Optimizing Air Ventilation Rates for Indoor Environmental Quality and Energy Consumption

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Abstract: The energy refurbishment of the existing building heritage is one of the pillars of Italian energy policy. Aiming at energy efficiency and energy saving in end uses, there are wide and diversified improvement strategies, which include interventions on the building envelope and Heating, Ventilation, and Air Conditioning (HVAC) systems, with the introduction of renewable energy sources. The research focuses on the evaluation of energy consumptions and Indoor Environmental Quality (IEQ) in buildings, varying the airflow rates handled by the HVAC system. A Case Study (the Aula Magna of a university building) is analysed; an in-situ monitoring campaign was carried out to evaluate the trend of some environmental parameters that are considered to be significant. Additionally, dynamic simulations were carried out, aiming at evaluating the energy savings resulting from the airflow rates reduction. The outcomes of this case study highlight the opportunity to achieve significant energy savings, with only slight variations in IEQ; a 50% reduction in airflow rate would decrease energy consumption by up to 45.2%, while increasing the carbon dioxide concentration from 545 ppm to 655 ppm, while the Particulate Matter and Total Volatile Organic Compounds increase is insignificant.

Keywords: Indoor Environmental Quality; Indoor Air Quality; energy savings; dynamic simulation; monitoring campaign

Introduction

Nowadays, people spend a large part of their time (60–90%) inside buildings [1]; for this reason, the quality of confined spaces is a major concern for healthy indoor environments in Europe and it has a decisive impact on wellbeing of occupants [2] and their productivity [3]. The EE-TC-IAQ (Energy Efficiency-Thermal Comfort-Indoor Air Quality) dilemma represents a significant issue for building design and management [4,5]. Nevertheless, examples of an integrated approach are present, such as [6,7,8], in which attention was simultaneously paid to the reduction of energy consumptions ensuring satisfactory internal environmental conditions.

This paper focuses on energy efficiency measures applied to the HVAC system in a public university building. Such buildings have been demonstrated to have a significant energy savings potential [9]. University and scholastic buildings have, in fact, large energy consumptions and broad occupancy schedules, thus offering several opportunities for efficient refurbishment [10]. The aim of this research is to assess the link between energy consumptions and IEQ through the variation of the airflow rate that is handled by the HVAC system by means of an integrated and holistic approach that covers energy consumption and temperature, relative humidity, and IAQ optimization. Particularly, the research wants to demonstrate the possibility of strongly reducing the energy consumption without heavily affecting the IEQ by adopting a performance-based approach instead of the traditional prescriptive one.

The results of this study can be used to define ventilation strategies, in order to minimize energy consumptions while providing the required IEQ levels. The proposed methodology could be replicated to evaluate similar situations in other university buildings and more generally in buildings equipped with HVAC systems managed by advanced control systems.

Materials and Methods

The target of this work consists in the evaluation of building energy consumptions and IEQ, varying the outdoor airflow rates handled by the HVAC system. The study was carried out integrating two different methodological approaches, namely: i) a dynamic simulation has been carried out for the building energy performance assessment, while ii) an in-situ measurement campaign has been conducted to evaluate the IEQ. Furthermore, the results of the in-situ measurement campaign, in terms of indoor temperature, relative humidity, and electric loads, have been taken as reference for the dynamic model calibration and validation. Dynamic simulation has been used to evaluate the energy consumption as well as the indoor temperature and relative humidity variation in different scenarios.

Regarding the dynamic simulation model, the in-house developed code explained in detail in [11] has been adopted. The model allows to performe single-zone hourly dynamic simulations fully responding to the specific simulation needs of the case study consisting of a single large space.

Regarding the IEQ assessment, a detailed analysis of data was performed that had been gathered by means of in-situ experimental campaigns, during which indoor air temperature, relative humidity, and the concentration of some significant pollutants have been monitored, namely: CO_2; PM_{10}; and, TVOCs. The measured concentrations of indoor air pollutants have been compared to threshold values; the ranges of thresholds concentration may vary, depending on exposure times. In this study, were used the intervals shown in **Table 1** [12], associating them with a synthetic qualitative classification.

Regarding dynamic simulations, four different operating conditions of the HVAC system were simulated, as shown in **Table 2**. Regarding the measurement campaign, only two scenarios have been tested; this is due to the current possibilities offered by the HVAC system consisting of two AHUs. Thus, the measurements were carried out under two different operating conditions: (i) the two AHUs operating simultaneously (Scen. #0); and, (ii) a single AHU operating (Scen. #3).

Table 1. *Measured pollutants: threshold values and classes.*

Classes	CO_2 [ppm]	TVOC [ppm]	PM_{10} [μg/m³]
Hazardous	1501 ÷ 5000	0.431 ÷ 3000	141 ÷ 750
Unhealthy	1001 ÷ 1500	0.262 ÷ 0.430	91 ÷ 140
Moderate	601 ÷ 1000	0.088 ÷ 0.261	31 ÷ 90
Good	340 ÷ 600	0.000 ÷ 0.087	0 ÷ 30

Table 2. *Summary of the analysed scenario.*

Scenario	Relative Airflow Rate	Analysed Parameters	
		Dynamic Simulation	Measurement Campaign
Scen. #0	100%	Energy consumptions; Thermal loads; T, RH	T; RH; CO_2, PM_{10}, TVOC concentrations
Scen. #1	85%	Energy consumptions; Thermal loads; T, RH	–
Scen. #2	70%	Energy consumptions; Thermal loads; T, RH	–
Scen. #3	50%	Energy consumptions; Thermal loads; T, RH	T; RH; CO_2, PM_{10}, TVOC concentrations

Case Study Description

The analysed Case Study is the Aula Magna of Valle Giulia, headquarters of the Faculty of Architecture of the Sapienza University of Rome. It can be considered to be a relevant example for other highly crowded educational buildings, particularly for those buildings of historical heritage in which HVAC or mechanical ventilation systems were installed in a later stage. All the data regarding the building envelope and HVAC system were collected in order to characterise the building energy performance. An abacus of the existing vertical dispersing surfaces was created through non-destructive surveys. The direct wall thicknesses measurement allowed to characterize the stratigraphy of the wall structures; historical sources analysis allowed to reveal the absence of thermal insulation that became mandatory only after the construction of the building. The front walls are made of reinforced concrete masonry and have a thermal transmittance (U) of 1.16 W/m²K. The side walls are made of solid tuff masonry blocks with a U of 1.73 W/m²K. The external roof consists of a mixed slab with a U of 1.66 W/m²K. The floor towards the ground consists of a concrete slab positioned above pebbles and crushed stones; its U value is equal to 1.1 W/m²K.

Regarding the dynamic simulation, the following thermal loads were considered: (i) loads due to the presence of occupants (full room occupation: 50 W/m² [13]); (ii) loads due to the lighting system (LED lighting: 20 W/m², evaluated considering the actual lighting systems as fully radiative); loads due to electrical appliances (14 W/m²: evaluated considering the presence of 1 projector, 500 W, and 50 laptop 90 W each one).

In order to evaluate the seasonal and yearly energy consumptions, the weekly occupancy schedule was set as follows:

- two days with morning lessons (occupancy 9 ÷ 12 a.m., HVAC system operation 8 ÷ 12 a.m.);
- two days with afternoon lessons (occupancy 14 ÷ 17 p.m., HVAC system operation 13 ÷ 17 p.m.); and,
- one conference day (occupancy 9 a.m. ÷ 17 p.m., HVAC system operation 8 a.m.÷ 17 p.m.).

The Aula Magna indoor temperature was set to comply with the standard comfort limits (winter 20°C, 50 % RH, summer 26°C, 50% RH). The Aula Magna is equipped with an external HVAC system, which processes airflow rate of 14,000 m³/h using two AHUs of 7,000 m³/h each. The AHUs consist of a classic configuration (pre-heating coil, adiabatic humidifier, cooling coil, and post-heating coil) and are equipped with a sensible heat recovery unit on the exhaust air.

Results and Discussion

Tables 3 and 4 summarize the results of the simulations carried out, respectively, for winter and summer operation, for each of the four simulated scenarios.

A comparison between the different scenarios shows a general reduction in energy consumptions, being higher during winter and lower during summer. Reducing airflow rate by 50% (scenario #3), during the winter season, energy savings of 58.6% were achieved, while lower savings (28.3%) were achieved during summer. On an annual basis, the savings reached 45.2% in scenario #3, 14.4% in scenario #1, and 27.8% in scenario #2.

Table 3. *Power and energy in winter operation for simulated scenarios.*

	$Q_{heat,average}$ [kW]	$Q_{heat,max}$ [kW]	$E_{heat,TOT}$ [kWh/y]	$P_{el,average}$ [kW]	$P_{el,max}$ [kW]	$E_{el,TOT}$ [kWh/y]	$\Delta E_{el,TOT}$ [%]
Scen. #0	64.46	131.49	36,741	16.87	43.25	9618	
Scen. #1	55.19	112.51	29,417	14.53	37.00	7745	–19.5%
Scen. #2	45.44	93.39	23,176	11.94	30.78	6088	–36.7%
Scen. #3	33.22	71.92	15,315	8.64	24.77	3984	–58.6%

Table 4. *Power and energy in summer operation for simulated scenarios.*

	$Q_{cool,average}$ [kW]	$Q_{cool,max}$ [kW]	$E_{cool,TOT}$ [kWh/y]	$P_{el,average}$ [kW]	$P_{el,max}$ [kW]	$E_{el,TOT}$ [kWh/y]	$\Delta E_{el,TOT}$ [%]
Scen. #0	96.92	178.84	34,817	20.95	48.11	7604	
Scen. #1	85.38	166.34	32,186	18.57	44.71	7000	–7.9%
Scen. #2	75.47	153.85	29,282	16.36	41.31	6349	–16.5%
Scen. #3	62.18	137.19	25,306	13.39	36.77	5451	–28.3%

Measurement Campaign — Summer Operation

The measures were carried out in conjunction with events taking place in the Aula Magna, which provided relevant occupancy values throughout the day. Parallel to the thermo-hygrometric measurements, air quality measurements were carried out by detecting the concentrations of the selected pollutants (CO_2, PM_{10}, TVOC); **Table 5** shows the results of the measurements.

Regarding temperature and relative humidity measurements the HVAC system, operating at nominal flow (Scen. #0), revealed to be able to maintain the environmental parameters within the comfort range. Otherwise, when it operates with a halved flow rate (Scen. #3), the temperature control is still maintained while critical issues have been noted in controlling relative humidity, which tends to higher values sometimes exceeding the comfort range. Indeed, when the flow rate is halved, the system is able to guarantee the thermal power balance, since it does not need to compensate for the maximum sensible load during the tests. Nevertheless, when the flow rate was halved, the system was not always able to guarantee the needed balance of the latent heat. Simulation was used in order to check the maximum load condition (sensible and latent). The simulations confirmed that the system is always able to maintain temperature control, while, as the flow rate decreases, difficulties in controlling relative humidity become evident. With regard to the concentration of CO_2, the value of the average concentration changes from 548 ppm (Scen. #0) to 663 ppm (Scen. #3), corresponding to a worsening of CO_2 index level, which passes from the "good" to the "moderate" value. Regarding PM_{10} and TVOC concentration, there are minimal differences between the two monitored conditions, which remains in both situations "good".

Measurement Campaign — Winter Operation

The measurements related to winter operation, as shown in **Table 6**, were carried out with the same conditions as the ones used for summer operation.

Table 5. *Measurement campaign results—summer operation.*

Date	Occup.	T; RH [°C; %]			CO_2 [ppm]			PM_{10} [µg/m³]			TVOC [ppm]		
		Out	In Sc. #0	In Sc. #3	Out	In Sc. #0	In Sc. #3	Out	In Sc. #0	In Sc. #3	Out	In Sc. #0	In Sc. #3
28/05/2018	250	24; 68.4	25.5; 50.3	26.1; 58.1	344	580	690	41.5	36.7	31.0	0.020	0.023	0.024
08/06/2018	270	27.2; 63	26; 48.9	26; 58.1	340	557	692	23.0	20.0	19.2	0.020	0.016	0.010
11/06/2018	250	28.5; 58.5	25.9; 50	26; 54.3	345	556	669	22.5	20.1	18.8	0.015	0.016	0.022
12/06/2018	250	28.3; 62.5	25.9; 50.7	26.1; 55.5	347	548	664	22.5	19.9	18.0	0.020	0.015	0.010
18/06/2018	300	28.5; 67.5	25.8; 50.1	25.9; 50.5	348	564	691	27.5	23.6	23.5	0.025	0.018	0.018
20/06/2018	250	29.6; 51.8	26; 50.1	25.9; 53.9	349	571	672	25.5	20.6	18.7	0.020	0.014	0.017
26/06/2018	300	28; 47.6	25.4; 49.8	26.1; 49.9	344	583	709	17.5	21.7	21.2	0.020	0.013	0.022
28/06/2018	270	27.2; 43.1	25.6; 48.9	25.9; 50.5	343	578	705	12.0	18.6	17.3	0.020	0.024	0.013
04/07/2018	250	30.3; 68.2	25.8; 49.2	25.9; 51.1	343	499	606	39.5	24.0	22.7	0.020	0.018	0.017
05/07/2018	230	29.8; 66.8	25.6; 48.9	25.9; 50.5	343	497	594	36.5	18.6	17.3	0.025	0.020	0.012
12/07/2018	200	29.2; 57	25.8; 48.9	25.9; 50.5	343	499	602	27.5	25.0	22.8	0.025	0.024	0.015
10/09/2018	250	25.3; 68.4	25.9; 50.7	25.9; 53.5	348	545	663	28.5	22.5	20.0	0.025	0.017	0.010

Table 6. *Measurement campaign results—winter operation.*

Date	Occup.	T; RH [°C; %]			CO_2 [ppm]			PM_{10} [µg/m³]			TVOC [ppm]		
		Out	In Sc. #0	In Sc. #3	Out	In Sc. #0	In Sc. #3	Out	In Sc. #0	In Sc. #3	Out	In Sc. #0	In Sc. #3
07/11/2018	250	14.8; 72	20.8; 50.8	20.8; 50.7	342	573	675	19.5	18.7	20.6	0.020	0.020	0.022
09/11/2018	280	14.7; 68.9	20.8; 50.6	20.8; 50.4	340	569	696	29.5	24.8	19.5	0.020	0.016	0.010
14/11/2018	240	12.1; 69.8	20.2; 50.4	20.4; 50.2	342	549	653	34.5	27.4	24.2	0.015	0.016	0.018
16/11/2018	300	12.6; 64.1	20.2; 50.2	20.5; 50.2	343	554	688	25.5	20.9	17.8	0.020	0.017	0.013
21/11/2018	200	12.9; 77.9	20; 50.6	20.5; 50.9	348	545	638	15.5	17.8	15.3	0.025	0.018	0.018
23/11/2018	220	14.9; 74.3	20.5; 50.1	20.5; 50.1	341	559	658	31.5	20.6	18.7	0.020	0.014	0.017
28/11/2018	280	8.1; 60.2	19.8; 50.1	20.4; 50.4	340	582	705	16.0	15.5	13.2	0.020	0.013	0.014
05/12/2018	300	10.8; 76.7	20.4; 49.6	20.4; 50.1	340	567	702	34.5	26.0	22.8	0.015	0.018	0.012
07/12/2018	250	10.1; 78.1	20.4; 49.3	20.5; 50.8	341	502	604	35.5	24.2	22.2	0.015	0.020	0.015
12/12/2018	270	4.9; 59.7	20.1; 50.1	20.5; 50.5	347	493	599	55.0	35.8	27.3	0.025	0.022	0.017
14/12/2018	180	7.2; 90	20.2; 50	20.4; 50.4	339	501	583	10.0	14.8	11.8	0.015	0.024	0.015
19/12/2018	270	6.9; 73.8	20.1; 50.5	20.3; 50.4	346	534	657	32.5	25.9	23.5	0.025	0.024	0.010
21/12/2018	160	9.8; 78.1	20.1; 49.9	20.4; 50.3	341	480	555	37.5	33.4	31.0	0.025	0.024	0.015

The HVAC system, operating at nominal flow (Scen. #3), is able to maintain the environmental parameters within the comfort range, which confirms what has already been seen for the summer season. However, there is an interesting difference with respect to the summer season; indeed, the HVAC system is able to maintain the environmental parameters within the comfort range, even in half-capacity operation during winter season. During winter, the Aula Magna was never fully occupied. Therefore, it was necessary to check the maximum load condition (sensible and latent) by using simulations whose results confirmed that the system is always able to guarantee temperature and relative humidity control. With regard to the CO_2 concentration, the results confirm what has already been verified during summer operation. The value of the average concentration varies from 539 ppm (Scen. #0) to 647 ppm (Scen.# 3), with a deterioration that affects the level of the carbon dioxide index, which passes from the "good" value to the "moderate" one. Regarding PM_{10} and TVOC concentration, there are minimal differences similarly to what has already been observed during the summer season and indeed both indexes remain within the "good" value.

Conclusions

As expected, simulations proved that reducing the airflow rate the energy consumption would also decrease; by reducing the airflow rate by 50% the energy consumption might be reduced by 28.3% in summer operation and by 58.6% in winter operation. On the other hand, the measurement campaign showed the following results:

- the HVAC system is able to control the indoor temperature, even under conditions of halved airflow rate;
- in summer operation, the relative humidity was increased, due to the lesser ability of the system to dilute the water vapour linked to the decreased airflow rate, but was still acceptable (i.e., 53%);
- in winter operation, the HVAC system was able to maintain the relative humidity within the design range by humidifying the halved external airflow rate to a lesser extent;
- CO_2 concentration with 50% of the nominal airflow rate resulted to be higher, but it was still within the moderate class, namely: it shifted from 539 ppm (good) to 663 ppm (moderate) in summer and from 539 ppm (good) to 647 ppm (moderate) in winter;
- concentration of other pollutants decreases proportionally with the airflow rate.

Hence, it is clear that a decrease in the airflow rate causes a decrease in IEQ; thus, it is required to set a threshold on IEQ level, in order to control the minimum airflow rate accordingly. Precisely, the approach should focus on setting the pollutants concentration instead of setting the airflow rate in order to ensure acceptable energy performance as well as IEQ level [14]. By doing this, the airflow rate should then be evaluated based on the actual occupancy rate in the indoor environment [15]. A building automation control system able to control the HVAC system by means of real-time measures and the evaluation of an omni-comprehensive Indoor Air Quality Index (IAQI) is required to maximise such an approach [12].

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