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Reducing the energy consumption of a conference centre—a case study using software

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Abstract

Efficient HVAC control is often the most cost-effective option to improve the energy efficiency of a building. However, the effect of changing the control strategy (i.e. on indoor comfort and energy consumption) is usually difficult to predict. To obtain this information more easily, a new simulation tool, QUICKcontrol, was developed. This new tool was then used to investigate the energy savings potential in a Conference Centre. The influences of fan scheduling, setpoint setback, economiser cycle, new setpoints, fan control, heating plant control, lighting control and various combinations thereof was investigated. The simulation models were firstly verified with measurements obtained from the existing system to confirm their accuracy for realistic control retrofit simulations. With the aid of the integrated simulation tool it was possible to predict savings of 744 MWh per year (32% building energy saving and 58% HVAC system energy saving) by implementing these control strategies. These control strategies can be implemented in the building with a direct payback period of less than 6 months.

Keywords: Energy simulation; Simulation software; Building retrofit; HVAC system; Energy saving

1. Introduction

The operating costs of a building could be improved upon if the heating, ventilation and air conditioning (HVAC) system of the building is made more energy efficient. This will not only result in a monetary saving for the building owner, but also less greenhouse gases will be released into the atmosphere.

It is very important that this HVAC system enhancement does not compromise the indoor air quality (IAQ). The reason is that the IAQ has a direct effect on the productivity of the building occupants [1]. A cost penalty is experienced if poor IAQ is traded for reduced energy consumption [2]. Studies have shown that energy savings of around 30% can be achieved through retrofit options in existing buildings without compromising the indoor comfort [3].

Approximately 50% of the energy used by the commercial sector in South Africa is utilised for air-conditioning [4,5]. This clearly shows that the HVAC system of a building has a large potential for energy saving.

A cost-effective way to improve the energy efficiency of an HVAC system, without compromising indoor comfort, is by implementing better control. A study was done on a Conference Centre to increase its energy efficiency, by optimising the HVAC system control, and in particular, the control of the heating plant.

To achieve these predictions a simulation tool, which can efficiently and accurately simulate the building with its HVAC system and controls in an integrated fashion, was firstly required.

There are many system simulation programs available. However, they do not satisfy the requirements of integrated, efficient and accurate simulation by the typical consulting engineer [6–8]. The simulation tool, QUICKcontrol, was the only software program available that could perform the required simulations.

The models on which the simulation tool is based are briefly discussed in the following section. The program has been verified in over 100 case studies to illustrate the value and verify the capabilities of this simulation tool. The potential for energy savings and enhancement of indoor comfort

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by implementing new control strategies in the Conference Centre were successfully investigated.

2. Simulation model

An electrical analogy [9] is used to model the heat transfer processes in the building for the accurate prediction of the thermal performance of the building zones. The HVAC component models link inputs of the basic thermodynamic variables in the system. These are based on the simplified fundamental principles combined with correlation coefficients derived from discrete empirical data [6].

The models are fully component-based and allow simulation of a wide range of operating conditions. The calculation of the energy consumption of each component is included in each model. The correlation coefficients for a specific make and model of equipment can be derived from data obtained during measurements or manufacturer's data sheets.

To simulate dynamic effects, a simple time constant approach is used. The user is responsible for suppling the time constants. The approach is as follows:

$$\tau \frac{\mathrm{d}\varphi}{\mathrm{d}t} = \mathit{function}$$

(model input parameters), with τ the time constant of the model and ψ one of the output parameters of the model. The relevant psychometric relationships are employed in all models dealing with moist air properties.

At present, the simulation model makes provisions for proportional, integral, derivative (PID), on/off and step controllers. These controllers are used in most HVAC applications.

With these controllers any measurable condition can be controlled from a sensor. Water flow rates, air flow rates, steam flow rates and the load capacities of the system components are controllable variables.

Controller output at each step is only dependent on the previous step values. This considerably reduces the complexity of the solution algorithm. From a system point of view this implies that the controller acts like a controller that has a sampling rate corresponding to the system integration time step size.

There are also energy management systems included in the simulation tool. With these, system energy consumption can be reduced by more energy-efficient control. The simulation tool provides the following energy management strategies:

Setpoint-related energy management system (temperature reset, zero energy band control, enthalpy economiser cycle and adaptive comfort control).

3. Building and HVAC system description

The Conference Centre is located in the eastern suburbs of Pretoria, South Africa. The building consists of 3 levels and has a total air-conditioned floor area of approximately 2900 m^2. The venues make provisions for a total of 1570 people. The air-conditioned areas include a restaurant on the lower floor, three conference halls, a restaurant and a foyer on the second floor and three conference halls on the first floor. The building has north, south, east and west facing windows, with conventional glazing.

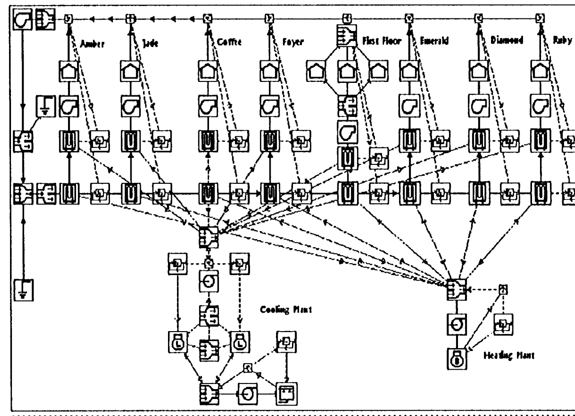

Fig. 1. Layout of the simulation model.

The entire system is located in a plant room on the lower level. The HVAC system is a constant volume, variable air temperature system. It consists of a central cooling and heating plant, and air handling units (AHUs) for the conference halls, restaurants and reception areas. In addition to the eight AHUs, which form part of the central system, there is a package unit that serves four smaller venues and an office on the ground floor. This unit is not included in the investigation.

The air is conditioned by cooling and heating coils located inside the AHUs. Air is supplied to the venues via ducting. It is returned from the lecture halls via grills and ducts back to the plant room where it mixes with outdoor air before returning to the AHUs.

Fresh air is supplied to the building via grills located on the north and south sides of the building. Dampers are responsible for the fresh/return air mixing ratio. A schematic drawing of the system layout is depicted in Fig. 1

The cooling of the air is done by cooling coils located inside each AHU. Digital PID controllers control the water flow through the coils to maintain a set temperature at sensors located in the venues or the return air ducts of the venues.

Two parallel, reciprocating water-cooled chillers supply chilled water to all the cooling coils in the AHU. Loading and unloading of the chiller compressors maintain a set return water temperature. Each has two compressors with a rating of 37 kW per compressor and a cooling capacity of 340 kW per chiller.

Two condensing units located on the roof of the building are responsible for cooling the chiller condensing water. Chilled and condenser water pumps are responsible for water flow through the two circuits, respectively.

Heating coils inside the AHUs are used when heat is required in the venues. Similar to the cooling coils, digital PID controllers are used to control the water flow through them to maintain a set temperature inside the air-conditioned areas.

A boiler, located in the plant room, supplies the hot water to these coils. The boiler is loaded and unloaded by a step controller in six phases to keep the water inside at a set temperature. The boiler has a total heating capacity of 246 kW and a storage volume of 10 m^3. A hot water pump is responsible for the flow through the hot water circuit.

4. Comfort and energy audit

It was necessary to determine the current indoor air conditions of the Conference Centre to assess whether it was up to standard, and also to be used for the verification of the simulation model. Measurements were taken to determine these conditions. If these indoor conditions were satisfactory it could be used as standards for the retrofit evaluations. A "walk through" audit was also conducted to determine any particular problem areas in the building.

An energy audit was done to determine the end-user breakdown of the energy consumption in the Conference Centre. This could be used to find the largest energy consumers, which are usually also the areas with the largest energy savings potential. The measuring of the energy consumption of the Conference Centre was a very labour intensive process. A "walk through" audit was conducted to identify the energy usage of lights and other diverse equipments. In this way it could be seen whether the energy consumption could be improved upon in that category.

HVAC, lights and other equipment were the categories used in the end-user breakdown (Fig. 2). The "other equipment" category includes the lifts, computers, overhead projectors, etc. The HVAC energy consumption was then devised into the chillers, boiler, fans and pumps (Fig. 3).

The HVAC system in the Conference Centre had the greatest potential for energy saving as it consumed approximately 57% of the total building energy. The reason for this is the large internal load in the form of people in the lecture halls, which can accommodate as many as 750 people.

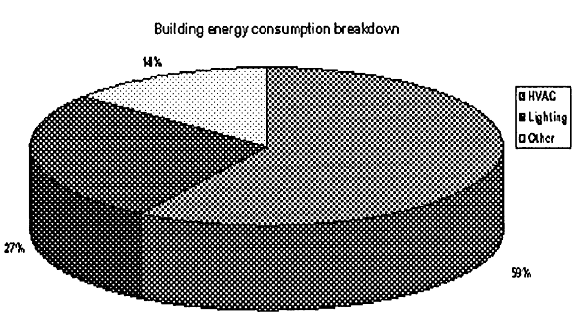

Fig. 2. Current building energy consumption breakdown.

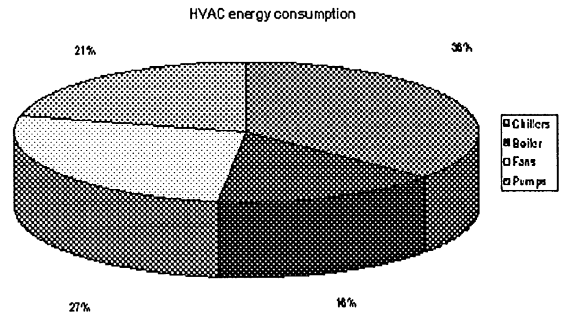

Fig. 3. Current HVAC system energy consumption.

The control strategy of the Conference Centre was investigated to determine its energy savings potential. The heating plant in particular was studied. The energy audit identified the major energy consumers as well as areas where retrofits could be made to obtain energy savings.

5. Verification study

A building and HVAC system input model was set up in the simulation program. A verification study was performed to verify the accuracy of the models, including the control parameters. An even more important aspect that needed to be verified, was the dynamic interaction between the building and HVAC system, including the influence of the controllers, working together in an integrated fashion.

The building model of the software has been verified over a very wide range of different building structures and climates in 140 case studies, with great accuracy. For this reason it was not necessary to verify the passive response of the building [9].

Measurements were taken for a period of one week. These measurements include temperatures, relative humidities, airflow rates, water flow rates and electrical power required by each HVAC system component. This data was necessary to set up the simulation tool, and also to have real life data to verify the simulation output data. From the measured data a single representative day was extracted to be compared to the 24-h day predictions provided by the simulation tool.

The inputs of the simulation program comprise the building structural data, outdoor climatic data, internal loads, occupancy data, all the HVAC component data and the control parameters. Some of these inputs vary with time, namely in our case, outdoor climate data, occupancy and internal loads. Most of the input data or if possible all of it should be available to perform a verification study with integrity.

The building was divided into ten zones. Most venues supplied by an AHU were taken as a zone. The first floor consists of three rooms, with a mutual AHU that supplies them. The zones include the Amber restaurant, Jade restaurant, Diamond hall, Ruby hall, Emerald hall, the foyer and coffee areas and the three first floor conference halls. Fig. 1 depicts the simulation model layout. The building structure

Table 1
Summary of indoor air verification

Zone	Average error (°K)	% Within 2°C of the time
Diamond	0.9	100
Ruby	1	100
First floor	0.6	100
Foyer	0.2	100
Coffee	0.4	100
Amber	0.6	100
Jade	0.4	100
Emerald	1.1	100

Table 2
Summary of supply air verification

Zone	Average error (°K)	% Within 2°C of the time
Diamond	1.5	75
Ruby	3.1	32
Emerald	2.8	27
First floor	1.4	81
Foyer	3.4	72
Coffee	0.6	99
Jade	1.1	89
Amber	1.6	74

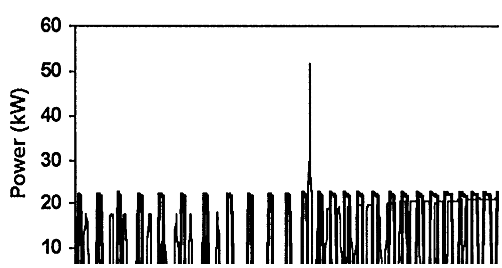

Fig. 4. Chiller power verification result.

data with the zone dimensions were obtained from building drawings and a database. All of this was read into the simulation program. The internal loads in the form of occupants were known from the building booking data of the building.

Regressions for the HVAC components were set up from measured and catalogue data. The control strategy, including operating times and control parameters for most system components was obtained from measurements and read into the simulation program.

The verification results are shown in the following tables and figures. Satisfactory results were obtained from all ten zones, as well as the boiler and chiller power simulations. The indoor and supply air temperature results are summarised, respectively in Tables 1 and 2.

The simulated and measured chiller power is compared in Fig. 4. The simulation tool successfully simulated the loading and unloading of the chiller capacity steps. The time constants of the building and HVAC system components are verified by the fact that the phase differences between the simulated and predicted values are small. The difference between the measured and simulated energy consumption over 24 h is only 13%.

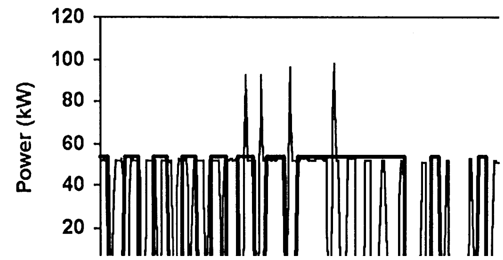

Fig. 5. Boiler power verification result.

Fig. 5 displays the boiler power verification results. There is a difference of 3% between the measured and simulated boiler energy consumption over the 24-h day. Thirty time steps per hour were needed to simulate the dynamics of the building zones and the HVAC system with its controls to this degree of accuracy.

One may look at the simulation results and feel that the accuracy of the integrated modelling is perhaps not that good, especially the air supplied to the zones. One should remember the idea was not to simulate the dynamics of the system to an accuracy of 100% but to predict accurate realistic daily (and yearly) system energy consumption and accurate average indoor air temperatures to ensure indoor comfort.

6. Retrofit control strategy

6.1. Preamble

An investigation was performed to establish the potential for energy savings in the building. The savings were calculated by executing numerous energy saving control retrofit simulations. These retrofit options include reset control on the AHUs, economiser cycle combined with carbon dioxide control on the lecture halls' outdoor air ventilation rates, and better HVAC system start–stop times. All the retrofit options investigated were done on the HVAC system of the building since 57% of the total building energy consumption is consumed by the HVAC system. This means that the biggest potential for building energy saving lies in HVAC system retrofit options.

6.2. Fan scheduling

The present HVAC system should be operated with fan scheduling, where the fans are turned off during the night and early mornings. This corresponds to the time when the building is not in use, and therefore does not need any air-conditioning. However, from the temperature and electrical measurements it was clear that this was in fact not the case.

Table 3
HVAC fan scheduling times

Zone	Day	Operating time
First Floor	Weekday	6 : 00–24 : 00
	Saturday	6 : 00–24 : 00
	Sunday	7 : 00–8 : 00
Amber, Jade	Weekday	6 : 00–22 : 00
	Saturday	6 : 00–22 : 00
	Sunday	7 : 00–8 : 00
Foyer, Coffee	Weekday	6 : 00–24 : 00
	Saturday	6 : 00–24 : 00
	Sunday	7 : 00–8 : 00
Diamond, Emerald, Ruby	Weekday	6 : 00–20 : 00
	Saturday	6 : 00–20 : 00
	Sunday	7 : 00–8 : 00

For this option we propose the following fan operating time schedules. The operating times differ for each zone, according to the times of use. These times can be seen in Table 3.

The return air fans, that work in tandem with their relevant supply air fans, can therefore be switched off according to Table 5.

6.3. Economiser

The economiser control manages the fresh air intake into the building. With this control the air intake can be controlled to let in as much as 100% fresh air, and as little as 40% during occupied times and 0% during unoccupied times.

The outside air can therefore be used for cooling if required when the outdoor temperature is lower than the return air temperature. If the outside air is at a higher temperature than the return air, it will be cut down as much as possible.

In the case of the Conference Centre there are two separate sets of fresh and return air dampers. One set on the North side and the other, on the South side. Each damper set will be controlled from a temperature sensor located in the relevant return air plenum and one just inside the fresh air dampers for monitoring the outdoor air temperature.

This strategy can be divided into two parts, an occupied strategy and an unoccupied strategy. Infrared motion detectors located in the venues will be responsible for selecting the relevant strategy. The occupied strategy will be active for 15 min after movement was detected by any of the sensors in the venue. This implies that the timer will reset itself if new movement is detected during this period and the 15-min countdown will start all over again. The unoccupied strategy will therefore only be activated when all the sensors in the venue are passive for a period of 15 min.

For this option all the relevant motion detectors of the venues which return air to the same set of dampers must be passive for 15 min to activate the unoccupied economiser control strategy.

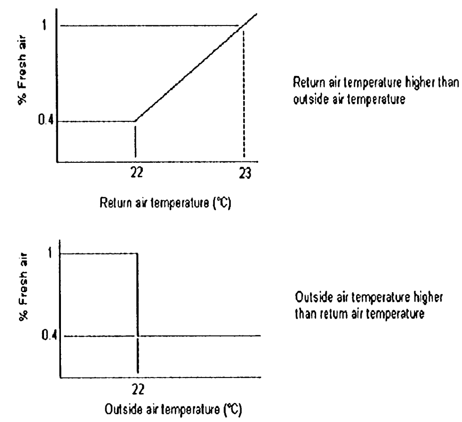

Fig. 6. Occupied economiser control strategy.

Occupied strategy

If the return air temperature is higher than the outdoor air temperature the following strategy will be followed:

- If the return air temperature exceeds 22°C the fresh air damper will open proportionally from its minimum setting (40% fresh air of total supply) until fully open at 23°C.
- For the same conditions the return air damper will start to close proportionally from its maximum setting (60% return air) to fully closed.
- If no cooling is required the fresh air damper will be at its minimum setting (40% fresh air) and the return air damper at its maximum (60% return air).

If the outdoor air temperature exceeds the return air temperature the fresh air damper will close to its minimum setting (40% fresh air) and the return air to its maximum, 60% return air. The strategy is graphically presented in Fig. 6.

Unoccupied strategy

If the return air temperature is higher than the outdoor air temperature the following strategy must be followed:

- If the return air temperature exceeds 22°C the fresh air damper will open proportionally from its closed position (0% fresh air of total supply) until fully open at 23°C.
- The return air damper will for the same conditions start to close proportionally from its fully open position (100% return air) to fully closed.
- If no cooling is required the fresh air damper will be closed and the return air damper fully open.

If the outdoor air temperature exceeds the return air temperature the fresh air damper will close completely and the return air damper will be fully open. The strategy is graphically presented in Fig. 7.

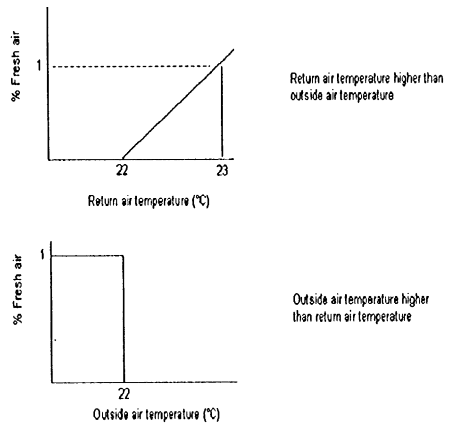

Fig. 7. Unoccupied economiser control strategy.

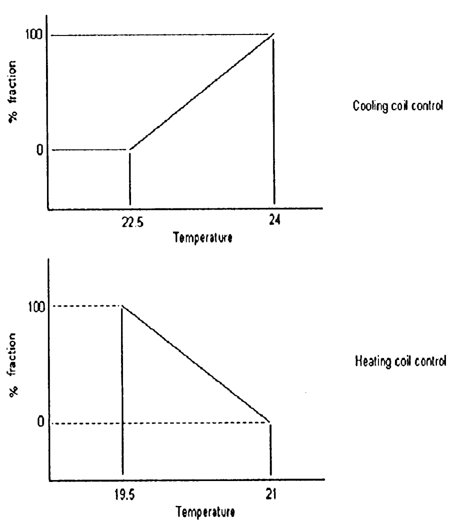

Fig. 8. New zone setpoints.

6.4. New setpoints

For this control strategy the cooling and heating setpoints were raised, but kept within the comfort band. See Fig. 8 for this control strategy. This strategy will result in peak reduction and energy savings due to a reduction in the cooling load.

If the indoor temperature exceeds 22.5°C the cooling valve will open proportionally from its closed position until fully open at 24°C.

If the indoor temperature drops below 21°C the heating valve will open proportionally from its closed position until fully open at 19.5°C.

6.5. Setpoint setback

This option allows setpoint drift if the venues are unoccupied. This control strategy also requires the installation

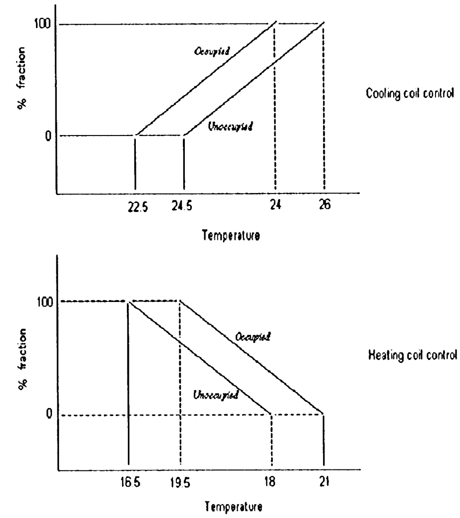

Fig. 9. Setpoint setback control strategy.

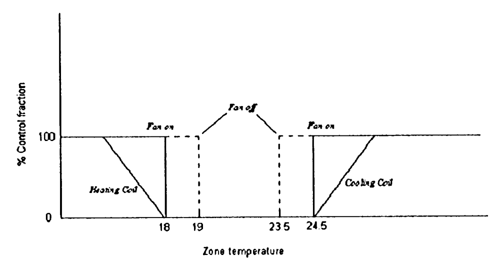

Fig. 10. Fan control strategy.

of motion sensors in the venues. It operates on the assumption that a venue does not need to be kept on setpoint if it is not in use. If a venue is unoccupied, the control will let both the cooling and heating coil setpoints to drift to hotter and colder temperatures, respectively. The zones will then require less cooling and heating from the HVAC system.

The unoccupied duration will be determined in the same fashion as discussed in the section concerning Economiser control. New temperature sensors will need to be located inside the venues for this option. For the unoccupied conditions the cooling coil will be fully open at 26°C and fully closed at 24.5°C. The heating coil will be fully open at 16.5°C and fully closed at 18°C. The strategy can be viewed in Fig. 9.

6.6. Fan control

This retrofit works on the assumption that the supply fan of a venue need not operate if the cooling and heating coil valves are closed during unoccupied times. See Fig. 10 for the fan control strategy.

This control strategy can therefore only be used during unoccupied venue times. This control has a strategy for both

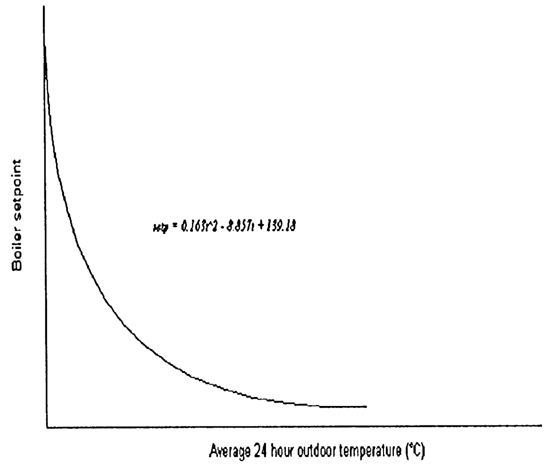

Fig. 11. Heating plant control.

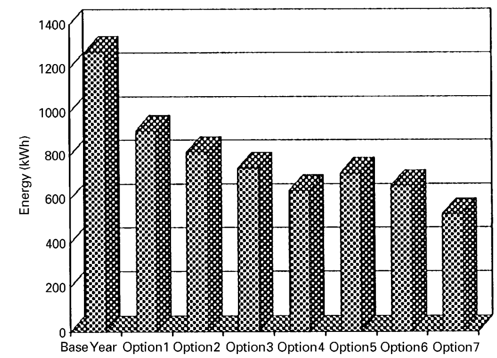

Fig. 12. System retrofit total energy simulation comparison.

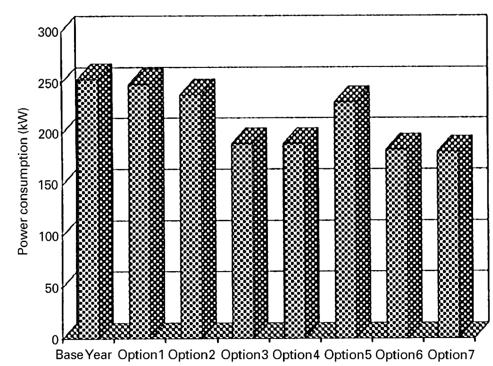

Fig. 13. System retrofit total power consumption comparison.

cooling and heating sides. For the cooling side, the fan is switched on when the cooling valve opens at 24.5°C. The fan will then stay on until the temperature drops 1°C below the opening temperature before it switches off. For the heating side the fan will switch on at 18°C. It will then switch off 1°C above the valve opening temperature.

The supply fans must run at all times if the venue is occupied. The return fans will operate in tandem with their correlating supply fans.

6.7. Heating plant control

The current heating plant control strives to keep the boiler water at 75°C throughout the year. The pump also runs right through the year. This wastes energy, as no heating needs to be done during the hot summer months of the year.

We propose the following boiler control strategy: The boiler setpoint will be a second order function (Fig. 11) of the average outdoor air temperature of the previous 24 h. The outdoor air temperature will therefore be monitored and locked at half hour intervals. A new average outdoor air temperature will be calculated for each new half hour by taking he previous 48 locked temperature points. A new setpoint will then be calculated for each half hour of the day by the following function:

$$\text{setp} = 0.162t^2 - 8.857t + 139.18,$$

where setp is the boiler in °C and t is the average outdoor air temperature in °C.

We propose the following hot water pump control strategy: The pump will only start running when one of the heating coils require hot water, in other words, when one of the heating coil's control valves open. If no heat is required the pump will shut down. To keep the pump from cycling, a time delay of 30 min can be incorporated before pump shut down can occur.

7. Retrofit result

This section is a summary of the retrofit results. Fig. 12 displays the energy consumption of all the retrofit options. Fig. 13 shows the average monthly peak demand of all the options.

Option 1—*Fan Scheduling*
Option 2—*Economiser control and new setpoints*
Option 3—*Economiser control and setpoint setback*
Option 4—*Economiser control*, *setback and fan scheduling*
Option 5–*Economiser control*, *setpoints and heating plant control*
Option 6—*Economiser control*, *setback and heating plant control*
Option 7—*Economiser control*, *setback*, *fan and heating plant control*

The temperature drift of the retrofits, for both winter and summer, can be seen in Fig. 14.

8. Economic analysis

The monetary energy and peak demand savings per year with the relevant implementation costs for each option are

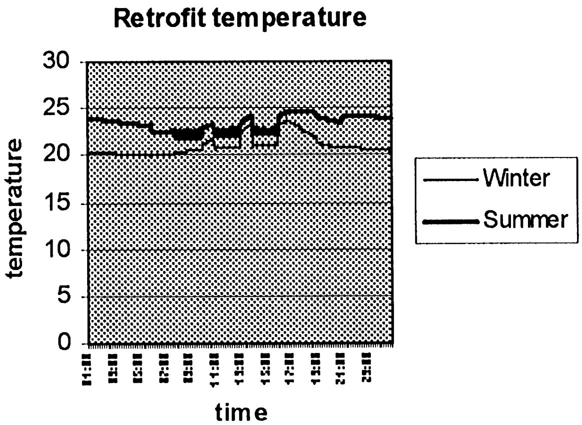

Fig. 14. Retrofit temperature drift.

Table 4
Economic analysis

Options	% Saving on HVAC system	% Saving on building energy	Payback period (months)
Option 1	28.4	17.4	0
Option 2	36.0	21.6	0.5
Option 3	41.8	25.1	5.6
Option 4	49.9	30.0	5.7
Option 5	43.8	26.9	1.1
Option 6	48.2	29.0	5.4
Option 7	58.3	31.0	5.3

displayed in Table 4. Direct payback periods can also be viewed here.

The implementation costs do not include any new PLC modules for the implementation of new control strategies. The savings are based on 8.34 cent per kWh and R 34 per peak kVA for each month. A possible monetary saving of R100 000 per year can be achieved by the proposed post control strategies with a direct payback period of less than 6 months.

Option 1—*Fan Scheduling*
Option 2—*Economiser control and new setpoints*
Option 3—*Economiser control and setpoint setback*
Option 4—*Economiser control*, *setback and fan scheduling*
Option 5–*Economiser control*, *setpoints and heating plant control*
Option 6—*Economiser control*, *setback and heating plant control*
Option 7—*Economiser control*, *setback*, *fan and heating plant control*

9. Closure

A verification study was conducted to ensure realistic and accurate retrofit energy savings and indoor comfort. The predicted indoor air temperatures of all the venues were within 2°C of the actual measurements for 100% of the time. The predicted energy consumption of all the components were within 13% of the measurements for a 24-h verification day.

The verification study showed satisfactory results for the use of the simulation model with confidence during the retrofit simulations. The combinations of the new proposed control strategies resulted in building energy savings of up to 32% and 58% on the HVAC system energy consumption per year. These resulted in monetary savings of R100 000 per year with a direct payback period of less than six months.

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