#5213

Energy and Buildings, *17* (1991) 87–96

Demand controlled ventilation by room CO_2 concentration: a comparison of simulated energy savings in an auditorium space

B. F. Warren and **N. C. Harper**

School of Architecture, University of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU (U.K.)

(Received August 4, 1990; accepted September 26, 1990; in revised form December 11, 1990)

Abstract

The investigation models the energy savings which can be made if the ventilation rates supplied to an auditorium located in a U.K. urban environment are controlled in response to CO_2 concentration. Ventilation profiles based on CO_2 concentration levels, generated from a step-by-step integration pre-processor, are supplied to a dynamic thermal simulation computer program which models a space with fluctuating occupancy levels. The simulations suggest that heating energy savings of as much as 50% may be achieved where auditoria currently using 100% fresh air ventilation systems are retrofitted to incorporate CO_2 controlled ventilation.

Introduction

It is generally accepted that considerable energy savings can be made if the ventilation supplied to buildings is no more than is necessary to maintain a healthy environment for the occupants [1]. It is also recognized that in mechanically ventilated buildings, the design ventilation rates are normally based on a maximum occupancy condition and that, for much of the time, occupation levels may be well below this value. In addition, the air supply by infiltration may, under certain conditions, satisfy the occupation requirements.

Several methods of relating the ventilation rate to the occupation level have been proposed and are currently being used in certain buildings, which in effect attempt to adjust the ventilation rate in direct proportion to the number of people [2]. The ventilation rate per person is normally selected by the designer in accordance with recommended practice [3] and the control system would seek to maintain this quantity irrespective of variations in the occupancy level. One method on which variable fresh air control is based is to use the carbon dioxide emitted by the occupants as a measure of occupation level. Various theoretical papers have been published on this control method [4] with, in some cases, reports of field trials [5–7], though not, to the authors' knowledge, in the U.K.

In the U.K., two buildings, a Bingo Hall and a Cinema operated by Top Rank, have had their heating and ventilating systems modified to incorporate CO_2 controlled ventilation. These buildings have both been monitored by others (The ECD Partnership) under an Energy Technology Support Unit (ETSU) contract [8] to determine their energy savings. The report on the monitoring of one of these buildings, the Bingo Hall, has been made available to the authors and information from this report has been used to provide input data for an energy prediction model to assess the possible theoretical energy savings [9]. Since the monitoring was not carried out by the authors and was directed primarily towards measuring energy use, the information available was limited. Some assumptions, therefore, had to be made where some data required for modelling purposes were not specifically available.

The building context

Located in Hounslow, London, the Bingo Hall [10], chosen to provide input data for this study, is typical of 1930s cinema architecture, comprising a large central auditorium

0378-7788/91/$3.50

© 1991 — Elsevier Sequoia, Lausanne

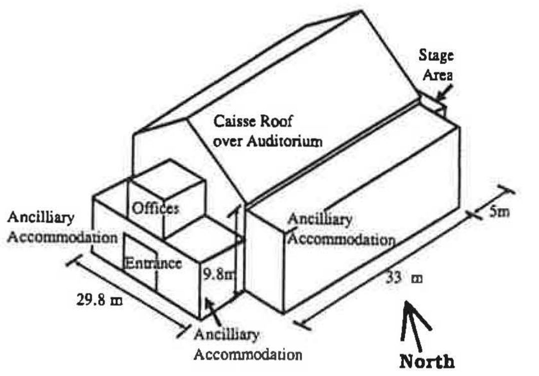


Fig. 1. Diagrammatic layout of hall accommodation. The main auditorium simulated has ancilliary accommodation on three sides.

rising through surrounding ancillary accommodation. Figure 1 shows the general arrangement of the hall for modelling purposes.

The auditorium is linked at a short edge to a deep, lobbied foyer which allows circulation to accommodation such as toilets, offices, stores and projection facilities, some of which are on an upper floor. The hall has further accommodation at two other edges, leaving one large wall and three surface patches on the short walls exposed to external influences. Other significant spaces are the open stage area, an adjacent refreshment area, and the pitched roof void which is asbestos sheeted externally. It is a framed structure clad mainly in solid three-leaf-thick brickwork.

The original heating and ventilating arrangements consisted of a radiator system designed to compensate for fabric losses and a low velocity 100% fresh air ventilation system comprising filters, centrifugal inlet fan and heater battery, and a separate centrifugal exhaust fan. Originally the radiators were uncontrolled and the heater battery was controlled via a sensor in the exhaust duct.

The system was modified by the introduction of four sets of opposed blade dampers, a main and subsidiary set in the supply ducting and a similar arrangement in the exhaust (Fig. 2). Control of the main supply and exhaust dampers was by means of a CO_2 sensor/controller which enabled them to be modulated to any position between closed and fully open to attempt to satisfy the CO_2 concentration set point selected on the controller. Sensing of CO_2 concentration was carried out in the exhaust duct, using a Horiba indoor CO_2 monitor model APBA 200 E. The subsidiary dampers in the supply and exhaust were controlled so as to open fully and remain open as soon as the fans were switched on, in order to provide a minimum amount of fresh air for ventilation and heat distribution purposes. Modulation of fresh air could thus be achieved between the minimum, with the two subsidiary dampers open, and the maximum, with all dampers open. At night with the fans off, all dampers were shut to reduce convective airflow through the system. The temperature control system was able to override the CO_2 control should free cooling be required in the summer.

The CO_2 controller was set at approximately 1000 ppm which would correspond to approximately 28 m^3/h per person. This figure was stated in the report of the field trials as being current practice for places of entertainment and corresponds to the current CIBSE Guide figure of 8 litres/second per person. The maximum fresh air flow rate was reported as being measured at 5.02 m^3/s, which would

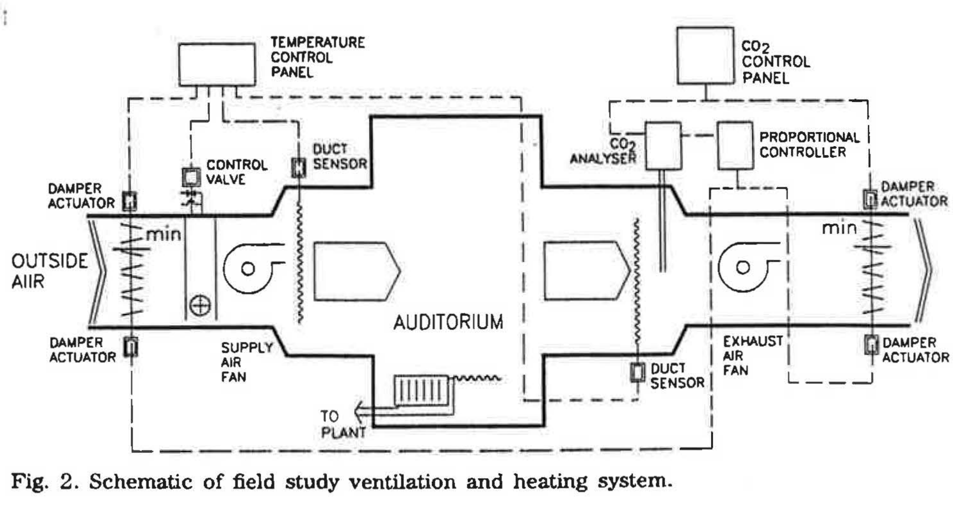


Fig. 2. Schematic of field study ventilation and heating system.

satisfy approximately 650 people, and the minimum 3.77 m^3/s.

Modifications to the temperature control system included the fitting of thermostatic radiator valves and an arrangement to increase the set point of the fresh air supply should the auditorium temperature fall. Typically the controller was set to provide air at 22 °C when the auditorium temperature was 20 °C and 42 °C should the auditorium temperature fall to 17 °C. The treatment of this arrangement is discussed later in the Section 'Simulation package'.

The basis of the ECD tests was to measure energy consumption over a 26-week period from mid-November to the end of May. During this period, the building was operated for alternate weeks with and without CO_2 controlled ventilation. Energy consumptions for the whole building were obtained from the main gas meter readings whilst the heater battery output was determined using a heat meter. No measurement was made of the radiator energy use. Internal temperatures were recorded at two representative positions in the auditorium and weather data in the form of daily maximum and minimum air temperatures were obtained from the London Weather Centre, the latter being used to calculate degree-days to base 15.5 °C. Presumably it was not considered necessary to obtain wind speed or solar radiation measurements as these would have had little effect on this virtually windowless building.

Maximum and minimum airflows were measured during site visits and the occupancy levels obtained from ticket office records. Spot measurements of the CO_2 concentration and occupancy level were used to make an estimate of the total fresh airflow. The measured fan flow was then subtracted from this figure to provide an estimate of the infiltration rate.

The field-trial energy savings were calculated by obtaining the linear correlation (least squares method) between weekly gas use and degree-days with and without the variable ventilation system and using the correlations to extrapolate the measurements to cover a full year of fuel use in both modes. The difference in energy consumption between the two modes gives the savings due to the variable ventilation system.

The calculations were carried out using degree-days to base 15.5 °C to obtain the energy savings and on this basis the saving was reported as being 17%.

Simulations

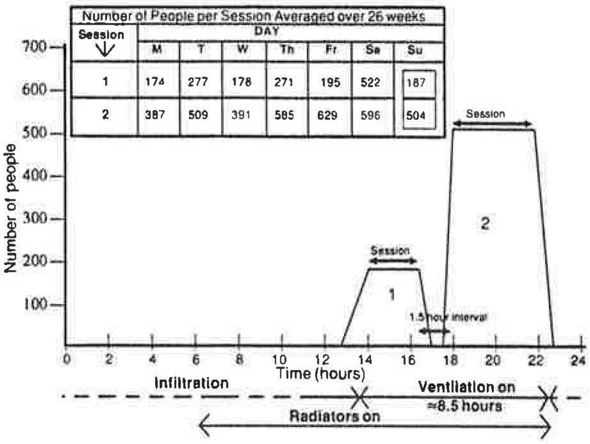
The ECD Partnership carried out the field tests with one major objective in mind, to assess energy savings for a particular building and system over a particular operation regime. Computer simulations, however, allow a number of repeatable scenarios to be investigated over a range of conditions. In order to achieve credible results, it is necessary to supply input data which in itself has the benefit of being derived from a real situation.

As well as the constructional information, some of the operational data from the field trials were used as guidelines for simulations of the main auditorium. These were measured maximum and minimum mechanical airflows, infiltration rates, internal temperature conditions, session starts and finishes, and deduced average fan on-time. Values used were as follows:

maximum airflow 5.02 m^3/s
minimum airflow 3.77 m^3/s
infiltration rate 0.4 ach
mean internal temperature 19.3 °C
session start (1) 14:00 (2) 18:00 (doors open at 12:00 and 17:00)
sessions finish (1) 16:30 (2) 22:00
mean fan operation period 8.5 hours

Additional information required, such as incidental gains due to lighting and equipment, was not available from the field trials and was calculated on the basis of standard practice for the simulations [11]. The occupants' gains allowed for were 95 and 45 watts, sensible and latent, per person, together with radiant-to-convective split factors of 0.2 to 0.8. The occupancy gains were profiled to the appropriate weekday, Saturday, and Sunday levels.

Lighting for this type of building which combines overall and local lighting together with stage lighting effects was assessed at 23 watts/m^2 of occupied floor area, with a radiant/convective split of 0.5/0.5. The latter proportion was also allowed for in the equipment loading for refreshments and the bingo console. The *incoming* ventilation fan consumption at 3 kW was accounted for with a 0.1/0.9 split of radiant to convective gains.



Number of People per Session Averaged over 26 weeks							
Session	DAY						
	M	T	W	Th	Fr	Sa	Su
1	174	277	178	271	195	522	187
2	387	509	391	585	629	596	504

Fig. 3. Occupancy profile for a typical Sunday. The building is occupied for periods longer than the two sessions. The Table shows daily occupations for each session averaged over the heating season.

Although most of the input data for the simulations was available from the field trials, the occupation figures were only on a weekly basis whereas the simulation required typical daily occupation profiles, taking into account the fact that there were two bingo sessions per day. The information provided, however, enabled the average total weekly admission over the test period to be obtained. In addition to this, the owners Top Rank supplied a breakdown of admissions for an average week in the heating season and information regarding the rate of filling and emptying of the hall for each Bingo session. This data, together with the measured average weekly admissions, was used to construct profiles for typical Saturdays, Sundays and weekdays for the measurement period. Figure 3 illustrates the complete profile for a typical Sunday shown in relation to the system operation, and Bingo session periods.

Although the air component of the energy supplied to the hall was measured, it was not possible to separate out the total energy to the hall since the heat to the radiators was unknown.

Pre-simulation

The field trials and assumptions provided the data on which to base the simulations but it was necessary to carry out some pre-simulation work to determine the relationship between CO_2 concentration, mechanical ventilation rate, and the occupation pattern.

The rate of change of CO_2 concentration is given by [12]:

$$\frac{\delta C_r}{\delta t} = \frac{G \cdot N(t)}{V} + \frac{R(t)}{V} \cdot (C_o - C_r)$$

where G is the CO_2 output per person, V is the volume of the space, C_r and C_o the respective inside and outside CO_2 concentrations, N the number of people, and R the ventilation rate in m^3/s. The values of G and C_o were taken as constant, being 4.7×10^{-6} m^3/s [13] (280 cm^3/min [14]) and 3.1×10^{-4} m^3/s, respectively. The generally accepted figure for outside air CO_2 concentration is 3×10^{-4} m^3/s [13] but will vary slightly depending upon local conditions. Measurements at urban locations in Newcastle upon Tyne gave an average figure of 3.1×10^{-4} m^3/s and, in the absence of Hounslow data, this has been taken as being representative of the site. The volume of the space was estimated from the drawings of the building as 11 150 m^3.

By using step-by-step integration in conjunction with the occupancy and system operation profiles, values of CO_2 concentration were determined over the occupation periods. Since at any time during the integration *either* the ventilation *or* the CO_2 concentration was known, it was possible to determine C_r and R to build up profiles of ventilation rate and CO_2 concentration. Should the computed CO_2 concentration tend to exceed the control limit, set as 1000 ppm, then the ventilation rate was increased accordingly to maintain this value.

Simulation package

Simulations using the Environmental Systems Performance package (ESP) [15] were carried out using data available from the field tests together with the synthesized ventilation profiles. ESP is a transient energy simulation system which models the energy flows within combined building and plant systems using an implicit finite difference technique [16].

The main simulation engine uses files of data comprising the geometry, construction, operation, zonal configuration, and systems control information. Having established the *geometry* and *construction* data for all the zones and their surfaces, the *operations* file sets up the ventilation rates and casual gains patterns for weekdays, Saturdays, and Sundays

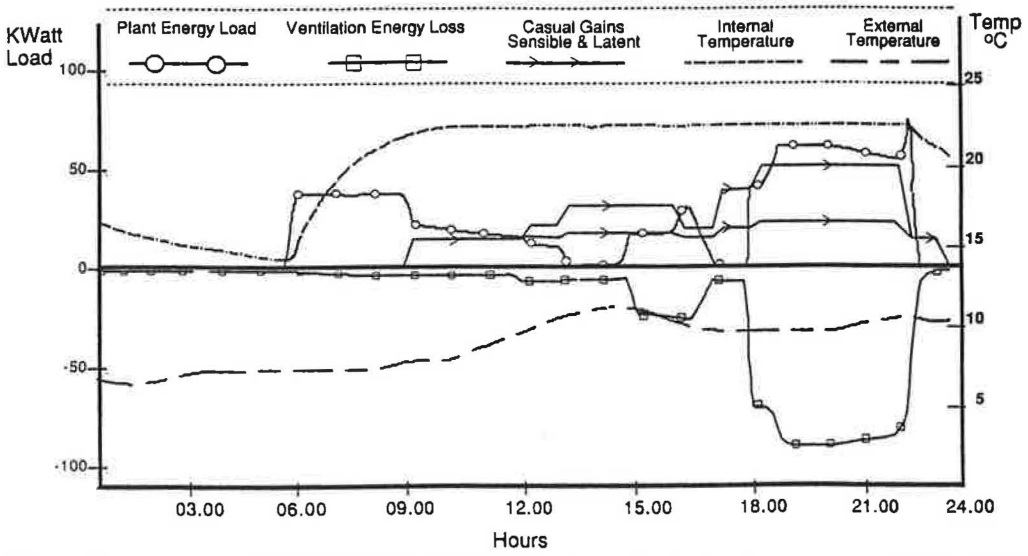


Fig. 4. Typical form of ESP graphical output. The graph illustrates internal and external temperatures, ventilation energy loss using variable ventilation from 0 to maximum air change rates, and energy inputs from plant, occupants and equipment. (Some annotation has been added.)

for each zone. The *system configuration* file contains site details, the building's participating zones, the construction data, any plant components used, and finally how the building zones and plant interlock.

The system configuration file together with the *system control* file which specifies plant on/off times, loadings, sensor and actuator locations, set points and any daily or weekday/weekend patterns, allows the user to simulate a large range of conditions with simple file editing prior to any simulation during which the appropriate files are picked up. The user defines which control file is to be used, the simulation time-step, the calendar simulation period, and the output detail required. The output detail may range from temperature profiles only, or energy inputs and outputs, to sets of intra-constructional temperatures plotted through any multi-layered construction. The output file may then be interrogated in a variety of ways to produce tabulations, or plots which can be overlaid to the user's requirements. Other selectable options enable statistical analyses to be carried out on specified data sets. Figure 4 shows the format of a typical output sheet, with some additional annotation.

The ESP package caters for the user-generated input of simulation time-step values of solar radiation, airflows, casual gains, shading/insolation, blind/shutter controls, surface view factors, and other aspects of simulation which may go beyond the default routines. In the case of this study, the control of CO_2 levels through modulation of ventilation rates was modelled through the use of an airflow file containing the air change rate information for each simulation time-step.

In the simulations carried out, the simulation time-steps were eight per hour and a complete heating season from November to April was simulated. The built-in weather-train of ESP [17], based upon Kew was used (being geographically very close to the site in Hounslow) and was a good match in terms of degree-days. The output option chosen included information about internal temperature profiles, energy inputs and outputs, which included a breakdown of building/plant gains and losses.

While the whole building's thermo-physical properties were derived from the drawings, the main assembly hall volume was investigated in detail. The average temperatures of the hall's adjacent zones, including the roof space, were arrived at from simulations undertaken prior to the main study.

The main simulations assume 'perfect' control, that is, the heating had immediate response and there was no deviation from the set point. Without CO_2 control, the interaction of the heating and ventilating system set points, sensors and controls could be modelled by ESP. However, CO_2 control required the airflows to be determined at each 7.5 min time-step, and

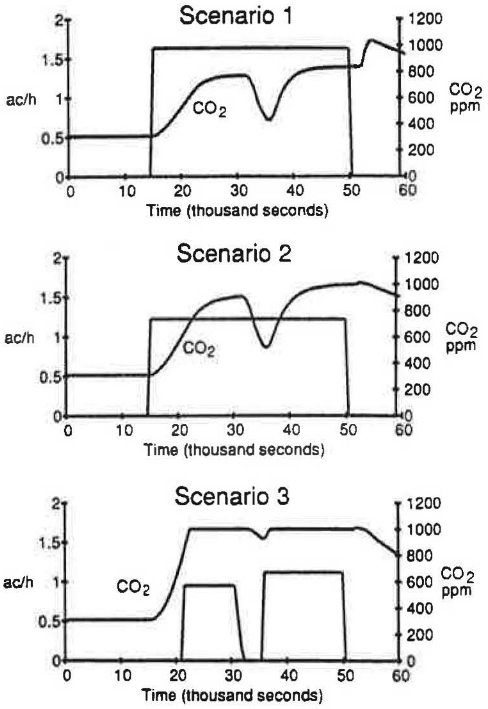


Fig. 5. Comparison of CO_2 levels due to ventilation control strategies for a typical Saturday. A CO_2 controlled strategy aims to maintain a concentration of approximately 1000 ppm. The effect of different schemes of ventilation modulation are clearly shown together with the pattern given by the filling and emptying of the building.

thus they could not be varied dynamically to achieve temperature set points. The choice of simulation period — the heating season — allowed the heater battery and radiator systems to be seen as a single system instantaneously responding to the energy demands of the hall. This gives 'perfect' control at the set points without needing ventilation over and above that already prescribed. To model the complete interaction necessary over longer simulation periods would require the CO_2 algorithms to be built into the program's source code. Integration of new code in the package was considered to be inadvisable whilst ESP was undergoing revisions and validation.

Three simulation scenarios were adopted as follows:

- *Scenario* 1. The ventilation rate was maintained at its maximum level to simulate the original Bingo Hall condition with no CO_2 control.
- *Scenario* 2. In this scenario the ventilation rate was modulated between its minimum and maximum values under the action of CO_2 control to provide a check with the field trials.
- *Scenario* 3. The fully controlled condition when the ventilation was modulated from zero to maximum in order to maintain the CO_2 concentration at a selected value (1000 ppm).

This last scenario simulated the best condition achievable with no minimum ventilation rate constraint; that is, the ventilation rate would always be appropriate to the number of people. It would apply in the case of a hall having its own heating and ventilation system with full modulation on fresh air *and* recirculation.

Figure 5 illustrates the computed ventilation rates and associated CO_2 concentrations respectively for each control strategy for a typical Saturday.

Results

Pre-simulation

The occupancy profiles previously constructed were used in the pre-simulation work to compute the ventilation rate and CO_2 concentration profiles for each control scenario.

From Figure 5 it can be seen that in the original control configuration, scenario 1, the fixed ventilation rate of 1.6 ach resulted in CO_2 concentrations during occupation which never exceeded about 820 ppm.

It was reported that during the field trials the ventilation with the CO_2 control system installed rarely exceeded the minimum value presumably because the occupation density was never very high. The scenario 2 pre-simulation results confirmed this observation in that the minimum ventilation rate was always sufficient to ensure that the CO_2 concentration never exceeded the control setting of 1000 ppm with the occupation pattern used. This result implied that the building physical and operational data used and the approach to the pre-simulation stage could be treated with a reasonable amount of confidence.

The results from scenario 3, with the ventilation rate allowed to modulate smoothly between zero and the maximum clearly show that the CO_2 concentration setting of 1000 ppm can be maintained with ventilation rates always below the minimum figure used in the field trials. The similarity of the ventilation profile to the occupancy profile shows how a perfect control system would respond to occupation levels.

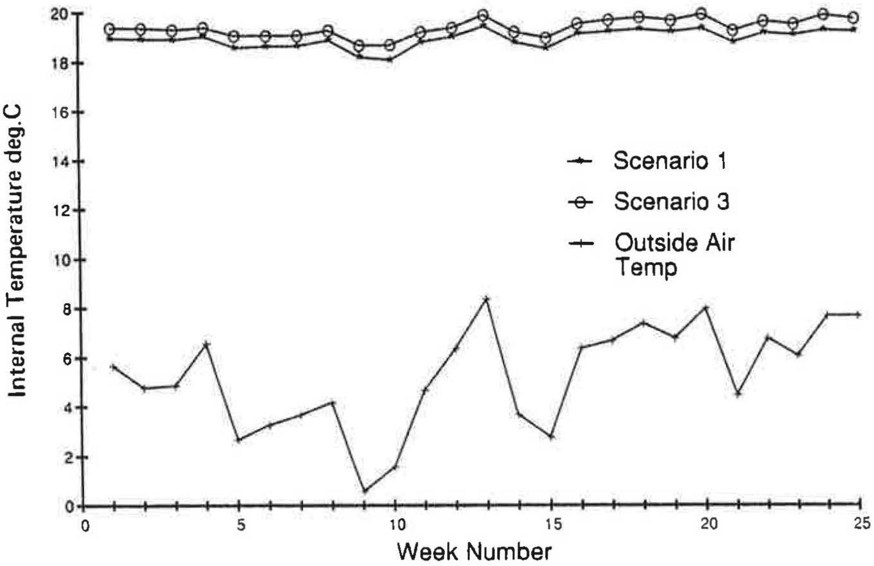


Fig. 6. Weekly average internal temperatures in the Auditorium for two ventilation control strategies. The finely controlled strategy (scenario 3) results in a higher internal temperature, due to the synchronization of the ventilation with the occupants ingress and egress.

Energy

The pre-simulation results were then used in ESP to predict the energy savings due to controlling the ventilation rate at each simulation time-step.

The simulated mean weekly 24-h internal temperatures are shown in Fig. 6 with the outside air temperatures for comparison. Scenario 2 results are omitted for clarity but lie between scenarios 1 and 3. Although the internal temperature was 'set' during the occupation period, the 24-h temperatures reflect the variation in outside temperature due to the influence of the nighttime conditions with the heating system off. Scenario 3 results in a slightly higher mean temperature than scenario 1 since when the heating turns off at the end of the occupation period the ventilation continues to modulate during the audience's gradual egress, and is therefore less than in scenario 1 when the maximum ventilation rate applies until *all* the people have left the building. The effect of this is that scenario 3 produces a lower rate of cooling and a correspondingly higher mean 24-h temperature.

The heating requirement for each week is shown in Fig. 7 for each scenario, while in Fig. 8 the weekly energy is shown as a function of mean weekly temperature difference between inside and outside. The regression equations for the lines in Fig. 8 are presented in Table 1. The cumulative energy losses broken down into ventilation and fabric components for each scenario are shown in Fig. 9 which illustrates that the fabric losses are similar for each scenario with virtually all the variation being due to the ventilation.

Over the 25-week simulation period, the mean inside-to-outside temperature difference was 13.7 K for scenario 1 and 14.1 K for scenario 3. Substituting the figures in the regression gives mean weekly heating energy requirements of 6297 kWh and 3023 kWh for scenarios 1 and 3 showing a computed saving of 52%. A more accurate assessment can be made by totalling the individual weekly energy requirements over the 25-week period which gives 157 510 kWh and 73 547 kWh for scenarios 1 and 3 respectively, a saving of 53.3%.

The estimated savings given above are based on simulation results which do not take into account the variations in system performance or building operation which may be expected to occur in a real situation and from that point of view may be considered to be optimistic.

The estimation of savings due to the introduction of energy conservation measures is, for convenience, commonly based on degree-day information rather than temperature differences as used here. Regression equations relating weekly energy requirements using standard degree-days (15.5 °C base) are presented in Table 2 for each scenario. For a mean weekly figure of 71.7 degree-days over the 25-week

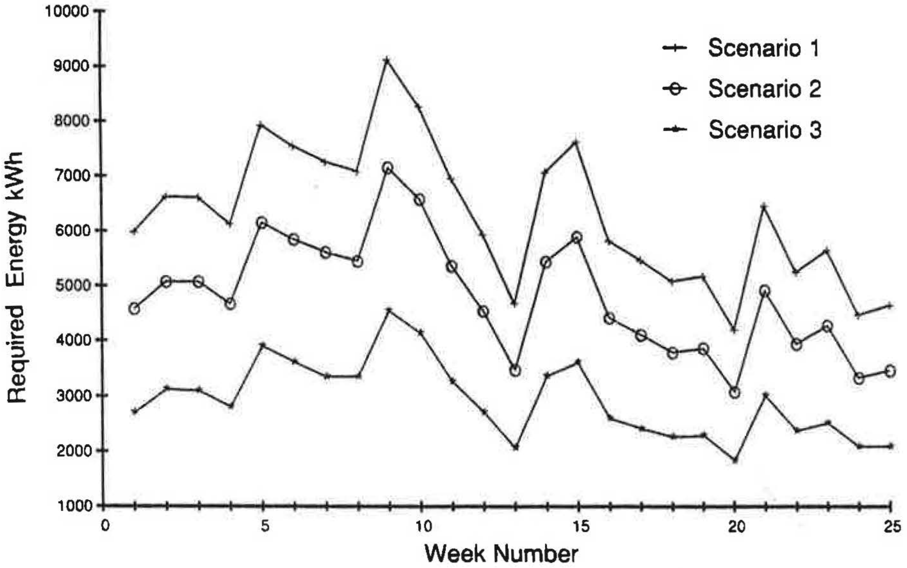


Fig. 7. Variation of required weekly energy for the three scenarios.

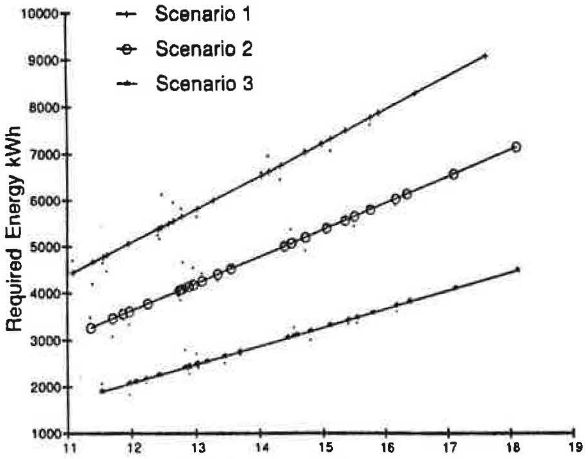


Fig. 8. Weekly energy required as a function of temperature difference between inside and outside.

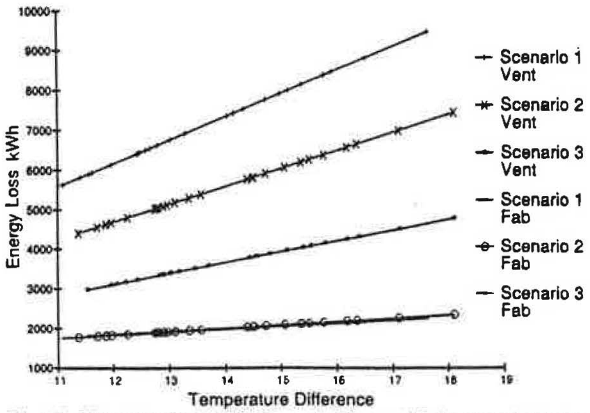


Fig. 9. Weekly energy loss — both ventilation and fabric — as a function of temperature difference between inside and outside. The fabric losses are almost identical for all scenarios. Modulations in ventilation and the operation schedule account for virtually all variations in energy loss.

TABLE 1. The regression equations corresponding to Fig. 8

Scenario	Equation	Correlation coefficient
1	$E_1 = 711.74 \cdot \Delta T - 3432.5$	0.9804
2	$E_2 = 576.74 \cdot \Delta T - 3266.6$	0.9797
3	$E_3 = 426.43 \cdot \Delta T - 3002.4$	0.9801

simulation period, mean weekly energy requirements of 6301 kWh and 2942 kWh are obtained for scenarios 1 and 3, respectively, giving an energy saving of 53.3%, i.e., the same as on a temperature difference basis.

Using the same mean weekly number of degree-days reported by ECD over their field trial period, an energy saving of 57.1% is obtained. On the same basis scenario 2 gives a saving of 26.4%, which is comparable with the savings reported from the field trials of 17.7% when one takes into account the various difficulties associated with the practical collection of data.

The savings achieved stem partly from the fact that when ventilation is required its rate is considerably reduced and partly because the period for which ventilation is needed is much shorter. In the case of scenario 3 the ventilation ON time was approximately 3.5 hours per day

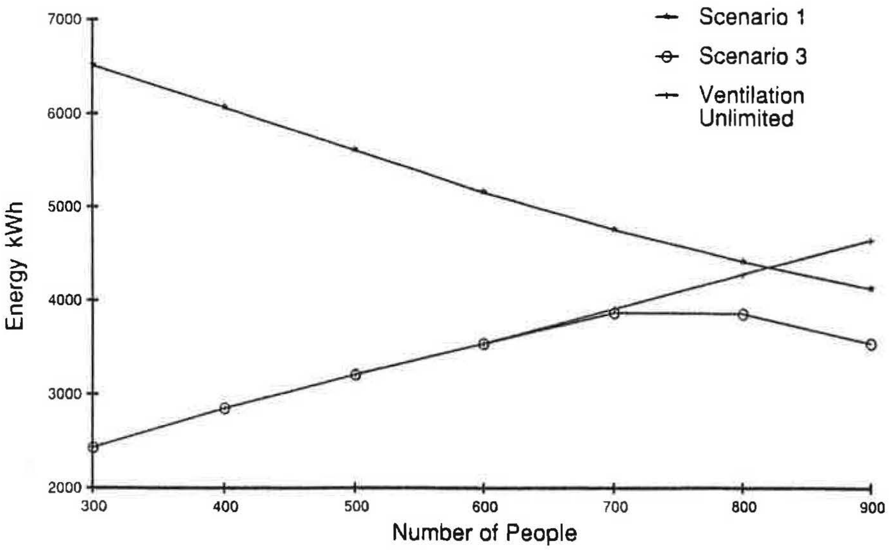


Fig. 10. Energy use for a sample week with a range of occupation levels. As the number of people increases, the ventilation losses in scenario 1 are offset by metabolic gains while ventilation losses in scenario 3 have to increase. The graph shows that the system could not cope with more than 720 people if 1000 ppm CO_2 concentration is an acceptable indicator of air quality.

TABLE 2. Regression equations relating weekly energy requirements using standard degree-days

Scenario	Equation	Correlation coefficient
1	$E_1 = 86.343 \cdot \mathrm{DD} + 108.6$	0.985
2	$E_2 = 72.259 \cdot \mathrm{DD} - 355.59$	0.986
3	$E_3 = 48.057 \cdot \mathrm{DD} - 504.379$	0.988

less than the averaged 8.5 hours for scenario 1. This is shown in Fig. 5.

In order to investigate the sensitivity of energy use to the number of people, a further set of simulations was carried out for a sample week with a range of mean occupation levels. The results of these simulations are shown in Fig. 10. Scenario 1 shows a reduction in energy use as the number of people is increased due to the constant ventilation loss being offset by increasing metabolic gains. Scenario 3, however, shows the opposite effect with energy use initially at a low value and increasing with the number of people since the increasing ventilation loss more than offsets the increasing metabolic gains. The final turn-down is due to the maximum ventilation rate being reached, although, if there were no limit on ventilation the original trend would continue.

Although one might expect the curves for scenarios 1 and 3 to merge when the common maximum ventilation rate is reached, a difference exists due to the different ventilation rates during the ingress and egress of the audience, and the inter-sessional periods. This effect would tend to decrease as the number of people is increased even more, i.e., beyond 900, until at very high occupancies the curves would become coincidental although environmental conditions would become untenable. If 1000 ppm CO_2 concentration is taken to be an acceptable indicator of air quality then Fig. 10 shows that the system modelled could not cope with more than about 720 people.

Conclusions

A simulation has been carried out using data derived from a live project which shows that energy savings using CO_2 concentration-based ventilation control may be considerable, up to 53% of the energy consumption of the original 100% fresh air system. A simulation using the same ventilation restrictions as were applied to the field trial gave an energy saving of 26.4% as compared with that measured of 17.7%. If the same ratio of saving (0.67) is applied to the simulated figure of 53.3% achieved under fully modulated ventilation conditions then the savings in practice would be expected to be about 36%.

The simulation resulted in a ventilation *on-time* of approximately 5 h compared with the average 8.5 h for the unmodified system. It can be inferred from this that savings of the order of 41% may be attributed to the reduced fan running time *regardless* of any reduction in ventilation rate when the fans are on. In addition there would also be a small saving in fan energy and maintenance costs.

Although the study has only considered one heated-only building type, additional savings would be achieved, though to a lesser extent, in air-conditioned buildings during the cooling season. In order to carry out simulations for this latter condition, the CO_2 algorithm would have to be incorporated in the computing code to interact with the existing control routines.

It is envisaged that further work will concentrate on the relationships between occupancy patterns, ventilation strategies, and building volumes in order to provide guidance for designers wishing to consider this form of control.

Nomenclature

C_o	outside CO_2 concentration (m^3 CO_2/m^3 air)
C_r	inside CO_2 concentration (m^3 CO_2/m^3 air)
DD	degree-days
$E_{1...3}$	energy requirement (kWh)
G	CO_2 output per person (m^3 CO_2/m^3 air)
N	number of people
R	ventilation rate (m^3/s)
t	time (s)
T	temperature (°C)
V	volume (m^3)

References

1 Energy Efficiency Office, *Energy Efficiency in Buildings – Entertainment*, Publication 1EB61, Department of Energy, London, Mar. 1989.

2 T. Kusuda, Control of ventilation to conserve energy while maintaining acceptable indoor air quality, *ASHRAE Trans.*, *82* (Part 1) (1976) 1169–1181.

3 *CIBSE Guide*, The Chartered Institution of Building Services Engineers, London, 1986, Section A1-9.

4 I. Turiel, C. D. Hollowell and B. E. Thurston, Automatic variable ventilation control systems based on air quality detection, *Proc. Second Int. CIB Symp. Energy Conservation in the Built Environment*, Danish Building Research Institute, Copenhagen, Denmark, 1979.

5 O. Strindehag and P. Persson, Demand controlled ventilation, *Air Infiltration Rev.*, *10* (2) (Feb.) (1989) 7–9.

6 J. Geerts, A. Grindal, H. Schiltknecht and W. Hardi, *Air Quality Control – Measurements and Experiences*, Stäfa Control Systems, Company Publ., SCS-okay, Nr5/85-2, Zurich, 1985.

7 J. E. Woods, G. Winakor, E. A. B. Maldonado and S. Kipp, Subjective and objective evaluation of a CO_2 controlled variable ventilation system, *ASHRAE Trans.*, *88* (Part 1) (1982) 1385–1408.

8 The ECD Partnership, *Ventilation Control by Measurement of CO_2 Levels in Public Entertainment Buildings, Rep. No. E/5C/2922/940, Sept. 1985*, An Energy Efficiency Demonstration Scheme carried out for the Energy Technology Support Unit (ETSU), Atomic Research Establishment (AERE), Harwell, U.K.

9 B. F. Warren, N. C. Harper and T. W. Wiltshire, *An Investigation into the Control of Ventilation in Mechanically Ventilated Buildings, Rep. No. GR/D/11432*, Science and Engineering Research Council, 1987.

10 Energy Technology Support Unit (ETSU), *Ventilation Control by the Measurement of CO_2 levels in Public Entertainment Buildings*, Project Profile 172, ETSU, AERE, Harwell, Feb. 1984.

11 *CIBSE Guide*, The Chartered Institution of Building Services Engineers, London, 1986, Section A7-4.

12 B. F. Warren, Energy saving in buildings by control of ventilation as a function of indoor carbon dioxide concentration, *Build. Serv. Eng. Res. Technol.*, *2* (1) (1982) 4–12.

13 *IHVE Guide*, The Institution of Heating and Ventilating Engineers, 1970, Book A, Section A1-9.

14 J. M. Penman, An experimental determination of ventilation rate in occupied rooms using atmospheric carbon dioxide concentration, *Build. Environ.*, *15* (1980) 45–47.

15 J. Clarke and D. McLean, *E.S.P. Documentation – A Plant and Energy Simulation System*, ABACUS, Strathclyde University, U.K., May 1986, Version 5, Release 3.

16 N. T. Bowman and K. J. Lomas, Empirical validation of dynamic thermal computer models of buildings, *Build. Serv. Eng. Res. Technol.*,*6* (4) (1985) 154–162.

17 J. A. Clarke and D. MacRandal, Extensions to the ESP building energy simulation model, *Proc. Int. Seminar, Energy Saving in Building, The Hague, Nov. 1983*, Commission of the European Communities, Dutch Ministry of Economic Affairs, 1984, pp. 356–366.