Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia

Energy Procedia 113 (2017) 151 – 157

International Scientific Conference "Environmental and Climate Technologies", CONECT 2016, 12–14 October 2016, Riga, Latvia

Using a calibrated building energy simulation model to study the effects of improving the ventilation in a school

Hermano Bernardo[a]*, Edgar Quintal[a], Filipe Oliveira[a,b]

[a]INESC Coimbra, DEEC, University of Coimbra, Polo II, Coimbra 3030-290, Portugal
[b]School of Technology and Management, Polytechnic Institute of Leiria, Leiria 2411-901, Portugal

Abstract

This paper aims at presenting the development of a calibrated building energy simulation model of a school building to study the impact of improving the ventilation system on energy performance. The simulation model was developed with the *DesignBuilder*/*Energyplus* software and it was calibrated based on data collected during an energy audit to the school building. Schools need high outdoor airflow rates to remove indoor air contaminants related to occupants and building components, thus requiring mechanical ventilation systems. Due to budget restrictions, school managers decided to schedule the building management system to keep the HVAC systems active only between 6:00 am and 10:00 am. According to the values measured in this school, it was patent that the CO_2 concentration was too high in certain periods. Too high peak values undermine the indoor air quality in the remaining occupancy time of the classroom, harming the work conditions for teachers and students. To solve this problem, an extended usage schedule of the mechanical ventilation was simulated (8:00 am to 5:00 pm) according to the required enhancement of indoor air quality, which together with the adoption of the new calculated fresh air flow rates will enhance air quality while avoiding excessive cost, thus increasing energy efficiency.

Peer-review under responsibility of the scientific committee of the International Scientific Conference "Environmental and Climate Technologies".

Keywords: building energy simulation model; energy efficiency; school building; mechanical ventilation

* Corresponding author: Tel.: +351239851040.
E-mail address: hbernardo@inescc.pt

1876-6102
Peer-review under responsibility of the scientific committee of the International Scientific Conference "Environmental and Climate Technologies".
doi:10.1016/j.egypro.2017.04.044

1. Introduction

For a proper learning environment, school buildings require adequate indoor environmental conditions, including adequate thermal comfort, indoor air quality, lighting, and a quiet atmosphere. In general, energy consumption increases with indoor environmental comfort requirements, which leads to an increase in energy costs [1–3].

Schools need high outdoor airflow rates to remove indoor air contaminants related to occupancy and building components. The ventilation system could be a traditional constant air volume (CAV), operating based on the prescribed number of occupants, or a demand controlled ventilation (DCV) system operating according to the effective occupancy of the rooms [4].

The mechanical ventilation systems of the building studied are CAV and were designed in accordance to Portuguese legislation implemented in 2006 [5], based on European Directive 2002/91/CE [6]. This regulation prescribed fresh air flows rates of 30 to 35 m^3/(h.occupant) for school buildings, depending on the type of space (classroom, library, etc.). Also, these requirements recommend for new buildings an oversizing of 50 % of the fresh air flow rate, in cases where there is no evidence of low level indoor contaminants emissions due to building materials. This leads, in most cases, to excessive air flow rates, corresponding to excessive energy consumption. The former legislation was revised and, in December 2013, it was replaced by a new one, which enables the use of two methods, taking into consideration the building materials' emissions of contaminants and the activity level and physical characteristics of the occupants for each space. The detailed analytical method takes into account the evolution of the predicted CO_2 concentration over a full occupancy day, according to the occupancy profile, the ventilation method and the physical characteristics of the occupants, limiting the average level of CO_2 concentration to 1,250 ppm over a full school day. The use of a prescriptive method, based on reference values established from a simplified application of the detailed analytical method [7, 8] is also allowed.

Due to budget restrictions, the HVAC system operates from 6:00 am to 10:00 am and does not reflect the nominal operation schedules previously considered in the design stage. Moreover, there is a limited use of natural ventilation due to the technical restrictions of the glazing, leading to a poor indoor air quality, mainly in the evening classes period. To address this issue, an extended usage schedule of the mechanical ventilation is proposed (8:00 am to 5:00 pm) in order to enhance IAQ, which together with the adoption of lower fresh air flow rates in classrooms, administrative zone and library, calculated according to the detailed analytical or the prescriptive methods of the recent legislation [7], would tend to increase IAQ while reducing energy consumption [9].

To assess the impact of extending the usage schedule of the mechanical ventilation and reducing the fresh air flow rate in the energy performance of the building, three different scenarios were simulated and compared with the present energy consumption. In scenario A, the mechanical ventilation schedule was extended and the current values of fresh air flow rate were kept. In scenario B, the mechanical ventilation schedule was extended and the fresh air flow rate was calculated according to the prescriptive method. Finally, in scenario C, the mechanical ventilation schedule was extended, but the fresh air flow rate was calculated according to the detailed analytical method.

The dynamic simulation model was developed with the *DesignBuilder/Energyplus* software [10] and it was calibrated based on data collected during an energy audit to the school building. Building energy simulation models provide accurate predictions of energy consumption and indoor thermal comfort of buildings [11]. The data required for simulating an existing building can be extensive, and ensuring the collection of all data required to develop accurate simulation models is fundamental to study energy efficiency improvements [12].

This paper is a specific case application of an innovative approach to compute the fresh air flow rates taking into consideration the building materials' emissions of contaminants and the activity level and physical characteristics of the occupants for each space. The upside of the study is the fact that ventilation can be improved without investment or increase on energy cost.

2. Model development

The secondary school presented in this paper as a case-study is located in the central region of Portugal, with the main facade predominantly facing SE. The school has a gross floor area of approximately 12,283 m^2 and a net floor area of approximately 10,569 m^2.

The building energy simulation model for the case study school was built using the *DesignBuilder* graphical interface to the *EnergyPlus* software. Building geometry was created in *DesignBuilder* from DXF files and on-site observation.

For the construction of the building's model, which was used as a reference model representing the existing building, a set of parameters had to be defined. Amongst these, highlights are on the usage and operation hours' schedules, 24 hours a day, for lighting, occupancy, equipment, fresh air flow rate, mechanical ventilation, heating and cooling [13].

Collecting comprehensive baseline data about the building's energy consumptions and systems' demand is recommended. Not all data collected is necessarily incorporated into the model, but it may be used to assess some specific model accuracy requirements. Thus, all collected information and inputs need to be well organized and documented, in order to allow effective reviews and verifications of the model results [14].

2.1. Weather data

In Portugal, the climate can have three types of influences: Atlantic influence, Mediterranean influence and Continental influence. The climate zone determination was based on monitored weather data and the existing legislation, which defines a division of Portuguese mainland into three Winter climatic zones (I1, I2 e I3) and three Summer climatic zones (V1, V2 e V3).

The climate file used to the work was that of the city of Coimbra, in International Weather for Energy Calculations (IWEC) format, which is, at present, the most similar and nearer to the location of the building. The file is need so that the simulation software generates the weather dependences of building energy consumption.

2.2. Building envelope

Table 1 shows the characteristics of the building envelope and glazing solutions. The heat transfer coefficient, U, of the opaque facade construction solutions was determined based on the building energy performance certificate and the ITE50 publication [15]. Regarding glazing solutions, the U value and the solar factor were estimated by the software CALUMEN [16], which is distributed by the glazing manufacturer Saint-Gobain.

Table 1. Building envelope and glazing characteristics.

Description	U, $W/m^2.ºC$	Solar factor
External brick wall	0.38 – 0.46	–
External concrete wall	0.36	–
Flat roof	0.28 – 0.36	–
Pitched roof	0.29 – 0.45	–
External brick wall	0.38 – 0.46	–
Double glazed thermal break aluminium frame	1.4	0.27 – 0.45
Double glazed thermal break aluminium frame (laminated glass)	1.5	0.27 – 0.45

2.3. HVAC systems

The HVAC solutions installed in the school are fairly diverse in terms of technology and usage profile. Table 2 shows the main characteristics of the HVAC systems in use in each space. Thermal energy distribution depends mostly on the respective source. In most cases, fan coil units are used, with wall and/or ceiling units. Air renovation in spaces is, as a rule, provided by air handling units (AHU) that include, in some cases, heating and/or cooling coils.

Table 2. HVAC systems per space.

Block	HVAC system
A+A1	Classrooms and laboratories: air-water heat pump with 274 kW for heating and 255 kW for cooling; Offices and administrative spaces: modular variable refrigerant volume (VRV) system with direct expansion heat-pump.
B+B1	All spaces: modular variable refrigerant volume (VRV) system with direct expansion heat pump.
C+C1+C2	Student's extra-curricular rooms: dedicated multi-split system; Medical office: individual split system unit.
D+D1	Meals hall: rooftop unit with an air-air heat pump, equipped with free-cooling unit and energy recovery system. Domestic hot water production (DHW): two natural gas fired boilers, each one with 85kW of power output, supported by 16 solar thermal collectors, with a total installed surface of 40.3 m^2.
E+E1	Laboratories and workshops: Air-water heat pump with 87.7 kW for heating power and 77 kW for cooling power.
F	Library and auditorium: Rooftop unit with an air-air heat pump, equipped with free-cooling unit and energy recovery system.

The HVAC system modulation was implemented using the "Simple HVAC" option in the DesignBuilder software, where energy consumption is computed considering seasonal CoP for thermal energy production (heat pumps, VRV, boilers, etc.).

2.4. Thermal zones and internal loads

Due to the building's size, some geometric simplifications were made in order to keep its geometry as simple as possible, without compromising accuracy. The summary of the internal loads considered for each typology of activity is shown on Table 3.

Table 3. Summary of internal loads considered by typology of usage activity.

Typology of activity	Number of thermal zones	Net floor area, m^2	Occupancy, occ/m^2	Lighting, W/m^2	Equipment, W/m^2
Administrative office space	3	334.65	0.06	7.40	7.05
Low occupancy	20	1,076.01	0.10	8.75	3.00
Library	1	328.08	0.11	6.74	9.39
Technical facilities	1	51.65	0.10	5.69	0.00
Circulation area	18	3,159.31	0.10	3.98	0.19
General classrooms	15	2,234.03	0.42	7.81	12.18
Electronics laboratory	2	319.65	0.31	8.74	9.07
Mechanics laboratory	5	696.93	0.10	8.37	3.23
ICT laboratory	2	450.40	0.39	8.27	23.31
Science laboratory	2	610.25	0.31	6.06	7.62
Kitchen facilities	1	108.60	0.05	5.87	195.00
Meals hall	1	192.65	0.10	8.14	0.00
Cafeteria	1	54.20	0.09	3.62	0.00
Sports hall	1	702.25	0.21	7.12	0.00
Toilets	8	171.15	0.08	12.64	0.00
Changing room with showers	1	227.35	0.11	5.48	0.00

Similar indoor spaces with the same geographical orientation, HVAC system, activity and occupancy schedule were grouped together into 83 different Thermal Equivalent Zones (TEZ). In each TEZ, internal load information was gathered, related to occupancy density, lighting power density, computer power density and fresh air flow rate. The power density of the kitchen catering equipment was also gathered.

3. Results and discussion

3.1. Model validation

In the process of calibrating the building energy simulation model, several input parameters, such as equipment and internal load power density, building envelope characteristics, HVAC parameters, usage and occupation schedules, amongst others, have to be adjusted to actual operation conditions of the building.

The calibration process of the model for existing buildings is accomplished by adjusting simulation input parameters to actual operating conditions and comparing simulation results with whole-building and/or end-use data until the model is considered calibrated according to some defined criteria. The common statistical indices used as calibration criteria for assessing model accuracy are the mean bias error (MBE) and the coefficient of variation of the root mean squared error CV(RMSE). The MBE indicates how close the energy consumption predicted by the model is to measured data. Positive values indicate that the model overpredicts actual values; negative values indicate that the model underpredicts actual values. However, it is subject to cancellation errors, where the combination of positive and negative values contributes to reduce MBE.

To account for cancellation errors, the CV(RSME) is also needed. This value is always positive and indicates the overall uncertainty in the prediction of whole-building energy consumption. The lower the CV(RSME), the better the calibration.

Comparing energy use predicted by the building model with monthly utility bills is the minimum level of calibration that should be conducted on any model of an existing building with monthly utility data available. When using monthly data, an additional check of the monthly variances should be made by calculating the MBE defining both the interval and the period as a month. The ASHRAE Guideline 14–2014 [17] stipulates that the calibrated computer simulation model should be accurate to within ± 5 % for the MBE and 15 % for CV(RMSE) relative to monthly measured data. The model was considered calibrated when the results presented on Table 4 were obtained.

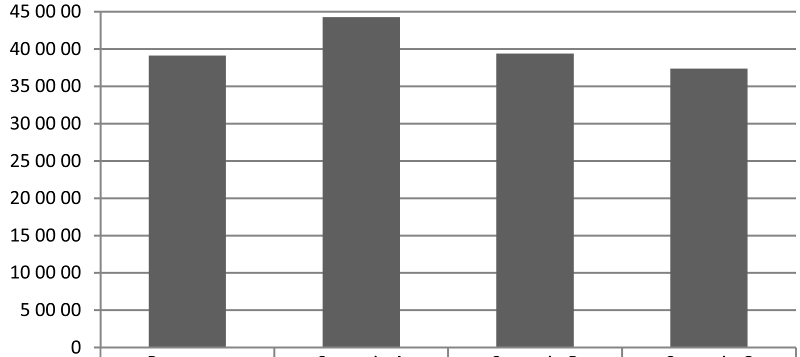
Table 4. Comparison of measured and simulated annual energy consumption.

Month	Measured energy consumption, kWh	Simulated energy consumption, kWh
Jan	47,008.0	42,036.1
Feb	39,481.0	37,095.2
Mar	33,397.0	32,432.8
Apr	32 019,0	34,314.5
May	32,724.0	35,017.7
Jun	27,994.0	30,302.4
Jul	22,177.0	22,903.3
Aug	20,859.0	19,619.4
Sep	29,888.0	30,561.9
Oct	36,273.0	36,579.8
Nov	39,109.0	39,529.4
Dec	32,680.0	30,799.2
Total	393,609.0	391,191.8
MBE = 1 %; CV(RMSE) = 6 %		

Comparing the energy consumption predicted by the building model with the monthly utility bills, there is a MBE of 1 % and a CV(RMSE) of 6 %, which complies with ASHRAE Guideline 14–2014 concerning monthly measured energy data.

3.2. Improvement of the mechanical ventilation system

Fig. 1 presents the comparison of the final results obtained through the simulated scenarios of extending the schedule of mechanical ventilation system.



	Base case	Scenario A	Scenario B	Scenario C
Energy consumption, kWh	39 11 92	44 26 28	39 38 62	37 35 81
Difference to base case	0,00%	13,10%	0,68%	-4,50%

Fig. 1. Summary of the results of presented scenarios simulations.

It is clear that scenario A leads to an expected increase in the energy consumption (13.1 %), since fresh air flow rates were kept in the current values. Scenario B, in which there was an average decrease of 34 % in the fresh air flow rate calculated according to the prescriptive method with respect to the current situation, resulted in an annual energy consumption which is approximately the same as the base case, but with the advantage of extending the working period of the ventilation system (8:00 am to 5:00 pm) and thus improving IAQ. Performing the calculation of fresh air flow rates using the detailed analytical method, in scenario C, with an average reduction of 84 % of fresh air flow rates with respect to the current situation, results in an energy consumption reduction of 4.5 % in the same extended working period (8:00 am to 5:00 pm).

4. Conclusions and final remarks

School buildings require high fresh air flow rates to remove indoor air contaminants related to occupants and building components, which increase the energy consumption and, thus the related operation costs. However, as it was demonstrated throughout the present paper, it is possible to achieve a balance between fresh air flow rates, according to methodologies prescribed in recent legislation, and the operating hours of the mechanical ventilation system, in order to achieve at least the same energy consumption while keeping the system working longer hours, instead of simply turn it off earlier and maintaining the original fresh air flow rates.

In future projects, the implementation of demand controlled ventilation is strongly recommended, through the use of CO_2 sensors to reset airflow intake in response to space occupancy levels, by reducing room airflow and lowering the use of outside air that needs to be heated or cooled to meet indoor thermal requirements. Nevertheless, natural ventilation is a possibility that should always be taken into account when designing school buildings.

The use of calibrated building energy simulated models proved to be useful to assess the impact of building technical systems improvements on energy performance, also supporting the choice of the most cost-effective retrofitting measures.

Acknowledgements

This work was developed under the Energy for Sustainability Initiative of the University of Coimbra and supported by 3Es - Energy Efficiency in Schools project and Fundação para a Ciência e a Tecnologia (FCT) under project grant UID/MULTI/00308/2013.

References

[1] Becker R, Goldberger I, Paciuk M. Improving Energy Performance of School Buildings While Ensuring Indoor Air Quality Ventilation. Build. Environ. 2007;42:3261–3276.
[2] Hong SM, Paterson G, Mumovic D, Steadman P. Improved benchmarking comparability for energy consumption in schools. Build. Res. Inf. 2014;42:47–61.
[3] Asere L, Mols T, Blumberga A. Assessment of Energy Efficiency Measures on Indoor Air Quality and Microclimate in Buildings of Liepaja Municipality. Energy Procedia 2016;95:37–42.
[4] Wachenfeldt BJ, Mysen M, Schild PG. Air flow rates and energy saving potential in schools with demand-controlled displacement ventilation. Energy Build. 2007:39:1073–1079.
[5] Decreto-Lei n.o 79/2006. [in Portuguese: Regulamento dos Sistemas Energéticos de Climatização em Edifícios (RSECE))]. Diário da República N.o 67, I série-A. Lisboa; 2006.
[6] 2002/91/EC, Directive of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. Official Journal of the European Communities. Belgium; 2002.
[7] Portaria n. 353-A/2013. [in Portuguese: Regulamento de Desempenho Energético dos Edifícios de Comércio e Serviços (RECS) - Requisitos de Ventilação e Qualidade do Ar Interior]. Diário da República, vol. 1.a série. Lisboa; 2013.
[8] Gameiro da Silva MC, Costa JJ, Pinto A, Margarida A, Santos P. The definition of ventilation requirements in the recent revision of Portuguese regulation. In the Proceeding of Energy for Sustainability 2013 - Sustainable Cities: Designing for People and the Planet, Portugal, Coimbra, 8–10 September, 2013.
[9] Pereira LD, Correia N, Gaspar, Gameiro da Silva MC. The impact of ventilation requirements on energy consumption in school buildings. In the Proceeedings of the 13rd SCANVAC International Conference on Air Distribution in Rooms – Roomvent 2014, Brazil, Sao Paulo, 19–22 October, 2014.
[10] DesignBuilder Software Ltd, “DesignBuilder: Design Simulation Package V3.” 2013.
[11] Alajmi A. Energy audit of an educational building in a hot summer climate. Energy Build. 2012;47:122–130.
[12] Kovac M, Kovacova K. Simulation of energy demand for HVAC in a shopping centre - Case study. Energy Procedia 2015;78:1105–1110.
[13] Roriz L. Climatização – Concepção, Instalação e Condução de Sistemas. Edições Orion; 2006.
[14] Penna P, Schmiedhofer S, Cappelletti F, Gasparella A, Tahmasebi F,Mahdavi A. A multi-stages approach to the calibration of a school building’s simulation model. In the proceedings of the 14th International Conference of the International Building Performance Simulation Association (IBPSA), India, Hyderabab, 7–9 December, 2015.
[15] Pina dos Santos CA, Matias L. Coeficientes de transmissão térmica de elementos da envolvente dos edifícios. Lisboa: ITE 50; 2006.
[16] Saint-Gobain. Calumen II – v. 1.3.3.; 2012.
[17] ASHRAE Guideline 14-2014: Measurement of Energy, Demand and Water Savings. USA, 2014.