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HVAC control strategies to enhance comfort and minimise energy usage

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Abstract

Good heating, ventilating and air conditioning (HVAC) control ensures comfort. It is usually also the most cost-effective way to improve energy efficiency of air-conditioned buildings. In this article, the comfort enhancement and energy saving potential with new control strategies are determined for the Human Science Building (HSB) at the University of Pretoria. A new software tool, QUICKcontrol, was used to perform the complex and fully integrated building, HVAC and control simulations. Various control strategies were investigated. These included air-bypass, reset control, setback control, improved start–stop times, economiser control and CO_2 control. The simulation models were firstly verified against measurements to ensure accurate and realistic retrofit simulations. It was then possible to ensure comfort and to predict savings of 60% in HVAC power consumption. This resulted in a simple payback period of 9 months. Preparing input data took about 2 days, while setting up the simulation model took another day. The typical run time for the fully integrated building, HVAC system and control simulation took approximately 90 s per day on an Intel™ Pentium 133 MHz personal computer. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: HVAC system; Integrated dynamic simulation; Energy retrofit study; Energy savings potential

1. Introduction

Energy consumption has become an important issue for policy makers on a global scale. This is due to additional strain on the environment due to the expected vast increase in world energy demand over the next 30 years [1].

In addition to the global concern, escalation in energy costs has made energy savings for building owners a viable option. More energy efficient buildings thus not only hold monetary reward for the owner but also reduce the production of greenhouse gasses.

Studies have shown that in South Africa, approximately 20% of all available municipal electrical energy is used in commercial and office buildings [2]. Further studies have shown that air conditioning is responsible for a substantial 50% [3] of this.

Air-conditioning energy savings will clearly have a sizeable impact on total consumption figures. In the quest to realise savings, maintaining acceptable indoor air quality (IAQ) levels is a restriction to be afforded careful consideration [4].

IAQ levels are of major concern, as inadequate levels result in discomfort of inhabitants, which in turn adversely affect productivity. Studies have shown that cost penalties resulting from poor IAQ may far outweigh potential energy cost savings [5].

To achieve the objective of sizeably reducing heating, ventilating and air conditioning (HVAC) related energy costs, while not compromising IAQ, requires the implementation of better control. The complex interactive dynamic nature of the HVAC system, building and its controls however makes the prediction of energy savings and IAQ resulting from modification to control a difficult task.

Realistic predictions of changes resulting from HVAC control modification, require a simulation tool with the ability to efficiently and accurately simulate the building with its HVAC systems and controls in an integrated manner. Although, many simulation programs are available, they do not meet these criteria [6–8].

A new simulation tool QUICKcontrol is thus presented. It was developed to bridge the requirement for an efficient and accurate integrated simulation program, and thus achieve air-conditioning energy savings without impairing IAQ.

QUICKcontrol uses an electrical analogy [9] to model the heat-transfer processes associated with buildings. The simulation models are fully component based to simplify the

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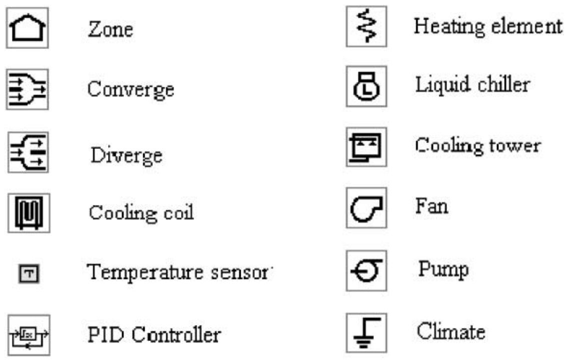


Fig. 1. Simulation model component legend.

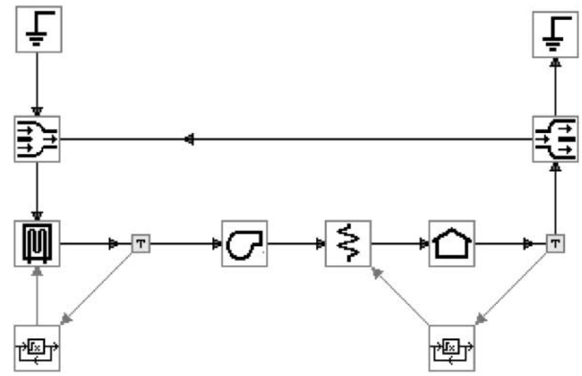


Fig. 2. Schematic layout of a standard AHU.

modelling and to enable the user to simulate a wide range of operating conditions. Each of the components (Fig. 1) are based on a combination of the fundamental thermodynamic principals and discrete empirical data [10,11].

The capability and accuracy of this new simulation tool was demonstrated through a case study. Having been successfully verified, it was then applied to evaluate the potential of new energy management strategies on substantially reducing air-conditioning energy consumption while enhancing indoor comfort. The Human Science Building (HSB) at the University of Pretoria was used as subject for this investigation.

2. Building and HVAC system description

The building under consideration is used for office and lecturing purposes and consists of 22 floors. It contains a total air-conditioned floor area of 4265 m^2 and houses ±1600 people per weekday. Two underground and ground to third floor levels constitute lecture halls, while the top 16 floors house offices. Half the offices face north and the other south.

In both the offices and the lecture halls, fluorescent lights are used for lighting. Most of the offices are provided with computers and the lecture halls with projectors.

Air conditioning is provided with a chilled water constant volume system. The lecture halls are conditioned with central air handling units (AHU). Each office is provided with its own fan coil unit (FCU) for conditioning purposes. Two AHU supply fresh air to the FCUs.

The HVAC system has a rated cooling capacity of 1300 kW, which constitutes approximately 300 W/m^2. This means that the system is notably oversized, which is not uncommon for office buildings in South Africa [12]. Furthermore, the system consists of a total of 14 AHUs spread out over four floors, of which two are dedicated to the offices and the FCU systems. The system operates between 5.00 and 13.00 h, 7 days per week.

The 12 AHUs situated on three floors supply a constant volume of air to five lecture hall zones, as illustrated in the schematic layout shown in Figs. 2 and 3. The air is conditioned by cooling coils situated inside the AHUs and an electric heater placed downstream of the coil in the supply air duct to each hall.

Air is returned from the lecture halls via grilles into return air ducts running down long central shafts. Here, it is mixed individually with outside air drawn into the shafts. Mixing ratios are set at 20% and remain constant as no economiser cycle is present.

The AHUs are set to supply a constant down-coil air temperature. In some of the units, an air-bypass control strategy is also implemented. This implies that the flow of supply air through the coil is controlled with a bypass damper system which allows for control of down-coil air temperature.

Temperature control of the lecture halls is achieved on a per zone basis through heaters situated in the supply air duct. The heaters are controlled from temperature sensors placed in each of the zone return air ducts.

Each office is conditioned with its own FCU together with heated outside air from two AHUs located on the roof of the building. These units make use of 100% fresh air and supply air which is heated to a minimum temperature to support the FCUs in heating mode. Indoor temperature control is then achieved with the FCUs.

Two water-cooled chillers supply chilled water to all of the cooling coils including those of the FCUs. Chiller

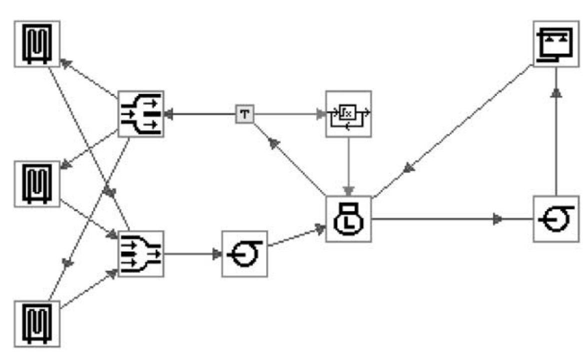


Fig. 3. Schematic layout of the water cycle of the building model.

condensed water is cooled via cooling towers situated on the roof of the building.

HVAC system control is achieved with PID controllers in cooling mode and step controllers while heating.

3. Comfort and energy audit

3.1. Comfort audit

The aim of the comfort audit was to evaluate the current indoor air conditions in the HSB. Measurements were required to assess current conditions to the applicable standards and also for the verification of the simulation model. These indoor conditions, being satisfactory in accordance with the code [13], could then be used as standards for the evaluation of retrofit options.

The audit was initialised with a walk through to pinpoint problem areas, such as out of order HVAC system components and neglected maintenance. Opinions from occupants with regards to indoor comfort levels were also collected. Measurements of indoor air conditions followed.

Indoor temperatures were compared to the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) standards [13] and found to be too low, varying between 16 and 21.6°C on a hot day.

In the process of decreasing energy consumption without affecting indoor comfort levels, it is advisable to determine the end-user energy consumption breakdown. This serves to point out the largest energy consumers which in turn often have the largest energy savings potential which will be discussed in Section 3.2.

3.2. Energy audit

The main aim of the energy audit was determining the energy consumption end-user breakdown. This included a walk through audit conducted to identify large diverse energy consumers, such as lighting and computers.

The energy audit results are summarised in Fig. 4. ''Other'' represents all diverse energy consuming equipment such as lifts, computers, etc. As shown, the HVAC system is by far the largest energy consumer and thus potentially an area where large energy savings may be realised.

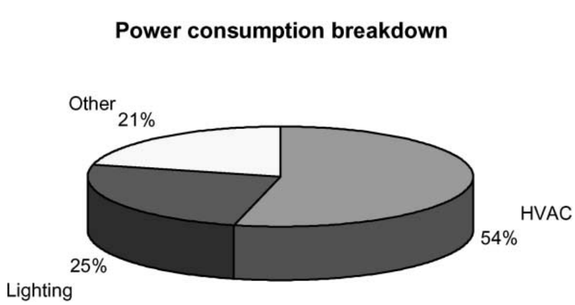


Fig. 4. Breakdown of the total building electrical energy consumption.

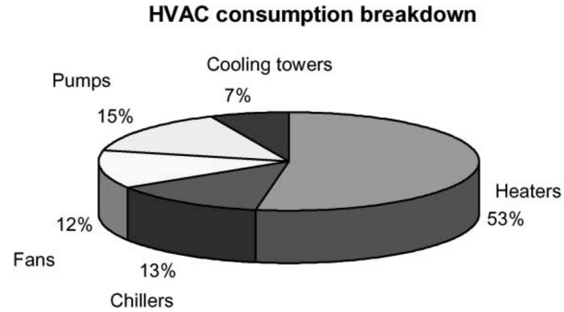


Fig. 5. HVAC system electrical consumption breakdown.

Fig. 5 shows a power consumption breakdown of the HVAC system for the measured period. As shown in Fig. 5, the heater elements consume the largest amount of energy. This energy is lost energy, as it is used for re-heating of cooled air. Control of the off-coil air temperature alone could salvage much of this energy. By increasing the cooling coil leaving temperatures and thus increasing the currently low indoor temperatures to more suitable values, further reduction in chiller energy consumption can be expected.

From above, it is clear that the HVAC system is the building's major energy consumer and that altered control strategies are expected to hold sizeable energy savings potential.

Due to the complex and interactive thermal nature of the building, HVAC system and its controls, the simulation tool QUICKcontrol will be used to investigate the energy savings potential of various control strategies. To ensure realistic predicted energy savings, the accuracy with which this tool can simulate the thermal behaviour of the system must however first be verified.

4. Verification study

The verification study comprised characterising the building, HVAC system and controls for simulation purposes and then validating the simulated outputs.

4.1. Characterisation of simulation models

Characterising the various building and HVAC system components requires a large number of inputs. These consist of building structural data, internal loads, outdoor climatic data, as well as all HVAC component data and control parameters. The required data was obtained from drawings, technical data sheets and measurements.

Measurements required for characterising and verification purposes were taken over a period of 2 weeks during August 1998. These included temperatures, relative humidities, air flow rates, water flow rates and electrical power consumption of each HVAC component. It may be noted that because the temperature swing of the drawn in outside air is dampened by the thermal mass of the central shafts (also called

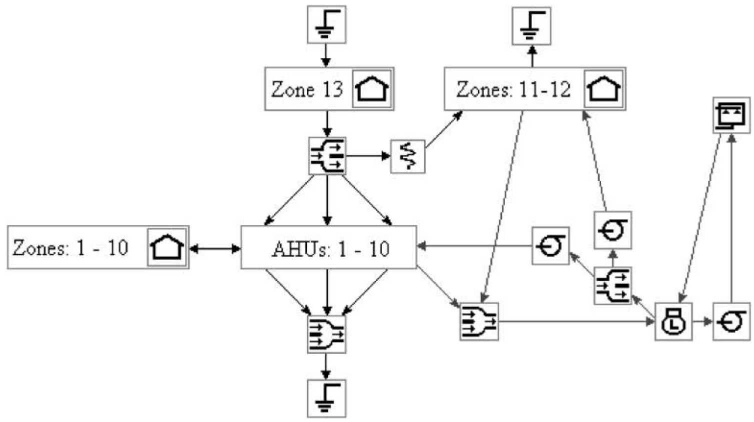


Fig. 6. Schematic layout of the HVAC system.

the temperature variant effect), intake temperatures were measured inside the shaft.

Figs. 6 and 7 depict the simulation model layout. For simulation purposes, the building was divided into 13 zones: 10 zones were allocated to lecture halls, while zones 11 and 12 represented the north and south offices, respectively. The 13th zone was created to serve as the outside air shaft which damped the outside air temperature swing. Walls and floors inside each zone were treated as partitions. Building structure data for each zone were obtained from building drawings and an inspection. All of this was read into the simulation program.

The input data needed for the HVAC system chiller, pump and fan models were obtained from suppliers' performance data sheets. Due to the age of the system, original data sheets for the coils, heaters and cooling towers were not available and were mainly substituted with data sheets from similar equipment and measurements.

Control strategy input included operating times and control parameters for most system components and were obtained from the HVAC system operating manuals. Other parameters like performance sheet data that were not available were obtained from onsite measurements.

4.2. Validation of accuracy of simulation

The integrated simulation tool was validated by comparing predicted indoor temperatures and HVAC system energy consumption to measured values for a specific day.

The verification results of indoor air temperatures, chiller power and electric heating power are represented in Table 1 and Figs. 8 and 9. It may be noted that indoor air temperatures of the offices were not verified due to the impracticality of measuring all the offices simultaneously. On one side of the building, some of the FCUs were out of order due to a faulty chilled water supply pump. This did not influence the verification study though. The assumption was made that the thermal load due to these FCUs will be negligibly small.

The measured indoor air temperatures of each zone was taken as the average of the lecture halls associated with that particular zone. The results from zones 1 to 9 are summarised in Table 1. It is clear from Figs. 8 and 9 and Table 1 that sufficiently accurate indoor temperature results were obtained.

Fig. 8 shows the measured and predicted electrical power consumption of the AHUs. The figures show sufficiently accurate results with a maximum total daily consumption error of 2.2%. Note that results for all the units are not shown due to low activity during the period of measurement.

The simulated and measured chiller power consumptions are compared in Fig. 9. As shown, step loading and unloading were successfully simulated. The realism of the simulated building and HVAC time constants is verified by the small phase difference between measured and predicted values. The measured and predicted energy consumption for the simulated 24 h day differed by only 0.61%. This is sufficiently accurate.

The verification study results show that the dynamics of the building, HVAC systems and its controls were simulated with appreciable accuracy. With the accuracy of the simulation tool successfully verified, it could be applied to retrofit investigations with the assurance of achieving credible predictions.

5. Control retrofit simulations

5.1. Preamble

A retrofit investigation was launched to obtain the energy saving potential of the building. The investigation focused on the HVAC system being responsible for more than 54% of the building's total energy consumption.

Various retrofit options were evaluated. These included adjusting indoor temperature set-points to more acceptable levels, air-bypass and reset control on the AHUs, setback control (motion detector driven) on lecture halls, improved

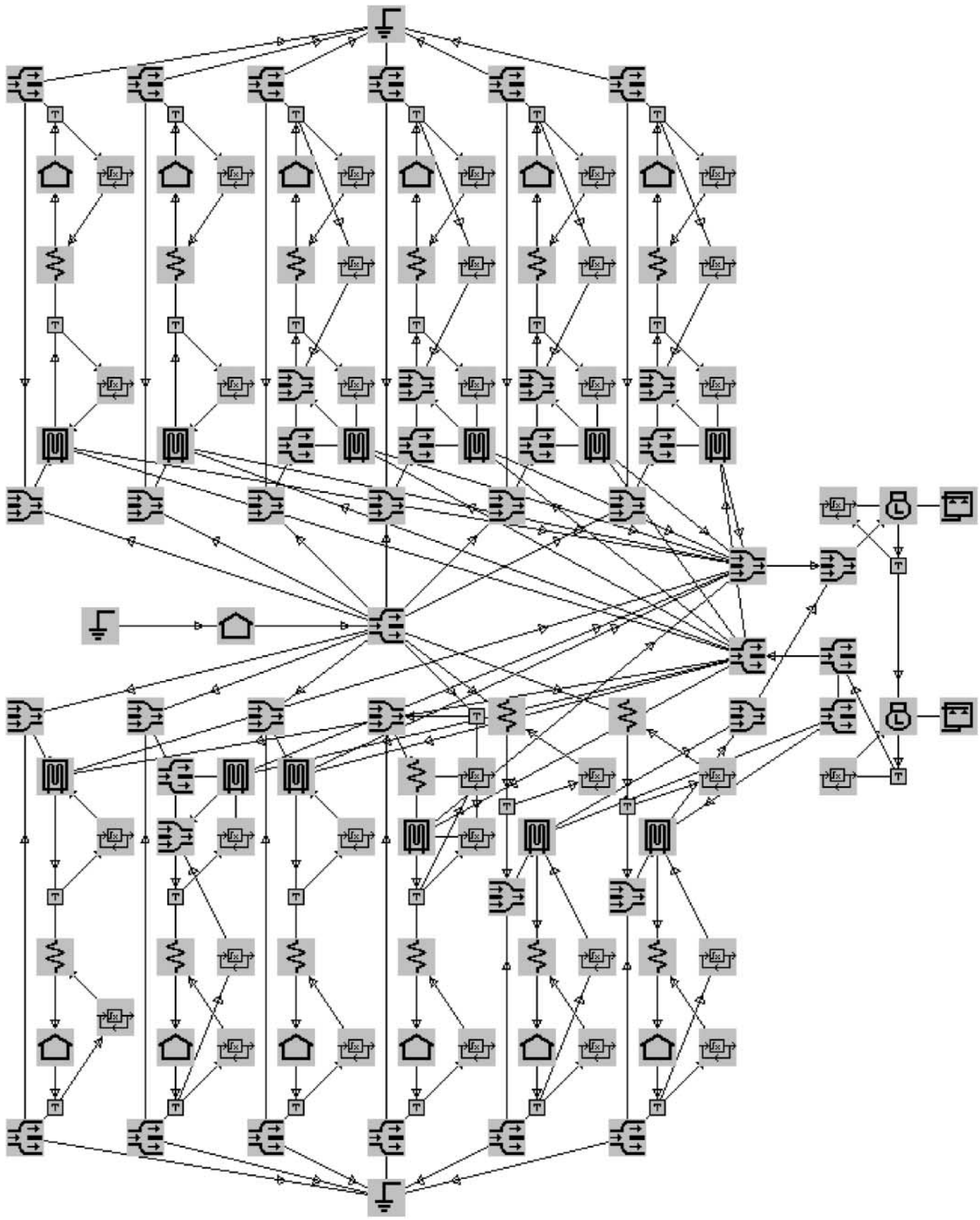


Fig. 7. QUICKcontrol model of the HSB HVAC system.

Table 1
Results of the verification study of the simulated vs. measured temperatures

Zone	Average error (°C)	Maximum error (°C)	Time within 2°C (%)	Time within 1°C (%)
1	0.56	3.88	83.3	81.4
2	−0.43	−0.44	99.4	84.2
3	0.12	2.64	98.1	83.3
4	0.59	1.95	100	84.7
5	0.21	1.48	100	100
6	0.27	1.84	100	85.6
7	0.57	5.61	98.9	81.7
8	0.06	3.17	98.6	95.8
9	−0.82	3.95	88.9	53.6

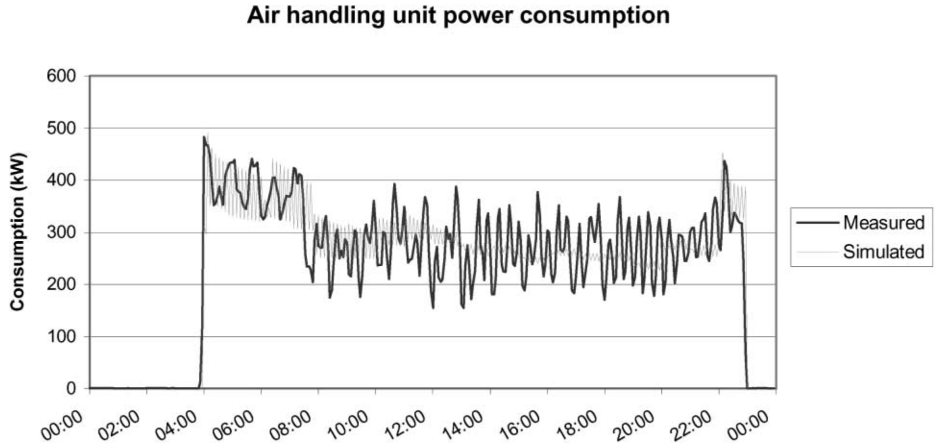


Fig. 8. AHU power verification results.

HVAC system start–stop times, economiser cycle combined with all of the above and CO_2 control.

Retrofit energy savings potential was evaluated by comparing new energy consumption figures to that of the present system. To obtain a realistic comparison, the current energy consumption figures were calculated for a system with the easily adjustable control set-points, e.g. indoor air temperature, set to correct values.

5.2. Air-bypass

The first energy savings retrofit option investigated was air-bypass to the AHU cooling coils. This system comprises damper control units fitted to the AHUs to regulate the portion of supply air to bypass the cooling coil. Currently, these units are fitted to the AHUs supplying five lecture facility zones and are either not operational or insufficient to efficiently regulate the mass flow rates applicable. The air-bypass retrofit consists of the repair and upgrading of these units.

The current and retrofitted system year simulation results are shown in Fig. 10. The total yearly energy saving came to 137 MWh which constitutes a 4.6% saving. This is clearly not substantial, however this retrofit being relatively inexpensive may be an option and will be considered in Section 5.9.

5.3. Reset control

To save more energy, reset control was investigated as a retrofit option. This means that the air-bypass system's AHU supply air temperature is controlled from return air and not supply air temperature sensors as shown in Fig. 11. Control is achieved by regulating the chilled water flow rate through the AHU coil. This will minimise the amount of cooling and re-heating required.

With the system as shown, it is likely that either one of the controllers may saturate at high output and thereby maximise simultaneous heating and cooling instead of minimising it. To overcome this problem, the set-points for the controllers will have to be set at sufficiently different temperatures (e.g. as the input air temperature decreases, the coil will have to stop cooling before the heater starts heating).

Furthermore, due to the multi-zoned nature of the zones, a digital system will be required to identify and control the chilled water supply rate from the zone with the largest heat load (highest return air temperature) at a particular time.

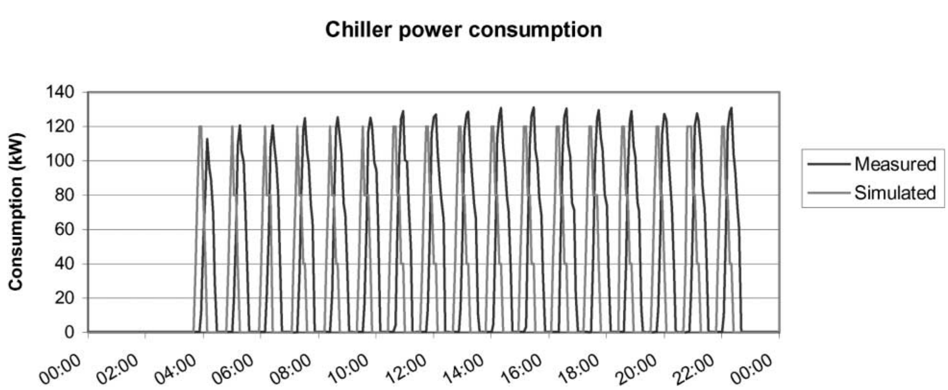


Fig. 9. Chiller power verification results.

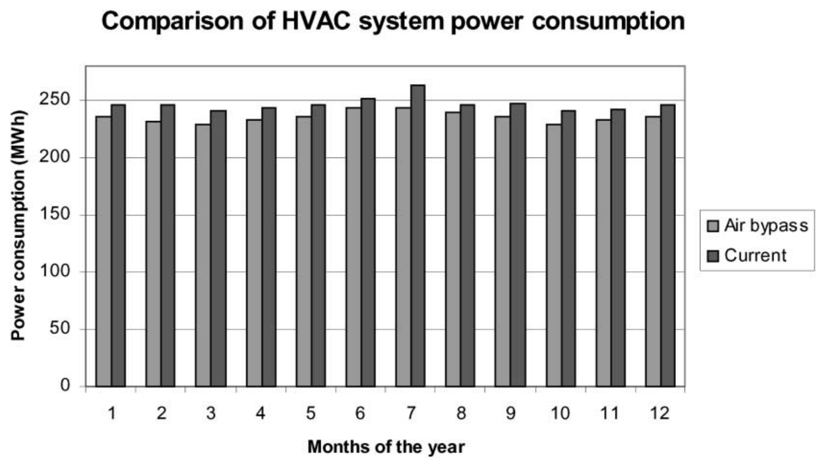


Fig. 10. HVAC power consumption due to the air-bypass strategy.

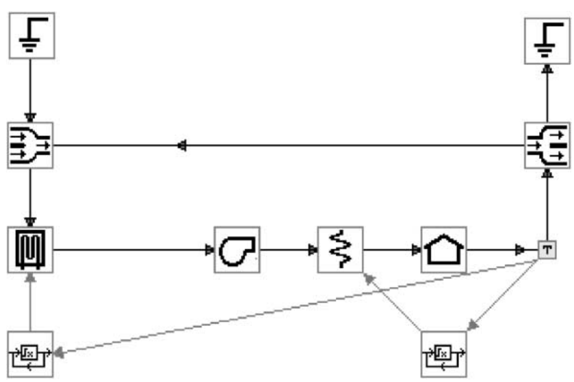


Fig. 11. The reset control strategy.

Final control of the indoor temperature of the other zones will be achieved through re-heating.

The year simulation results are shown in Fig. 12. The results showed a substantial energy saving of 45% on the HVAC system's total energy consumption. This is a saving of 1337 MWh per year.

5.4. Setback control

Setback control involves selectively relieving HVAC component set-points. A typical example would be the relaxation of return air temperature constraints from unoccupied zones. This could be implemented through the use of motion detectors. It can be viewed as an extension of the air-bypass system together with reset control.

Return air set-points were allowed to drift between 16 and 27°C when the zones were unoccupied. A typical application would be the implementation of motion detectors. This range was chosen to assure that the lag period (time constant) of the system was insignificant enough not to influence comfort levels should sudden changes in thermal load occur.

Retrofit simulation showed setback control to effect substantial annual energy savings of 60% or 1763 MWh (simulation results are shown in Fig. 13). Bearing in mind that digital control is most likely to form part of the retrofit on account of its relative low cost, versatility and robust nature, this option poses to be an even further possible lucrative choice worth evaluating in the economic analysis.

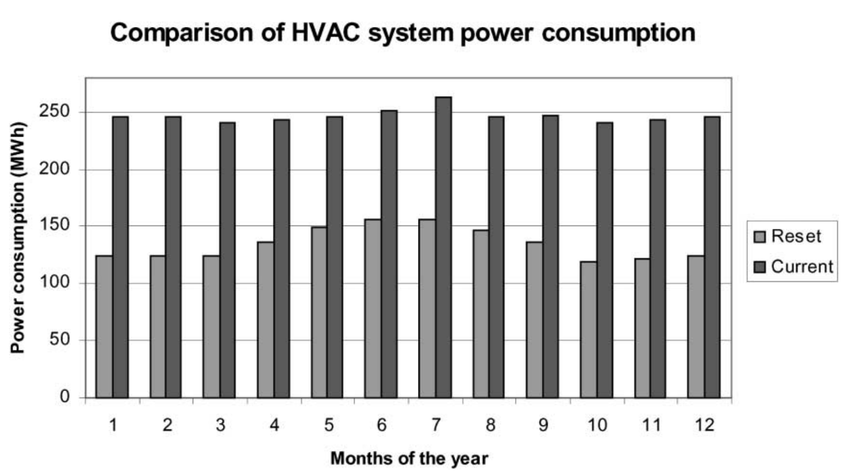


Fig. 12. HVAC power consumption due to the reset control strategy.

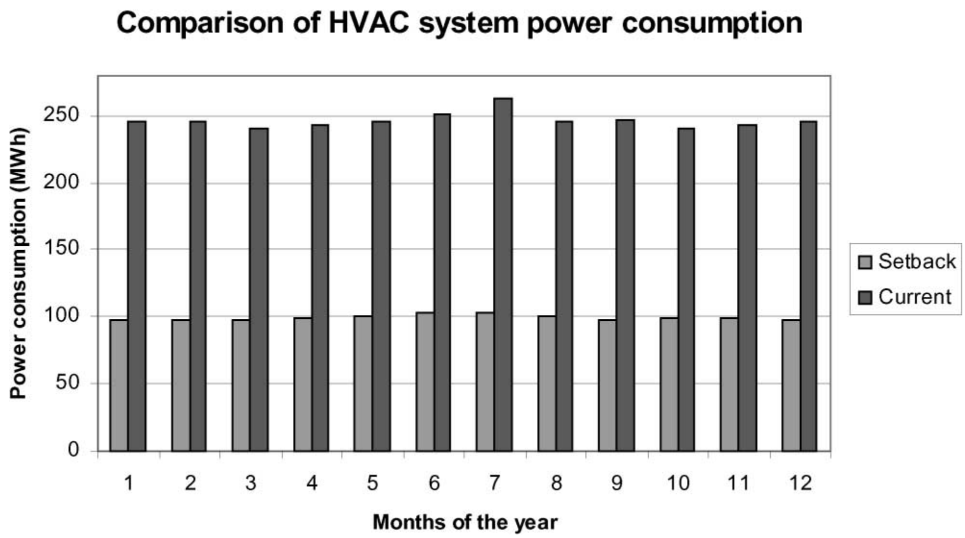


Fig. 13. HVAC power consumption due to the setback control strategy.

5.5. Improved HVAC system start–stop times

In all the above simulations, the HVAC system was in operation every day of the year as is the present system. For the intended use of this building, this is clearly unnecessary. Retrofit simulations comprised of switching off of the system on obviously vacant days, e.g. Sundays and public holidays.

The improved start–stop time retrofit simulations predicted annual energy savings of 66% or 1953 MWh. The simulation results are shown in Fig. 14. Bearing in mind the relatively inexpensive nature of this retrofit (involves the addition of timers or mere manipulation of operation set-points in the case of digital control), this retrofit option poses to be the most lucrative thus far.

5.6. Economiser control (including air-bypass, reset and setback control and improved start–stop times)

To illustrate its cumulative effect, fresh air economising was investigated in simultaneous application with air-bypass, reset and setback control and improved HVAC system start–stop times.

With the economiser cycle, the amount of fresh air into the system is controlled. This proposes to save on unnecessary cooling of supply air if cool outside air can be bled into the system instead. Conversely available warm air can also be used. Economiser set-points were chosen at 22 and 23°C for cool and warm intake air, respectively.

Resulting predicted savings came to 66% or 1951 MWh annually. Compared to the other options economiser control adds but little value in terms of energy saving (Fig. 15). This is mainly due to the specific climatic conditions not lending to cooler air during summer or warmer air during winter being drawn in from outside.

5.7. CO_2 control (including air-bypass, reset and setback control and improved start–stop times)

An improvement on the above economiser system is through carbon dioxide control. This system minimises

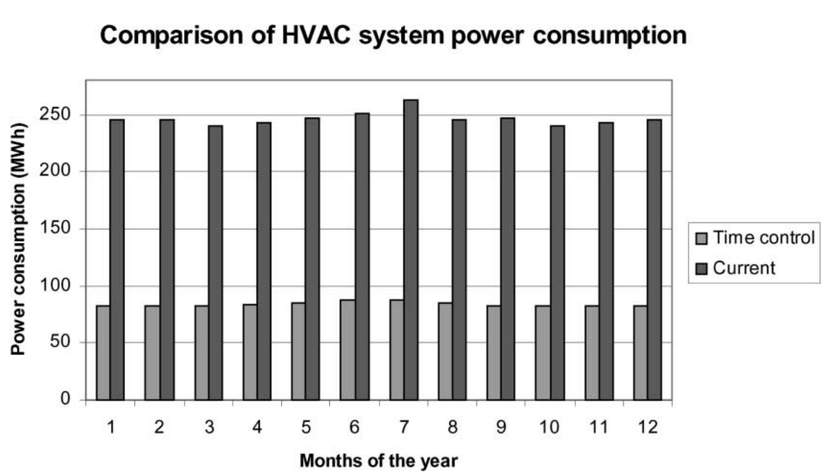


Fig. 14. HVAC power consumption due to the improved start–stop times strategy.

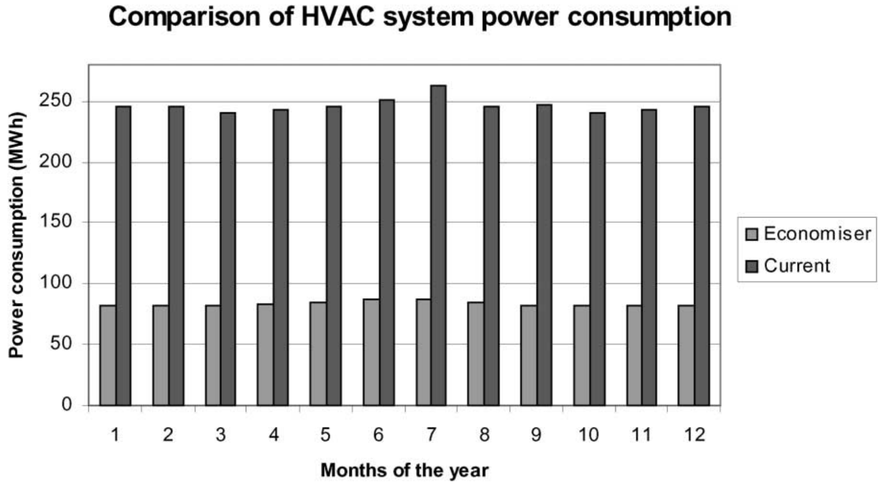


Fig. 15. HVAC power consumption due to the economiser control strategy.

on fresh air intake by controlling oxygen and odour levels through the measurement of CO_2 concentration. This control strategy was again simulated in conjunction with the first four to determine its cumulative effect.

In accordance with the World Health Organisation, CO_2 concentration levels are limited to 1300 ppm (parts per million),while 600 ppm is recommended [13]. As the outside air in this case has relatively high CO_2 concentration levels, a level of 900 ppm was chosen for the indoor air (Fig. 16).

The CO_2 retrofit option resulted in predicted savings of only 66%. Similar to the economiser option, CO_2 control is expected to have a marginal effect on the energy efficiency of the building.

5.8. Summary of retrofit options

The retrofit options investigated showed that the building under investigation has considerable energy savings potential. The results are summarised in Fig. 17. As shown, HVAC system energy savings of as much as 66% are attainable without compromising indoor air comfort levels. A 66% saving in HVAC energy constitutes a saving of more than 30% of the total building energy consumption.

Section 5.9 focuses on determining the most economically viable retrofit option.

5.9. Economic analysis

An economic analysis was conducted to weigh up retrofit cost with expected monetary savings. A summary of the results is shown in Fig. 18 with the payback period compared in months. The air-bypass system alone had a relatively long payback period (120.4 months) due to the high implementation cost needed to upgrade the current system. It is therefore not shown in the figure.

However, if air-bypass control is installed together with the other retrofit options, this scenario changes.

From the results, it is clear that the application of air-bypass, reset control, setback control and better start–stop times will result in a straight payback period of only 9 months. This option, having the smallest payback period, is thus recommended as the retrofit option of choice.

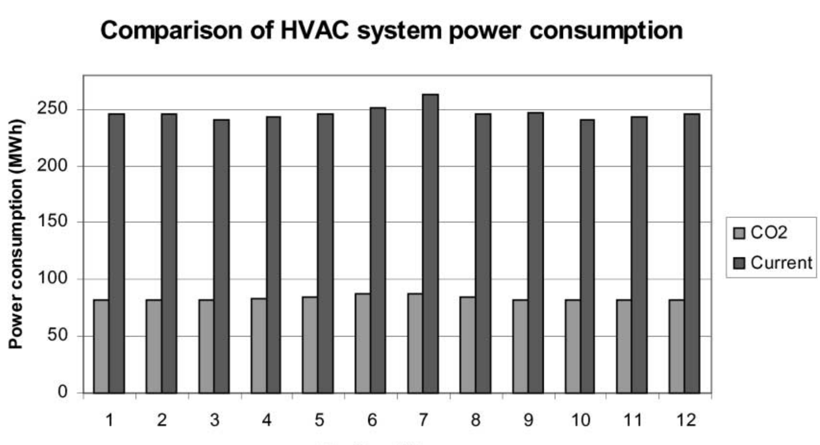
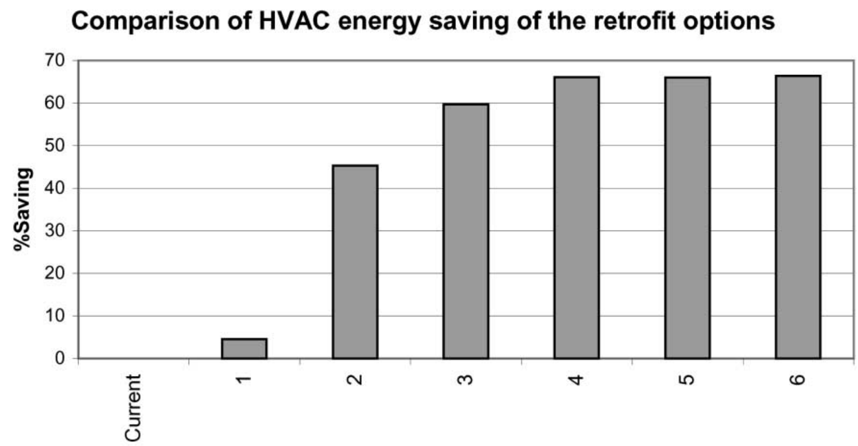
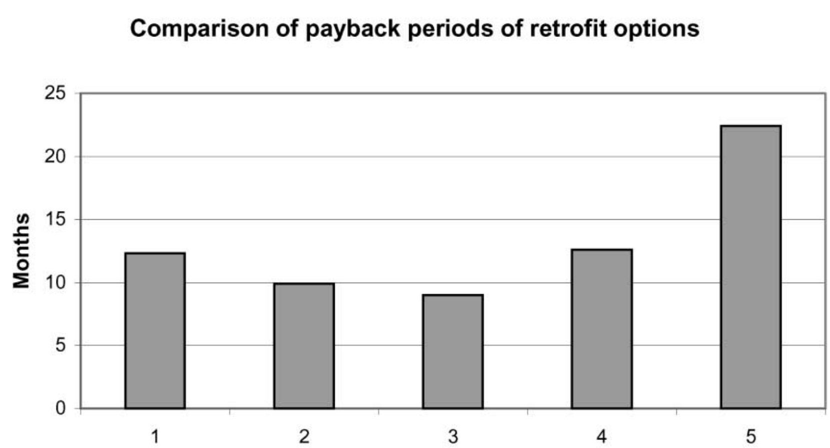


Fig. 16. HVAC power consumption due to the CO_2 control strategy.



Legend	
1	Air-bypass
2	Air-bypass + Reset
3	Air-bypass + Reset + Setback
4	Air-bypass + Reset + Setback + Better Start-Stop times
5	Air-bypass + Reset + Setback + Better Start-Stop times + Economiser
6	Air-bypass + Reset + Setback + Better Start-Stop times + Economiser + CO_2

Fig. 17. Comparison of the different energy saving retrofit options for the HSB.



Legend	
1	Air-bypass + Reset
2	Air-bypass + Reset + Setback
3	Air-bypass + Reset + Setback + Better Start-Stop times
4	Air-bypass + Reset + Setback + Better Start-Stop times + Economiser
5	Air-bypass + Reset + Setback + Better Start-Stop times + Economiser + CO_2

Fig. 18. Comparison of the retrofit option payback times.

6. Conclusions

This article documents a case study aimed at developing cost-efficient HVAC control strategies to ensure optimal energy use and sufficient indoor comfort. Through the use of an integrated simulation tool various retrofit options could be investigated and evaluated in these terms.

Investigated retrofit techniques included air-bypass control on cooling coils, reset and setback control, improved HVAC system start–stop times and economising on outside air intake. Through the integrated simulation of the building, HVAC system and its controls, these were optimised and compared in terms of expected indoor comfort, energy savings and resulting payback periods.

Of the retrofit techniques investigated, improved HVAC system start–stop times together with air-bypass, reset and setback control was found to be the most lucrative. Predicted annual energy savings were 66% (1900 MWh) which will result in an expected straight payback period of 9 months. This saving translates to a 30% reduction of the building's total energy consumption.

Acknowledgements

TEMM International (Pty) Ltd. commercialised QUICKcontrol: we thank them for the use of the software.

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