate the HVAC systems' energy flexibility will be developed. Finally, in the fourth objective, a multi-criteria decision-making method will be developed to prioritize ventilation strategies. This includes defining an overall HVAC-oriented risk score and a time-responsive decision support dashboard and an integrated decision support model to assist decision-makers in the prioritization of HVAC investments.

Methodology: IAQ4EDU framework

In the following section the methodology and framework of the project will be presented. Based on the aforementioned aspects related to ventilation strategies in educational buildings considering the indoor air quality, thermal comfort, energy use and global costs, the approach of the IAQ4EDU project includes (i) just natural ventilation by opening windows and doors, (ii) low-cost mechanical ventilations systems (i.e. ceiling fans or fans installed in the facade), (iii) the implementation of mechanical systems at constant flow or using demand controlled ventilation rates and (iv) hybrid implementation approaches. Figure 1 shows the framework designed to achieve the objectives of the IAQ4EDU project.

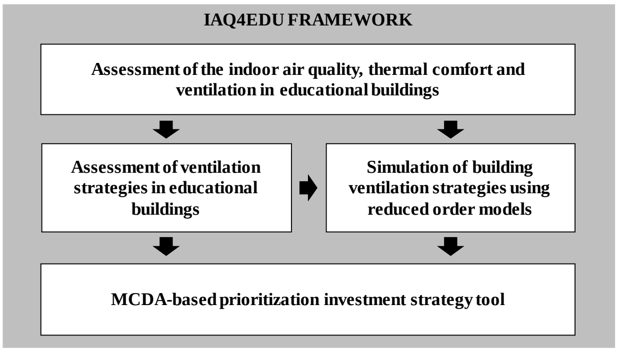

Figure 1: IAQ4EDU framework

Assessment of the indoor air quality, thermal comfort and ventilation in educational buildings

Educational buildings will be characterised in terms of year of construction, building construction characteristics, type of ventilation and also to know their willingness to take part of the measurement campaign through a survey. From those educational buildings willing to take part in further activities, a set of 20 educational buildings will be selected to be part of the measurement campaign. Selection will be made according to main construction characteristics, ensuring that naturally ventilated and mechanically ventilated buildings are well represented. Efforts will be done to achieve the minimum sample size for a 95 confidence interval within 5% accuracy.

The monitoring process of indoor air quality and thermal comfort of 40 classrooms (2 classrooms in each of the 20 selected educational buildings) will be continuously conducted during one working day. Measurements will be repeated for three different HVAC modes (heating mode, cooling mode and neither heating nor cooling mode). Previously, a CO_2 monitoring protocol for classrooms and other teaching areas will be developed. Instrumentation and tools for the monitoring process is detailed in Table 1.

Table 1: Instrumentation and tools for the monitoring process

Data monitoring	Instrumentation and tools
Indoor environmental data	Thermal microclimate data logger (x2)
Outdoor environmental data	Portable weather station
Ventilation air change rates	Airflow hood balometer
Occupants' personal data	Visual inspection

Data recorded will be analysed in order to determine (i) the ventilation air change rate using stochastic procedures based on reduced order models, (ii) the thermal comfort using the Predicted Mean Vote (PMV) comfort model and (iii) risk of infection due to aerosols using the model proposed by Riley et al. (1978) and upgraded by Gammaitoni and Nucci (1997).

Assessment of ventilation strategies in educational buildings

The identification of ventilation strategies for educational buildings will include a review: (i) just natural ventilation by opening windows and doors, (ii) low-cost mechanical ventilations systems (i.e. extraction fans in the facade, ceiling fans with ducts to the roof or façade, air recovery units, etc.), (iii) the implementation of mechanical systems at constant flow or using demand controlled ventilation rates and (iv) hybrid implementation approaches. A score will be assigned to each of the identified strategies according to its feasibility of implementation.

The identified ventilation strategies will be characterised in terms of energy consumption, energy flexibility potential, investment and operating costs. In order to estimate the investment and operating costs, ventilation strategies will also be parametrized according to the characteristics of the building where they will be implemented.

Simulation of building ventilation strategies using reduced order models

Reduced order models for heat dynamics and indoor air quality of educational buildings will be developed and validated. In case of forced ventilations strategies, these models are the base for estimating the corresponding buildings' energy consumption, depending on the degree of intelligence the building might have. These models enable to forecast when HVAC systems (if any) should be turned on to keep the building within the comfort temperature standards and at the same time to keep indoor air quality controlled to minimize any health risk. In case of having no ventilation system, users are obliged to use natural ventilation strategies, which also has a direct effect on indoor comfort and, thus, on energy consumption.

The optimization of HVAC energy demand in educational buildings will consider different function objectives, such as minimization of the energy demand or minimization of the energy cost, among others. This is achieved by continuously adapting the temperature setpoints or the ventilation air flows. The capability of changing the building energy demand, maintaining the levels of comfort and safety, is called energy flexibility and it is only achievable by incorporating a certain level of smartness in the building. With this, the IAQ4EDU is capable to estimate the energy or cost savings that the building should obtain thanks to the incorporation of smart systems and to compare the thermal comfort and indoor air quality inside the building.

Flexibility potential for building ventilation systems will be simulated. The amount of flexibility per hour each building might provide for a determined period of time according to its construction characteristics and technical heating and ventilation devices will be computed. This flexibility values can be upwards or downwards (depending on the necessity to increase or decrease the energy demand of the building respectively). The use of flexibility deviates the demand of the building from the optimal energy use considered by behind the meter strategies, but it reverts into new revenue streams.

Development of a MCDA-based prioritization investment strategy tool

For the definition of a HVAC risk score and a time-responsive decision support dashboard an in-depth literature review will be first carried out to identify the fundamental parameters to be considered in the risk score -such as the air quality and other outputs from previous steps. All parameters identified will be used in the calculation for the risk score as a composite of the likelihood (the probability of a risk event occurring) and impact index (the consequences a risk event has). Both inputs (likelihood and impact index) will be developed thus having a baseline risk score algorithm ready to be used. Then, and in order to validate the risk score, different but limited number of scenarios will be used for benchmarking and eventually better attune the proposed risk score (tuning its parameters). Finally, it will be defined a connected and time-responsive decision support dashboard that allow managers to select the optimal and most sustainable ventilation operational strategies and good practices to immediately lower the HVAC risk index at each moment and depending on each circumstance.

An integrated decision support model for the prioritization of HVAC investments considering the uncertainty of the environment as well as the economic, social and environmental implications of the decision will be defined. Considering the features of the project, different MCDA approaches will be analysed and compared, and the most suitable for synthesizing heterogeneous considerations in order to evaluate and prioritize among different alternatives considering the sustainable framework will be used. To gather all the previous expertise on the topic, regular meetings with health policy makers, experts and educational stakeholders will be carried out together, thus co-creating de sustainability and resilience-based prioritization framework which takes into account different scientific, technical, social, economic, environmental, ethical and political indicators as well as stakeholder interests together with the HVAC-oriented overall risk score.

The validation of the integrated decision support model for the prioritization of HVAC investments will take place among different education institutions, stakeholders and experts to confirm the usefulness of the approach for the decision-makers that will have to exploit the outcomes of the project.

Case study and expected results impact

The IAQ4EDU project uses Spanish educational buildings as a case study. The sample includes 20 schools distributed throughout four different climate zones in Catalonia. In each educational centre 2 classrooms will be continuously monitored during one working day in 3 different periods depending on the HVAC mode: heating mode, cooling mode and neither heating or cooling mode. The monitoring process will last 4 weeks in each period.

Expected results impact

The educational, medical and scientific communities have persistently insisted on the importance of addressing poor ventilation in educational centres as it has been linked not only to many adverse health effects such as transmission of infectious diseases and acute respiratory symptoms, but also to students and teachers' wellbeing, attention and productivity. The crossing of indoor air quality with thermal comfort and energy consumption for natural and mechanical ventilation strategies has not been explored before. The expected results of this project are the following:

- A protocol for CO_2 monitoring in classrooms and teaching spaces.
- Improve knowledge about indoor air quality and ventilation requirements in Spanish educational buildings.
- Identify specific ventilation rates to prevent infections caused by aerosol while maintaining adequate levels of thermal comfort, taking into account the energy efficiency of educational facilities.
- An operating guide intended to help users of educational buildings adopt optimal natural ventilation strategies to ensure an appropriate balance between indoor air quality, thermal comfort and energy efficiency.
- Energy optimizer taking into account indoor air quality, comfort and the tool for estimating the HVAC energy flexibility.
- Establishment of a prioritization framework for decision makers, oriented toward both short- and long-term investments on how, when and where to perform maintenance or improvement schemes, in an informed, profitable and safety-oriented manner. This, considering different technical, social, economic, energy and political indicators along with a novel and integrated overall HVAC-oriented risk score.

Conclusions

Poor ventilation of indoor spaces has been linked to many adverse health effects such as transmission of infectious diseases (i.e. SARS-CoV-2, tuberculosis or rhinovirus) and acute respiratory symptoms. Within education buildings, proper ventilation is also needed to ensure professors and students' wellbeing and improved learning processes. Natural ventilation is highly encouraged to prevent virus' spread and therefore the recommendation is to keep the windows open as long as possible. However, and especially during the cold seasons, users may not always follow opening windows recommendations due to low thermal comfort and thus, compromising indoor air quality. On the contrary, when occupants follow recommendations, energy consumption will increase to reduce thermal discomfort.

This paper presents the IAQ4EDU project, which seeks to optimize ventilation strategies in educational buildings considering indoor air quality, thermal comfort, energy consumption and global costs (including investment and operation costs). Strategies will include (i) just natural ventilation by opening windows and doors, (ii) low-cost mechanical ventilations systems (i.e. ceiling fans or fans installed in the facade), (iii) the implementation of mechanical systems at constant flow or using demand controlled ventilation rates and (iv) hybrid implementation approaches.

To do so, first characterization of indoor air quality in Spanish scholarly centres (i.e. primary and secondary schools and universities) will be performed by means of an experimental campaign measuring indoor environmental parameters (mainly CO_2 concentration levels and temperature) in 40 classrooms located in 20 educational buildings under three different conditioning modes (heating mode, cooling mode and neither heating nor cooling mode). Modelling of potential ventilation strategies and their implications on thermal performance and energy consumption will be carried out through reduced order models. The flexibility potential of building ventilation systems, or what is the same, the capability of changing building energy demand while maintaining the required comfort and safety levels, will also be explored. Finally, a multi-criteria decision-making method will be developed to prioritize ventilation strategies towards both short-term and long-term investments on how, when and where to perform maintenance or upgrade schemes, in an informed, cost-effective and safety-oriented manner.

The IAQ4EDU project is expected to improve the knowledge about indoor air quality and ventilation requirements in Spanish educational buildings. Obtained results will allow the identification of specific ventilation rates to prevent infections caused by aerosol while maintaining adequate levels of thermal comfort, taking into account the energy efficiency of educational facilities. This will be reflected into a detailed operating guide intended to help users of educational facilities adopt optimal natural ventilation strategies to ensure an appropriate balance between indoor air quality, thermal comfort and energy efficiency. Being aware that identifying the most relevant and sustainable maintenance strategies and priorities becomes a critical activity as the gap between the funds available and investment needs widens, an integrated decision support model for the prioritization of HVAC investments in educational buildings will be provided.

The educational community (including teachers, students and families but also educational building maintenance teams) is the main beneficiary of the results expected in the IAQ4EDU project as they will be able to use the operation guide to adopt the optimal natural ventilation strategies to ensure adequate indoor air quality, improve thermal comfort and increase energy efficiency. Public authorities (i.e. public offices related to education and health) and managers of public and private educational buildings (i.e. city councils, educational departments of regional governments and universities) will take advantage of the integrated decision support model for the prioritization of HVAC investments. Reduced order models will be used by companies willing to participate in the electricity market. Building operators will take advantage of the energy optimizer tool by embedding it within existing building energy management systems. The tool to estimate the HVAC energy flexibility will be useful for energy service companies wanting to improve their technical services.

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