Building automation system to control natural ventilation in school buildings. The case study of “Michelangelo School” in Bari

Francesco Iannone*, Giuseppe Carbonara, Alessandro Rinaldi, Marco D’Elia, Guido R. Dell’Osso

Highlights

This work focuses on natural ventilation controlled by a Building Automation System (BAS) with the aim of guarantee adequate levels of Indoor Air Quality (IAQ) in an existing building. The case study is a three-story school building, morphologically complex, located in the suburbs area of Bari, characterized by a Mediterranean climate. The simulations showed how the designed natural ventilation system allow to obtain adequate levels of thermal comfort and IAQ as the climatic conditions and internal energy supply vary, optimizing the ventilation flow rates in relation to the need to limit the energy consumption.

Abstract

In school buildings high levels of Indoor Air Quality are required for the specific susceptibility to airborne pollution of occupants, but most of the data published in the scientific literature indicate that classroom ventilation in many schools is still inadequate. The low investment costs and the easy implementation of the Building Automation Systems allow a widely application in the existing buildings. This work studies the natural ventilation mechanisms based mainly on the stack effect of the central atrium and of the stairwells in order to design the building automation control systems.

Keywords

Building and design techniques, Natural ventilation, Building Automation, Indoor Air Quality, Multizone airflow models

1. INTRODUCTION

In school buildings high levels of performance in terms of Indoor Air Quality (IAQ) are required for the specific susceptibility to airborne pollution of occupants and for the significant time they spend in classrooms [1-9]. In spite of this growing body of evidence, most of the data published in the scientific literature indicate that classroom ventilation in many schools is still inadequate and that the outdoor air supply rates in schools are insufficient, especially during the heating season and in cold climates [1-9, 25-33]. The low investment costs and the easy implementation of the Building Automation Systems (BAS) can allow a widely application in the existing school buildings, usually characterized by the absence of mechanical ventilation systems. BAS

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are generally devoted to the control of active systems, such as the Heating Ventilation Air Conditioning (HVAC) systems. For instance, in [10] an intelligent controller was designed to determine the optimal ventilation rate in active systems, by maintaining the indoor CO₂ concentration in the comfort zone and by reducing energy consumption. Castilla et al. [11] propose a multivariable nonlinear model predictive control system to maintain thermal comfort and IAQ by means of HVAC systems and natural ventilation. Sun et al. [12] present an integrated control of active and passive heating, cooling, lighting, shading and ventilating system with the aim of minimizing total energy costs.

Differently from previous studies, in this study BAS are studied with the goal to reduce thermal discomfort conditions and guarantee IAQ conditions. From this point of view, some studies [13-15] show that it is possible to achieve a significant reduction of energy consumption through the adoption of natural ventilation strategies as an alternative to Air Conditioning (AC) systems. In [16] an interesting application of BAS in school buildings for controlling windows opening/closing based on thermal comfort and IAQ demonstrated good performances in terms of thermal comfort and users’ satisfaction. The case study was located in the city of Ancona in central Italy (latitude: 43°58′49″30 N; longitude: 13°52′57″01 E; altitude: 67 m a.s.l.), characterized by a hot-summer Mediterranean climate (Köppenclimatic classification) and by 1688 heating degree days. The findings were limited to the non-heating period when natural ventilation is not restricted by low outdoor temperature or strong wind. Furthermore, this system was applied to a test classroom, but further insights should take into account the ventilation mechanism of the whole building.

In the last few years, the diffusion of low cost BAS can allow the reduction of the mechanical system usage by means of natural ventilation strategies controlled by a sensor network and control units with programmable logic. These systems can be easy implemented in existing buildings [13, 15].

This work focuses on the definition of natural ventilation control system by BAS with the aim of guarantee adequate levels of IAQ. The case study is a school building of 1990, located in the suburbs area of Bari (latitude: 41°06′03.1″N; longitude: 16°52′45.1″E; altitude: 23 m a.s.l.). Due to the morphological complexity of the building, this work focuses on the study of the ventilation mechanisms based mainly on the stack effect of the central atrium where several classrooms overlook and on two stairwells serving all floors. Several simulations are conducted by TRNSYS/TRNFLOW [17, 18] software by combining dynamic energy simulations and ventilation flow...
rates by means of air flow network model. The simulations showed how the design of the natural ventilation system, based on the air quality and a wider performance of thermo-hygrometric comfort, allow to obtain adequate levels of thermal comfort and IAQ, optimizing the ventilation flow rates in relation to the need to reduce the energy consumption.

2. IAQ IN SCHOOL BUILDINGS

The IAQ plays an important role in the design and management of school buildings due to the high required hygienic conditions to be satisfied in the workplace. Students can be considered a susceptible population due to their age: in fact, compared to adults, children are more vulnerable to environmental pollutants as they breathe more, relative to their body weight, and they are also less well able to deal with toxic chemicals. In addition, considering the age of the users between 8 and 14 years old, children spend almost one third of their life in schools and about 70% of their time inside a classroom during school days [3]. The classrooms are the second most important indoor environment for children, after their homes, where they are exposed to various airborne pollutants to a much greater extent than outdoors [4]. Insufficient air exchange conditions increase the students’ exposure to pathogens coming from healthy or asymptomatic carriers, but also less concentration performance during the lesson hours [5-9]. Some European studies, such as the “Health Effects of the School Environment” (HESE) [2] and the “School Environment and Respiratory Health of Children” (SEARCH) [1] highlighted the close relationship between the indoor pollutants and the respiratory and allergic symptoms. Such symptomatology can significantly compromise the life quality of the students and their academic performance. HESE studies highlighted the relationship between CO₂ levels and the greater risk of nocturnal dry cough and rhinitis. The risk of these diseases is 2-3 times higher for children exposed to a CO₂ concentration higher than 1000 ppm (standard for a good IAQ proposed by the American Society of Heating Refrigeration and Air-Conditioning Engineers – ASHRAE) [19].

It is well documented that IAQ affects the cognitive performance [20-24]. Several experimental studies highlighted that IAQ affects schoolwork. Cross-sectional surveys in 100 classrooms in 100 schools in the USA, based on measured CO₂ levels, showed that poor ventilation reduced the number of pupils managing to pass language and mathematics tests. A linear relationship was found suggesting 3% more pupils passed the tests for every 1 L/s per person increase in ventilation up to 7 L/s per person [21]. Using a multilevel
approach, the effects of classroom ventilation rate and temperature on academic achievement has been estimated in [22]: students’ mean mathematics scores were increased by up to eleven points (0.5%) per each 1 L/s per person increase in ventilation rate within the range of 0.9–7.1 L/s per person.

In Italy, the SIDRIA4 and SIDRIA-2 (Studi Italiani sui Disturbi Respiratori nell’Infanzia e l’Ambiente) [25] projects carried out as part of the international project International Study of Asthma and Allergies in Childhood (ISAAC). Within this last survey, the presence of asthma in 9.5% of children and 10.4% of adolescents has been observed during the school hours. The standard value of maximum CO₂ concentration in school, suggested by ASHRAE, was exceeded in 80% of cases and the average of CO₂ measured concentration was equal to 1900 ppm. Monitoring studies carried out in three schools in Turin recorded CO₂ concentrations systematically higher than 1800 ppm, with peaks close to 3000 ppm after about three hours of the students’ permanence [26]. Several health and hygiene problems of IAQ can be attributed to the indoor conditions of the buildings. Such problems are added to the low level of energy efficiency of most of the school heritage, but also the energy requalification interventions could cause the aggravation of indoor air quality conditions due to the increased air tightness of the newly installed building components.

The Italian school building heritage in the 97% of the cases is equipped with traditional heating systems that do not provide control of the IAQ; in the 22% of cases it is equipped with cooling systems without mechanical ventilation systems [27, 28]. As consequence, the natural ventilation is generally managed by the users causing in most cases poor air quality conditions in the classrooms. This picture is common worldwide, especially in warmest climate. Almost all studies related to school buildings in the Mediterranean area analysed naturally ventilated schools [29-33] and in few cases the mechanical ventilation systems are installed.

In mechanically ventilated schools, IAQ is not influenced by the outdoor conditions, including location of the school (urban or rural) and climatic conditions (wind speed and direction, outdoor temperatures), as well as on window opening behaviour of pupils and teachers [24]. Demand controlled ventilation and heat recovery significantly improve the energy efficiency of a mechanical ventilation system, however the benefits that can be obtained should be subject of specific technical-economic assessments taking into account not only the efficiency of heat recovery (which depends on the climatic context and the exchange rates of air), but also the global costs of replacement costs (influenced by reduced life cycles of mechanical components), the
operational costs (electricity for fans) and the maintenance costs (filters and ducts cleaning).

3. OBJECTIVES AND METHODOLOGY

The objective of this work is the study of a natural ventilation system controlled by BAS within a complex school building with the aim of guarantee adequate IAQ levels in classrooms and energy consumption reduction. The natural ventilation system and the BA logic control are evaluated by dynamic regime with a flow network with concentrated parameters by TRNSYS/TRNFLOW software [17, 18]. The air flow network, for computational simplicity e analysis results, is built by merging into macro areas classrooms with homogeneous orientation characteristics, wind exposure and occupation. The CO$_2$ is assumed as the key performance indicator of air quality, generally considered an appropriate IAQ indicator for environments characterized by a high crowding [19, 34, 35]. For a correct evaluation of thermo-hygrometric and air quality aspects, the management modality, the occupancy profile, the activities and the consequent metabolic level, as well as the plant and technological equipment are taken into account as elements that strongly influence the performance level.

4. THE CASE STUDY

4.1. THE BUILDING DESCRIPTION

The analyzed case study is the “Michelangelo School”, a middle school built in the early 90s. The school building is located in a semi-peripheral area in the south-east of the city of Bari (south of Italy, 1185 heating degree days). The climate is typical of a coastal city of the mediterranean area. The outdoor pollution and noise can be considered low because low-traffic roads are at the boundary. So, it can be argued that IAQ depends mainly on indoor-generated pollutant and that it’s possible to operate natural ventilation for the whole school period if the draught risk is avoided and if the heating power is adequate.

The building is morphologically constituted by two slats configured in L and it consists of three levels above ground for a total surface of about 7000 m$^2$ for about 700 students and 28 classrooms. On the first and the second floors there are classrooms and laboratories, on the raised floor there are administrative offices and spaces for the school community, such as the auditorium and the gym, while in the ground floor there are rooms for specialized teaching,
musical laboratories, environments for school-family communication, storage rooms and the guardian’s home (Figure 1).

From a technological point of view, the solutions adopted are typical of the construction period: walls in lightweight clay hollow brick, aluminum window frames with insulating glass (double glazing). In the first and second floor’s classrooms, the windows have recently been replaced in aluminum with thermal break and low-e double glazing, in accordance with Italian current energy and safety limits, with fixed frames at the bottom, while casement and hopper windows are only in the upper part. The daily inspections in the school building showed that the IAQ control is generally occasional, on the basis of students or teachers’ olfactory perception. The heating system is centralized with a combustion heat generator powered by methane gas and cast iron terminals equipped with thermostatic valves in all the classrooms except the gym and auditorium.

The school building is made up of 35 thermal zones and the classrooms conditions have been examined to simplify the airflow network (Figure 2). The main morphological elements of the natural ventilation system are the central atrium (highlighted in blue in the figure 2), on which stand out part of the raised floor classrooms and first floor classrooms (in cyan) and the two service stairwells of all levels (orange).
Different scenarios have been analyzed with different modes of natural ventilation. The first scenario is the «as built» case (“Scenario 0”), while the other following analysis have been aimed at finding more effective ways of ventilation and control logics related to the CO\textsubscript{2} maximum concentration threshold (assumed equal to 1000 ppm higher than the external one, constant imposition and equal to 350 ppm). To this aim, various configurations of windows opening in the classrooms and the common spaces have been simulated with the aim of guaranteeing a CO\textsubscript{2} concentration lower than the set limit and a number of air change close to the current legal limit in Italy (3.5 ach for middle schools) [36]. When the heating system is off (that is March 31 - June 15 and September 17 - November 15) the discomfort hours for overheating and undercooling in the classrooms have been calculated according to adaptive thermal comfort theory [34, 37, 39]. Due to the variability of the IAQ parameters of interest, the chosen analysis time step is 15 minutes.

In detail, Scenario 2 involves the application of BAS which regulates the windows opening based on two parameters, such as the CO\textsubscript{2} concentration
and the temperature of the classroom. The window will be open if these two conditions are satisfied:

- \( \text{CO}_2 \) concentration > 1000 ppm;
- room temperature > 19.9 °C.

This choice is adopted to prevent the opening of the windows in the colder rooms and the increasing of undercooling discomfort, guaranteeing comfort from the IAQ point of view. The four scenarios are summarized in the following Table 1.

### Table 1. Summary table of ventilation strategy.

For each scenario, the average \( \text{CO}_2 \) concentrations of the 8 classrooms and the number of discomfort hours (limited to the actual classrooms’ occupation hours) have been analyzed and compared to the effective occupation of the school building (1113 hours).

Tables 2 and 3 show the main results of the simulations, divided into the classrooms zones shown in figure 2. Table 2 shows the average \( \text{CO}_2 \) concentration and the value of hourly air changes, Figure 3 shows the comparison between the thermal comfort conditions in Classroom 1_S_2 in “Scenario 0” and “Scenario 1 + B.A.”, while Table 3 adaptive comfort data divided by the overheating and under-cooling risk.

The modelings showed that natural ventilation is mainly due to the stack effect and that the atrium and the two stairwells are essential for the IAQ performance purpose in the classrooms. The outside air, entering from the classrooms on the raised floor and from the classrooms on the first floor, mixes with the unpolluted air present in the distribution spaces, allowing a sufficient dilution of the pollutants for the air exchange in the classrooms on the second floor, to then be expelled to the outside. In particular:

### 5. RESULTS

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• the analysis of “Scenario 0” shows that the manual ventilation cause pollution levels above acceptability set limits, for a significant percentage around of 60% of the building’s actual occupation (Table 2). These results are confirmed by the low number average air change per hour during the occupation, lower than the minimum values prescribed by the regulations in force [36, 38]. This performance is generalized on the whole building, but the classrooms on the second floor are more penalized. This result highlights that natural ventilation performed during breaks is not adequate;

• the analysis of the “Scenario 0 + B.A.” shows that the classrooms’ windows opening managed by the BAS leads to an adequate level of CO₂ average concentration, reducing at the same time the low IAQ number of hours (dropped to about 40%). The ventilation surfaces’ balancing absence determines significant performance differences among the different classrooms penalizing those at the first level;

• the analysis of “Scenario 1 + B.A.” shows the improvements due to an adequate modulation of the opening angles of the classroom’s windows, together with the corridor windows opening on the first and second floor, aimed at the balancing of the incoming and outgoing air flow rates. In detail, pollutants average concentrations are around 700 ppm (for a percentage of discomfort hours equal to 28% of actual occupation hours) and the hourly air changes are in line with the prescribed italian regulations [36,38]. The management of natural ventilation flow rates improves the thermal comfort during the non-heating season, achieving lower risks of overheating. However, the renewal air simultaneously increases the risks of undercooling in the coldest days or in the early hours of the morning (Table 2). The classrooms zone located north on the first floor (1_N_1) is the zone where this system is less effective,
• the “Scenario 2”, hypothesized to reduce the risk of undercooling, leads to a CO₂ concentration in zone 1_N_1 equal to 727 ppm, compared to 618 ppm recorded in scenario 1, and the number of air changes also decreases, from 3.25 l/h to 2.75 l/h. The IAQ performance is lower due to the undersizing of the heating terminal in the zone 1_N_1, as espulsa all’esterno. In particolare:
  • l’analisi dello “Scenario 0” mostra come la ventilazione manuale causa livelli di inquinamento superiori ai limiti di accettabilità, per una percentuale significativa, circa il 60%, dell’effettiva occupazione dell’edificio (Tabella 2). Questi risultati sono confermati dal

![Figure 3. Adaptive thermal comfort in the Zone 1_S_2 in the period 01/04-15/06: comparison of “Scenario 0” and “Scenario 1+B.A.”. Upper and lower limits based on II category [34].](image)

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Table 3. Summary results of thermo-fluid dynamics simulations: adaptive thermal comfort analysis in non-heating season (periods 17/09-15/11 and 01/04-15/06).
a consequence the temperature is sometimes lower than 19.9 °C, then the B.A. system closes the window without taking into account the IAQ leading to an increase in CO₂ concentration. By carrying out a study of adaptive comfort in the non-heating season the double logic set leads to a slight decrease both in the hours of overheating and of the hours of undercooling. Furthermore, there is a reduction of the undercooling conditions, from 129 hours of scenario 1 to 115 hours of scenario 2.

6. CONCLUSIONS

The designed natural ventilation control logics guarantee adequate IAQ conditions in complex buildings, such as the school buildings. This work shows that the management of windows opening by the users can be not effective, both because the smell is susceptible to adaptation in a short time to conditions of poor IAQ, and both because the user is generally unaware and he cannot manage the overall ventilation mechanism of the building. The great increasingly usage of low-cost BAS and the possibility to customize the control logic can give a lot of development of this type of application, implementing controls that take into account a complex set of indoor and outdoor parameters, such as climatic conditions and air pollution. Future developments of this research will focus on refining the control logic in order to differentiate the intervention priority (for IAQ or thermal comfort) depending on the heating system activation and the climatic conditions.

7. REFERENCES


basso numero di ricambi d'aria medi orari durante l'occupazione, inferiori ai valori minimi prescritti dalle normative vigenti [36,38]. Queste prestazioni sono generalizzate sull’intero edificio, più accentuate nelle aule al secondo piano. Questo risultato evidenzia che la ventilazione naturale effettuata durante le pause non risulta adeguata; 
• l’analisi dello “Scenario 0 + B.A.” mostra come l’apertura degli infissi nelle aule gestita dal sistema di B.A. potrebbe portare ad un adeguato livello di concentrazione media di CO₂ riducendo allo stesso tempo il numero di ore di scarsa IAQ (scena a circa il 40%). L’assenza di bilanciamento delle superfici di ventilazione determina notevoli differenze di portata tra le diverse aule penalizzando quelle al primo piano;
• l’analisi dello “Scenario 1 + B.A.” mostra come un’adeguata modulazione degli angoli di apertura degli infissi delle aule, unitamente all’apertura di alcuni infissi negli spazi di connettivo al primo e secondo piano, consenta il bilanciamento delle portate d’aria in entrata e in uscita. In dettaglio, la concentrazione media di inquinante è pari a 700 ppm (per una percentuale di ore di discomft pari al 28% delle ore di occupazione effettiva) e i ricambi orari sono in linea con le normative italiane [36,38]. La gestione delle portate di ventilazione determina un’apertura degli infissi nelle aule gestita dal sistema di B.A. potrebbe portare ad un adeguato livello di concentrazione media di CO₂ riducendo allo stesso tempo il numero di ricambi d’aria medi orari durante l’occupazione, inferiori ai valori minimi prescritti dalle normative vigenti [36,38]. Queste prestazioni sono generalizzate sull’intero edificio, più accentuate nelle aule al secondo piano. Questo risultato evidenzia che la ventilazione naturale effettuata durante le pause non risulta adeguata;
[28] CRESME Ricerche Rapporto RIUSO03 Ristrutturazione edilizia, riquadramento energetica, rigenerazione urbana. (2014)
[34] EN15251:2007, European standard on indoor environmental input parameters for design
and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.


[38] UNI 10339:1995, Impianti aerulici a fini di benessere.