A NEW INTEGRATED PROCEDURE FOR ENERGY AUDITS AND ANALYSES OF BUILDINGS

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ABSTRACT

Title:	A new integrated procedure for energy audits and analyses of buildings
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A rapid growth in the national electricity demand is placing an ever-increasing demand on the national electricity supply utility, Eskom. Projections show that the load demand in South Africa may exceed the installed capacity by as early as 2007. This is mainly due to the increase in demand in the residential sector as a result of the electrification of rural and previously disadvantaged communities. However, the industrial and commercial sectors also have a role in this increase.

In an attempt to reduce the demand for electricity Eskom has adopted its Demand Side Management (DSM) initiative. This initiative is aimed at lowering the electricity demand in peak times through energy efficiency (EE) or load shift, out of peak demand times. Eskom is implementing the DSM strategy by financing Energy Service Companies (ESCOs) to reduce the demand load of major electricity end-users during peak times.

Buildings consume a large percentage of the total energy supply in the world. Most of the energy consumed in buildings is used by the heating, ventilation and air-conditioning (HVAC) systems, as well as lighting. However, a large potential for energy savings exists in buildings. Studies have shown that up to 70% of the electricity consumption of a building can be saved through retrofit studies.

However, to capitalise on these opportunities, the ESCOs require tools and procedures that would enable them to accomplish energy savings studies quickly and efficiently. It should be a holistic approach to the typical ESCO building audit. A study of current available software programs showed the lack of holistic tools aimed specifically at retrofit audits, and therefore also the need for such a program.

The building simulation program most suited to the retrofit study was chosen and it was used in a retrofit audit. By emulating a retrofit audit with this software, its performance in the field, both positive and negative, could be established. With the experience gained from the retrofit study, as well as input from ESCOs in the industry, a need for such a retrofit tool was established.

The simulation program that was tested in the retrofit study is the tool QuickControl, as well as the newer version of the program, entitled QEC. The case study showed that even though these packages are well suited to ESCO work, they have certain drawbacks in view of the holistic project approach. The ESCOs require a simple, fast, and integrated procedure for energy audits. This procedure should be embodied in a software program.

This study proposes a new integrated procedure for energy audits and the analyses of buildings, in the form of a software tool. This new tool is geared towards the ESCO building audit, in both South Africa and internationally. It is designed to enable a diplomate engineer to accomplish a building energy and retrofit analysis in two weeks, leading the user through all the main project steps, from data acquisition to writing of the final project report. This is a significant improvement, since it normally takes 50 man-days for an experienced and trained engineering team to complete a full building audit.

This tool was used in a case study to test its validity and accuracy. It was found that certain situations would arise in which the criteria that were set for the program would not be adequate. The results from the case study were favourable and satisfied the criteria that were set for the procedure.

SAMEVATTING

Titel:	'n Nuwe geïntigreerde prosedure vir energy oudit en gebou analise
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Skool:	Meganiese en Materiale Ingenieurswese
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Sleutelterme:	Energie Diens Maatskappy; Termiese simulasie; Energie effektiwiteit; Gebou termiese gedrag; Aanvraags kant bestuur; Piek las vermindering

Die snelle groei in die nasionale energie vraag is besig om stygende druk op die nasionale energie leweransier, Eskom, te plaas. Huidige vooruitskouinge dui daarop dat die vraag na elektrisiteit, die aanbod alreeds sal oorskry teen 2007. Die toename is hoofsaaklik as gevolg van die elektrifisering van die platteland en voorheen minderbevoorregte gemeenskappe. Die industriële en kommersiële sektore speel egter ook 'n belangrike rol hierin.

In 'n poging om die vraag na elekrisiteit te verminder het Eskom die DSM (*Demand Side Management*) inisiatief geloods. Hierdie inisiatief is gemik daarop om die elektrisiteit vraag in spits tye te verminder, deur energie effektiwiteit of deur las verskuiwing na buite spits tye. Eskom implimenteer hierdie strategie deur Energie Diens Maatskappye (*ESCOs*) te finansier, om die las van groot eind-verbruikers te verminder gedurende spits tye.

'n Groot deel van die wêreld se energie produksie word in geboue gebruik. Die meeste van hierdie energie word op hulle beurt weer deur verhitting, ventilasie en lug versorging stelsels en beligting gebruik. Daar lê egter 'n hoë energie besparing potensiaal opgesluit in geboue. Studies het getoon dat tot 70% van die elekrisiteit wat gebruik word in geboue bespaar kan word deur herinstallering studies en implementering.

'n Energie Diens Maatskappye het egter die regte gereedskap nodig om van sulke besigheids geleenthede gebruik te maak. In hierdie geval moet dit 'n alomvatende oplossing vir die tipiese

gebou energie besparing oudit wees. 'n Studie van huidig beskikbare metodes en sagteware pakette het gewys dat daar 'n behoefte bestaan na 'n paket wat spesifiek gemik is op gebou energie besparing oudits.

'n Gebou oudit is ook gedoen met 'n paket wat die meeste geskik is tot hierdie tipe werk. Met die ondervinding wat opdedoen is deur die gebuik van die program, sowel as insette van die industrie, is die spesifikasies vir so 'n paket opgestel.

Die paket wat gebruik is om die studie te doen is *QuickControl*. 'n Meer resente weergawe van die program, naamlik *QEC*, is ook gebruik. Die gevalle studie het getoon dat alhoewel die programme goed inpas by hierdie tipe werk, daar wel gebreke in terme van die algehele projek benadering is. Wat die energie diens maatskappy nodig het, is 'n eenvoudig, geïntigreerde, en vinnige metode vir gebou energie oudits. Hierdie metode moet dan ook in 'n sagteware paket omvat word.

In hierdie studie word 'n nuwe, geïntigreerde prosedure vir energie oudits en analise van geboue, in die vorm van 'n sagteware paket, voorgestel. Die gereedskapstuk is gemik op gebou oudits in Suid Afrika asook internationaal. Dit is ontwerp om 'n diploma ingenieur in staat te stel om 'n volledige energie en besparing oudit van 'n gebou in twee weke te doen, en die gebruiker te lei deur die algehele oudit proses: van data insameling tot die skryf van die projek verslag. Dit is dan ook 'n groot verbetering op die vorige tipiese tydperk van 50-man dae wat so 'n projek opneem. Die paket is ook in 'n gebou studie gebruik. Daar is egter gevind dat die spesifikasies wat vir die program gestel is, self nie voldoende sal wees vir alle gevalle nie. Die program het aan die spesifikasies en verwagtinge voldoen.

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A very special thanks to my wife, and my parents, for their continuous love and support.

LIST OF ABBREVIATIONS

DSM	Demand Side Management
RH	Relative Humidity
MD	Maximum Demand
EE	Energy Efficiency
LM	Load Management
HVAC	Heating, Ventilation and Air-Conditioning
ESCO	Energy Service Company
IAQ	Indoor Air Quality
CAV	Constant Air Volume
VAV	Variable Air Volume
BMS	Building Management System
AHU	Air Handling Unit
RMP	Revolutions per Minute
FAR	Fresh Air Ratio
PDA	Personal Digital Assistant
PC	Personal Computer
ETB	ESCO toolbox
PF	Power Factor
kVA	Kilo Volt Ampere (Standard unit for peak demand)
kW	Kilo Watt (Standard unit for power consumption)
MW	Mega Watt
kWh	Kilo Watt Hour (Standard unit for electricity consumption)
MWh	Mega Watt Hour
PID	Proportional Integral Differential
COP	Coefficient of Performance

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1

AN INTRODUCTION TO ENERGY SAVINGS IN BUILDINGS

In this chapter, the background, problem statement, and objectives are given. The most important contributions of the study are also listed. The section concludes with a brief summary of the remaining chapters.

1. AN INTRODUCTION TO ENERGY SAVINGS IN BUILDINGS

1.1. Background

International studies have shown that building operational costs account for approximately one third of the total energy consumption of most countries [1]. In 1989, 37% of the world primary-energy-consumption was used in building operation [2]. In developed countries, 57% of all the electricity generated is utilised in commercial buildings. In developing countries, commercial buildings account for 38% [3].

In South Africa, studies have shown that 20% of the total municipal energy is utilised in commercial buildings [4] (shown in Figure 1-1). Rousseau and Mathews concluded that 10% of all energy consumed in the world is expended by building air-conditioning systems [5]

Studies done by TEMM International (Pty) Ltd. in South Africa have shown that in the commercial sector approximately 50% of energy is used for air-conditioning [6]. According to the South African Department of Minerals and Energy, this figure can be as high as 74% in summer, for temperate climates [7].

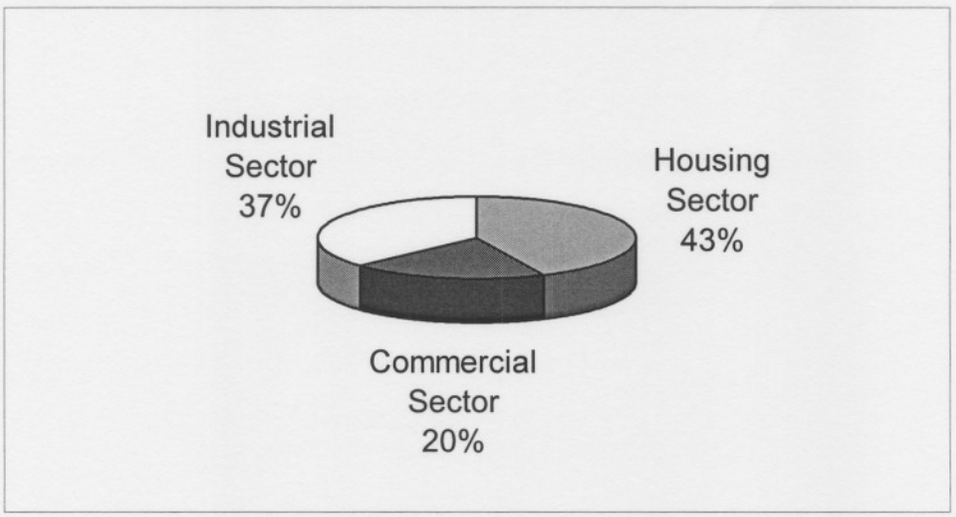


Figure 1-1: Breakdown of electricity in South African buildings by sector

The United States Department of Energy predicts that the world primary energy consumption will increase by 59% over the period 1999 to 2020 [8], as shown in Figure 1-2. From the figure,

it can be seen that the highest growth is expected in developing countries. The electricity used in developing countries during the 1980s has grown by more than 11% per year [9]. Especially in South Africa a possible energy crises may arise in the near future.

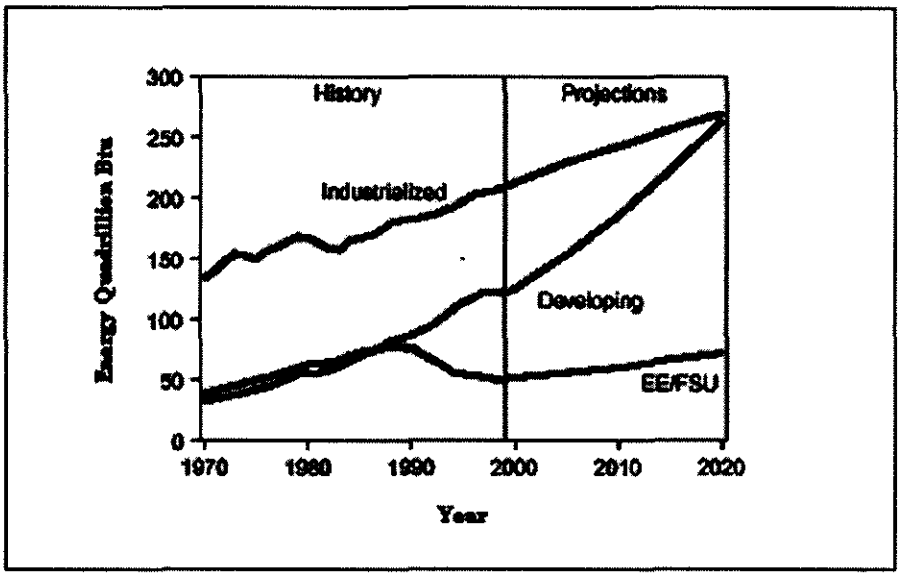


Figure 1-2: Prediction of world energy consumption

Currently there is a surplus in electricity supply and peak demand capacity in South Africa. A typical daily demand profile is dominated by a morning and afternoon peak. This peak can mainly be attributed to the residential sector, with the commercial and industrial sectors also contributing to this. The main reason for this peak is the electrification of 3.5 million homes since 1993, which added and additional 750 MW to the system [10]. A typical daily load profile can be seen in Figure 1-3 [11] below.

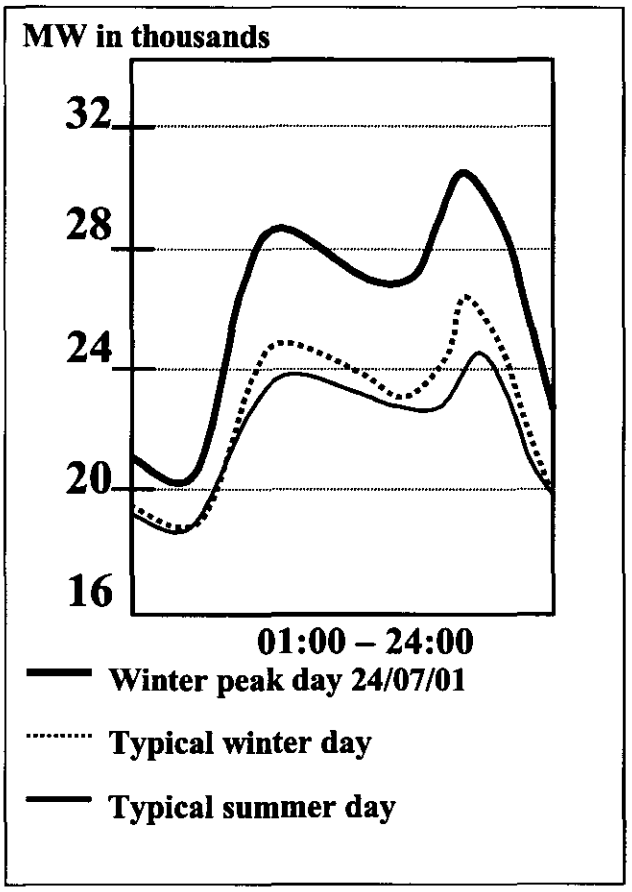


Figure 1-3: Typical daily load profile for South Africa

Approximately 40% of all homes in South Africa, as well as numerous schools and clinics are without ready access to electricity supply [12]. Eskom, which is by far the largest supplier of electricity in South Africa (95%) [13], plans to electrify an additional 1 750 000 homes in the near future [14]. This will place additional strain on the electricity utility and is one of the main reasons why the peak demand is expected to increase within the next five years [15] (See Figure 1-4 [15] where the demand profiles till 2015 are forecast). This means that the peak demand will become higher than the present delivery capacity of the system. Additional required capacity is expected by 2007 if the present demand growth prevails [16][12].

In accordance with Eskoms latest planning, building a new peaking load power station can take up to seven years to build [17] at a cost of around R16 billion [18], and three years for the return of mothballed and gas-fired plants. It is therefore clear that there will be a potential peak demand shortage within the next five to seven years if no corrective actions are taken soon. At the very least the price for electricity, especially in the peak periods, will become much higher due to higher long run marginal costs resulting from the investment in new plants.

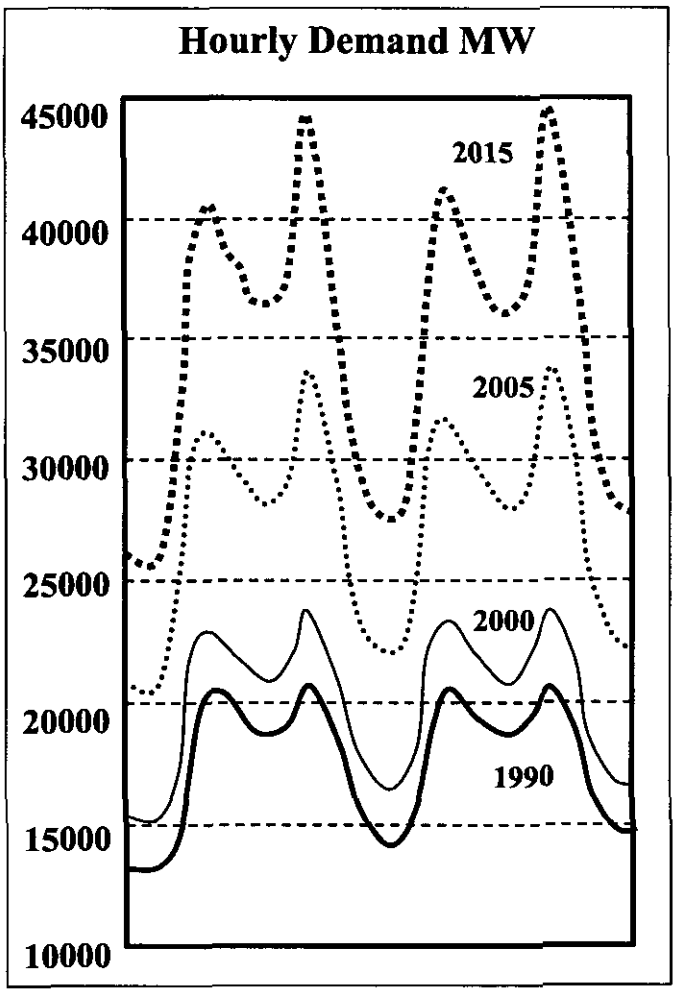


Figure 1-4: Typical average winter load profile forecast until 2015 for two days

As a short-term solution, Eskom has launched its Demand Side Management (DSM) initiative. The term DSM is used to describe the planning (Scheduling) and implementation of activities to influence the time, pattern and amount of electricity usage in such a way that it produces a change in the load profile of the industry, while still maintaining customer satisfaction [17]. In short, DSM is designed to change the current load shape of electricity usage in South Africa by shifting or reducing consumption peaks. The two main areas of focus in this regard are Load Management (LM) and Energy Efficiency (EE). A graphical explanation of these concepts is given below.

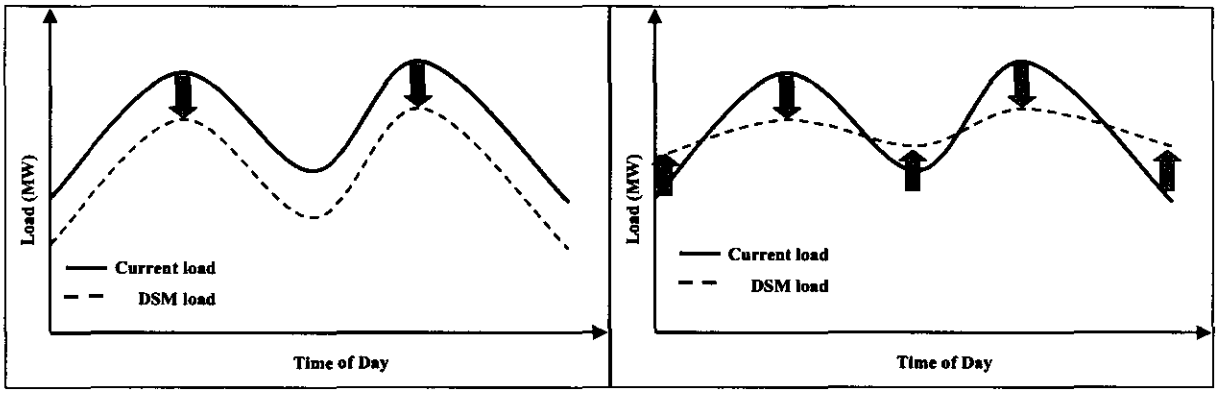


Figure 1-5: DSM through EE and LM

Eskom has set specific goals and targets for DSM to be realised by 2025 (Or over the next 25 years). To achieve these objectives it is imperative that the initiative is sustainable and acceptable for all parties and stakeholders involved. The goal is set at a deferral of 3.67 GW over the period. For the industrial and commercial sectors, it is envisaged to defer some 535 MW by 2020 by means of load management [15]. The capital costs associated with these deferrals are R 1.6-million per MW for Energy Efficiency programmes and R 1.45-million per MW for LM programmes. These values are estimated costs [17].

One could also expect the area of energy conservation and energy efficiency to become an issue increasingly driven by government. The Reconstruction and Development Program of the South African government states that "Energy efficiency and conservation must be a cornerstone of energy policies" [19]. One could expect that such policies from government could make it worth while for end users to be more energy conscious.

Up to now we have seen that buildings consume a large amount of energy, and that the energy consumption of the world is going to increase in the near future. We have also seen that the demand for electricity is going to exceed supply within the next decade. But why is this important?

Audits in India suggest that 33% of the annual electricity use in a typical building could be saved through management and technological changes [20]. Similarly, estimates from the former Soviet Union suggest that 25% of the energy used in existing buildings could be saved [21]. A study done in the USA of over 1 700 building-energy retrofits, reports annual savings of 18% of whole building energy usage with a medium payback period of 3.1 years [22]. In some instances

very large savings have been achieved, large individual projects have saved in excess of $800,000 in a single year [23]!

Optimistic sources estimate savings of as high as 70%, with the use of improved design and management, as well as through retrofit projects of existing commercial buildings [24]. However, it is more generally agreed that energy savings of around 30% might be realised through improved design management procedures and retrofit projects of existing buildings [25][26]. If a 30% penetration in the industry with a 30% saving per building could be realised in South Africa, it could result in energy savings of approximately R2 000 million per year (in 1989 terms) [27]. This would also result in a substantial reduction in electricity demand.

Such retrofit studies would in most cases be of more worth in older buildings than in new buildings. However, one must remember that a building can be considered outdated even after 15 years of use [28]. Depending on the system and the maintenance history, newer buildings may also have potential for energy saving.

Heating, ventilation, and air-conditioning (HVAC) system energy efficiency in buildings means reduced electricity consumption, monetary savings for the owner and less greenhouse gases being released into the atmosphere. Although very important, energy saving measures must never compromise indoor air quality (IAQ). The reason is that IAQ has a direct effect on the productivity of the occupants [29]. The cost associated with poor IAQ far outweighs savings due to reduced energy consumption [30].

Popular belief in the past was that good IAQ and energy efficiency were in direct conflict [31]. A cost-effective way to improve the energy efficiency of an HVAC system, without compromising indoor comfort, is by implementing better control. The most effective way to predict the impact of the system changes on the energy efficiency and indoor comfort is with the use of computer simulations [32]. It is also very important that the implementation of energy saving measures do not affect the indoor comfort [33].

Additionally to the energy saving that a building retrofit study brings, also other improvements may result. For a lighting retrofit it could include improved colour quality, improved light levels, and from HVAC improvement one may find reduced run time during operating hours,

improved temperature control, equipment failure notification, preventative maintenance, additional safety and security and improved information on the system [34]

Increasing the energy efficiency of HVAC systems is typically done by Energy Service Companies (ESCOs). The World Energy Council, a global organization that promotes sustainable energy use, defines an ESCO as: "... an organization that provides a wide range of services related to the implementation of energy-efficient products, technologies and equipment to owners of industrial, commercial, institutional, agricultural and/or domestic facilities" [35].

NAESCO, an important representative of the ESCO industry in the USA, defines an ESCO as "... a business that develops, installs, and finances projects designed to improve the energy efficiency and maintenance costs for facilities over a seven to 10 year time period." [36]. Currently the worth of the ESCO market in the USA is estimated at $2 billion annually [37]. The global market for energy efficiency has been conservatively estimated at US$ 80 billion per year [38]. While the energy service trade is well established in the developed world, it is still in its infancy in developing countries, like South Africa.

What the industry in South Africa and internationally needs is a procedure that would enable them to accomplish a building energy audit and retrofit study in the shortest possible time [39]. A recent study by Stein identified common mistakes that are frequently repeated during energy efficiency projects. Some of these mistakes include selection of inappropriate analysis tools, poor data collection, inadequate definition of baseline, inadequate reporting, inappropriate solutions and neglect of interaction between building systems [40]. To minimise potential mistakes such as this, the procedure should be embodied in the form of a computer program that integrates all the retrofit audit steps.

1.2. Energy audits and analyses of buildings

Numerous audit schemes have been performed internationally to determine the energy saving for buildings in their country. These schemes consisted mainly of comfort and energy audits. These studies provided the researchers with information on energy use and internal building environmental conditions. From the collected data the areas with the biggest potential for energy saving could be determined.

Most energy audits fall into three categories. These are walk through audits, mini audits, and maxi audits [41].

The walk through audit is the least expensive of these and therefore the most widely performed. It identifies preliminary savings by making a visual inspection of the building and facilities. This type of audit does not usually incorporate tests or measurements.

The mini audit is slightly more complex than the walk through audit and requires tests and measurements to quantify energy losses and use. The data collected from both the walk through and mini audits allow the consultant to determine a need for a more detailed study.

The most detailed of the three is the maxi audit [42]. It contains an evaluation of how much energy is used for each building function, such as air-conditioning, lighting, diverse equipment, and the like. It could also require a model analysis, i.e. computer simulation, to determine energy usage patterns and predictions on a year-round basis, taking into account such variables as weather data and load trends. A maxi audit is required to accurately predict the energy savings potential of a building [42].

Retrofit project protocols can vary depending on the consultant and the required project output. In general, all projects consist of measurement of certain building and HVAC system parameters, analysis of the data and reporting of results [43]. In South Africa, the typical audit consists of five basic steps. These include:

- Comfort audit
- Energy audit
- Verification and calibration of the computer simulation model
- Simulation and evaluation of various retrofits using the computer simulation
- Calculation of energy savings.

These steps are described below.

Comfort audit

The aim of the comfort audit is to evaluate the prevailing indoor air conditions. These conditions are needed for the retrofit calculations to ensure that the introduction of energy savings measures

will not cause deterioration of the indoor conditions. It is also important to determine if the actual comfort levels inside the building is up to standard, and therefore acceptable. The comfort conditions, especially the temperature, can also be a good indication of components that use excess energy. The comfort audit thus consists of the measuring of certain comfort indices.

These measurements include dry-bulb temperatures, relative humidity, air movement, fresh air supply and the lighting intensity, although air movement and lighting intensity are rarely taken. In some cases, the air quality is measured to determine variables like carbon dioxide (CO_2), carbon monoxide (CO) levels, etc.

Of the above-mentioned variables, the dry-bulb temperature is the most important. It is also the principal comfort index, especially where the relative humidity level is within allowable levels. The dry bulb temperature is the air property that is the easiest to manipulate through control changes in most cases and therefore the most cost effective.

Airflow is often overlooked, as it is fairly easy to measure on a macro scale, but that is not the case on a micro scale when one views the individual areas within a building space. The occupant may perceive airflow conditions like stagnant air or a draft, as a temperature induced discomfort.

Energy audit

The aim of the energy audit is to obtain the end user breakdown of the energy consumption and to identify the areas with the largest energy savings potential. In some cases, the retrofit audit will start with this step [44]. The total energy consumption of the HVAC system, lighting system and other diverse equipment like personal computers, photocopiers, lifts, etc. is determined. Sometimes the total building energy consumption is measured, and often the HVAC system and total building load is measured over time to determine operational trends. This identifies the major end users. A further breakdown of the HVAC end users, like the fans, chillers, boiler, etc. is made because the largest energy savings is usually achieved in this area.

The typical measurement taken for the energy audit is the power consumption value (kW). Other measurements may include the voltages, currents, energy demand, and power factors. The energy audit, together with the comfort audit, can also give a good indication of faulty

equipment, or equipment that may not be operating as specified which may otherwise go undetected.

Computer simulation: Verification and calibration

The most accurate method to determine the effects of retrofits on the building, is by using integrated, dynamic simulation. A simulation model of the building and integrated HVAC system is set up in the software program. This model must be calibrated to represent the real life building structure and accompanying air conditioning system. The calibrated model must then be verified to confirm the accuracy of the building model with the associated loads and climatic conditions, as well as the HVAC system components with the relevant time schedules and integrated operation. It is especially important to verify the base year simulation against yearly measured energy values, as this scenario would be used to calculate the possible savings of the retrofits.

Computer simulation: Recommendation for retrofit

The aim of this part of the study is the application of the computer simulation and associated information to make recommendations on acceptable indoor comfort levels and realising potential energy savings. Usually only a limited amount of options is investigated, including options to the building, lighting system, HVAC system, and the controllers.

Normally, the retrofits that are investigated in a building come from a typical set of retrofits. The consultant may, depending on the applicable building and the influencing factors, sometimes investigate options other than the ordinary.

Calculation of potential savings

The savings can be calculated by comparing the energy consumption of the retrofit to the energy consumption of the base year case [45]. The difference between the annual energy consumption of the simulated base year and the retrofit simulation gives the actual savings that should be realised if the retrofitting option is implemented.

1.3. Typical retrofit options used in South Africa

Retrofitting the building envelope

Energy can be saved if the building envelope can be made more energy efficient. The typical methods used in South Africa is insulation inside the ceiling void, increased shading on the outside windows with overhangs, and reflective glazing on the windows.

Fan scheduling

At times when the building is not in use, no air conditioning is needed. If the fans operate during these periods, it will waste electricity. A reduction in power consumption could be achieved if the fans are scheduled to operate only during certain time of the day.

These times would typically be when the building is occupied, unless heating or cooling is required at other times. Possible examples of this would be the application of night ventilation, or if the building is required to be at a specified temperature when the occupants arrive.

It has been the author's experience that typically many buildings' system fans are designed to operate on a schedule. It has been found from measurements that in some of these buildings it is not the case. Therefore, this option is used as a retrofit in many cases.

Economiser

The economiser control manages the fresh air intake into the building. With this control the air intake can be controlled to let in any amount, from a specified minimum up to 100% during occupied times, and 0% during unoccupied times.

The outside air can 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, the outside airflow will be reduced as much as possible.

Another control possibility would be the use of enthalpy control. This type of control is preferable to temperature control. The method uses outdoor air to mix with return air if the

outdoor air enthalpy is less than the return air enthalpy. This would result in lower energy consumption by the cooling coil for a given sensible cooling load.

The economiser strategy can be divided in two parts, an occupied strategy, and an unoccupied strategy. Typically, infrared motion detectors located in the venues, or a set schedule will be responsible for selecting the relevant strategy. The occupied strategy will be active for a preset period (eg. 15 minutes) after detection of movement by any of the sensors in the venue.

This implies that the timer will automatically reset if new movement is detected during this period and the timer countdown will start again. Therefore, the unoccupied strategy will only be activated when all the sensors in the venue are passive for a period exceeding the specified period.

The occupied strategy will generally operate in the following manner. If the return air temperature is higher than the outdoor air temperature, the following strategy will be implemented:

- If the return air temperature exceeds 22°C (the typical lower cooling setpoint), the fresh air damper will open proportionally from its minimum setting (40% fresh air of total supply) until fully open at 23°C (the typical upper cooling setpoint).
- The return air damper will, for the same conditions, 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 setting (60% return air).

If the outdoor air temperature higher than 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). This strategy is graphically presented in the figure below.

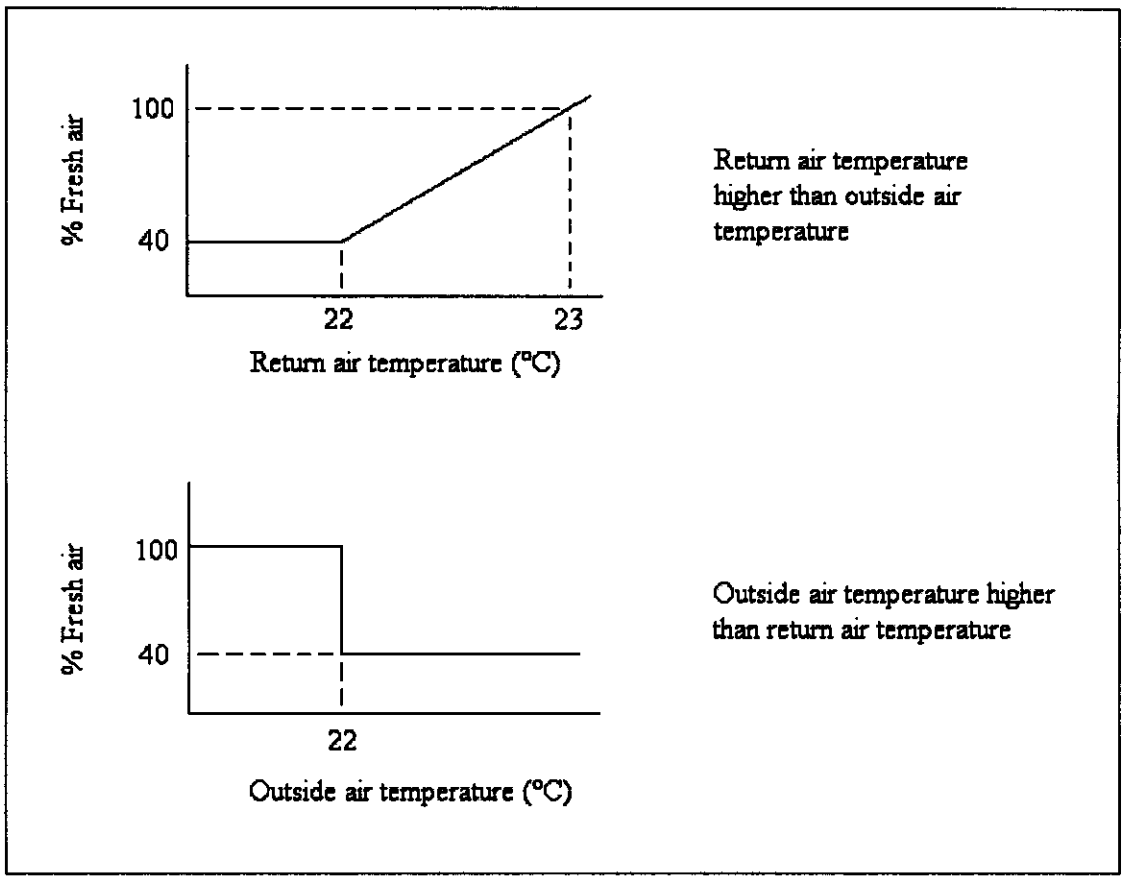


Figure 1-6: Occupied economiser control

The unoccupied strategy will operate as follows. If the return air temperature is higher than the outdoor air temperature, the following strategy must be implemented:

- 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 will be 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 the following figure.

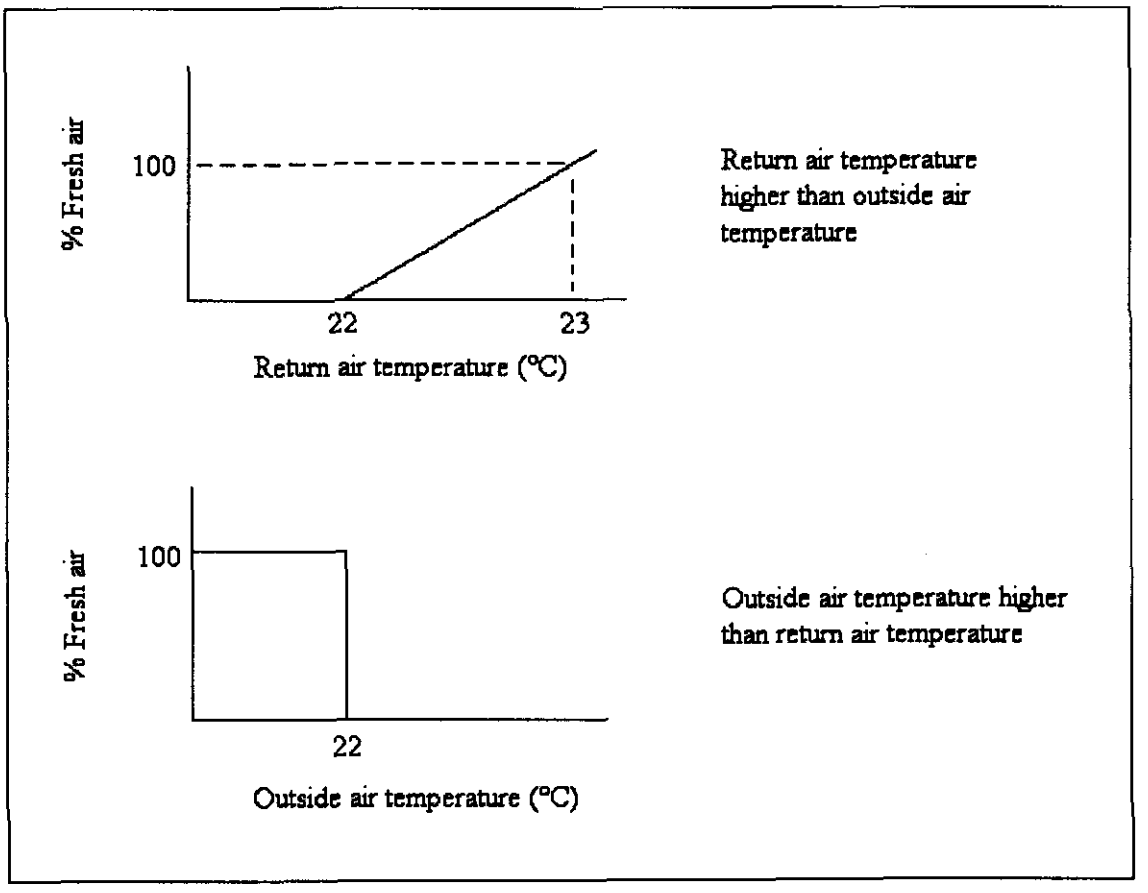


Figure 1-7: Unoccupied economiser control

New setpoints

Many buildings are set to temperatures that are outside the required comfort band. If the setpoints were set below and above the comfort band (or even the outer limits) in the case of cooling and heating respectively, then the AHU serving that particular space would be using too much energy. On the other hand, if this scenario would be reversed it would be beneficial from an energy perspective but would have a negative effect on the comfort of the occupants.

Therefore, altering the setpoints of a space that is set outside the comfort band could be beneficial either from a comfort viewpoint or an energy efficiency viewpoint. The setpoint should typically be as shown in the figure below.

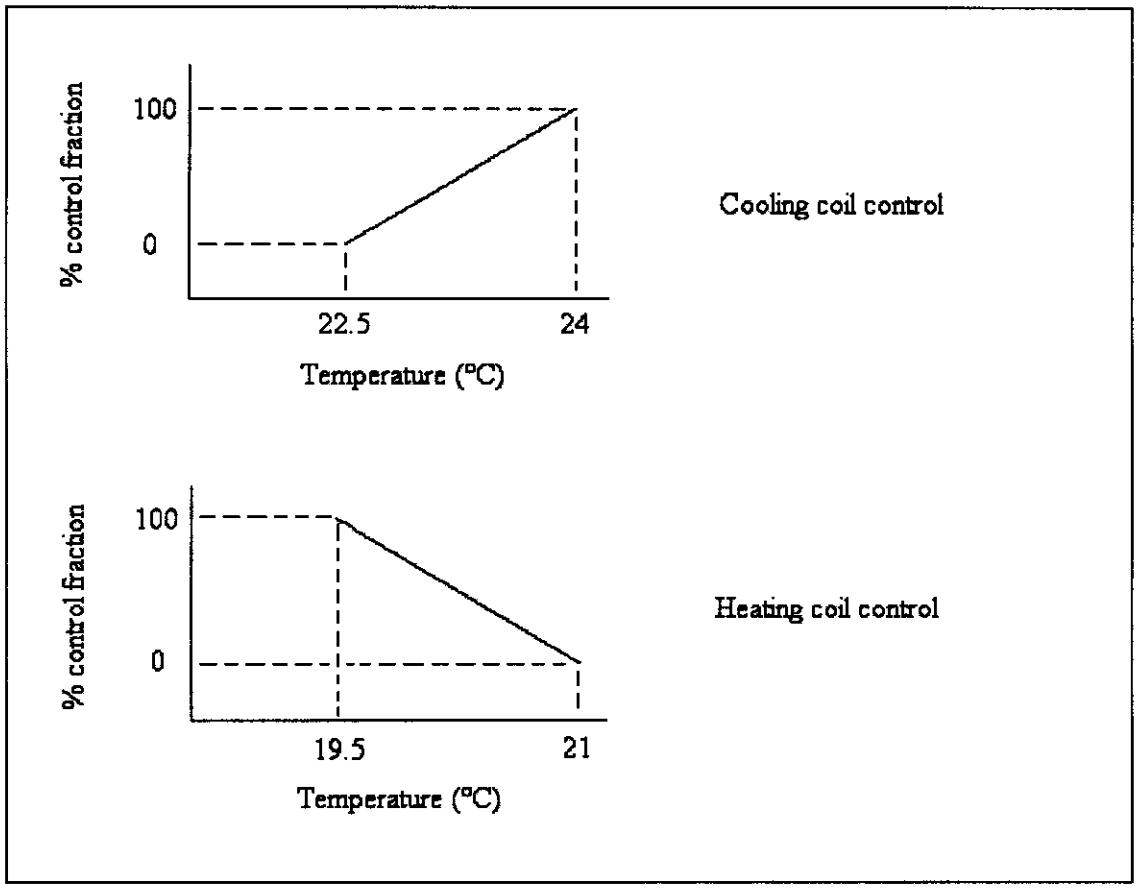


Figure 1-8: New zone setpoints

The upper graph shows that if the indoor temperature exceeds 22.5°C, the cooling valve will open proportionally from its closed position until fully open at 24°C.

The lower graph shows that if the indoor temperature drops below 21°C, the heating valve/element will open proportionally from its closed position until fully open at 19.5°C.

Setpoint setback

This option allows setpoint drift if the venues are unoccupied. This control strategy also requires the presence 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 setpoint to drift to hotter and colder temperatures respectively. The zones will then require less cooling and heating

from the HVAC system. The following figure gives a graphical representation of this control logic.

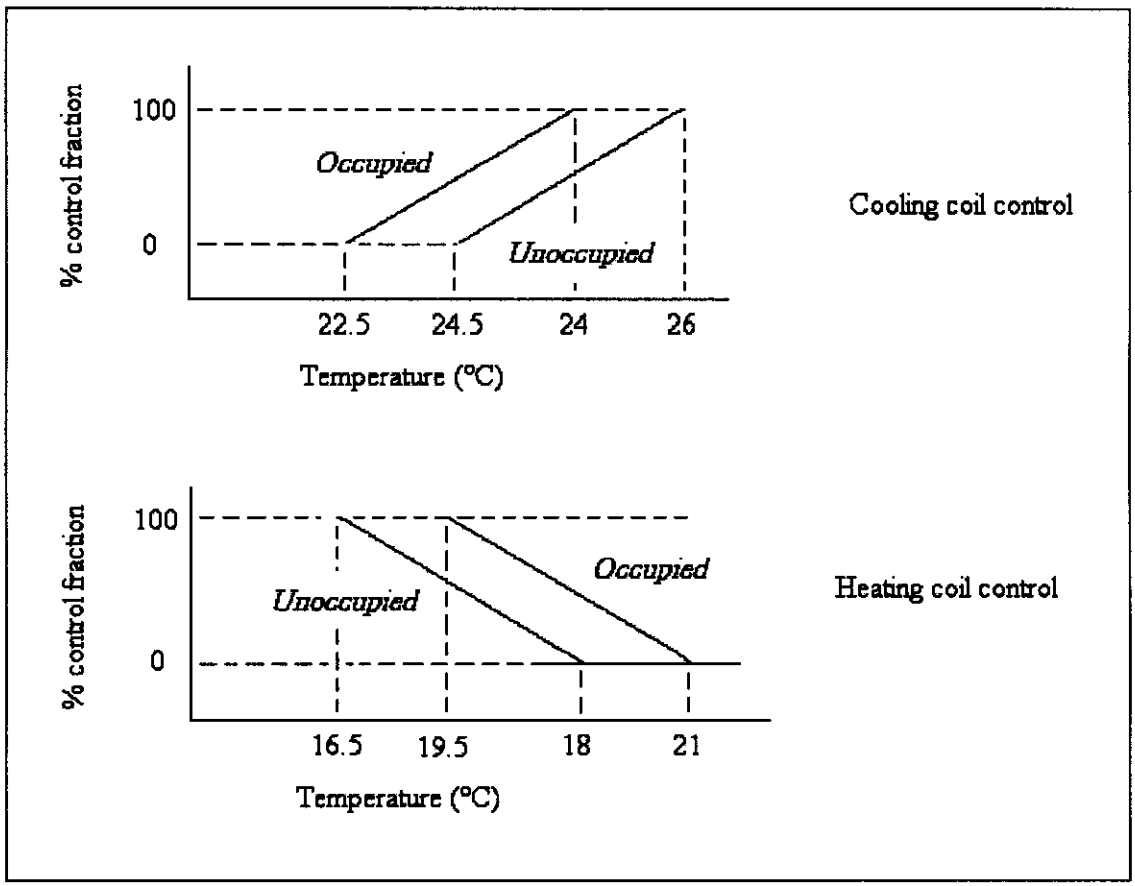


Figure 1-9: Setpoint setback control

The occupied and unoccupied times are determined in a similar fashion as for the economiser logic. For the unoccupied condition, 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

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. Figure 1-10 shows the fan control strategy.

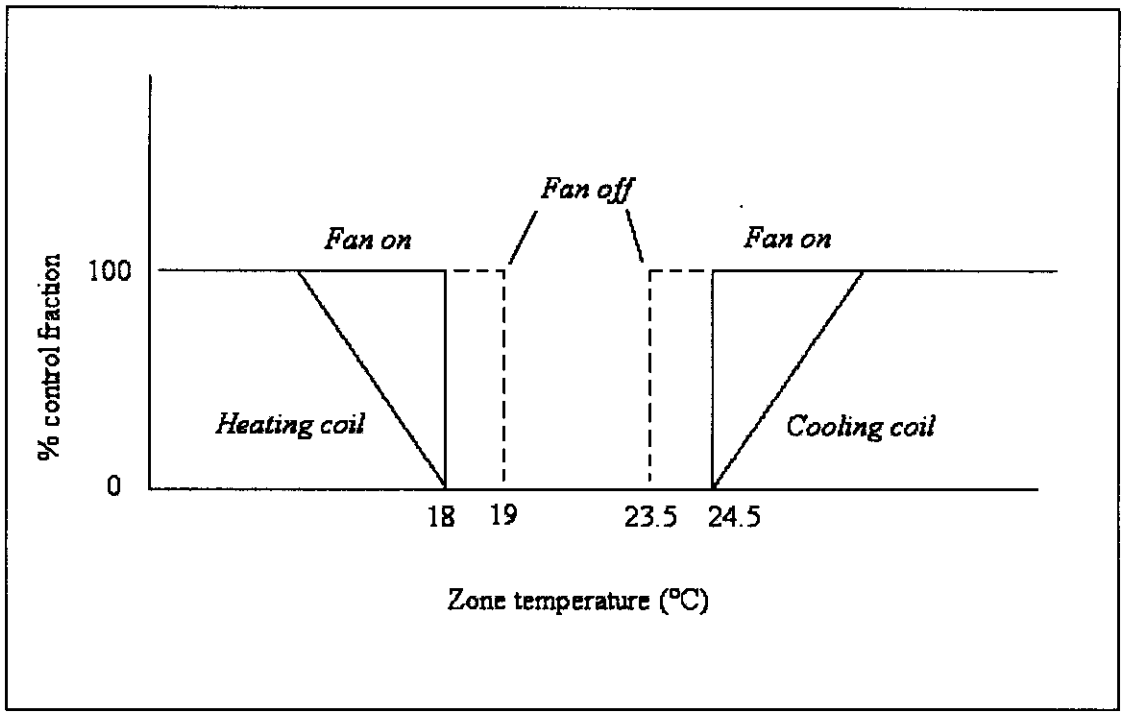


Figure 1-10: Fan control

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

If the venue is occupied the supply fans must run at all times for ventilation purposes. The return fans will operate in tandem with their corresponding supply fans.

Heating plant control

In many cases, the boiler of a building operates constantly throughout the entire year. The corresponding pump also operates continually right through the year. This wastes energy, as no heating is necessary during the hot months of the year.

A possible boiler control strategy should operate as follows. The boiler setpoint will be a second order function of the average outdoor air temperature of a previous timeframe, typically 24 hours (see Figure 1-11). The outdoor air temperature will therefore be monitored and logged at half

hour intervals. A new average outdoor air temperature will be calculated for each new half hour by taking the previous 48 recorded temperature points. A new setpoint will then be calculated for each half hour of the day using the following function (for a timeframe period of 24 hours):

$$setp = 0.162t^2 - 8.857t + 139.18$$

Where *setp* is the boiler setpoint in °C and *t* is the average outdoor air temperature in °C.

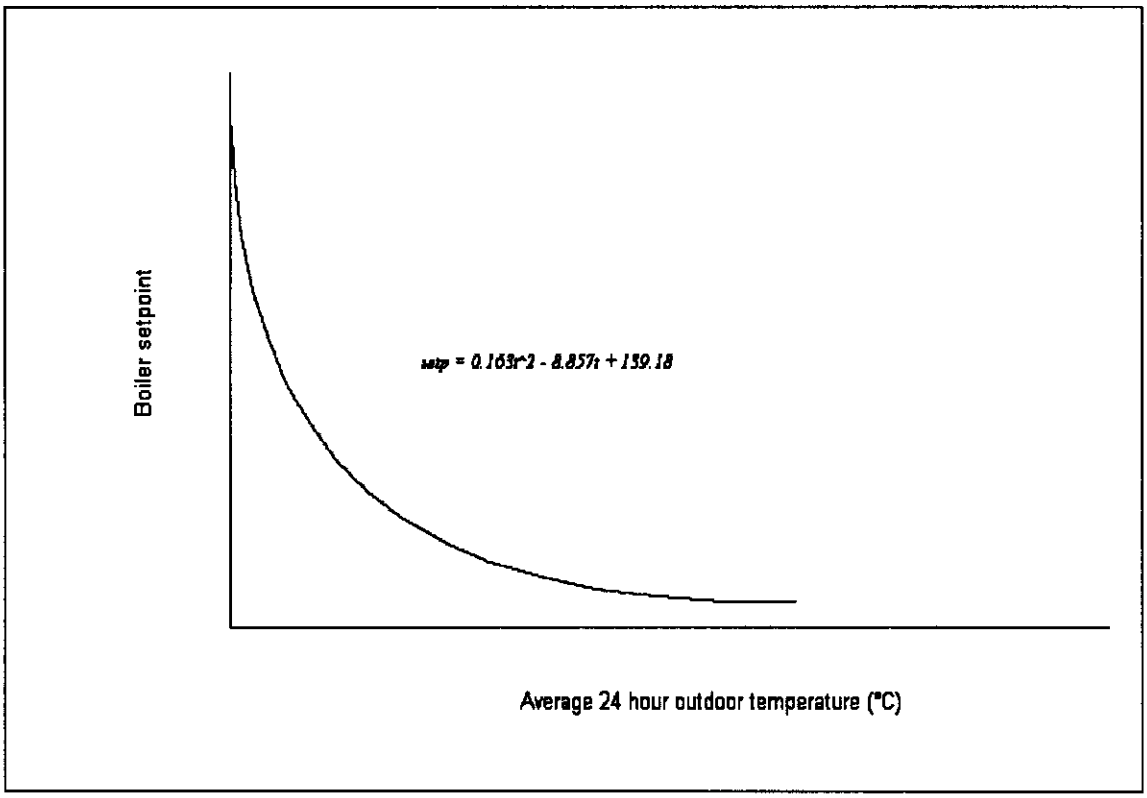


Figure 1-11: Boiler control

1.4. Overview of software tools

Most building simulation tools can be grouped into two types, namely system simulation programs and energy analysis programs [46]. The main aim of system simulation programs are to predict the dynamic response of the HVAC system and building, including the indoor air conditions, system operation points and energy consumption. Energy analysis programs endeavour to calculate the system energy consumption. There is plenty of building energy tools

available in the world today. A website sponsored by the United States Department of Energy hosts an online directory with a listing of over 200 programs [47].

System simulation programs generally are component based, making them more versatile with fewer restrictions placed on applicability [48]. Examples of such programs are (adapted from [5]) APACHE [49], Caberets [50], HVACSIM+ [51], HVAC-DYNAMIC [52], TRNSYS [53], and QuickControl [54].

With energy analyses programs various HVAC systems can be compared to find the system with the lowest energy consumption. Some programs of this type include DOE-2 (VISUAL-DOE) [55], BLAST [56], TAS [57] and TRACE [58], as well as the new EnergyPlus, a new program based on DOE-2 and BLAST [59]. DOE-2 is probably the most popular of the energy analysis tools.

Many of the energy analysis programs perform the calculations in three sequential steps [60]. Firstly, a load calculation is performed using the building model to a set indoor air temperature. Secondly, the thermodynamic response of the various components of the air-handling units are calculated when the system calculations are performed. Lastly, the plant equipment (responsible for the energy conversion) like boilers and chillers, are calculated.

This type of calculation can pose certain problems. For instance, it could happen that the system requires a larger capacity than the plant can deliver. In reality, this would result in the indoor temperature drifting above the fixed setpoint (in the case of cooling requirement). In DOE-2 an overload will be reported. In addition, when the system cannot maintain the indoor temperature, certain factors, like the mass temperature storing effect, will not be correctly simulated.

Although BLAST and DOE-2 are the two major public domain tools [61], according to the author the tools most suited to HVAC simulation are QuickControl and TRNSYS. However, according to Hanby [62] TRNSYS "generally have long execution times, often in the order of real time...". The author has had similar experiences with QuickControl. Also, in a recent verification study that validated a number of simulation program with the BESTEST diagnostic method showed errors of up to 48% for TRNSYS, and 36% for DOE-2 was found in some of the cases [63]. An evaluation of DOE-2 by Arndt [64] showed that the program requires extensive input data that is time consuming and difficult to obtain.

Many of simulation programs are available today, with various aspects of the building environment that is covered [65]. However, none could be found that contains a procedure to solve the holistic building retrofit audit in an integrated fashion.

1.5. Need for the study

The literature survey showed that:

1. The energy consumption of the world is set to rise dramatically in the coming years, especially in the developing countries,
2. The electricity consumption in South Africa has also risen drastically in the previous 10 years, and will continue to do so in the future,
3. Energy efficiency is going to play a large role in the energy policies of the South African government, which may lead to energy price increase,
4. The supply of electricity in South Africa is going to be exceeded by demand in the near future,
5. Buildings consume a large portion of the national and international energy,
6. Definite potential for energy savings exist in buildings and can be realised by ESCOs,
7. Such studies are best done with the help of building simulation programs,
8. Although many such programs exist, none could be found that is a dedicated retrofit audit program, geared towards the holistic project.

Therefore, the need was established for a holistic procedure for building retrofit studies. This procedure should be embodied in a software program.

1.6. Contributions of this study

This study focused on the need for an integrated procedure and software program that would enable the consultant to accomplish an entire building retrofit audit. The study identified the requirements of such a program. It proposes an integrated retrofit audit procedure embodied in a software program. Thereafter, the program was tested in a retrofit audit, which in turn identified certain limitations of the program, and identified the requirements for additional work on the subject.

1.7. Overview of the thesis

As far is possible, the chapters in this dissertation have been written so that they may be read independently of one another. Each has its own abstract, introduction, conclusion, and list of references where required. This has the advantage of greatly enhancing readability. However, some repetition of important concepts was necessary. A brief overview of each chapter is given below.

Chapter 1 discusses the energy situation in buildings. This includes a summary of the energy use and potential for energy saving in buildings. Typical retrofits used in South Africa are also described, as well as a short summary of the current building energy audit tools available.

In Chapters 2 and 3, the simulation program most suited to the retrofit audit is discussed and tested. Firstly a description of the program is given, as well as the shortcomings of the tool from the viewpoint of the full building audit. Thereafter the program is used in a building audit to demonstrate both the usefulness of a simulation tool in a building audit study as well as the drawbacks of the program in a practical manner.

Thereafter, in Chapter 4, the new building audit procedure in its embodiment in a software tool is described. This includes the need and requirement for a new ESCO tool, the manner in which the program optimises the procedure and a description of the inner workings of the program.

The procedure and program must be tested to determine the validity of the assumptions and new systems. In Chapter 5, a building audit is done to replicate a real-life retrofit audit, as one would do in practice, using the new program.

The dissertation is concluded in Chapter 6. A brief overall summary is given, where the most important results are discussed in conjunction with the dissertation's objectives. This includes areas of shortfall of the program. Several suggestions for future work are also listed.

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2

DESCRIPTION OF THE CURRENT AUDIT TOOL: QUICKCONTROL AND QEC

This chapter describes the current audit tool most suited to the building retrofit project. This description also includes certain enhancements that were made to the program to make it more suited to the retrofit environment, and is therefore applicable to this study. These programs were found to have certain drawbacks and negatives and these are described.

2. DESCRIPTION OF THE CURRENT AUDIT TOOL: QUICKCONTROL AND QEC

2.1. Preamble

As stated in the previous chapter, QuickControl is one of the programs that most closely satisfies the requirement of the ESCO audit. QuickControl was developed to satisfy the need of the consulting engineer for a dynamic, integrated simulation platform. This platform could be used for design and retrofit work. Although the program was created with both tasks in mind, it has mainly been used for the retrofit project typically done by an ESCO.

In such a retrofit study, it is obvious that the simulation tool forms a large part of the typical energy savings project. The reason for this is that most of the project steps (as discussed in chapter one) are driven by the requirements that the platform places on the user. This includes data acquisition, simulation model set up, verification and calibration simulations, retrofit simulations and the reporting and manipulating of the outputs.

The creators of the program, TEMM International (Pty) Ltd [1], identified the need for changes to the program to make it more efficient from the audit point of view. The main aims of the changes were to improve the speed and stability of the simulation, as well as the simulation time. A new platform was developed from QuickControl by implementing the changes identified by TEMM International, with the new program entitled QEC. Where QuickControl is a program that has been used in commercial retrofit projects, QEC was developed as a successor to QuickControl. QEC is currently not commercially available.

2.2. Description of QuickControl

QuickControl is a fully integrated, dynamic building simulation program. It has a Windows based graphical user interface. The input screen for the system simulation uses icon based drag-and-drop objects. The program is aimed specifically at the consulting engineer who needs fast results to the best control strategies. The specifications for the program are the following [2]:

- The tool should solve the building, the HVAC system and its controls in a fully integrated fashion.
- The tool should be easy to use. The specification for this is that a new user should be able to operate the program independently within two days.
- The tool should be stable. No prior knowledge of simulation should be needed to operate the program.
- The computer running time for a fully integrated simulation of a building, HVAC system, and complex energy management system, should be less than 30 min for a day simulation.
- The tool should be flexible enough to simulate all commonly used systems without undue simplifications.
- The answers should be accurate.

2.3. Description of improvements of QEC

Building

The input of the building data into the program has greatly been simplified, allowing for fast and easy construction of the zones. A building zone can be created in minutes without the need of any detailed building drawings.

No complex technical data is required of the user during the building construction phase. Instead, the user is given a set of choices, for example orientation, dimensions, surface structure, ventilation, etc. This prevents the input of unnecessary data that will have a small effect on the building performance [3].

HVAC system

The new program is sufficiently flexible to configure any system type found in the industry. It also employs a drag-and-drop interface that enables a fast and easy set up of the system. The simulation tool is component based, making it possible to configure any system type intuitively from the actual system (This feature in itself is not new and forms part of many of the simulation platforms available).

The model can be set up as a replica of the schematic drawing. This enables each component in the tool to be identified with the respective component of the real system in the same location. To accomplish this the program uses a graphical interface to configure the system and input the data.

The user is not required to input data that is not freely available or easily understandable. Each component can be configured from only one operating point. This operating point is readily available from the manufacturer's catalogue data, or from measurements taken of the existing system. This decreases the time required to acquire the measurements for the system components. The user can thus easily set up the HVAC components in the program.

The component models of the tool are derived from both fundamental principals and empirical correlation coefficients. Regression coefficients of the models are set up from typical system curves and scale models. These system curves and scale models are obtained from the single operating point described above.

The component-based philosophy of the program makes it possible to identify any problem areas during verification. This philosophy makes it easy to identify the component that does not perform according to specifications, and it can then be calibrated. This helps to ensure accurate and realistic simulations.

The output of each component is readily available. The system output trends, as well as the power consumption, are accessible for each 24-hour period throughout the year.

Simulation procedure

The most significant improvement over QuickControl is in the area of the simulation procedure of the program. Two of the most important aspects of any computer simulation are speed and stability. Nowhere is this more important than in a trade where time is of great value, the energy savings industry being one of many. Not only is a slow, unstable simulation tool very frustrating to use, but it also has financial implications for both the consultant and the client.
The use of explicit equations, as opposed to implicit equations, to calculate the output of the components, is the main improvement over QuickControl. This has the effect of increasing the

stability of the program and decreasing the simulation time. The building zones are similarly solved. Each building zone is described by a set of explicit equations without being coupled with the other zones.

Implicit equations require a solver for simultaneous solution of the equations. The use of explicit equations reduces the need for such a solver in the program. This has an advantage in both stability and simulation speed. Firstly, there is no need for time consuming iterations, thereby decreasing the simulation time. Secondly, explicit equations always give an answer, and in so doing increase stability.

2.4. Shortcoming of QEC

Although QEC was found to be the program most suited towards energy audit projects, it still does not satisfy the need for a software package geared towards the holistic building energy retrofit study.

It has shortcomings in the following areas:

- Data acquisition. The consultant is still required to carry logging sheets or memo paper together with the various measuring equipment. This makes it very uncomfortable for the consultant.
- The user is not lead directly to what information is required for the simulation inputs.
- Simulation model. Firstly, the user must build the model anew as no templates are given with the program (The user can create own templates and keep them for later use). In addition, the measurements taken on site must again be taken down, in this instance to characterise the various system components and zone models.
- Retrofit simulation. No default retrofit options are given with the program. Thus, the user must build the retrofit models anew each time a new building is simulated.
- Post-retrofit data evaluation. Although the results of the program can be seen graphically in the program, the test outputs of the energy consuming elements are given in a text file. The user is required to process this data and compare it to the base-year case manually before saving results can be seen.

- Financial evaluation of the retrofits. The user must also do any financial evaluation of the retrofits manually once the retrofit simulations have been done.
- Reporting. Once the project has been completed, it is left up to the user to compile a report of the project proceedings and results.
- Procedure. No inherent procedure is found in the program. This means that the program must fit into the user's own procedure before it is truly useful.

2.5. Conclusion

QuickControl is an integrated, dynamic component based program that has been used in commercial projects with success. QEC is a program based on QuickControl, but it has certain enhancements aimed to increase the efficiency of the simulation and program use. However, both the programs lack in the area of the holistic retrofit audit, and does not have an inherent protocol that forms part of the retrofit study.

2.6. References

[1] TEMM International (Pty) Ltd, P.O. Box 2156, Fearie Glen 4, Pretoria, 0043.

[2] E.H. Mathews, E. Van Heerden, D. Arndt, "A tool for integrated HVAC, building, energy and control analysis Part1: Overview of QuickControl", Building and Environment, Vol.34, Issue 4, pp.429-449, July 1999.

[3] M.W. Ellis, "New simplified thermal and HVAC design tools", Dissertation presented in partial fulfilment of the requirements for the degree Philosophiae Doctor, Faculty of Engineering, University of Pretoria, Pretoria, 1999.

3

A BUILDING AUDIT USING QUICKCONTROL AND QEC

Chapter 3 is concerned with the use of the simulation programs, QuickControl and QEC, in a building audit. This included all steps of the project from data acquisition to the analysis of the retrofit options. The results include the building retrofit audit with QuickControl, and the verification between QuickControl and QEC.

3. A BUILDING AUDIT USING QUICKCONTROL AND QEC

3.1. Preamble

In this case study, QuickControl was used to establish the energy savings potential of a building (a typical ESCO audit in South Africa). This included the verification of the electricity consumption and temperature trends of a building. Various retrofit options could then be simulated to determine the savings' potential that exists in the building.

QuickControl is a building simulation program established as a commercial program and used in various projects. This case study would then establish the positives and negatives of a commercial audit tool in a retrofit project. QEC is a program based on QuickControl, but with certain simplifications programmed in to make the program more stable and fast. By using QEC in a case study in conjunction with QuickControl, the validity and accuracy of the simplifications could be established.

The same project was therefore simulated with QEC. For this simulation, the focus was on the electricity consumption of the building and temperature swing of the building zones. The results of the simulation with QEC could then be compared with the measured data, as well as the results obtained with QuickControl.

The study was done on a conference centre located in Pretoria. The part done with QuickControl followed the same protocol as a typical ESCO audit. These step are:

- Date acquisition,
- Simulation model calibration and verification,
- Simulation of retrofit options,
- Economic analysis of the simulated retrofits.

3.2. Description of the building

The building under inspection is the Conference Centre of the CSIR, which is located in the eastern suburbs of Pretoria. It is a three-story building and has a total air-conditioned floor area of approximately 2,900 m^2. The building is commonly used for lectures, conferences, and meetings.

The air-conditioned areas in the three storeys include the following. There is a restaurant on the lower floor. On the ground floor, three conference halls, a restaurant, foyer, and coffee serving area, and on the first floor three conference halls. Together the venues accommodate a total of 1,570 people. The building has north, east, south, and west facing windows.

The zones will hereafter be referred to by the name of each particular space. These names are:

- Lower floor restaurant: Jade,
- Ground floor restaurant: Amber,
- Ground floor hall 1: Diamond,
- Ground floor hall 2: Emerald,
- Ground floor hall 3: Ruby,
- Ground floor foyer: Foyer,
- Ground floor coffee area: Coffee,
- First floor halls: First floor

Note: There are three halls on the first floor. These are the Onyx, Garnet, and Crystal halls. The first floor is supplied by one AHU, therefore for most instances the three halls were combined to form one zone.

3.3. HVAC system description

Air distribution system

Air is supplied to the building via a constant volume, variable air temperature system. It consists of a central cooling and heating plant, and air handlers for the conference halls, restaurants and reception areas. The entire system is located in a plantroom on the lower level.

Cooling and heating coils located inside the AHUs condition the air. Air is supplied to the venues via ducting. It is returned from the lecture halls via grilles and ducts back to the plantroom where it mixes with outdoor air before returning to the AHUs.

Fresh air is supplied to the building via grilles located on the north and south sides of the building. Dampers are responsible for the mixing ration of the fresh/ return air.

Cooling plant

Cooling coils located within each AHU cools the air. Digital proportional, integral, and differential (PID) controllers control the water flow through the coils to maintain a set temperature at sensors located inside 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 cooling towers 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 plant

Heating coils inside the AHUs are used when heat is required in the venues. Like 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.

3.4. Comfort Audit

The aim of the comfort audit was to evaluate the prevailing indoor air conditions in the Conference Centre at the time of the study. The measurements were necessary to determine whether the current indoor air conditions were up to standard, and to verify the simulation model.

These indoor conditions could then be used as standards for the evaluation of retrofit options. The audit consisted of measurements of actual comfort levels. In addition, a walk through audit was conducted to determine any particular problem areas.

Return and supply air temperature (dry bulb) measurements of each zone were taken, as well as the temperature and relative humidity of the climate. The measurements were taken over a period of one week from 26th August 1999 to 1st September 1999.

Other measurements taken included the system water flow rates and the air flow rates through each AHU. Table 3-1 gives a brief summary of the measured data. More detail is given in Appendix A - *Comfort Measurements*.

Zone	Average indoor temperature (°C)	Air flow (m^3/s)
Amber	21.1	7.5
Coffee	21.4	1.8
Diamond	20.6	4.7
Emerald	18.7	1.0
First Floor	21.2	3.0
Foyer	21.4	7.0
Jade	20.4	2.0
Ruby	20.0	2.3

Table 3-1: Summary of comfort measurements

Note: The comfort band is between 21 °C and 24 °C [11]

The measurements showed that the average temperature inside the venues was very low. This could cause possible discomfort for the occupants, and it might be an area for energy saving.

The fresh air dampers were found to be out of order. The dampers on the south side of the building allowed for a constant fresh air flow of 10 m^3/s, and the north side dampers allow for a flow of only 1 m^3/s as they were almost completely closed. Therefore, the AHUs located close to the north side fresh air intake received almost no fresh air supply. Apart from the health aspects, this could also be a possible cause of discomfort for the occupants.

Table 3-2 shows the fresh airflow to each zone on the assumption that each of the zones receives 30% fresh air (This figure is derived from the relation of the total fresh air flow into the building and the sum of the air flow to each zone). It also shows the maximum number of people that each zone can accommodate. The numbers are based on seven litres per second (*l*/s) fresh air per person [1].

Zone	**Fresh air flow (m^3/s)**	**Max number of people**
Jade	0.7	100
Amber	2.3	321
Coffee	0.5	77
Foyer	2.1	300
Diamond	1.4	201
Ruby	0.7	96
Emerald	0.3	42
First Floor	0.9	128

Table 3-2: Zone fresh air maximum amount of people per zone

The calculated maximum occupation, based on fresh airflow is 1,265. Although it is unlikely that the building would be occupied to capacity at any stage, this is well below the designed capacity of 1,570 people.

3.5. Energy Audit

In order to decrease the energy consumption of the building without affecting the comfort of the occupants, it was necessary to determine an end-user breakdown of the energy consumption of the Conference Centre. This could then be used to determine the largest energy consumers. The largest energy consumers usually constitute the areas with the largest energy savings potential.

The energy audit was begun with a walk through audit, followed by detailed measurements. The walk through audit was conducted to identify the usage of lighting and other miscellaneous equipment such as lifts, computers, etc. It is important to determine the consumption of these energy consumers in order to establish if their consumption can be reduced.

The categories used in the total energy breakdown are HVAC, lighting, and other diverse equipment. Figure 3-1 shows the percentage of energy consumed by these categories. Measuring the HVAC system energy consumption, calculating the energy consumed by the lights, and comparing these figures to the total measured energy consumption determined the breakdown.

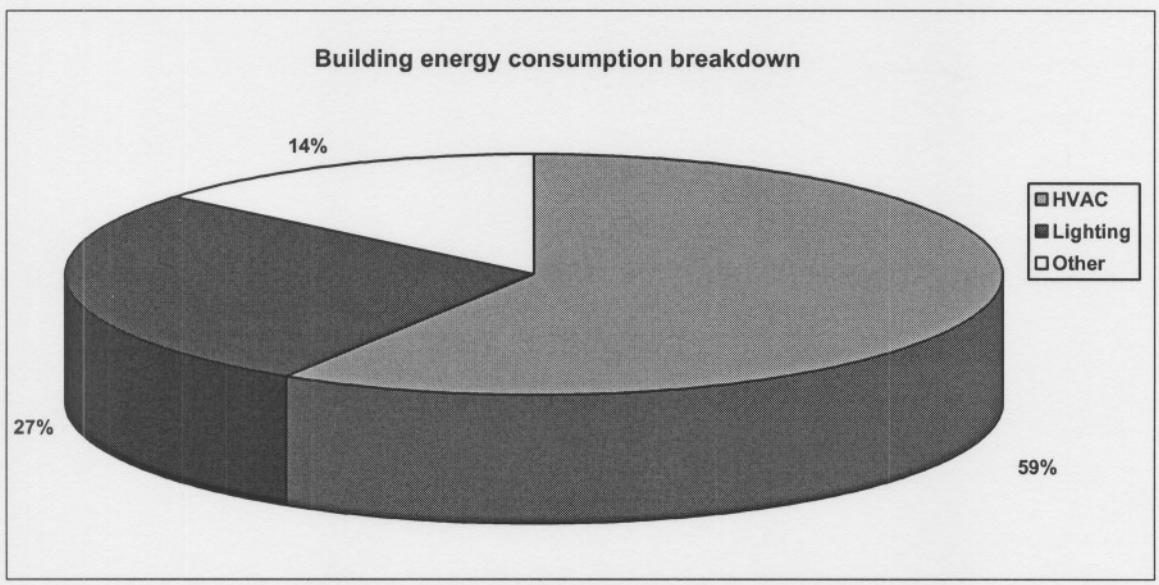


Figure 3-1: Current building energy consumption breakdown

The HVAC system in the Conference Centre was the major energy consumer, and thus had the greatest potential for energy saving. It consumes approximately 59% of the total building energy.

HVAC energy consumption was then broken down into the various components of the HVAC system, like chillers, pumps, fans, etc. This breakdown can be seen in Figure 3-2.

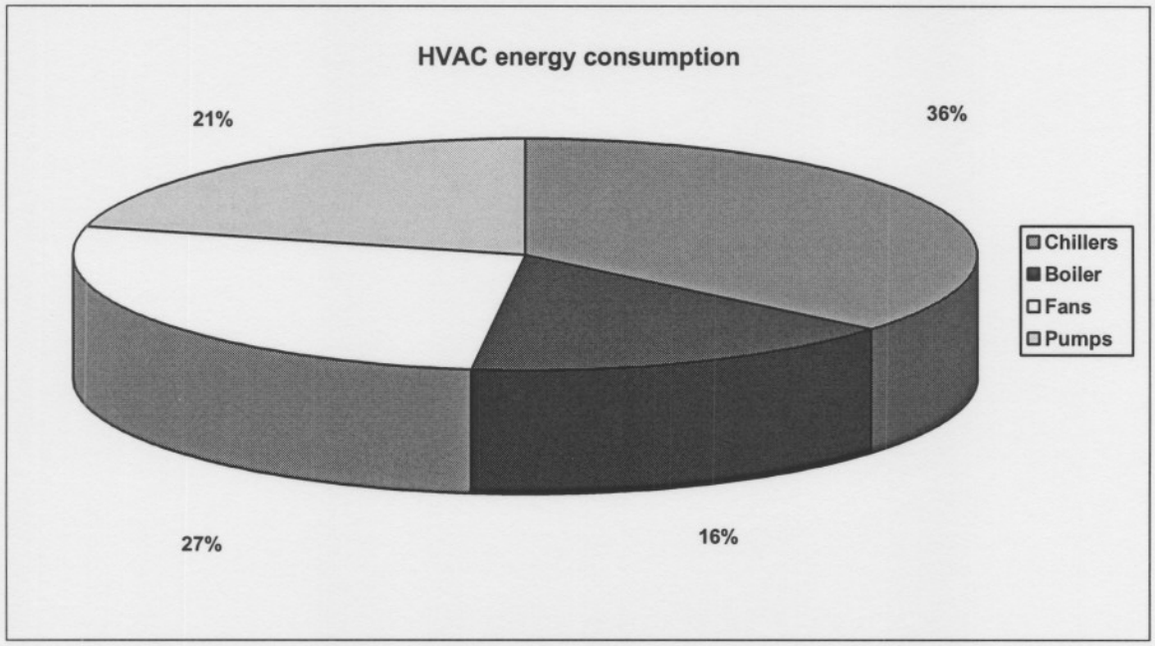


Figure 3-2: Current HVAC energy consumption breakdown

From the Figure 3-2 it can be seen that the chiller has the greatest energy consumption of the HVAC system. As with the temperature measurements, the energy measurements were taken for the same period of one week. These measurements can be seen in detail in Appendix B - *Energy Measurements*. The measurements were taken during August.

3.6. Verification study

A verification study was performed to verify and confirm the accuracy of the simulation models (including control parameters) in order to calculate realistic energy savings with the retrofit simulation. The main purpose of the verification study was not so much to verify the building

model and the HVAC models individually, but to verify the "real life" dynamic interaction between the building model and the HVAC system models with the influence of the controllers in an integrated and dynamic fashion.

The building model of the program has already been empirically verified over a wide range of different building structures and climates in 140 case studies with great accuracy as described in references [2][3]. The building model can therefore be used with confidence without verifying it again, provided it is properly constructed.

Simulation model

For the verification study it was necessary to take measurements, set up the simulation tool, execute the simulations and compare the measurements with the predicted values. The measurements include temperatures, relative humidity's, airflow rates, water flow rates, and electrical power required by each HVAC system component. From the measured data a single representative day was extracted, and compared to the 24-hour day predictions provided by simulation tool.

The simulation tool requires a large number of inputs. These inputs comprise 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. These inputs are outdoor climate data, occupancy, and internal loads. Most, or if possible all, of the input data should be available to perform a verification study with integrity.

For this part of the study the building was divided into 10 zones. Each venue supplied by an AHU was taken as a zone. These include the Amber restaurant, Jade restaurant, Diamond hall, Ruby hall, Emerald hall, the foyer, coffee area and the three first floor conference halls.

Figure 3-3 depicts the simulation model layout. The building structural data, including the zone dimensions and materials, were acquired from building drawings and a database that was obtained from the building operators. The building model could be set up in the simulation program using this information.

The internal loads, in the form of occupants, were known from the booking data of the building. Other loads included the lights, computers and kitchen equipment, and were obtained in the walk through audit.

Regressions for the HVAC components were set up from measured data and the manufacturers 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.

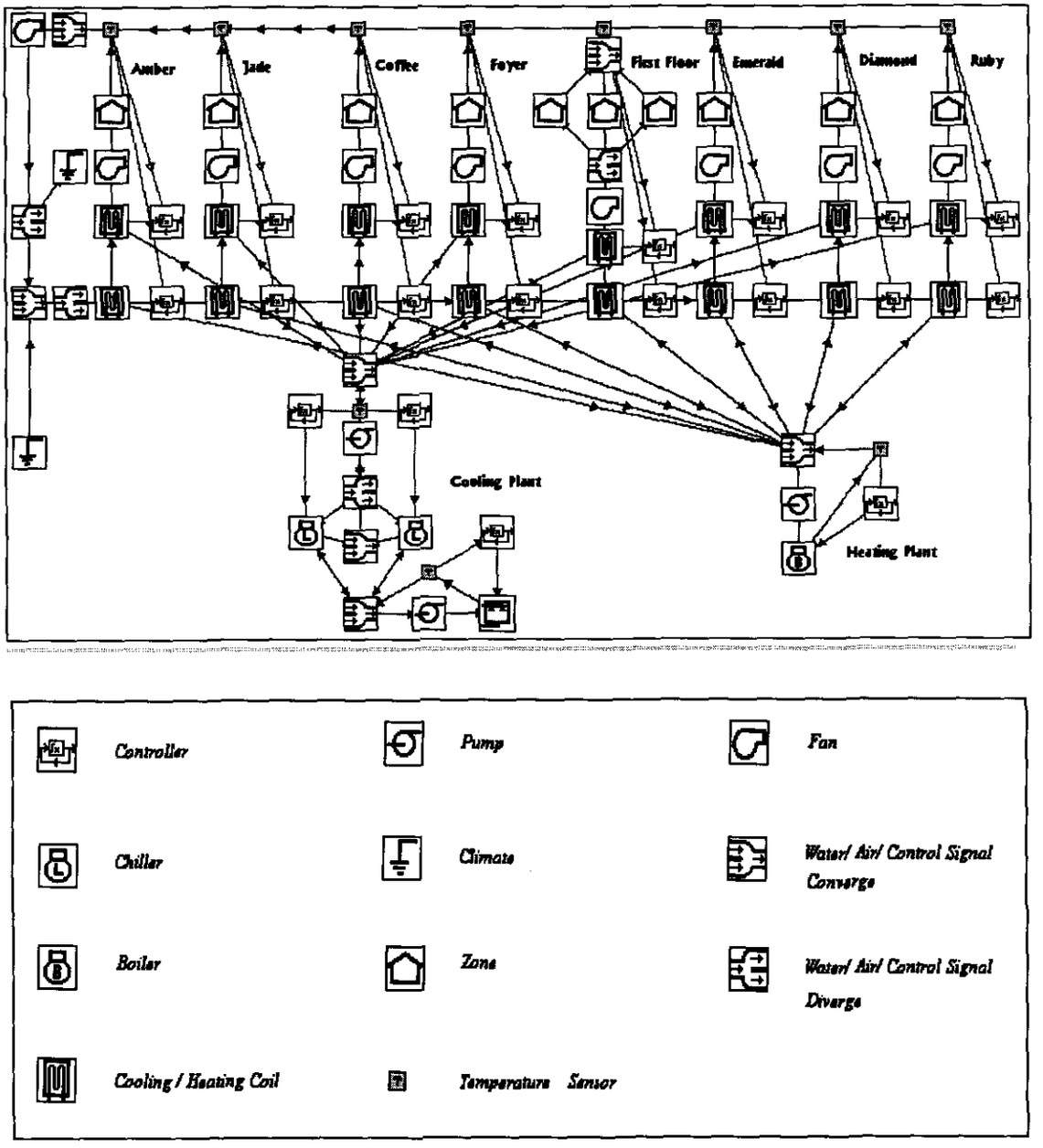


Figure 3-3: Simulation model

Verification results

The verification results of the indoor air temperatures, AHU supply air temperatures, the chiller power, and the boiler power are discussed in this section. In the case of the first floor the measured indoor air temperature of the zone is the average temperature of all the conference halls in that zone.

The figures in Appendix C – *Verification Results*, display the simulated and actual measured indoor air and supply temperatures of each zone. The indoor and supply air temperature results are respectively summarised in Table 3-3 and Table 3-4. From the figures in Appendix C and the tables below, it seems that the supply air temperature verification is perhaps not that good. This could be explained as follows.

In the simulation model the assumption is made that all the AHU's receive a similar fraction of the outdoor air. In the actual plantroom this is not the case. The layout of the plantroom is such that some AHU's are situated close to the closed north side dampers, and others to the more open south side dampers. Also, the AHU's are placed in such a way that the mixing of the air inside the plantroom does not seem adequate. Therefore, where the simulation model assumes a uniform supply air temperature to the air handlers, this is not the case and may contribute to the discrepancies in the results.

Additionally, during the study it became clear that although the setpoints are normally kept at a certain value, it is often changed throughout the day by the BMS operators at the request of the occupants of the venues. As the setpoints are not logged, it is impossible to simulate the actual change in setpoints.

The tables show the maximum and average error in °C between the measured and simulated temperatures, as well as the percentage of the time over a 24 hour period that the simulated values are within two °C of the measured data.

Zones	Max error (°C)	Average error (°C)	% Of the time within 2°C
Diamond	1.5	0.9	100
Ruby	3.1	1.0	100
First Floor	2.5	0.6	100
Foyer	4.9	0.2	100
Coffee	1.0	0.4	100
Amber	1.6	0.6	100
Jade	1.8	0.4	100
Emerald	2.1	1.1	100

Table 3-3: Summary of indoor air temperature verification

Zone	Max error (°C)	Average error (°C)	% Of the time within 2°C
Diamond	6.8	1.5	75
Ruby	20.0	3.1	32
Emerald	5.4	2.8	27
First Floor	12.0	1.4	81
Foyer	3.4	3.4	72
Coffee	3.2	0.6	99
Jade	12.0	1.1	89
Amber	6.3	1.6	74

Table 3-4: Summary of supply air temperature verification

The simulated chiller power and measured chiller power are compared in Figure 3-4.

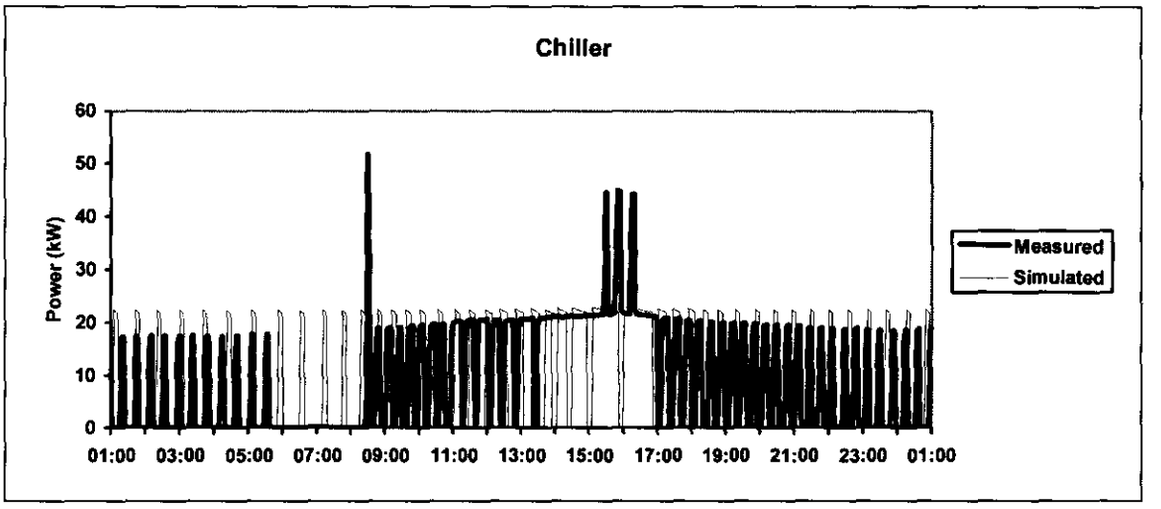


Figure 3-4: Chiller power verification result

The simulation tool successfully simulated the loading and unloading of the chiller capacity steps. There is not a large phase difference between the predicted and simulated values. This verifies the time constants of the building structure and the HVAC system components. The difference between the measured and simulated energy consumption over 24 hours is only 13%.

One must keep in mind that the main focus of the simulation model was not to simulate the exact working of each component, but to simulate the realistic interaction of the whole building and HVAC system. In this case of a chilled water system, it is not only the chiller that plays a part but also the accompanying piping network, with the enclosed volume of water and the resultant temperature loss. In QuickControl, this is approximated by a time constant specified by the user. In this case, the chiller in the simulation model was input at design specifications. The actual chiller could possibly be operating at reduced COP, therefore requiring more energy to accomplish the same task.

Figure 3-5 displays the boiler power verification results.

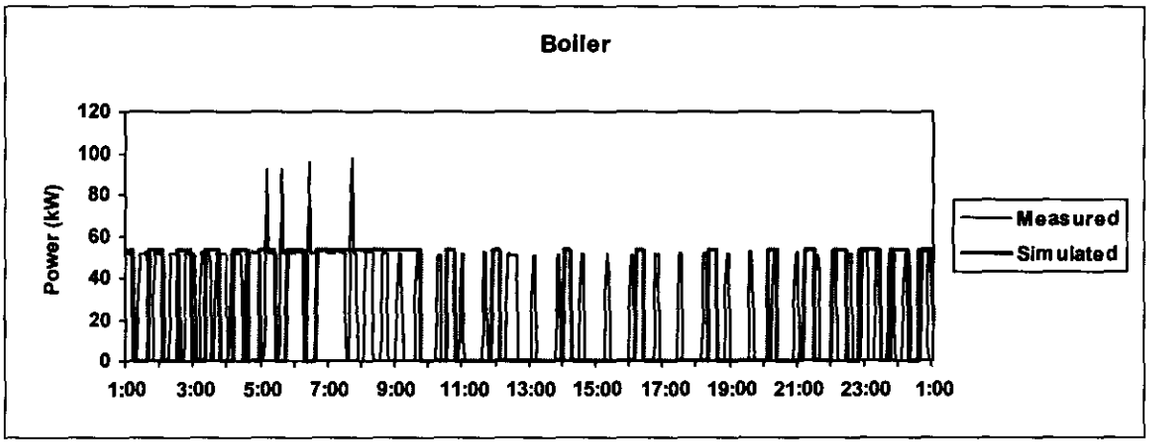


Figure 3-5: Boiler power verification result

The simulated values do not follow the measured values exactly but the total energy consumed over 24 hours compares well. There is a difference of 3% between the measured and simulated boiler energy consumption over the 24-hour 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.

As with the chiller, it aim was not to accurately simulate the exact detail dynamics of the component. Certain assumptions have to be made in the setup of the component, for example the construction and associated UA value, as well as the piping losses. This leads to an approximated component that is simulated. When the output of the program is accurate to a certain degree measured to a particular variable, it is deemed accurate. In this case, it is the total daily energy consumption that is important.

In order to predict the energy saving of the retrofit, a benchmark must be set against which the retrofit energy consumption can be measured. This benchmark is called the base year case. The simulated result of the monthly energy consumption and peak demand over the period of a year is taken as the base year. The base year simulation must be verified to measured data. The verification results are shown below.

This base year simulation was done with the current building system, HVAC system and control configuration. According to our power and temperature measurements, the fans were operational 24 hours per day, seven days per week. This assumption was incorporated into the base year simulation. Average yearly occupancy and average monthly climate data were used

during the execution of the simulations. The average monthly climate data is based on the past 20 years.

Figure 3-6 and Figure 3-7 show the measured and simulated energy consumption (in MWh) and the peak demand (in kVA) of the HVAC system of a typical year. The data used was the municipal electricity account obtained from the building operator.

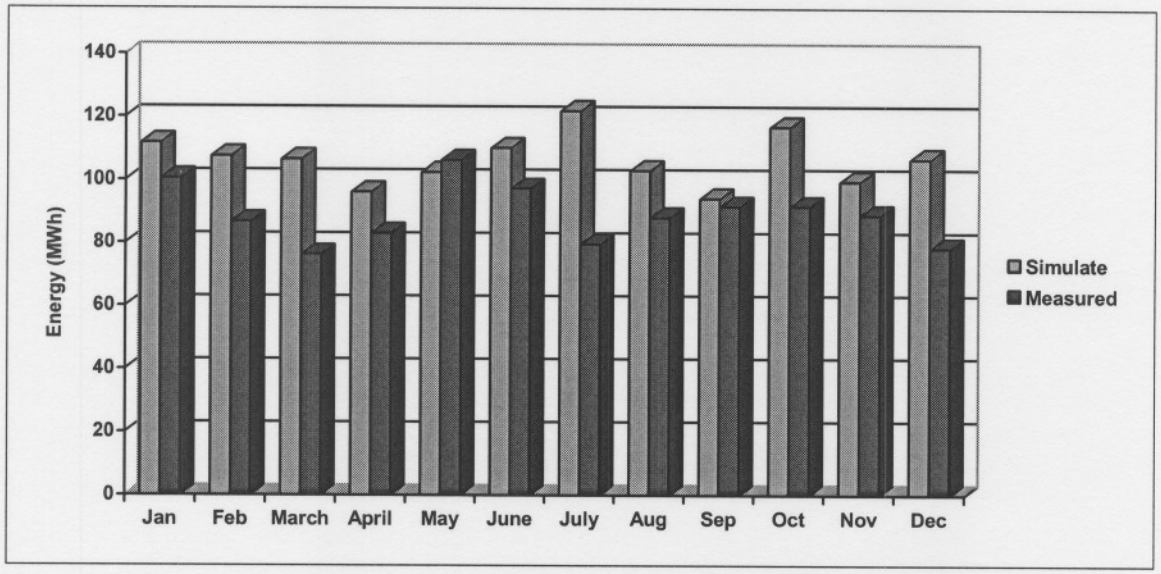


Figure 3-6: HVAC system energy consumption

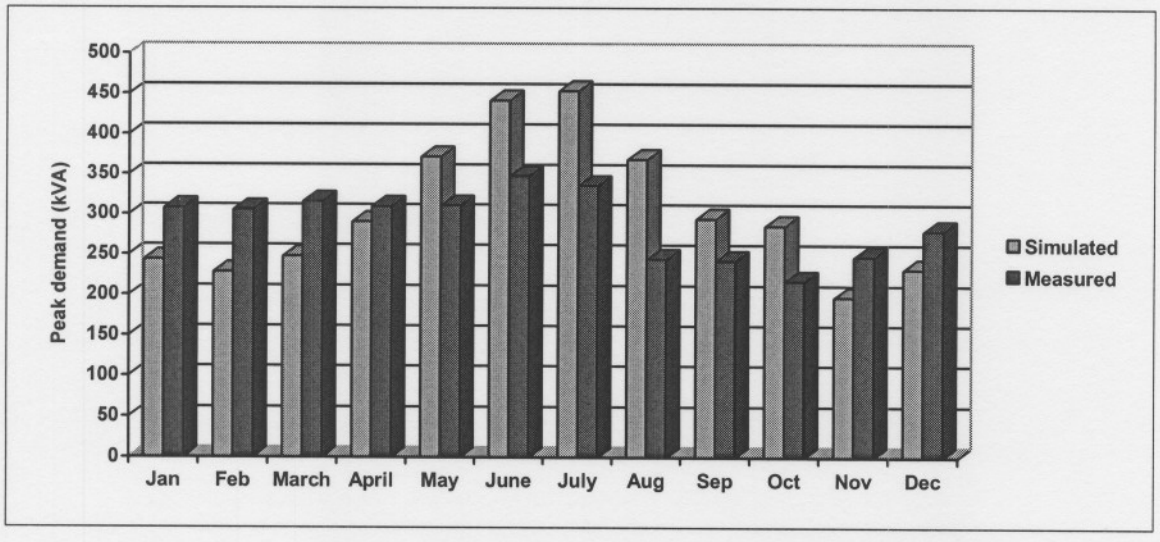


Figure 3-7: HVAC system peak demand

The yearly energy consumption of the simulation differs only with 15% from the measured data. The difference between the predicted and measured peak demand is somewhat bigger and differs by an average of 24%.

This could be because it only takes one extreme half an hour per month to produce a high peak demand. The monthly simulations were based on average occupancy and average climate data. In both cases, it is the colder months that do not correlate well. The reason for this could be higher occupancy loads in the real building during those times.

Looking at the simulation results it appears that the accuracy of the integrated modelling is not that good. In some instances, the predicted and measured values are out of phase and the graphs do not always have exactly the same profiles. However, the intention was not to simulate the dynamics of the system with 100% accuracy, but rather to predict accurate realistic daily (and yearly) system energy consumption and accurate average indoor air temperatures to ensure indoor comfort. These discrepancies could result in potential errors in simulating of retrofit options. This problem is reduced by comparing the possible saving of each retrofit to the energy consumption of a simulated base year scenario. Thereby the predicted savings is translated to a relative value, a percentage value as opposed to an absolute monetary saving.

3.7. Retrofit simulation results

Various retrofits and retrofit combinations were simulated to obtain the potential for energy and peak demand savings. In this section the retrofit simulation results are compared to a base year simulation. A description of the retrofits investigated is given in Chapter 1.

The following retrofit options were considered:

- Option 1 - Fan scheduling
- Option 2 - Fan scheduling, economiser control and new setpoints
- Option 3 - Fan scheduling, economiser control and setpoint setback
- Option 4 - Fan scheduling, economiser control and fan control
- Option 5 - Fan scheduling, economiser control and heating plant control

- Option 6 – Fan scheduling, economiser control, setpoint setback, and heating plant control
- Option 7 – Fan scheduling, economiser control, new setpoints, setpoint setback, fan control, and heating plant control

The results of the retrofit simulations are described below. For each retrofit, firstly the energy consumption of the retrofit is compared to the energy consumption of the base year, thereafter the peak demand of the retrofit is compared to that of the base year.

Fan scheduling

Figure 3-8 shows the comparison between the retrofit option and the base year energy consumption.

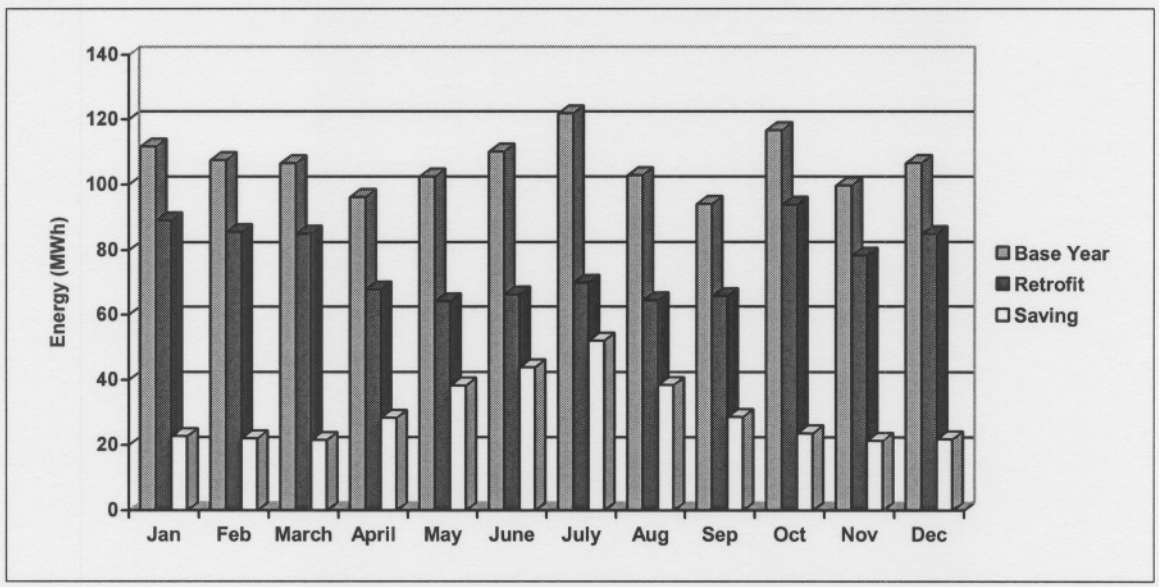


Figure 3-8: Fan scheduling energy consumption

Figure 3-9 shows the comparison between the retrofit option and the base year peak demand per month.

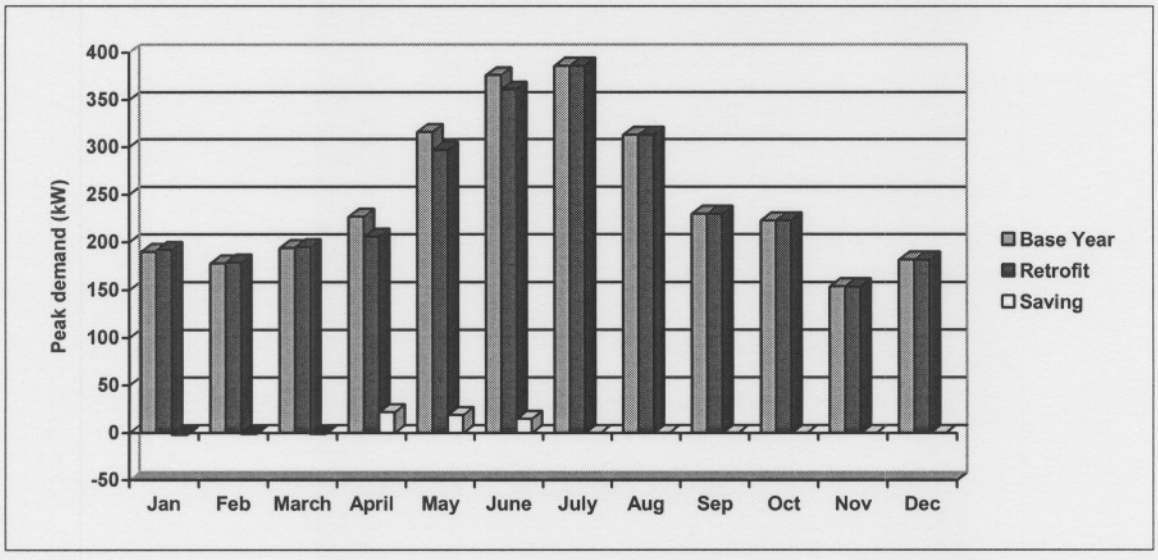


Figure 3-9: Fan scheduling peak demand

The yearly energy saving for this option is 364.5 MWh. This translates into a 28.4% saving on the existing HVAC system's energy consumption. The average monthly peak demand savings is four kW. This is a saving of 1% on the average system peak demand.

Fan scheduling, economiser and new setpoints

This option includes the combination of fan scheduling, economiser control, and the new coil control setpoints. Figure 3-10 shows the comparison between the retrofit option and the base year energy consumption.

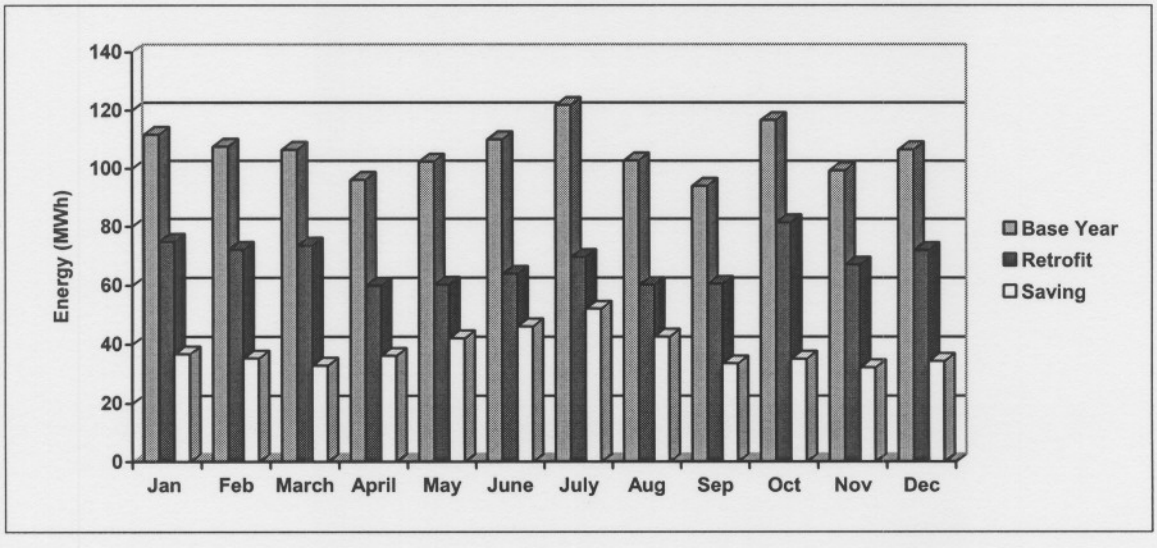


Figure 3-10: Fan scheduling, economiser, setpoint energy simulation

Figure 3-11 shows the comparison between the retrofit option and the base year peak demand per month.

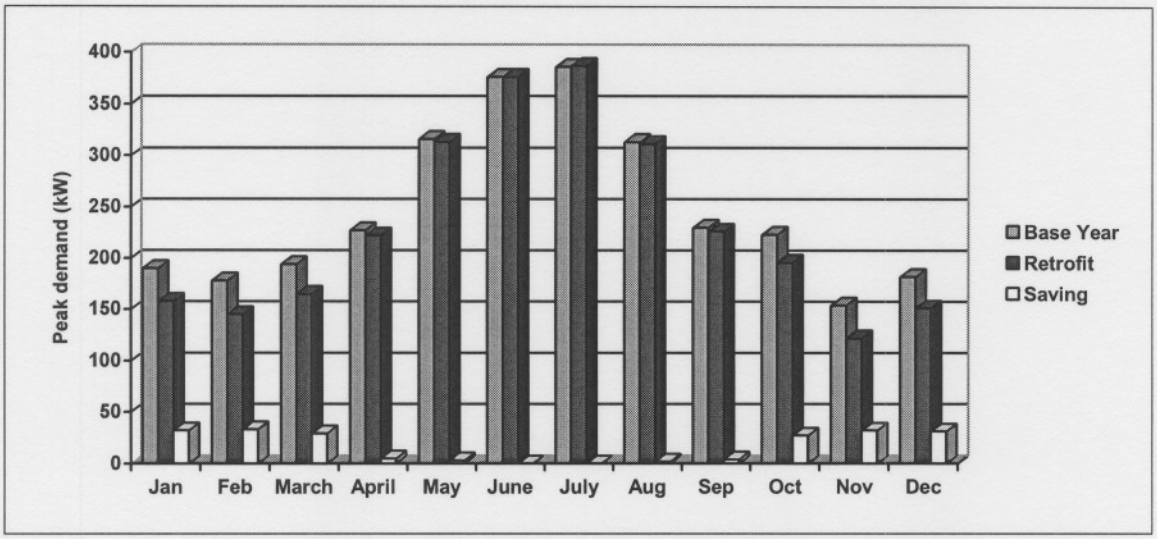


Figure 3-11: Fan scheduling, economiser, setpoint peak demand

The yearly energy saving for this option is 459.5 MWh. This translates into a 36% saving on the existing HVAC system's energy consumption. The average monthly peak demand savings is 16 kW. This is a saving of 9% on the average system peak demand.

Economiser and setpoint setback

This option includes the combination of fan scheduling, economiser control and setpoint setback on the cooling and heating coils. Figure 3-12 shows the comparison between the retrofit option and the base year energy consumption.

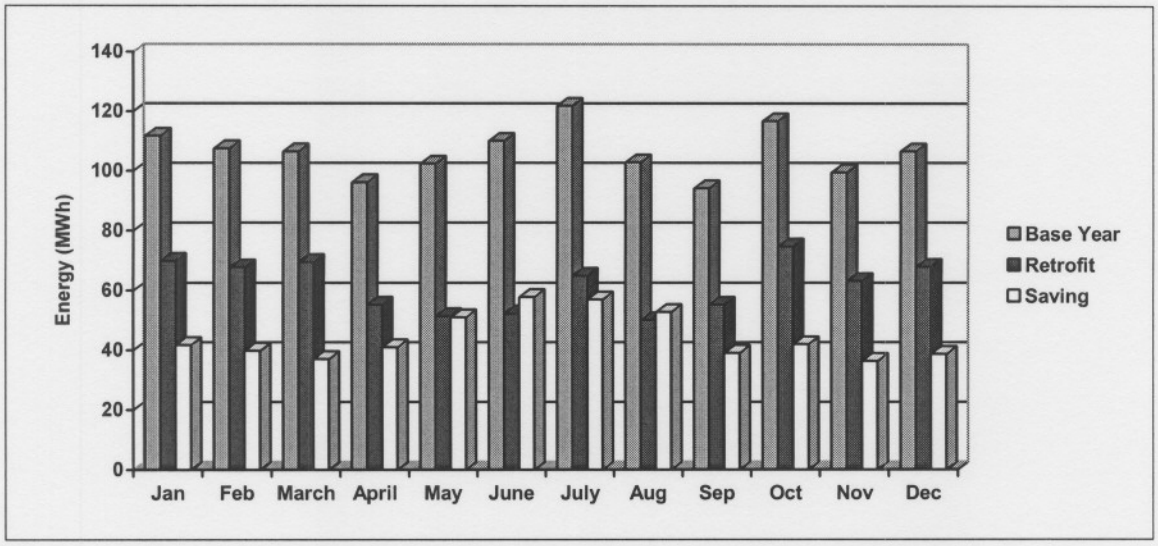


Figure 3-12: Fan scheduling, economiser, setback energy simulation

Figure 3-13 shows the comparison between the retrofit option and the base year peak demand per month.

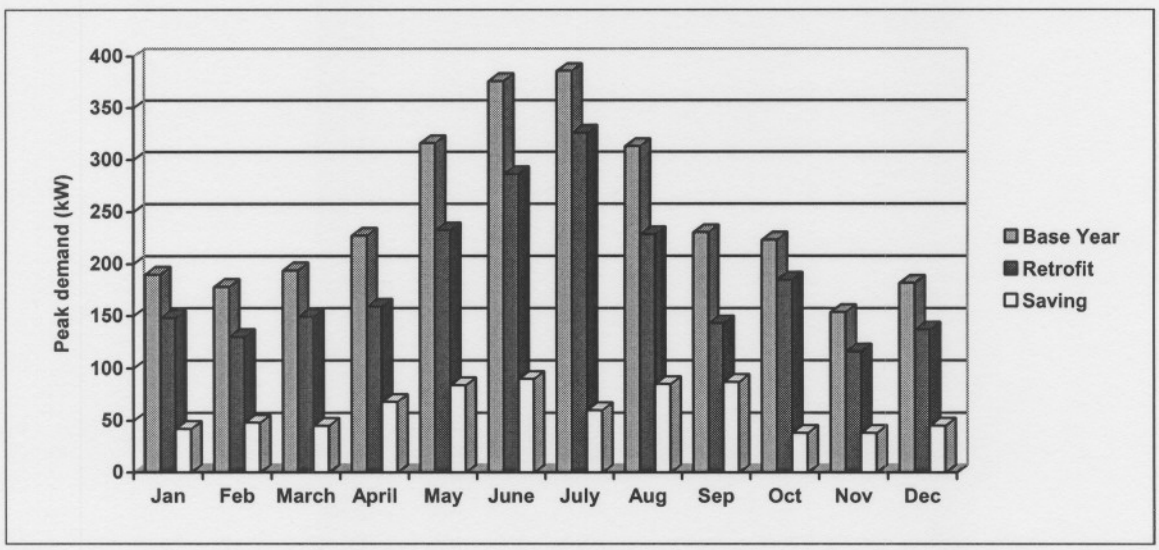


Figure 3-13: Fan scheduling, economiser, setback peak demand

The yearly energy saving for this option is 533.7MWh. This translates into a 43.8% saving on the existing HVAC system's energy consumption. The average monthly peak demand savings is 61 kW. This is a saving of 25% on the average system peak demand.

Economiser, setback and fan control

This option includes the combination of fan scheduling, economiser control, and fan control. Figure 3-14 shows the comparison between the retrofit option and the base year energy consumption.

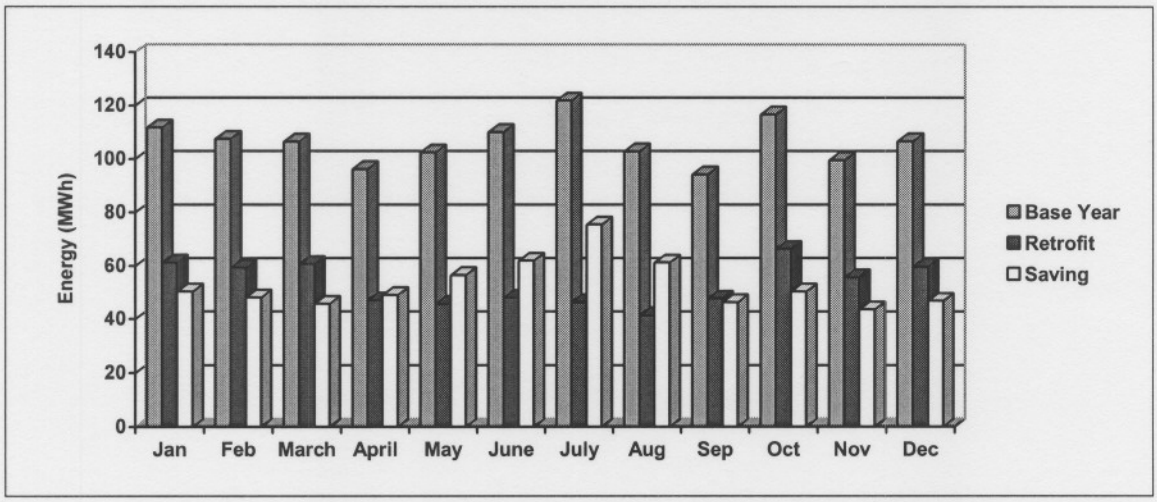


Figure 3-14: Fan schedule, economiser, setback, fan control energy simulation

Figure 3-15 shows the comparison between the retrofit option and the base year peak demand per month.

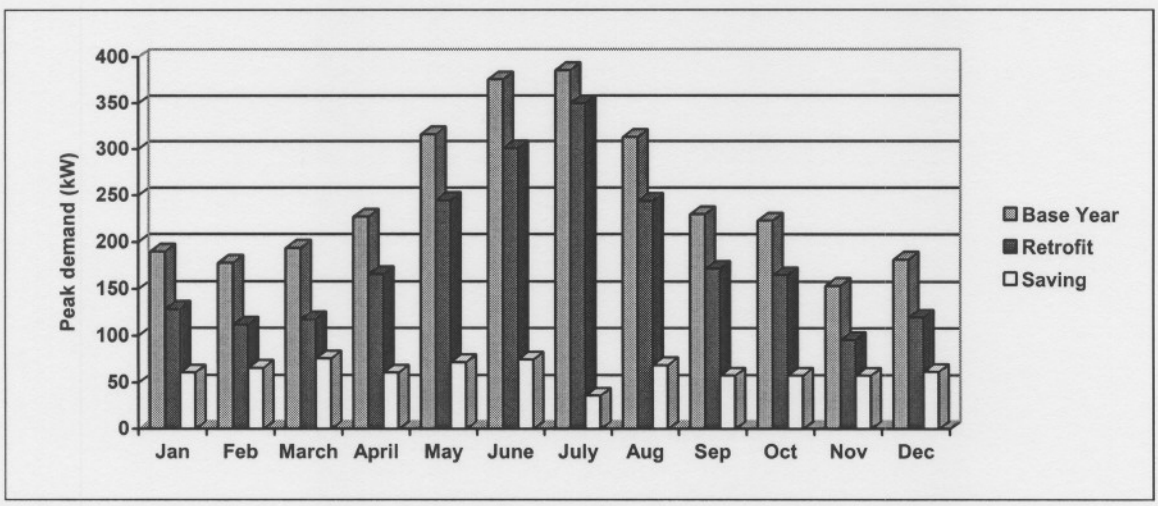


Figure 3-15: Fan schedule, economiser, setback, fan control peak demand

The yearly energy saving for this option is 636MWh. This translates into a 49.9% saving on the existing HVAC system's energy consumption. The average monthly peak demand savings is 63 kW. This is a saving of 28% on the average system peak demand.

Economiser, new setpoints and heating plant control

This option includes the combination of fan scheduling, economiser control, and new control strategies on the heating plant. Figure 3-16 shows the comparison between the retrofit option and the base year energy consumption.

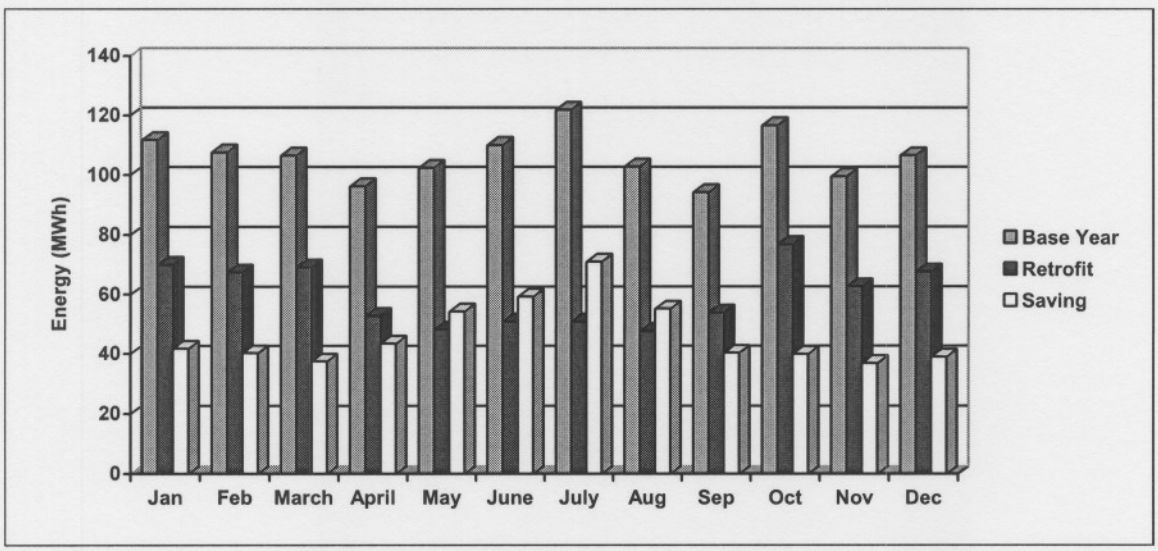


Figure 3-16: Fan schedule, economiser, setpoint, boiler energy simulation

Figure 3-17 shows the comparison between the retrofit option and the base year peak demand per month.

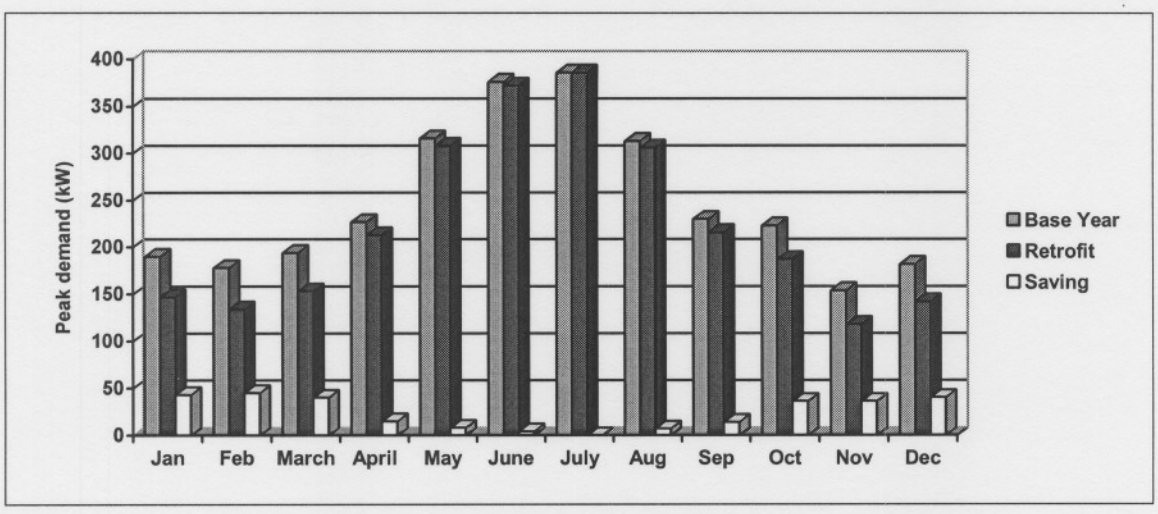


Figure 3-17: Fan schedule, economiser, setpoint, boiler peak demand

The yearly energy saving for this option is 558.3 MWh. This translates into a 43.8% saving on the existing HVAC system's energy consumption. The average monthly peak demand savings is 24 kW. This is a saving of 12% on the average system peak demand.

Economiser, setback and heating plant control

This option includes the combination of fan scheduling, economiser control, setpoint setback, and new control strategies on the heating plant. Figure 3-18 shows the comparison between the retrofit option and the base year energy consumption.

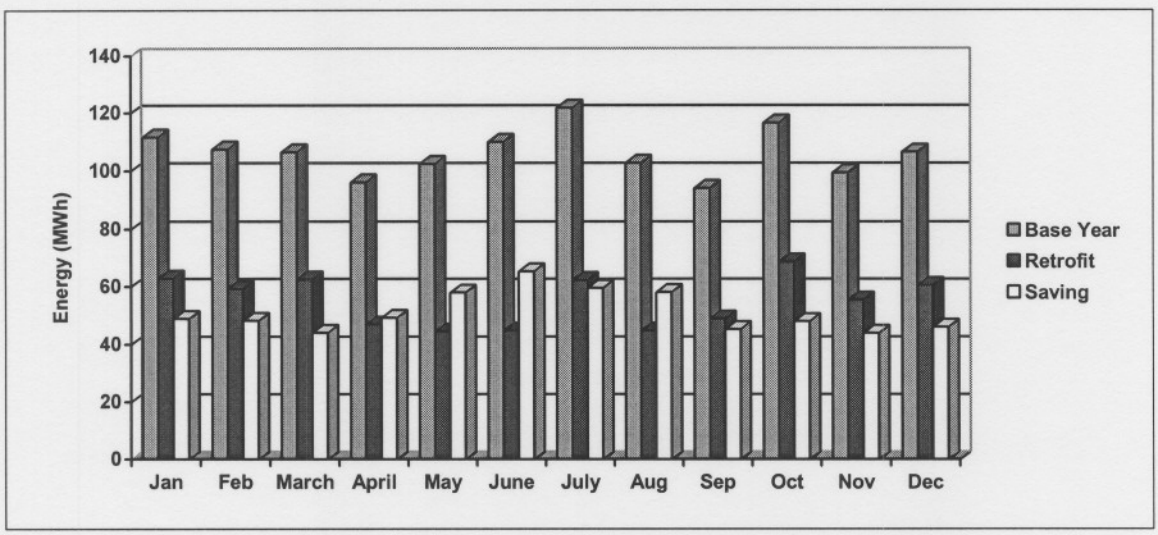


Figure 3-18: Fan schedule, economiser, setback, boiler energy simulation

Figure 3-19 shows the comparison between the retrofit option and the base year peak demand per month.

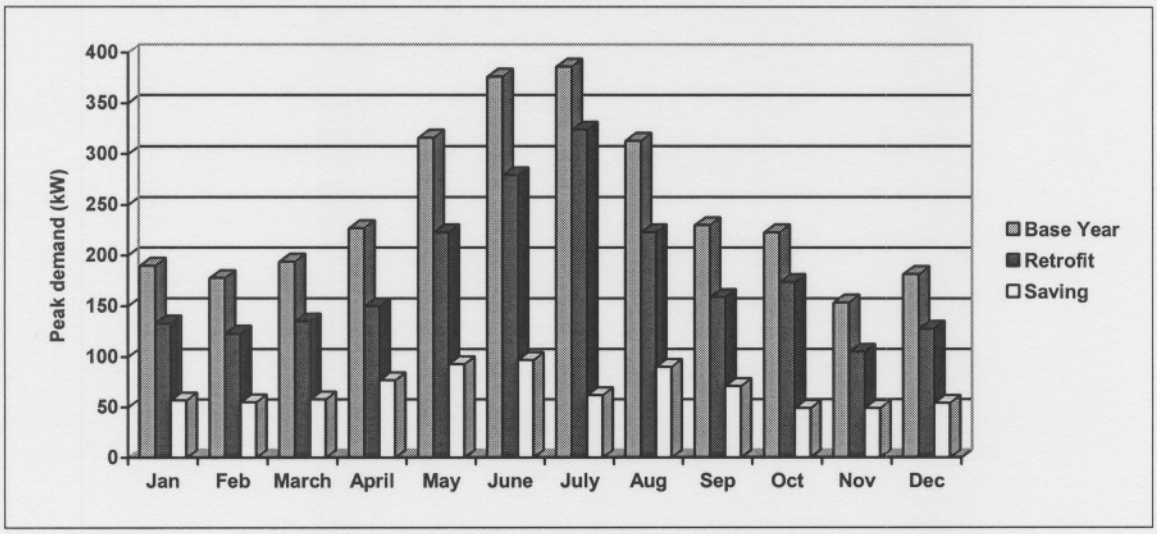


Figure 3-19: Fan schedule, economiser, setback, boiler peak demand

The yearly energy saving for this option is 614.4 MWh. This translates into a 48.2% saving on the existing HVAC system's energy consumption. The average monthly peak demand savings is 68 kW. This is a saving of 28% on the average system peak demand.

Economiser, setback, fan and heating plant control

This option includes the combination of fan scheduling, economiser control, setpoint setback, fan control, and new control strategies on the heating plant. Figure 3-20 shows the comparison between the retrofit option and the base year energy consumption.

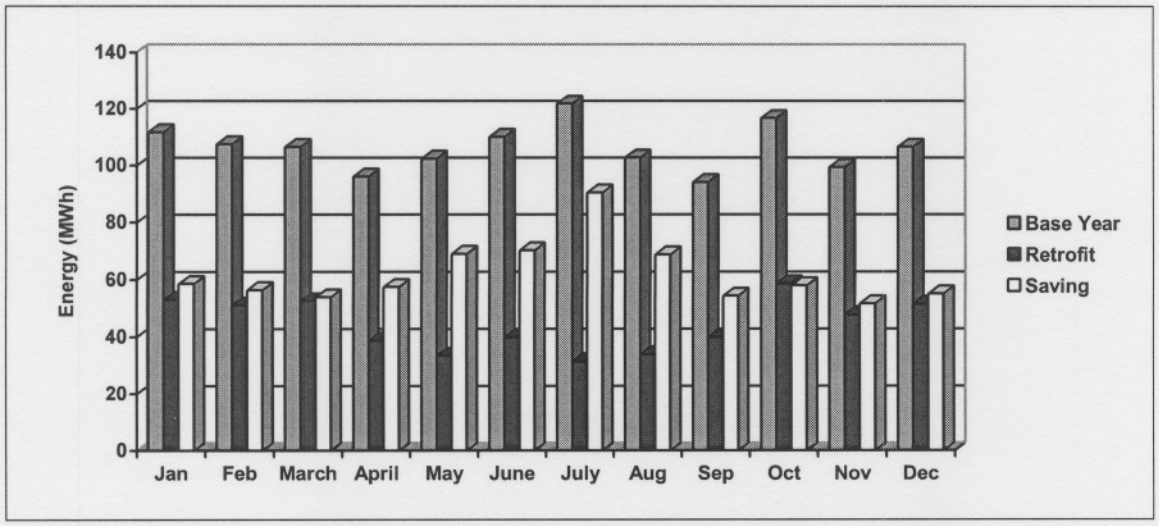


Figure 3-20: Fan schedule, economiser, setback, fan control, boiler energy simulation

Figure 3-21 shows the comparison between the retrofit option and the base year peak demand per month.

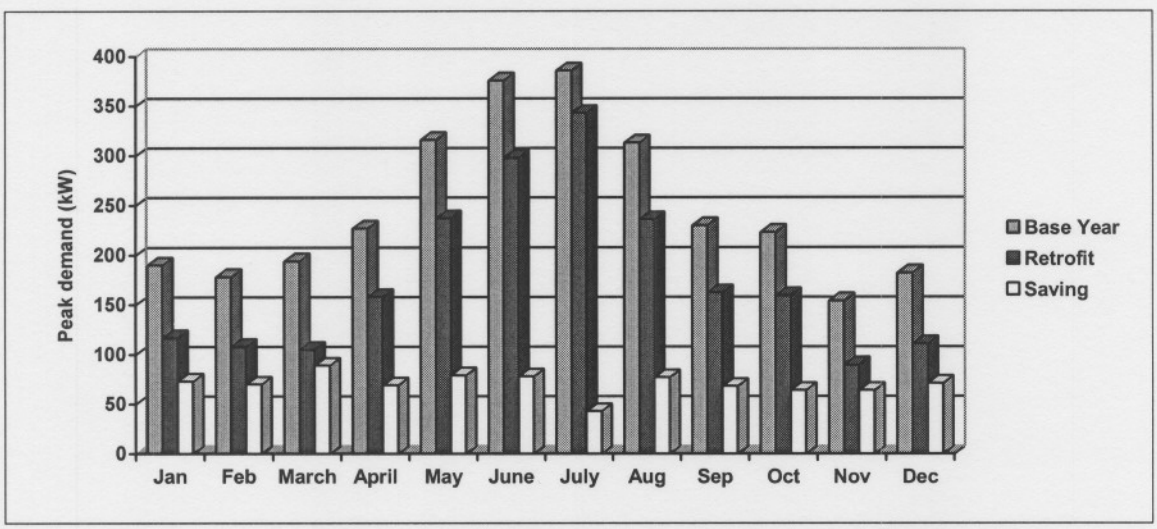


Figure 3-21: Fan schedule, economiser, setback, fan control, boiler peak demand

The yearly energy saving for this option is 744 MWh. This translates into a 58.3% saving on the existing HVAC system's energy consumption. The average monthly peak demand savings is 70 kW. This is a saving of 31% on the average system peak demand.

Lighting control

The lights of the venues can be switched on and off by using the same motion detector philosophy as for a setpoint setback control strategy. This implies the lights will be off when the venues are unoccupied during the day and the process will happen automatically.

Approximately 60 400 kWh can be saved per year if this option is implemented in the building's venues. This saving is based on the assumption that the lights are presently switched on at 06:00 and off at 18:00 from Mondays to Saturday, and that the lights are off during Sundays.

No peak demand savings are possible with this option because the lights will be on during building peak demand times. The big advantage of this option is that lighting control will be automatic when the building is in use, including night times and during weekends.

3.8. Economic analysis

This section gives a short summary on the possible monetary savings produced by the proposed inventions and the cost to implement these inventions into the building. The monetary energy and peak demand savings per year with the relevant implementation cost for each option are given in Table 3-5. Direct payback periods are also included. The implementation costs are based on figures obtained in 1999, and consists mainly of re-programming of the BMS system.

The savings are based on 8.34 cent per kWh and R 34 per peak kVA for each month (the relevant tariff of the building at the time of the study). A possible monetary saving of R100 000 per year can be achieved by the proposed interventions with a direct payback period of less than six months.

Retrofit option	% Saving on Building	Saving on peak (R)	Saving on energy (R)	Total saving per year (R)	Implementation Cost (R)	Payback period (months)
Option 1	17.4	2 355	30 224	32 580	0	0
Option 2	21.6	8 864	38 321	47 186	2 000	0.5
Option 3	25.1	32 740	44 513	77 253	36 000	5.6
Option 4	30.0	33 711	53 055	86 767	41 000	5.7
Option 5	26.9	12 892	46 563	59 455	5 500	1.1
Option 6	29.0	36 474	51 242	87 716	39 500	5.4
Option 7	31.9	37 939	62 054	99 994	44 500	5.3
Lighting	3.0	0	5 037	5 037	5 000* / 13 000	12.0* / 31.2

Table 3-5: Economic analysis

* With option four installed

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

3.9. Verifying the measures incorporated in QEC

The measures identified by Arndt [4], as discussed in Chapter 2 was incorporated into QuickControl by TEMM International (Pty) Ltd [5]. This resultant program is called QEC (QuickEasyControl). The building under question was simulated with this program to test the changes made to QuickControl. The results of the simulation with the enhanced program could then be compared to QuickControl and the measured data.

Simulation model

The simplification of QuickControl resulted in a much-reduced number of inputs required for QEC. All the information required for QEC had already been gathered for QuickControl; therefore, no additional measurements were required.

The external driving elements of the simulation is still essential. These include the outdoor climate, internal building load, and occupancy data. The building envelope requires less, and more simple inputs. These inputs are described in Chapter 2. The system components especially require much less inputs than QuickControl. The elements can be configured from between one and three operating setpoints with information easily measurable from the component.

For the retrofit study done with QuickControl, the building was divided into 10 zones. Each venue supplied by an AHU was taken as a zone. Since simplification has such an important place in ESCO audits in South Africa, the building was divided into four zones for the comparison study. By reducing the number of zones, the simulation time and simulation model set up time could be decreased.

Various factors were taken into account to decide how the zones would be divided. Attributes that were considered included the nature of the space, daily load variation, geometry, and structure.

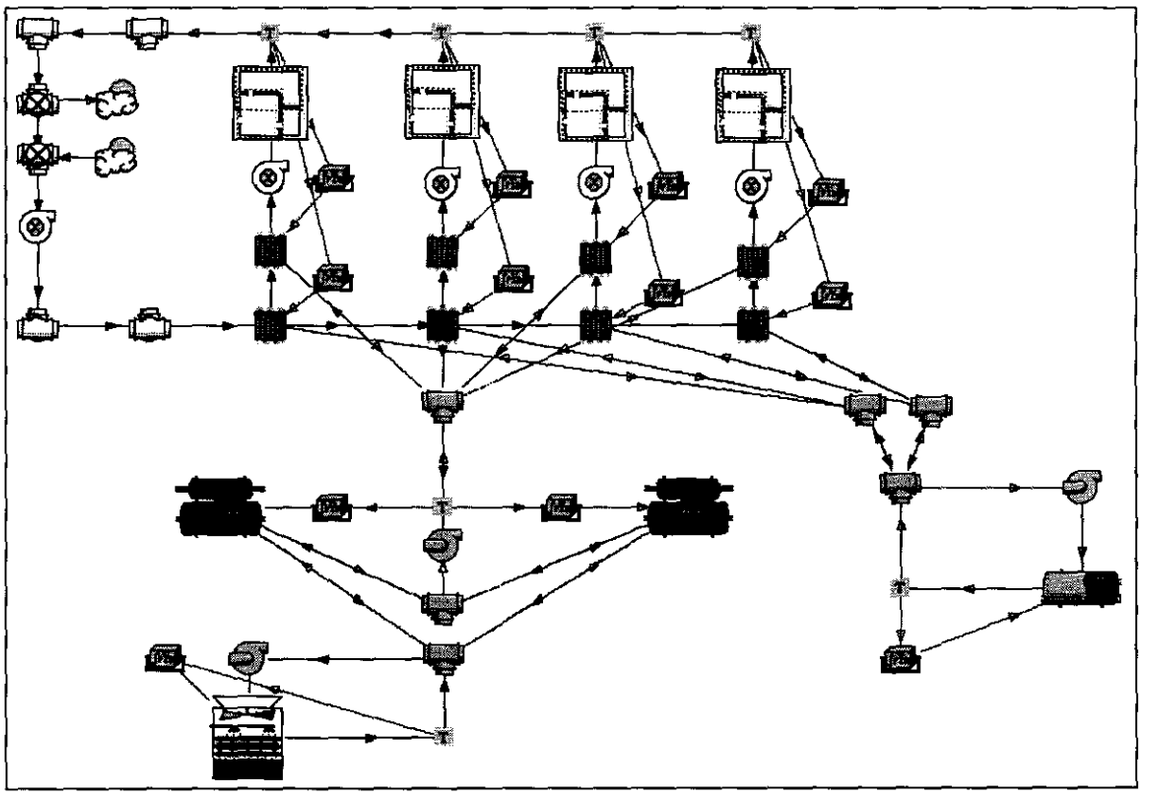
The zones were divided as follows:

- The restaurants, Amber and Jade. These venues have similar loads, the natures of the spaces are similar with similar occupation times. Additionally the geometry and construction is similar.
- The first floor conference halls, Diamond, Emerald and Ruby were taken as the next zone. These venues have similar internal loads and geometry. Although the external walls face different directions, there are no windows and the respective outside wall areas are small compared to the zone area. This reduces the influence of solar radiation.
- The first floor conference halls were taken as one zone. The Onyx, Crystal and Garnet halls in the building were already supplied by the same AHU, the zones were roughly the same size with the same percentage of window area and external wall area, making it a logical choice.

- The coffee area and the foyer. Although these spaces are supplied by their own AHU, in the building there are no physical division between them. These two venues were taken as one zone.

The apportioning of the zones also determined the configuration of the system. The measurements were taken for the 10-zone system. The components had to be adapted from the 10-zone format to the four-zone format. For water and air flows, as well as the cooling and heating capacities and energy consumption the value of the variable of the new component was calculated by the sum of the variables of the parent components. For other variables the value of the new component was calculated by the airflow weighted average of the values of the parent component.

The simulation model is shown below, in Figure 3-22.



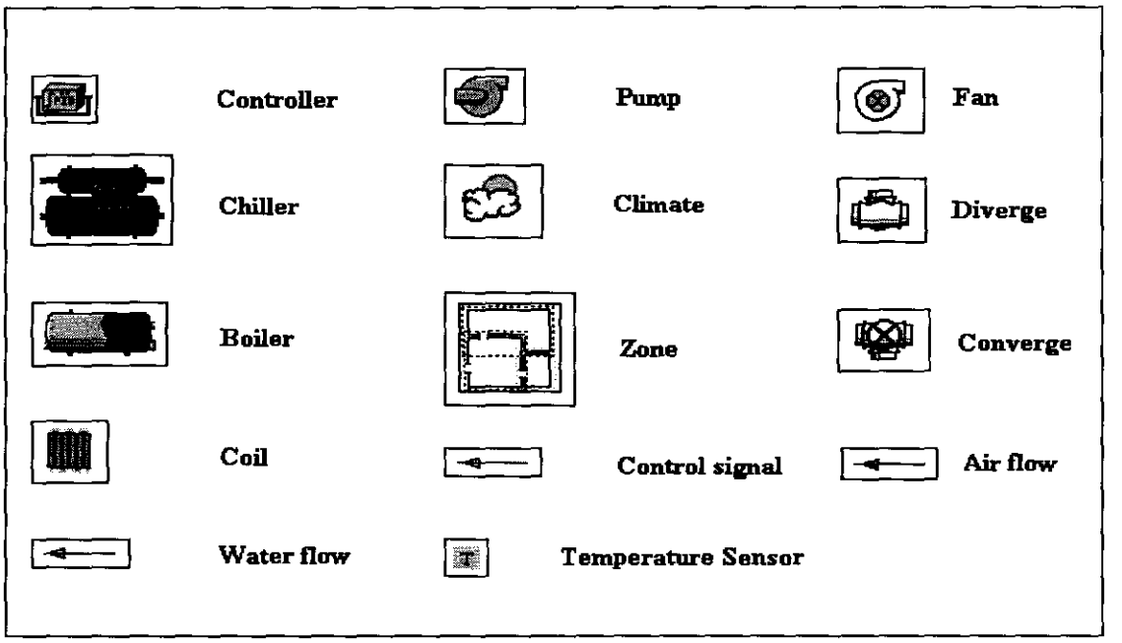


Figure 3-22: QEC simulation model layout

Temperature verification: Return air

Table 3-6 and Table 3-7 give the summary of the results of the verification study of the return air temperatures between QEC and QuickControl, and QEC and the measured data. The tables give

the average error and maximum error (in °C), and the percentage of time in 24 hours that the simulated data is within 2°C of the data to which it is compared.

	Halls	Foyer/Coffee	Restaurants	First floor
Average error (°C)	0.7	0.4	0.3	0.5
Max error (°C)	1.9	0.9	0.9	1.3
% Time within 2°C	100	100	100	100

Table 3-6: The variation between QEC and QuickControl for return air temperatures

	Halls	Foyer/Coffee	Restaurants	First floor
Average error (°C)	0.4	0.4	0.3	0.6
Max error (°C)	1.4	1.1	1.1	1.4
% Time within 2°C	100	100	100	100

Table 3-7: The variation between QEC and the measured data for return air temperatures

Temperature verification: Supply air

The following tables again show the average error and maximum error (in °C) between the simulated temperatures and the data it is compared to, as well as the percentage of time in 24 hours that the simulated temperatures is within 2°C of the comparing temperatures, for the supply air temperatures. Table 3-8 shows the comparison between QEC and QuickControl and Table 3-9 the comparison between QEC and the measured data.

	Halls	Foyer/Coffee	Restaurants	First floor
Average error (°C)	1.0	0.8	1.1	1.3
Max error (°C)	4.2	3.2	3.7	2.8
% Time within 2 °C	92.4	96.1	85.4	85.3

Table 3-8: The variation between QEC and QuickControl for the supply air temperatures

	Halls	Foyer/Coffee	Restaurants	First floor
Average error (°C)	2.2	1.5	0.7	1.1
Max error (°C)	5.9	3.6	2.5	11.1
% Time within 2 °C	51.8	72.5	96.8	88.3

Table 3-9: The variation between QEC and the measured data for the supply air temperatures

From the tables it is clear that the results obtained from QEC are satisfactory. These results compare well to QuickControl and to the measured data. In some cases, the simplified model preformed even faired better than QuickControl. Appendix D – *QEC Verification Results* gives the graphical comparison of the supply and return air temperatures over a 24-hour period.

Chiller and boiler verification

Figure 3-23 to Figure 3-26 show the chiller and boiler power consumption, as determined by QEC, as compared to the verified output of QuickControl and the measured data.

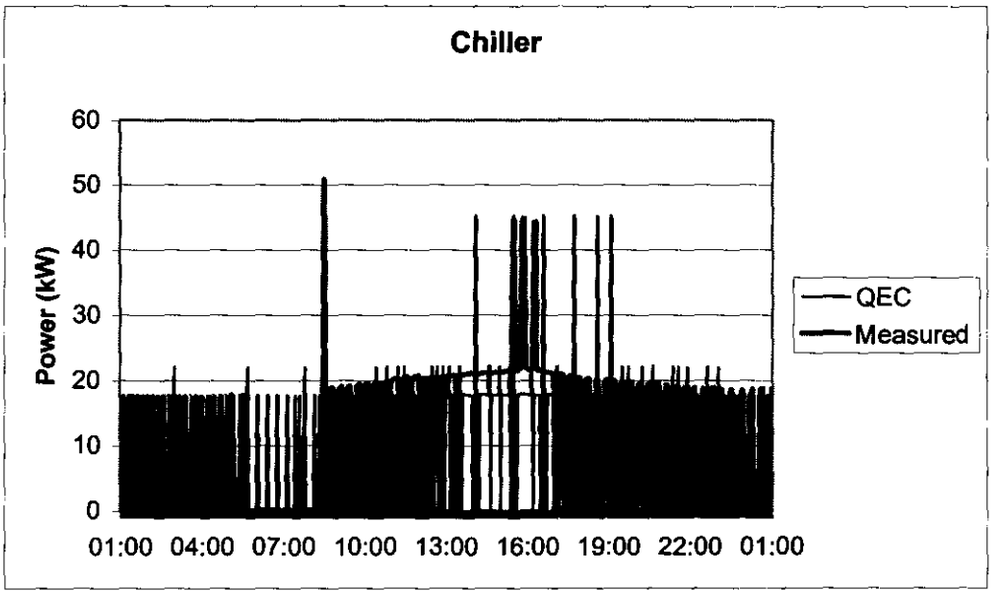


Figure 3-23: QEC vs. measured data for the chiller outlet temperature

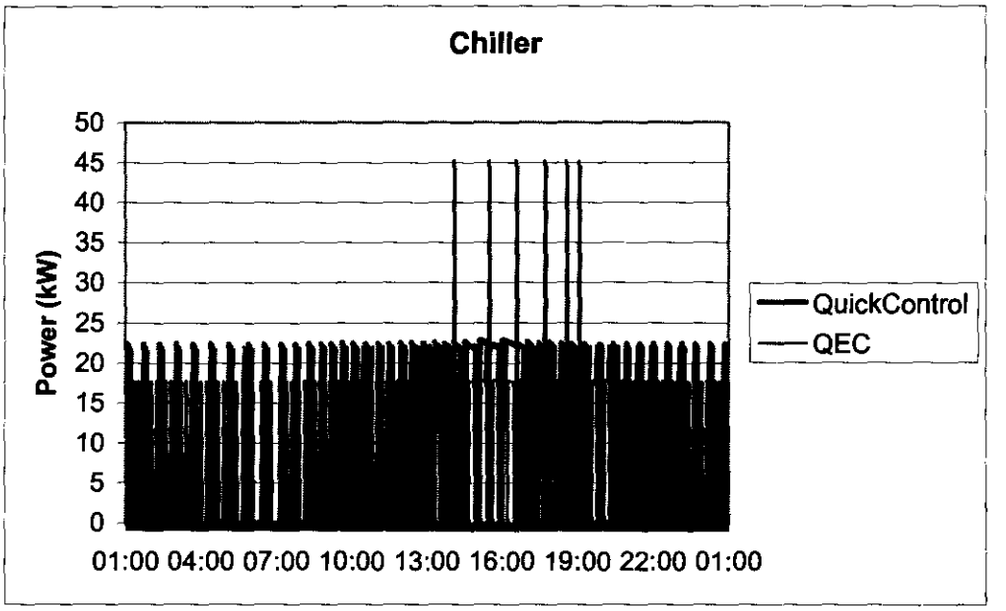


Figure 3-24: QEC vs. QuickControl simulated values for the chiller outlet temperature

The difference between the QuickControl simulation and the measured data is 13%, while the difference between the QEC simulation and the measured data is only 2%. From the graphs, one can see that the loading and unloading of the chiller in the simulation by QEC is more accurate than QuickControl's simulation results.

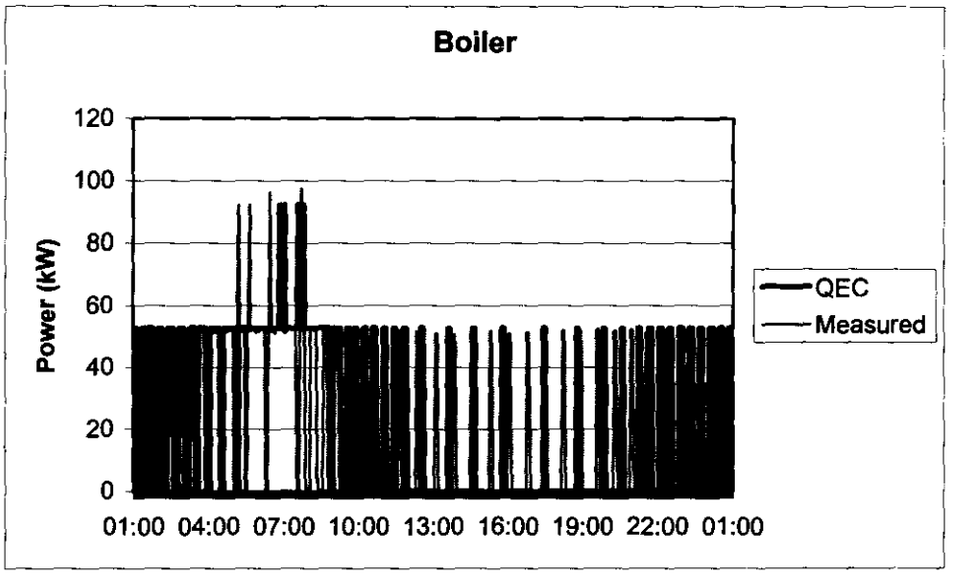


Figure 3-25: QEC vs. measured data for the boiler outlet temperature

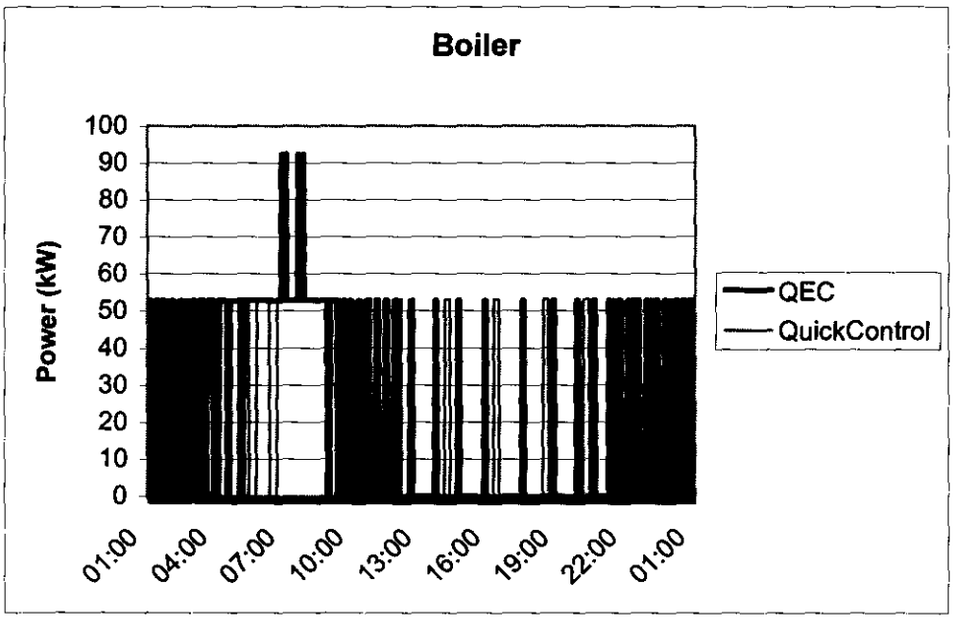


Figure 3-26: QEC vs. QuickControl simulated data for the boiler outlet temperature

QuickControl simulated the boiler energy consumption with an accuracy of 3%. The difference between the measured data and QEC is 5%. In this regard, it compares well with both QuickControl and the measured data. However, QEC simulated the loading and unloading of the boiler capacity more accurately than QuickControl.

Yearly energy consumption and peak demand

The following figure displays the yearly energy consumption of the building as QuickControl and QEC simulated it, as well as the measured yearly energy consumption.

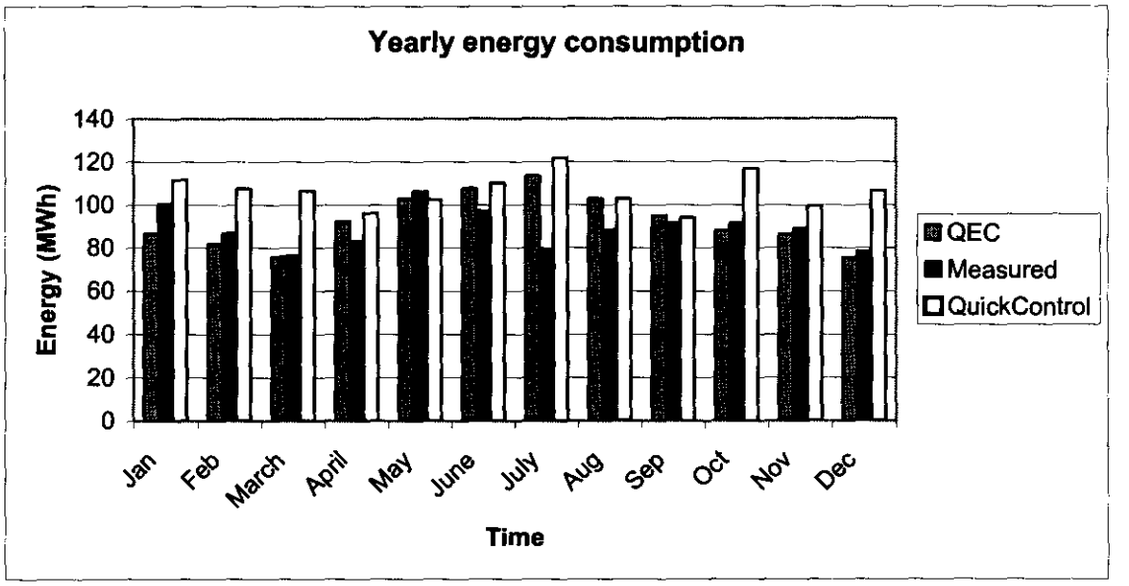


Figure 3-27: Yearly energy consumption comparison

The difference between QEC and the QuickControl simulation is 15%, and the difference between QEC and the measured data is 4%. It is apparent that QEC was more accurate in its results of the energy consumption over the simulated period of a year. On a month-by-month basis, it was closer to the measured data than the QuickControl simulation.

As in the case with the QuickControl simulation, it is only the cold months that differ markedly from the measured data. The discrepancy between QEC and the measured data in these months could be because of a higher occupancy load on the building during those times.

3.10. Conclusion

In this case study an established simulation tool, QuickControl, was successfully used to emulate a typical ESCO audit, ranging from data acquisition through model verification to retrofit simulation. The simulation model was set up with measurement taken on site, and various

retrofit options simulated to establish the energy savings potential of the conference centre. The energy savings figures could be used to calculate the cost savings potential. The study showed potential for cost savings of R 100 000 per year, with a cumulative energy saving of 740 MWh, and a peak load reduction of 71 kW.

Thereafter the enhancements made to QuickControl in the program QEC were tested to establish the relevance and accuracy of the particular improvements. These improvements were aimed towards the ESCO project. The results showed that the accuracy of QEC was on par with QuickControl, which proved that the changes did not influence the accuracy of the tool. The enhancements did improve the stability of the simulation, decreased the simulation time and model set up time, also decreased the amount of required measurements and resulting time for taking measurement.

3.11. References

[1] ASHRAE, BSR/ASHRAE Standard 62-1989R, "Ventilation for Acceptable Indoor Air Quality", Public Review Draft, Atlanta, Georgia, August 1996.

[2] E. van Heerden, "Integrated simulation of building thermal performance, HVAC system and control". Dissertation presented in partial fulfilment of the requirements for the degree Philosophiae Doctor, Faculty of engineering, University of Pretoria, Pretoria, 1997.

[3] E. van Heerden, E.H. Mathews, "A new simulation model for passive and low energy", In Proceedings of the 1996 PLEA Building and Urban Renewal conference, Louvain-la-Neuve, Belgium, 1996.

[4] D.Arndt, "Dynamic integrated simulation of large thermal systems", Dissertation presented in partial fulfilment of the requirements for the degree Philosophiae Doctor, Faculty of Engineering, University of Pretoria, Pretoria, 2000.

[5] TEMM International (Pty) Ltd, P.O. Box 2156, Fearie Glen 4, Pretoria, 0043.

4. DEVELOPING A NEW PROCEDURE FOR BUILDING RETROFIT AUDITS, ETB

4.1. Preamble

In the commercial building sector of South Africa, approximately 50% of the energy consumption is due to air-conditioning [1]. Furthermore, it is widely agreed that energy savings of around 30% may be realised through retrofit projects on existing buildings without compromising indoor comfort [2].

Traditionally, improved control of the HVAC system is the mechanism that probably gives the best return on investment. To ensure that a proposed HVAC control retrofit saves on energy cost while maintaining comfort, the retrofit should be analysed with an integrated HVAC simulation tool.

Other methods of energy management employed, are the use of new HVAC system equipment, changes to the system design or fixing the installed components if they are operating below design specification. However, the only way to accurately predict the result and effectiveness of such measures is with the use of dynamic, integrated simulation software [3].

But why is energy saving in buildings important? Currently, South Africa is experiencing a rapid increase in electricity demand. It is projected that the demand for electricity could exceed the installed capacity as early as 2007 [4]. In the short term, this compels the utility company to force a reduction in the demand.

One solution would be to encourage energy efficiency by a sharp increase in prices of electricity. This will make it worthwhile for the building owner to evaluate measures for energy efficiency. Eskom has also initiated the DSM initiative [5]. If the retrofit audit is worth the risk and effort there is an incentive for ESCOs to take up the Eskom offer. To minimise the risk an ESCO has to determine the most effective retrofit options and estimate the potential cost savings. This requires an integrated analysis of the building and its related energy systems.

One of the most popular simulation tools is DOE-2 (Visual-DOE), which was developed by the U.S Department of Energy [6]. However, an intensive evaluation of this program by Arndt [7] had shown that it requires a lot of detailed information that is difficult and time-consuming to obtain. It is also not well suited for typical South African commercial buildings and weather conditions.

Case studies done with tools such as QEC, developed in South Africa, also showed that it can be further improved from the viewpoint of the whole ESCO project. The next section discusses a specific need that arose for a new procedure incorporated in a software tool, which would aid South African ESCOs to capitalise on the potential business opportunity that lies in energy management of buildings.

4.2. The need and requirements for a new ESCO tool

TEMM International (Pty) Ltd [8] and TSI (Pty) Ltd [9] jointly identified the need for a software tool that is aimed specifically at ESCO work in South Africa. The former company specialises in developing software solutions for the energy industry. TSI, on the other hand, is a subsidiary of the state owned electricity utility Eskom. It has won a contract to analyse and retrofit 48 buildings owned by a number of large property companies. The project needed to be completed in two years.

It was soon realised, though, that this was an impossible target. The first buildings took up to four months to analyse and retrofit. One of the biggest problems was the lack of software that specifically catered for their needs. Current HVAC simulation software requires many detailed inputs.

These programs are not geared to produce good estimates of retrofit savings potential in a short time (in the order of 10 days). Considering that the analysis part of an ESCO project is usually financed by the ESCO itself and that the cost of the analysis is in the order of R 10 000 per week it is clear that this part of the project needs to be done in as short a time as possible.

Given the background of ESCO work in South Africa it can be stated that the primary requirements for a new ESCO software tool are that it should be simple, stable, and fast. TSI and TEMM International set the detail requirements for a new software tool in the areas of:

- User profile,
- Project time,
- Scope,
- Data gathering,
- Simulation model.

These requirements are explained below:

User profile

The required level of expertise of the user must be a diplomate engineer. The user must build the simulation model simply and intuitively. No intricate simulation, or mathematical options, should be set. All the standard retrofit options must be very easy to set up and analyse.

This will reduce the overhead cost of the project, as less personnel would be required for the audit. Also, the typical enumeration of the required skill level is less.

Overall time to analyse a commercial building

A trained user should be able to complete an analysis of a 10 000 m^2 commercial building in two weeks. This must include the drafting of the project report for the building owner (or client) detailing the study, possible retrofit options, as well as the detail of the technical specifications of the chosen retrofit option.

This could result in a faster project turnover for the ESCO. That, in turn, will result in an increased financial income, as more projects can be done for a given period. From the client's standpoint, this will consequently lead to a lower project bill if the client is liable for the costs. In shared-savings contract, both parties will benefit, because of a reduced project time.

4.3. How *ESCO Toolbox* optimises the ESCO project

The requirements listed above were used as guiding principles to develop the new ESCO tool. The new tool has been named *ESCO Toolbox (ETB). ETB* consists of four components that reflect the main steps in the analysis phase of a typical ESCO project, namely:

- Data gathering,
- The simulation of retrofits options,
- Analysis of the simulated retrofits,
- The generation of a report and technical specifications of the selected retrofit option.

The components are discussed below.

Data gathering: *ETB-Input*

Data gathering in *ETB* is done mainly with the PDA. A PDA is a handheld electronic device used mainly as a diary and phonebook, but can also operate programs. A picture of a typical PDA is shown below.

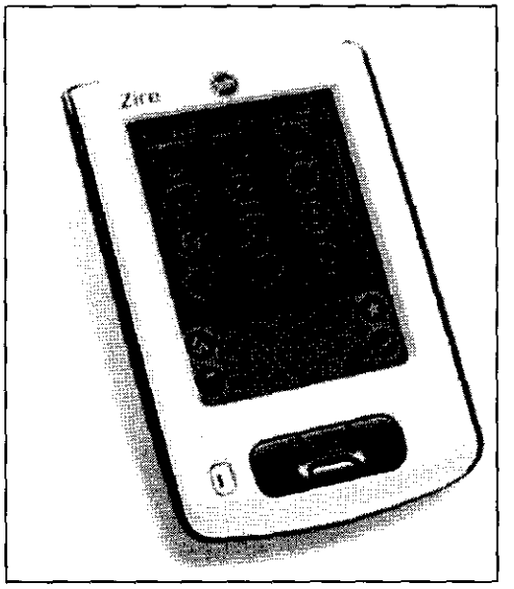


Figure 4-1: Personal digital assistant

The software that is used with the PDA is entitled *ETB-Input.* The required data includes certain parameters for the simulation and building model, as well as information regarding the air-and-water states. These are required to characterise certain HVAC equipment. With the use of this component virtually all input data for the ESCO project is collected during the walk-through audit. Appendix E gives screen prints of *ETB-Input.*

By supplying the user with a standard set of inputs it is ensured that only the required data for the simulation model is taken. Also, the PDA makes it more manageable, because it replaces the typical clipboard, notepad and pen, which the consultant must normally use to retrieve the data.

The following five-step process describes the collection of the necessary information for *ETB-Input.* These steps are:

1. Collect preliminary data,
2. Plan the building simulation model set up,
3. Audit the zones and enter the information into *ETB-Input,*
4. Audit the HVAC equipment and enter the information into *ETB-Input,*
5. Audit the HVAC equipment controls and enter the information into *ETB-Input.*

The steps are briefly described below:

Collect preliminary data

Preliminary data includes the tariff that applies to the building, as well as the electricity accounts for the previous year. Also, the user should get a general feel for the building and HVAC system and its operation.

Plan the building simulation model set up

The user should decide on the set up of the simulation model. This can only be done if the user has a good understanding of the operation of the system.

Audit the zones and enter the information into *ETB-Input*

When the user has decided on the zone layout, *ETB-Input* is used to gather the required information.

Audit the HVAC equipment and enter the information into *ETB-Input*

When the user has decided on the zone layout, the information of the accompanying HVAC components can be gathered. This information is entered into *ETB-Input.*

Audit the HVAC equipment controls and enter the information into *ETB-Input*

The control logic of the HVAC components must be entered into *ETB-Input.*

The simulation unit: *ETB-Simulate*

The simulation unit of the program is entitled *ETB-Simulate.* It operates on a regular PC. Appendix F gives a schematic diagram and screen prints of *ETB-Simulate.* This unit incorporates the entire simulation section of the project. This includes the calibration, verification, and retrofit simulations. A simulation protocol is also included with *ETB-Simulate.* The user is led through the protocol by seven steps laid out in the unit. These steps should preferably be followed in a linear fashion, although it is not required and it is possible to do any step separately.

These steps are:

1. Specify environmental options,
2. Download data from *ETB Input,*
3. Configure the simulation model,
4. Enter the calibration data,
5. Calibrate,
6. Verify,
7. Define and simulate various retrofit options.

These steps are briefly described below:

Specify environmental options

The environmental options required include the climate, electricity tariff, number of summer months of the year and the power factor of the building. The option to add new climates and tariffs to the database is available. The data required for the climate includes the location in terms of latitude, longitude, and elevation, as well as the average hourly temperature, relative humidity, global and diffuse radiation for every month. The electricity tariff includes the

average hourly values for active energy charge, reactive energy charge, and MD charge, for each of the three-day types for summer and winter seasons. It also requires the reactive energy supply percentage and the MD charge type.

Download data from *ETB-Input*

The components that were recorded in *ETB-Input* can be downloaded from the PDA into the *ETB-Simulation* software. After this is done, the components are available for use in *ETB-Simulate*.

Configure the simulation model

The building system can be configured in the air and water circuits available in the template. The program presents a set of templates from which the building system model can be set up.

Enter the calibration data

The calibration data is required to calibrate the building model to measured values. The data required is average hourly temperatures and relative humidity for the calibration day, as well as the total building load for a weekday, Saturday and Sunday during the calibration period. The date of the measured electrical and climate data must correspond.

Calibrate

The simulation model is calibrated in this step. The base for calibration is the percentage of time that the results of the simulation model are within 10 % of the measured values. This figure is given for the three day types (weekday, Saturday and Sunday). Additionally, the program also displays (for each day type) the supply and return air temperatures for each zone, as well as the simulated and measured building load. This gives additional verification of the response of the system.

Verify

The simulation in this section of the project verifies the yearly energy consumption and maximum demand (MD) of the simulation model. The simulation output is the total seasonal energy consumption, as well as the average seasonal MD for the building. This is compared to a measured value, and the percentage error is calculated automatically by comparing the measured and simulated data.

Define and simulate various retrofit options

To ascertain the energy savings potential of the building, various retrofits must be investigated. In *ETB* the user is presented with typical retrofits that can be chosen from a list.

Analysis of the retrofits: *ETB-Economic analysis*

After the various retrofit options have been simulated, these need to be compared to determine the best option. Normally this can only be done through time-consuming data manipulation and calculations. *ETB* calculates the most important indices regarding retrofits and energy consumption in buildings. The values calculated are the cost, cost saving, percentage saving and energy saving of each retrofit, the direct and discounted payback period of each retrofit, given the capital loan rate it calculates the net present value of each retrofit over a specified timeframe. It is then left to the user to interpret the data and choose the best options. Screen prints of this section of the program can be seen in Appendix G: *Screen prints of ETB Economic Analysis.*

Reporting the results: *ETB-Report*

ETB enables the user to compile a report of the project quickly and easily. The software that gives the user this functionality is entitled *ETB-Report.*

ETB-Report automatically generates a report in a word processing environment. The report summarises the financial and technical results of the base case and the retrofit options including the retrofit option that has been selected for implementation. The user can modify the report as needed. The report is for the benefit of the building owner. It summarises the vital information of the analysis part of the ESCO project. It should allow the building owner to make an informed decision regarding investment in the proposed retrofit.

The user is led to answer certain questions regarding the building and HVAC system. These include general questions like the building location, air conditioned area, HVAC system type and the like. The user is also presented with generic report portions, for sections like the introduction, certain report paragraphs, executive summary etc. These portions are written specifically for the South African situation. The user can edit any of the sections at will.

When the user has entered all the required information, a report is generated, integrating the data entered by the user and the generic report sections. After the report is generated, the functionality is given for the user to edit the report to his, or her own specification.

4.4. The audit procedure

ETB mainly consists of the sections described above. The program then forms part of the protocol that is used to do a building audit in 10 man-days. The protocol is displayed in the following table. This table also gives the proposed timeframe, with the assumption that the start of the project falls on a Monday.

Step	Description	Time frame
1. Gather building information	Building drawings, HVAC system drawings, HVAC specifications, and walkthrough investigation.	Monday 1 - Tuesday 1
2. Customise simulation templates	Decide on building zones and customise simulation circuits. Create component lists on the palm.	Wednesday 1
3. Building data acquisition	Complete all the palm component inputs.	Wednesday 1 - Monday 2
4. Calibration measurements	Capture climate conditions integrated with the total building electricity load. (Capture internal electrical loads of typical building section)	Thursday 1 - Monday 2
5. Configure simulation models	Download the palm components onto the PC. Configure all the operating and internal load time schedules.	Tuesday 2
6. Calibrate simulation models	Calibrate the simulated electricity load against the measured load to ensure accuracy. Make sure temperature profiles are realistic.	Tuesday 2
7. Verify simulation outputs	Compare year energy results to the previous 12 months electricity accounts.	Tuesday 2
8. Retrofit analysis	Investigate combinations of different energy savings retrofits.	Wednesday2 - Thursday 2
9. Financial analysis	Calculate savings, payback periods and rate of returns of all the retrofit options.	Thursday 2
10. Compile report on findings	Summarise all the findings in report format.	Friday 2

Table 4-1: Project protocol

The protocol is divided into 10 main steps, each addressing a certain part of the project. These steps are described below.

Step 1: Gather building information

(Proposed timeframe: Monday 1 - Tuesday 1)

This step is used to gather background information on the building and the HVAC system. In this part, the consultant should become familiar with the building, HVAC system, and components, and obtain certain data required for the simulation.

The *ETB-Input* program forms part of this step.

Building drawings

Certain building dimensions are required to configure the building zones in the simulation tool. Building drawings will therefore assist the users in obtaining these dimensions. Without any building drawings, the user will have to measure all the dimensions required for input. Floor plan drawings will further assist the user to divide the building into realistic simulation zones.

HVAC system drawings

Schematic HVAC system drawings will assist the user when customising the air and water circuit templates. Important system input information required for simulation such as air flows, water flows, and system capacities could also be obtained from the drawings.

HVAC design and operating specifications

The HVAC system design specifications (service and maintenance manuals) will supply the consultant with all the original design data such as flows, capacities, setpoints, control strategies, and operating time schedules required to perform simulations. Without these specifications, each component will have to be measured to obtain the required input data.

Electricity accounts

Detailed electricity accounts of the past 12 months will be required as input to verify the simulation models' energy consumption.

Walkthrough investigation

A comprehensive walkthrough investigation on site will give the consultant a better feel and understanding of the building. This will also help when planning the calibration measurements and PDA acquisition phases.

When conducting the walk though audit, the overall layout of HVAC system, the thermal characteristics of the building and the heat loads in the building should be noted. This should best be done together with the building maintenance officer, or a building operations officer that has current knowledge of the building, HVAC system, and the operation thereof. After the completion of the walkthrough audit the consultant must have gathered enough information to customise the building simulation circuit templates.

Step 2: Customise the simulation template

(Proposed timeframe: Wednesday 1)

In this step, the building simulation model is set up in *ETB*. This step is done with *ETB-Simulate.*

Building zones

The first step is to divide the building in the least possible number of simulation zones. The number of zones in the simulation model has a direct influence on the simulation time. The more zones in the model result in more elements in the model and an increased number of equations that must be solved. This increases the simulation time. Building spaces with similar load time schedules, thermal characteristics and similar AHUs can be grouped as a zone. Zones can be characterised into two main groups: air-conditioned zones and non air-conditioning.

Air-conditioned zones: Most of the time, the rooms in a building that are served by the same AHU, can be simulated as one building zone. For further simplification, building zones with the same cooling load and heat requirements, AHU characteristics and control strategies, can form one building zone.

Zones with no air-conditioning: All the building zones (rooms) without air conditioning can form one building zone. The construction of this zone is not very important since we are not

interested in its thermal performance but only its internal electricity loads. This zone will be used to calculate all the electricity loads such as lights, extraction fans, lifts, etc. of all the zones without air-conditioning.

Circuit templates

Here the user must make a few assumptions and simplify the buildings air circuit if necessary to match one of the previously defined circuit templates available in the simulation tool. Remember, HVAC equipment with the same characteristics can be simulated as one template component. This can be done through flow weighted average normalisation. A schematic representation of the air circuit and water circuit is shown below.

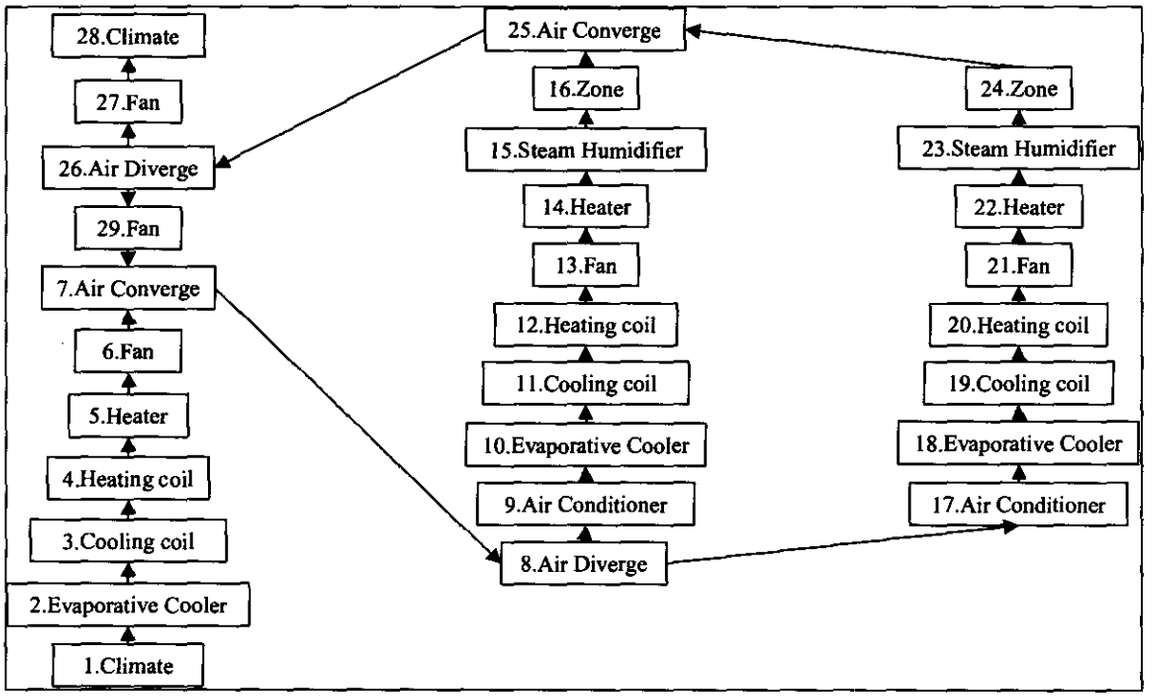


Figure 4-2: Schematic of the air circuit template

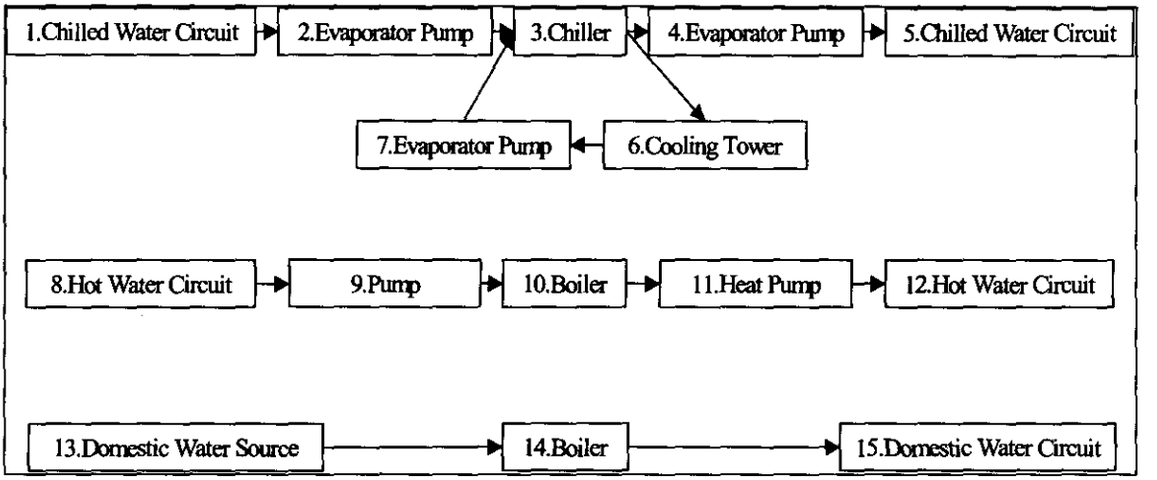


Figure 4-3: Schematic of the water circuit template

Step 3: Building data acquisition

(Proposed timeframe: Wednesday 1 - Tuesday 2)

The PDA is used to collect all information obtainable from the building site. This includes the building zones and HVAC components. This forms part of *ETB-Input.*

Zones

The handheld data logger will be used to collect all the information obtainable from the building site that is required to simulate the building. The building zones, as it was decided on in the first two steps, are configured.

The data required for a project is structured in such a way that no detailed building drawings, or prior knowledge of the building, are necessary. However, building plans will be very valuable. Comprehensive assistance is also available electronically to the user to support in this process.

HVAC system components

The PDA will be used to collect all the information obtainable from the building site that is required to simulate the HVAC equipment. In a similar fashion to the zones, the equipment models are configured as it was decided upon and selected in the simulation circuit template.

The data required for a project is structured in such a way that no detailed system specifications are necessary. Although system specifications will be very valuable to lead the consultant in the

process and understanding of the system, it is recommended that the inputs required by the program be measured directly from the unit if possible, and not taken from designer specification. Thereby the current building operation will be simulated, and not the designed system.

By using the measured data (versus designer specifications) the "current, real" building is simulated. Also, when the measurements are compared against the designed operating points it will help to determine any faults or inefficient operation of the equipment. This could give a good indication of possible areas of energy wastage.

Step 4: Calibration measurements

(Proposed timeframe: Thursday 1 - Monday 2)

The data required to calibrate the simulation model must be measured on site. These measurements mainly include two areas. These are:

Total building electricity demand (kWh, kVAh)

Average hourly measurements of the total building energy demand (kWh, Power Factor(PF)) for a typical Friday (weekday), Saturday, and Sunday are required to calibrate the simulation model for realistic retrofit results. If available, the Building Management System (BMS) can be used to capture this data, else portable, standalone data loggers could be used.

Climate data

Average hourly climate measurements of the temperature and RH for a typical weekday are required to calibrate the simulation model for realistic results. These measurements can be captured either by the BMS system or by standalone data loggers. It is very important that the climate data be measured during the same time as the electricity demand measurements.

Step 5: Configure simulation models

(Proposed timeframe: Wednesday 2)

Download system components from PDA

The first step to configure and complete the simulation model is to download all the PDA components onto the PC. Drag and drop all the downloaded components to their respective locations on the air and water circuits of the simulation program.

Configure component time schedules

The time schedules can typically not be measured on site with the walk-through audit. This information must be obtained from a person that has current knowledge of the building operation. Visit all the components in the project component list and set-up all the building and system time schedules for all the seasons and day types.

Step 6: Calibrate the simulation models

(Proposed timeframe: Wednesday 2)

Total building electricity demand

The simulated total building electricity demand should fit (80% of time within 10%) the measured load. However, this figure is only a guideline. The calibration and verification simulations form a unit. A bad calibration figure does not necessarily translate into a building model error. The period simulated in the calibration simulation period is short and compared to the measurements from a similar time. Any events out of "character" in the building during the calibration measurement may reflect negatively on the calibration figure. Therefore, the final decision rests with the consultant.

Step 7: Verify simulation outputs

(Proposed timeframe: Wednesday 2)

Energy consumption and maximum demand

This is a year verification, where the summer and winter simulated energy consumption and MD of the total building are compared with the respective measured data of the previous 12 months

(electricity accounts). This result will give a good indication of the accuracy of all the assumptions made during the project. The result should be within 10% of the measured values to ensure realistic retrofit cost savings during the retrofit analysis.

Step 8: Retrofit analysis

(Proposed timeframe: Thursday 2)

Set up retrofits and simulate

A large number of typical retrofit simulations can be performed by *ETB*. These retrofits are divided into three groups:

- Schedule changes,
- Control changes,
- Implementation or replacement or repair of old equipment.

ETB presents the user with a typical set of schedule change retrofits and control change retrofits. The required retrofit can be chosen from a list and simulated. To simulate hardware changes, one must change the specifications of the relevant component in the simulation model.

Step 9: Financial analysis

(Proposed timeframe: Friday 2)

A financial analysis tool is available to calculate the feasibility of all the simulated retrofit options. Annual cost savings, payback periods and rate of returns can be calculated. The tool captures all the required simulation data of all the selected options for immediate calculations. This makes it very easy to compare the different simulated retrofits with one another to find the best suited solution.

Step 10: Compile report on findings

(Proposed timeframe: Friday 2)

The writing of the project report is normally a time-consuming work, also not very much liked by most consultants. *ETB* comes with a complete word processing tool to summarise the findings of the project in report format. A report-writing wizard is available for systematic guidance. Relevant simulation and financial data are automatically imported into the report. A new report can be created within a few minutes.

The next section shows how *ETB* addresses the requirements for the simulation characteristics

4.5. The simulation characteristics of *ETB*

Introduction

ETB-Simulate is a successor to the QuickControl and QEC programs that were developed by TEMM International [8]. Therefore, many of the characteristics of these two programs have been inherited by *ETB*-Simulate. The similarities and differences between *ETB-Simulate* and its parents are listed in the following section.

Differences and similarities between *ETB-Simulate* and its predecessors

Similarities between *ETB-Simulate* and predecessors:

- Element models represent the HVAC equipment. Most models are empirical or semi-empirical.
- The conservation of energy and mass are solved.
- The conservation of momentum is not solved. The solving of momentum is not required in this application since the mass flow rates are known beforehand or can be calculated easily.
- Control is represented by a set of simple equations and is solved.
- The flow of air and the flow of water are both regarded as incompressible.

Differences between *ETB-Simulate* and its predecessors:

- *ETB-Simulate* uses an explicit procedure to solve the resulting set of non-linear equations whereas QuickControl uses an implicit approach. QuickControl uses the Newton method to solve the set of simultaneous equations whereas *ETB-Simulate* uses a hybrid successive approximation method. It was found empirically that this approach was much more stable than the Newton method. The Newton method in QuickControl was prone to divergence due to its sensitivity to starting values and because many of the mathematical models used in QuickControl are discontinuous.
- QuickControl uses a complex scheme to solve the continuity requirement. Since the user specifies the mass flow on certain components, the program has to calculate the mass flows in the remaining components. It has to ensure that no conflicting mass flows are specified. In large networks, as one could expect in a building, it becomes a complex task to ensure that the user enters a consistent set of mass flows. *ETB-Simulate* solves this problem by using templates for the HVAC network. The templates were designed such that the continuity equations could be resolved in advance.
- In *ETB-Simulate* all the element models are explicit. Thus, the outlet conditions can be calculated explicitly if the inlet equations are known. In QuickControl, a number of the element models, notably the cooling coil model, were represented by a set of implicit non-linear equations.
- In *ETB-Simulate* only two models consider transient behaviour, namely the zone and the boiler model. All other models are steady state models. This is not an unrealistic simplification. Transients are introduced from the boundary conditions like the changing internal heat loads and the weather conditions. The time scale for changes in these conditions is in the order of hours. The changes are therefore small and even. Quasi-steady state conditions therefore prevails for most of the day. Additionally, the time-constants for the most equipment would be in the order of minutes, whereas *ETB* is only interested in the fluid states at one-hour intervals.
- For a year-simulation, *ETB-Simulate* simulates five days in summer and five in winter whereas QuickControl simulates five days of every month of the year. It is expected that this simplification will not impact significantly on the accuracy of the final results from *ETB* however it reduces the simulation time by a factor six.

ETB simulation calculations

This section presents the simulation calculations in mathematical form. The following statements represent the order of all the simulation calculations for one time step. The statements are assignment statements, and not true mathematical equations, as would be used in a programming language (like Pascal). Symbols that only pertain to a certain time step are indicated with the subscript j.

For i:= 0 to n-1 do

$$Ce_i := f_i(\tilde{Y}, \tilde{X}, \tilde{M}, T^j_{amb}, s^j_i)$$

4-1

where

- n is the number of elements in the simulation;
- Ce_i is the control fraction relating to the energy equation of element i;
- f_i is the energy control fraction function of element i. It is an explicit piece-wise linear equation. The equation depends on the element type of element i. f_i is such that $0 \le Ce_i \le 1$;
- $\tilde{Y}$ is the outlet state vector of all the elements in the simulation ($\tilde{Y} = \{\tilde{y}_0,...,\tilde{y}_i,...,\tilde{y}_{n-1}\}$);
- $\tilde{y}_i$ is the outlet state vector of element i. The vector specifies the fluid properties of all the fluid streams that exit the element. The vector depends on the element type of element i. An element can have water and/or air outlet streams. For each water outlet stream this vector contains a water temperature scalar. For each air outlet stream this vector contains an air temperature and an air humidity ratio scalar. If element i has a water and air outlet stream its outlet state vector would look as follows: $\tilde{y}_i = \{T_a, w_a, T_w\}$;
- $\tilde{X}$ is the inlet state vector of all the elements in the simulation ($\tilde{X} = \{\tilde{x}_0,...,\tilde{x}_i,...,\tilde{x}_{n-1}\}$);
- $\tilde{x}_i$ is the inlet state vector of element i. The components of this vector are analogous to the outlet state vector described above. However, it differs from the outlet state vector in that (in the computer implementation) its values are not stored separately in memory. Its values are simply a function of the outlet state vector since the inlet state of a certain element in the simulation is equal to the outlet state of its upstream neighbour. In its

simplest form this means that each scalar component of the inlet state vector of element i is specified by a so-called pointer. The pointer addresses the memory of the relevant outlet state scalar.

- To increase the flexibility of *ETB-Simulate* a *TFormula* class was developed. It allows the inlet conditions of an element to be a function of the outlet conditions of a number of other elements. Each scalar component of the inlet state vector of element i is represented by an instance of this class. The class has the feature that it can represent any mathematical formula that is needed to calculate a scalar component of the inlet state vector of element i. *TFormula* can accommodate any combination of mathematical operators, left and right brackets, numerical values, and pointers to the scalar components of outlet state vectors, mass flow vectors, and control fractions (see equation 4-5). For example, consider the water inlet of a boiler that is provided by the flow from two heat exchangers that converges before it enters the boiler. The water temperature component of the boiler's inlet state vector can then be represented by a formula that calculates the weighted average temperature of the two water streams. In this case, the formula object would include addition and division mathematical operators, brackets, and pointers to the mass flows and outlet temperatures of the two heat exchangers.
- $\tilde{M}$ is the mass flows vector of all the elements in the simulation ($\tilde{M} = \{\tilde{m}_0,...,\tilde{m}_i...,\tilde{m}_{n-1}\}$);
- $\tilde{m}_i$ is the mass flow vector of element i. The vector specifies the mass flows of the streams that are associated with the element. The vector depends on the element type of element i. The vector contains an entry for each stream that is associated with it. If element i has a water and air stream its mass flow vector would look as follows: $\tilde{m}_i = \{m_w, m_a\}$;
- T_{amb}^j is the ambient temperature at time step j.
- s_i^j is the on/off schedule for element i at time step j. The user of *ETB-Simulate* specifies this schedule.

For i:= 0 to n-1 do

If element i is a mass flow specifier then:

$$Cm_i := g_i(\tilde{Y}, T^j_{amb}, s^j_i),$$

4-2

where

- A so-called mass flow specifier element is an element that represent an independent variable in the mass flow calculations. The following elements fall in this category: zone, heating coil, cooling coil and cooling tower.
- Cm_i is the control fraction relating to the mass flow equation of element i;
- g_i is the mass flow control fraction function of element i. It is an explicit piece-wise linear equation. The equation depends on the element type of element i. f_i is such that $0 \leq Cm_i \leq 1$;

For i:= 0 to n-1 do

If element i is a mass flow specifier then

$$\tilde{m}_i := \tilde{h}_i(Cm_i)$$

4-3

where

- h_i is the mass flow function of element i, which is a mass flow specifier element. It is an explicit linear equation. The equation depends on the element type of element i.
- m_i is the mass flow vector of element i. It is a vector since some of the mass flow specifiers have more than one fluid stream associated with it.

For i:= 0 to n-1 do

If element i is not a mass flow specifier then

$$\tilde{m}_i := \tilde{k}_i(\tilde{M})$$

4-4

where

- k_i is the mass flow function of element i, which is not a mass flow specifier element. The mass flows of these elements are a direct function of the mass flows of the mass flow specifier elements. The equation is explicit and linear. It depends on the element type of element i.

For i:= 0 to n-1 do

$$\tilde{x}_i := \tilde{l}_i(\tilde{Y}, \tilde{M}, \tilde{C})$$

4-5

where

- l_i represents the mapping between the inlet and the outlet states of the connected elements in the simulation. The equation is explicit and linear. It depends on the element type of element i.
- $\tilde{C}$ is the control fraction vector of al the elements in the simulation ($\tilde{C} = \{Cm_0, ...Cm_{n-1}, Ce_0 ...Ce_{n-1}\}$)

For i:= 0 to n-1 do

$$p_i, \tilde{v}_i, \tilde{y}_i := \tilde{q}_i(\tilde{x}_i, Ce_i, \tilde{b}^j, \tilde{v}_i, \tilde{m}_i)$$

4-6

where

- q_i is the energy function of element i. It primarily relates the element's outlet state vector with its inlet state vector. In general, the energy equation is non-linear and discontinuous.
- p_i is the electrical power input of element i.
- $\tilde{v}_i$ is the internal state vector of element i. It is only applicable to elements that have model transient behaviour. Currently this applies to the zone and the boiler models.
- $\tilde{b}^j$ is the ambient boundary conditions of the simulation at time step j. The conditions include the ambient temperature (T^j_{amb}), humidity ratio, global radiation, and diffuse radiation.

This section discussed the simulation calculations in general terms. The next two sections illustrate the simulation models of two selected element types namely an air heater and a building zone. A description of these element types would give the reader a good understanding of *ETB-Simulate*. The heater and the zone are probably the simplest and most complex element types respectively. The zone also acts as a mass flow specifier.

4.6. Heater model

The heater model was developed by Arndt [7]. It simulates the behaviour of an electric heater element that heats the air that passes through it. The power input to the heater is normally controlled in one of two ways:

- Supply setpoint control: The power input of the heater is varied to ensure that the temperature of the air that leaves the heater (the so-called supply temperature) remains within certain boundaries.
- Zone setpoint control: It is assumed that the heater heats the air that is supplied to a certain zone. The power input of the heater is then varied to ensure that the temperature of the air in this zone remains within certain boundaries.

The control fraction function is reduced from equation **4-2**:

$$Ce_{Heater} := f_{Heater}(y_{Heater}\_T_a, y_{Zone}\_T_a),$$

4-7

where

- $y_{Heater}\_T_a$ and $y_{Zone}\_T_a$ are scalar components of the outlet state vectors of the heater and the zone elements respectively.
- f_{Heater} is the control fraction function. The function is based on the control fraction diagram of Figure 4-4. The function is given in Pascal code in Figure 4-5.

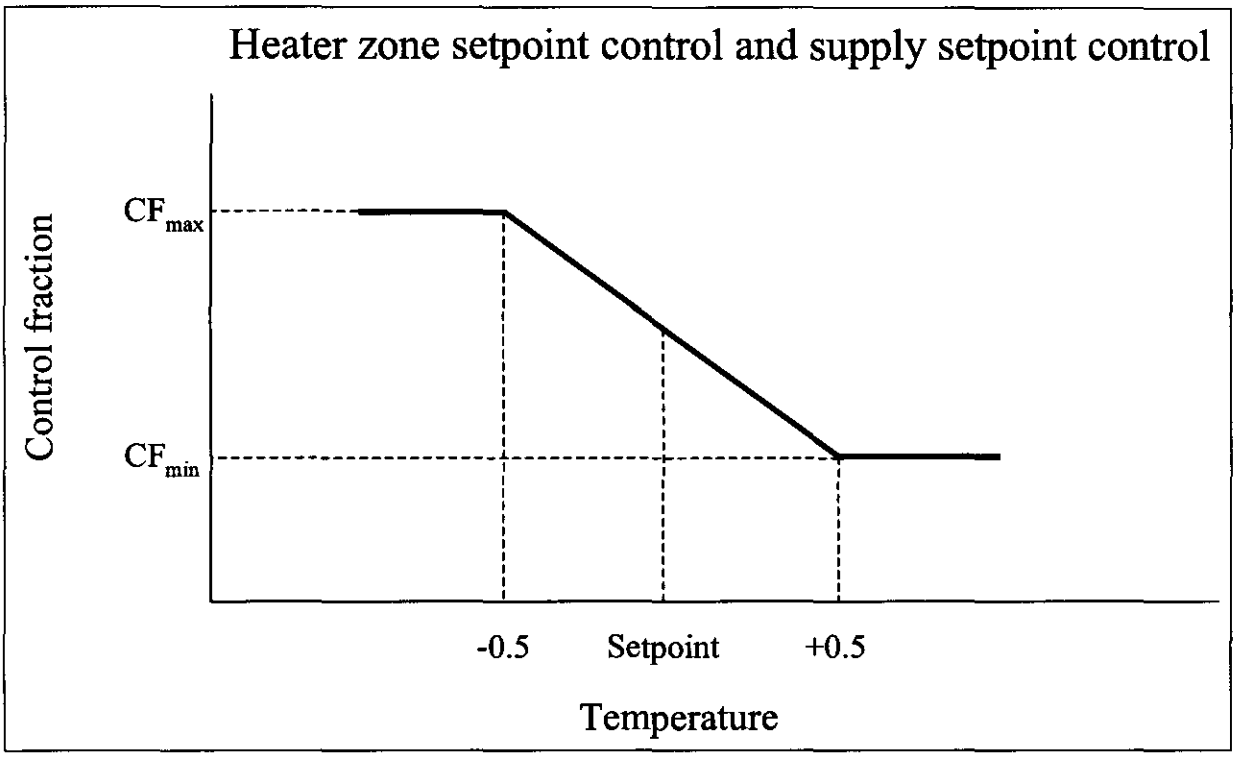


Figure 4-4: Heater control diagram

```
function f_Heater(THeater, TZone:Real): Real;
const
 CFmax=1; CFmin=0; {Maximum and minimum control fractions}
var
 Tlow, Thigh,{Upper and lower boundary of set point range, °C}
 a, {Gradient of control diagram, 1/°C}
 c: Real{Intercept of control diagram, °C}
begin
 case ControlMode of
 cmZoneSetpointControl: begin
  Tlow:= TZoneSetpoint-0.5;
  Thigh:= TZoneSetpoint+0.5;
  a := (CFmax-CFmin)/(Tlow-Thigh);
  c:= CFmax-a*Tlow;
  if TZone > Thigh then Result:= 0
  else if TZone < Tlow then Result:= 1
  else result:= a*TZone + c;
 end;
 cmSupplySetpointControl: begin
  Tlow:= TSupplySetpoint-0.5;
  Thigh:= TSupplySetpoint+0.5;
  a := (CFmax-CFmin)/(Tlow-Thigh);
  c:= CFmax-a*Tlow;
  if THeater > Thigh then Result:= 0
  else if THeater < Tlow then Result:= 1
  else result:= a*THeater + c;
 end;
 end;
end;
```

Figure 4-5: Heater control fraction function

The heater is not a mass flow specifier therefore equations **4-2** and **4-3** do not apply to it. Its mass flow is given by **4-4**, which reduces to:

$$m_{a,Heater} := m_{a,UpstreamElement}, \qquad \textbf{4-8}$$

where $m_{a,UpstreaElement}$ refers to the air mass flow of the upstream element connected to the heater. According to the arrangement in the air circuit template of *ETB-Simulate* (see Figure 4-2) this can be the air mass flow of a fan or a heating coil. The calculation of the inlet state vector of the heater element (equation **4-5**) is given by:

$$x_{Heater}\_T_a := y_{UpstreamElement}\_T_a$$

$$x_{Heater}\_w_a := y_{UpstreamElement}\_w_a$$

4-9

The energy function (equation 4-6), which gives the power input to the heater and the outlet state becomes:

$$p_{Heater}, y_{Heater}\_T_a, y_{Heater}\_w_a := \tilde{q}_{Heater}(x_{Heater}\_T_a, x_{Heater}\_w_a, Ce_{Heater}, m_{a,Heater})$$

4-10

The function is given in Pascal code in Figure 4-6.

```
procedure q_Heater(x_Heater_Ta,x_Heater_wa,Ce_Heater,ma_Heater: Real;  var p_Heater,
 y_Heater_Ta,y_Heater_wa:Real);
const
 MaxPwr=10000; {Rated power of heater, W}
 cp_air=1042; {J/kgK}
begin
 p_Heater:= MaxPwr*Ce_Heater;
 if (ma_Heater > 0) then
 begin
  y_Heater_Ta:= p_Heater/(cp_air*ma_Heater)+ x_Heater_Ta;
  y_Heater_wa:= x_Heater_wa;
 end
 else
 begin
  y_Heater_Ta:= x_Heater_Ta;
  y_Heater_wa:= x_Heater_wa;
 end;
end;
```

Figure 4-6: Heater energy function

4.7. Zone model

The zone model was developed by Van Heerden [10]. It models the heat flow in a building zone with an appropriate electric circuit analogy. The circuit involves the following electrical elements:

- Capacitors account for the heat capacity of the zone structure (C_{lm},C_{hm},C_{im}) as well as the capacitance of the air inside the zone (C_i). The zone envelope is divided into a high mass (three nodes) and a low mass (single node) heat flow path. All internal mass such as intermediate floors and internal walls are represented by a single resistor and capacitor combination (C_{im},R_{im}),
- Resistors model the heat flow resistance of the zone structure (R_{lm},R_{hm},R_{im}), the ground (R_{ss}) in case the zone is in ground contact, the various structure surfaces (R_{shm},R_{shm},R_{sim}), and the ventilation resistance (R_v). The ventilation resistance is simply the inverse of the number of zone air changes.
- Potential sources represent temperature boundaries (T_v,T_o,T_{sahm},T_{salm}). T_v is the temperature of the air that enters the zone. T_o is the ambient temperature whereas T_{sahm} and T_{salm} are the sol-air temperatures of the high and low mass structures respectively.
- Current sources are used for the heat flow boundaries of the zone (Q_{rlm},Q_{rhm},Q_{rim},Q_c). Radiation internal heat loads produced by the occupants, office equipment, lights and solar radiation that enters through the windows are added to the surface nodes (T_{shm},T_{slm},T_{sim}). The ETB-Simulate user specifies these loads. Convective heat loads (Q_c) are added directly to the internal air node (T_i).

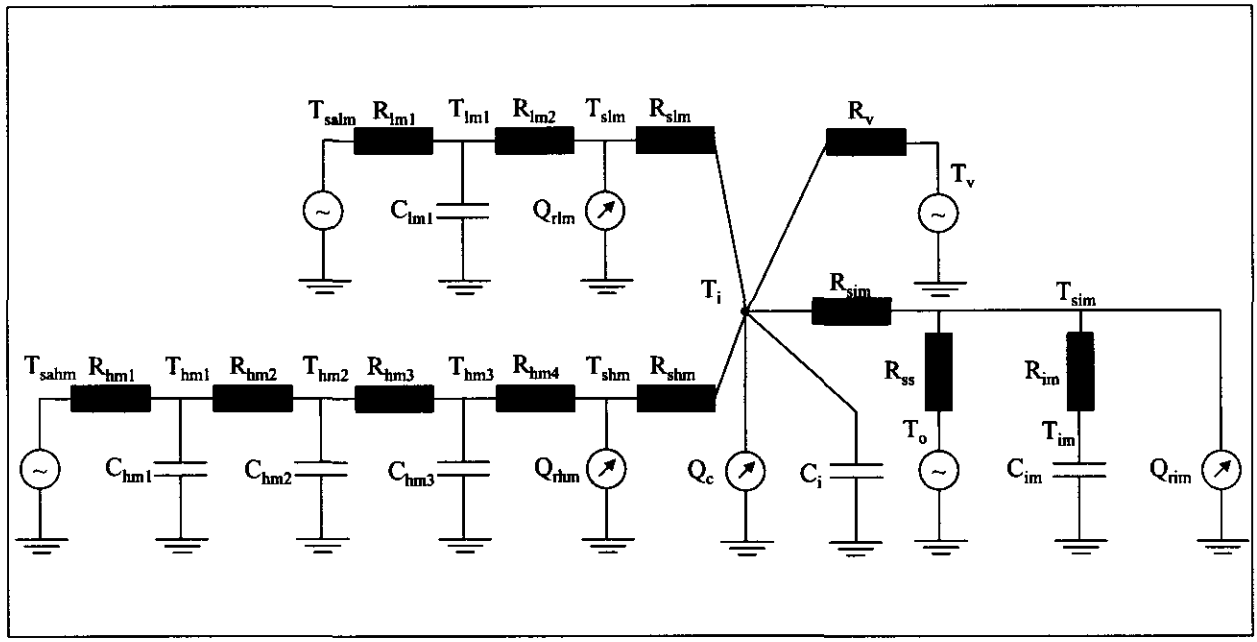


Figure 4-7: Zone model electrical circuit analogy

The values of the low and high mass resistances (R_{hm},R_{lm}) and capacitances (C_{hm},C_{lm}) are calculated by comparing the response of the electrical analogy with the response of the so-called transfer matrix description of the same structure (this calculation was developed by Van Heerden [10]. The transfer matrix elements are a function of the properties of the structure elements such as the walls, roof, and floor. The user specifies these properties by selecting construction types from a pre-defined list.

The surface convection resistances (R_{shm}, R_{slm}, R_{sim}) are calculated with a convection coefficient of 9 W/m^2K. The sol-air temperatures (T_{sahm}, T_{salm}) are a function of the climatic conditions throughout the day, the orientation of the zone structural elements with respect to the sun and the outside convection coefficient. The effect of ground contact is seen as a thermal resistance (R_{ss}) between the ground floor and the mean outdoor air temperature. According to a model used by Mathews et al. the ground is introduced as another layer underneath the floor with a certain thickness. The depth is a function of floor perimeter and area [11].

It is clear that many user inputs are needed to completely specify all the elements in the building zone model. Ellis did a sensitivity analysis to find the most important parameters for this model [12]. The user interface of the building zone element in ETB-Simulate reflects the results from this study. Inputs have been minimised to ensure speedy simulation results with adequate accuracy.

The solution of the building zone model involves nine equations, one for each node. Six of the equations are differential equations with respect to time due to the capacitor elements. The equations were discretised using an implicit (forward-in-time) approach. This results in nine linear equations that have to be solved for each time-step. It is unnecessary to invert the matrix at every time step. The solution to the nine equations was determined symbolically in terms of the matrix coefficients. This effectively gives nine equations that give each zone model variable in terms of known values:

$$\tilde{T}^{j+1} = \tilde{r}(\tilde{T}^{j}, \tilde{R}^{j+1}, \tilde{C}^{j+1}, \tilde{Q}^{j+1}, \tilde{T}_b^{j+1}),$$

4-11

where

- $\tilde{T}$ is the variable temperature vector
  $(\tilde{T} = \{T_{hm1}, T_{hm2}, T_{hm3}, T_{lm1}, T_{im}, T_{shm}, T_{slm}, T_{sim}, T_i\})$;
- $\tilde{R}, \tilde{C}, \tilde{Q}, \tilde{T}_b$ are the vectors for the resistances, capacitances, heat flows and boundary temperatures respectively.

At this stage the zone model can be written in the same form as the heater model. The zone has no power input of its own, therefore, equation **4-1** is not applicable. Equation **4-2** is applicable since the zone element is used as a mass flow specifier in *ETB-Simulate*. The mass flow through a zone is normally supplied with a constant air volume (CAV) or a variable air volume (VAV) air distribution system. For a CAV system the mass flow is either zero or some constant value, depending on the ventilation schedule (s_{Zone}) for the zone. For a VAV system the mass flow is varied linearly between a specified minimum and maximum value according to the temperature in the zone. The mass flow control fraction of the zone is then given by:

$$Cm_{Zone} := g_{Zone}(y_{Zone}\_T_a, s^j_{Zone})$$

4-12

The mass flow of the zone is then:

$$m_{Zone} := h_{Zone}(Cm_{Zone})$$

4-13

The component models were also developed with simplicity in mind. The philosophy was to get the maximum accuracy for the minimum inputs. These models were all well verified [7][13][14][15][16].

4.8. Conclusion

This chapter deals with a procedure embodied in a software program called *ESCO Toolbox.* Firstly the different elements of the program are discussed, thereafter the protocol which is found in the tool. More detail is given on how one would use the program in the protocol to accomplish a retrofit audit, including the proposed timeframes of each step. Additionally, the simulation procedure, a very simplistic model and a highly complicated model used in the program are discussed.

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5

A BUILDING AUDIT WITH ETB

The new program was used in a case study. The aim of this study was to complete a retrofit project using the program, in the same manner that an ESCO would. The prescribed steps were followed from data acquisition, through the simulation of the building, retrofit studies and analysis of the results. This chapter describes that study.

5. A BUILDING AUDIT WITH ETB

5.1. Preamble

The new program was used in a case study. The aim of this study was to complete a retrofit project using the program, in the same manner that an ESCO would. The audit compromised the entire process and included the following:

- Data acquisition using the palm handheld,
- Measuring of the required data,
- Calibration and verification simulation,
- Simulation of the available retrofits,
- Economic analysis of the simulated retrofit options,
- Report writing using the report writer supplied with the program.

5.2. Description of the building

The building under consideration was the TSI building situated in the south of Johannesburg. It is operated by a subsidiary of Eskom, and consists of research laboratories, offices, and workshops. The building is a two-storeyed building with a total floor area of approximately 21,000m^2, most of which is air-conditioned.

The building is made up of three individual buildings divided into parallel blocks. Four spines then interconnect these blocks. The names given to the sections of the parallel blocks are B West, C West, C East, D West and E East. The interconnecting sections are named Link B West, Link C West, Link D West and Link C East. A schematic drawing of the building is given in the figure below.

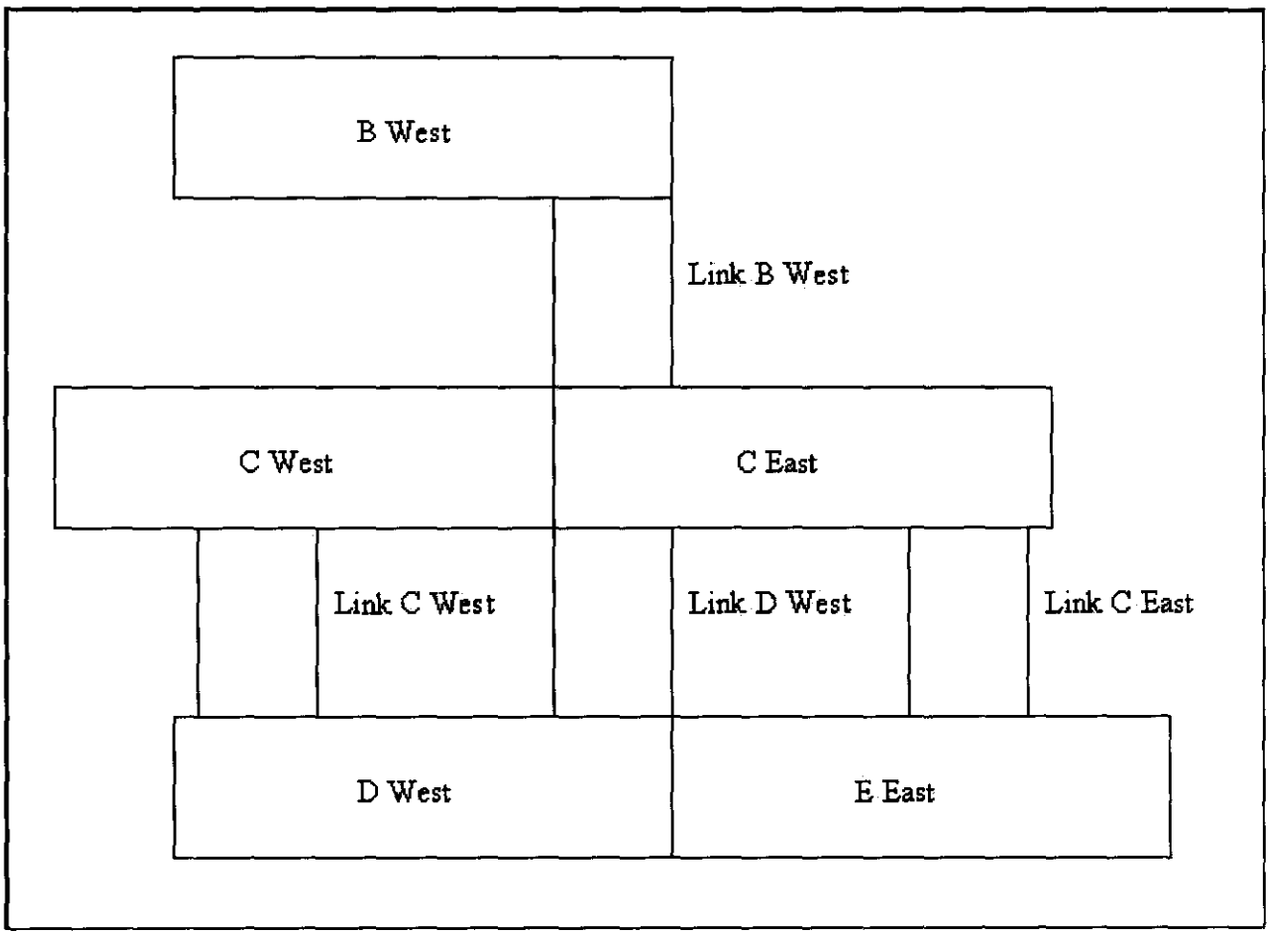


Figure 5-1: Schematic layout of the building

5.3. HVAC system description

The building is fitted with 20 AHUs. These air-handling units can be divided into three distinct types. These types are a full fresh air system, with reheat, a VAV system with reheat and fan packs, and lastly a variable air volume system with reheat only.

Type one is a full fresh air system. The areas that are supplied with this type of AHU are also equipped with fume-extracting cupboards that are connected to the extraction fan system. The following figure gives a schematic layout of this type.

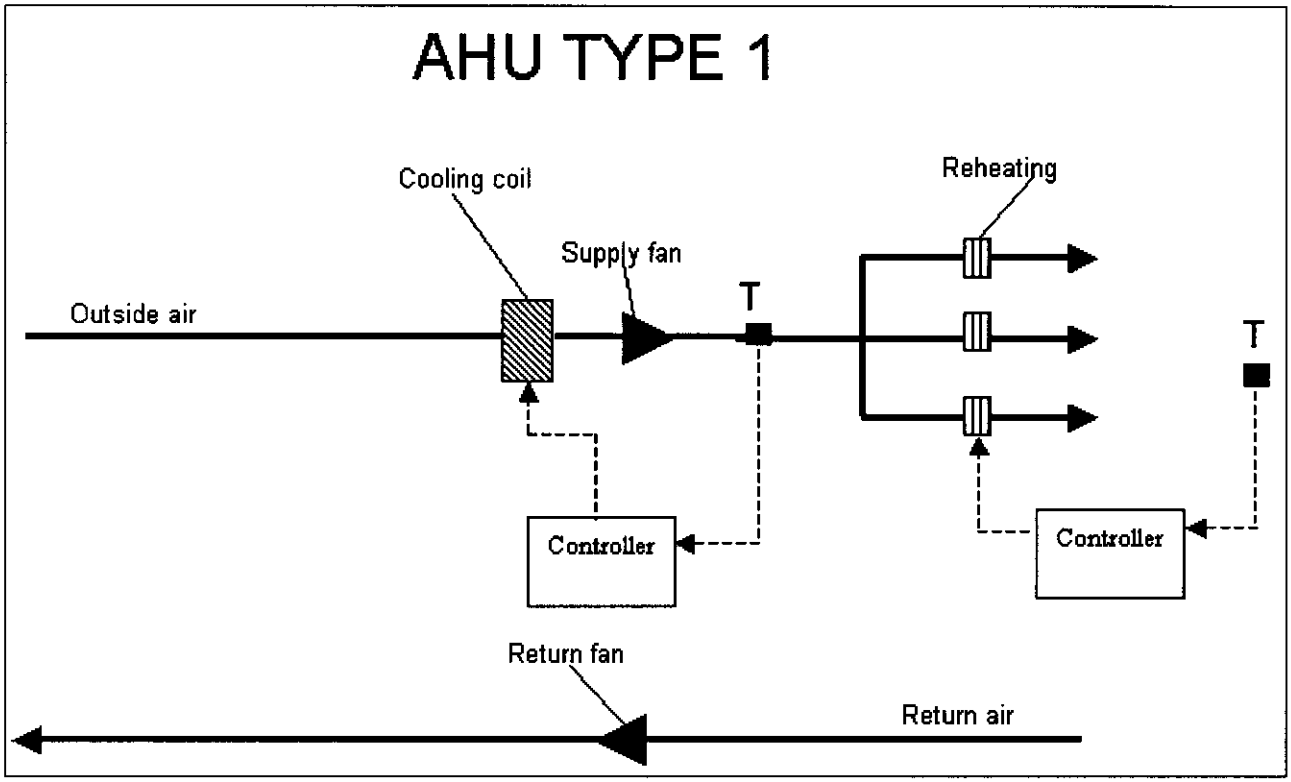


Figure 5-2: Schematic layout of type one air handling unit

A constant speed centrifugal fan draws outdoor air through the outdoor louvers and filter banks. The cooling coil cools the air and is controlled by a PID controller. The cooling coil is controlled to deliver a set supply temperature. The air is then heated (if required) by electric heating elements situated within the ducts. These heaters are controlled by PID controllers and are set to maintain a constant indoor air temperature. Block B, which is used as laboratories, is equipped with this type of unit.

A schematic drawing of the second type is shown in the figure below.

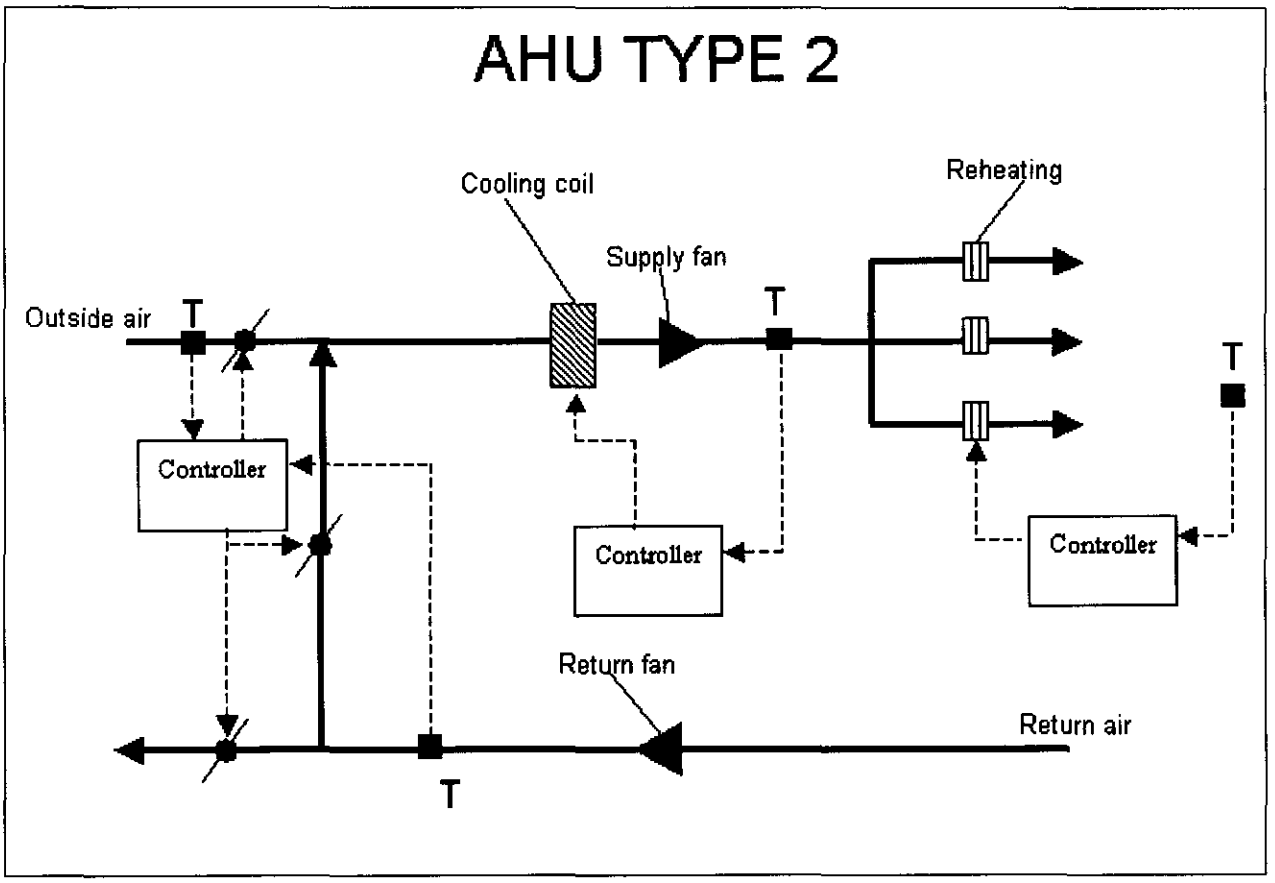


Figure 5-3: Schematic layout of type two air handling unit

Two of the spines, namely Link B West and Link D West, are equipped with this type of unit. In this case, the return and outdoor air are drawn into the system. A temperature-controlled economiser regulates the amount of outdoor air and return air. Only supply air is cooled by the cooling coil which is set to deliver a constant supply air temperature. Reheating and final temperature control is performed by heaters installed in the ducts before the air outlet into the zone.

The type three unit can be classified as a VAV system. The return and outdoor air is supplied and conditioned in the same way as for the previous system. The difference is that fan pack units with their own centrifugal fan and heating elements are used additionally to the rest of the system. A damper at the inlet of the fan pack controls the cold air supply. The damper closes if less cooling is required. More return air is thus recycled locally.

A bypass damper, controlled by the static pressure differential between the supply and return air ducts, ensures that a constant pressure is maintained in the supply duct. The fan pack damper

closes if less cooling is required. To counter the increasing duct pressure the bypass damper opens to feed cold supply air directly back into the return air stream. Blocks C West, C East and D West is equipped with this type of unit. Block E is not air-conditioned. A schematic drawing of the system is shown below.

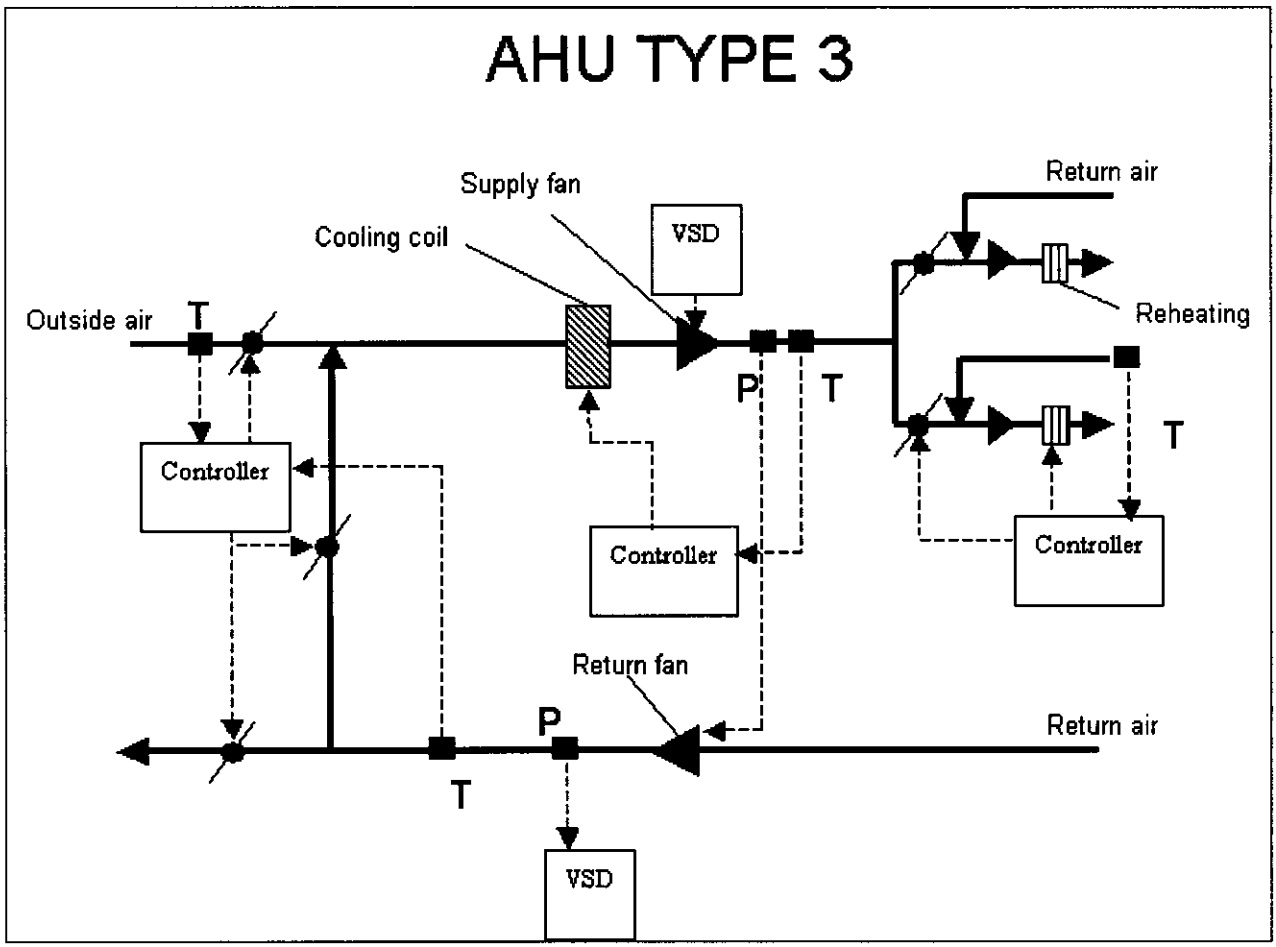


Figure 5-4: Schematic layout of type three air handling unit

These air-handling units are connected to nine air-cooled chillers situated on the roof of the building. Each chiller has a cooling capacity of 357 kW and a power rating of 78 kW. One 3.4 kW pump per chiller is responsible for water flow through the system.

The table below gives a summary of the building and HVAC system:

BUILDING DESCRIPTION	
Building name	Office building
Building description	Commercial building
Building location	Rosherville
Number of floors	2
Total floor area	21000 m^2
Air-conditioned floor area	18000 m^2
HVAC system	Multi zone
Cooling plant	Air cooled, reciprocating
Cooling capacity	702 kW
Heating plant	Electric heating elements
Heating capacity	1223 kW
Air distribution	Variable air volume
Control System	BMS

Table 5-1: Description of case study building

5.4. Building simulation

Model calibration

Continuous measurements were taken over a three day period (Friday to Sunday) to calibrated all the building time schedules (loads and equipment) of the simulation tool. This would ensure that the current status of the building will be simulated correctly for realistic energy cost savings predictions.

These measurements included the hourly average temperature and relative humidity, as well as the total building energy demand (kWh, PF) over this period. The relevant information for the system components was recorded in *ETB-Input*. Each zone is supplied by more that one air handler, while the system template in the program only allows for one air handler per zone. The combined function of *ETB-Input* was thus used to combine the relevant components to make up one unit. These components were downloaded onto the computer and the software program.

The system model was built op from the template provided. The components in the model were set up with the elements that were recorded in *ETB-Input*. The measurements, together with the system components could be used to set up the building and HVAC system simulation model. The building air circuit and water circuit simulation models are shown below:

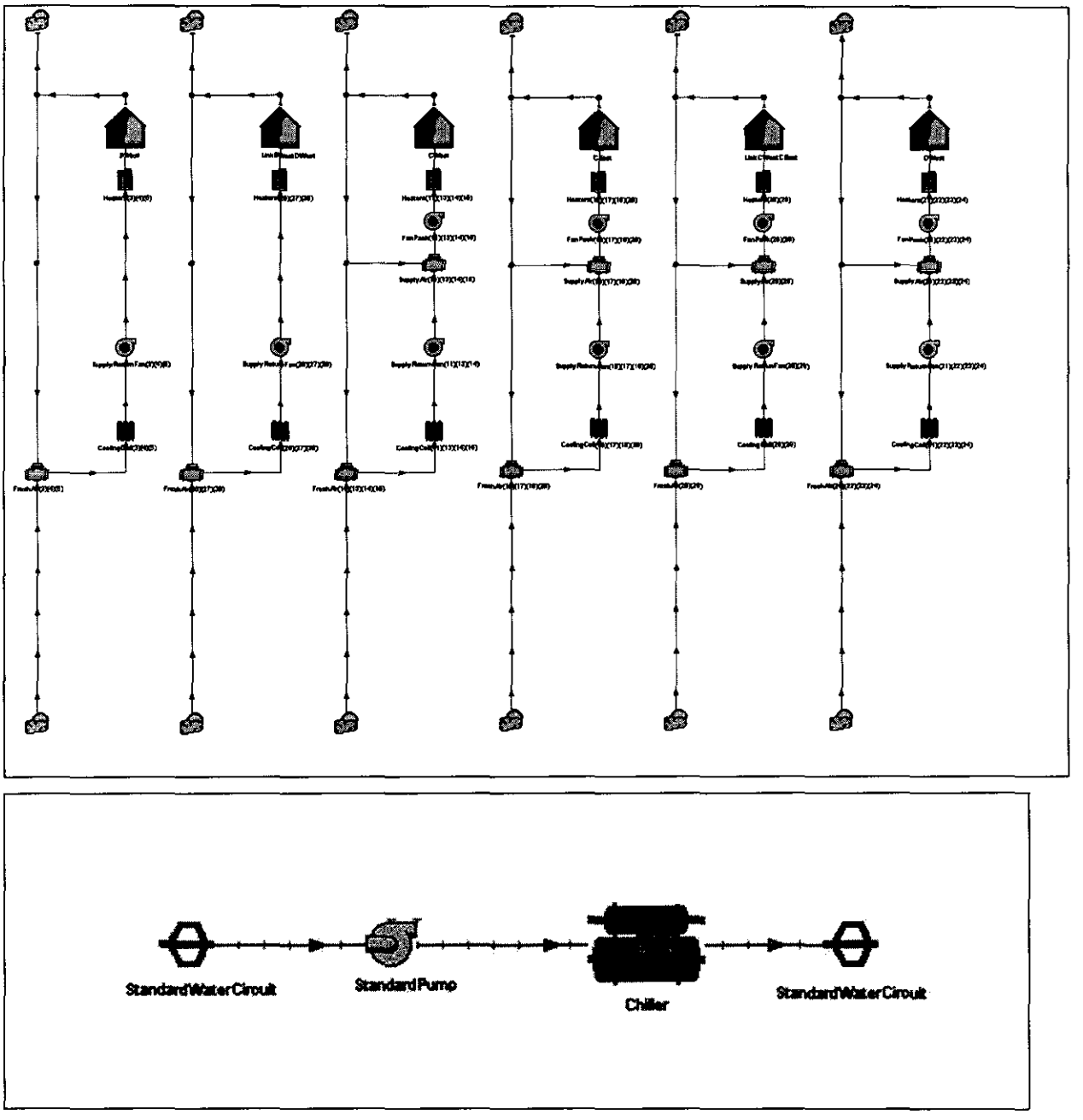


Figure 5-5: Simulation model

The results are displayed in the following table:

Demand Load	
	% Time within 10 %
Weekday	79
Saturday	46
Sunday	58

Table 5-2: Calibration results

When one looks at these figures, it may seem that the weekend calibration is not so good. This can be explained as follows. The lights in the building are grouped per block. The group of lights can be turned on by a phone call to the lighting controller. Once the lights have been turned on, then stay on for one hour before then automatically switches off. It was found that the security personnel that patrol the area, turn the lights on when they walk past the relevant block. This block will then turn off after one hour. This manual use of the lights was not simulated.

With the help of the trend outputs, it was decided that the simulation model was adequately calibrated. In addition to the calibration, which validates the short-term response of the model, a verification simulation is also done, which verifies the long-term simulation of the model.

Model verification

A verification study was performed to verify the accuracy of the simulation model's energy consumption over a typical year. The results of the study are displayed in the following tables:

Total energy consumption (MWh)		
	Summer	**Winter**
Simulated	6111	3462
Measured	6908	3801
% error	12	9

Table 5-3: Total energy consumption verification results

Average MD (kW/kVA)		
	Summer	**Winter**
Simulated	1496	1963
Measured	1996	2344
% error	25	16

Table 5-4: Average maximum demand verification results

The results shown in the above tables seem more accurate than the calibration results. The results of the maximum demand simulation are slightly higher than the energy consumption figures. One must keep in mind that it takes only half an hour to influence the MD figures of the entire period. A possible explanation of the figures could be the pump station on the premises that is used for experimentation purposes, (and therefore not used on a regular or predictable basis), and can therefore not be simulated.

ENERGY COST AUDIT

An end-user energy cost breakdown was determine through simulation to identify all the large energy consumers in the building. These consumers will also have biggest potential for energy cost savings. A building and an HVAC system energy cost breakdown are displayed in the following tables:

Building energy cost breakdown				
Description	**Energy (MWh)**	**Cost (R)**	**R/kWh**	**% of total**
HVAC system	2677	587644	0.22	28
Lights	1500	329287	0.22	16
Other	5396	1184557	0.22	56
Total	9573	2101487	0.22	100.00

Table 5-5: Building energy cost breakdown

HVAC system energy cost breakdown				
Description	**Energy (MWh)**	**Cost (R)**	**R/kWh**	**% of total**
Cooling	417	91473	0.22	16
Heating	1081	237214	0.22	40
Ventilation	912	200114	0.22	34
Pumping	268	58844	0.22	10
Total	2677	587644	0.22	100

Table 5-6: HVAC system energy cost breakdown

From the table it can be seen that the HVAC system consumes close to 30% of the total building energy consumption. Potential for energy saving must therefore exist in this section. It is also apparent that the heating and ventilation systems of the HVAC system are the highest energy consumers. As the cooling system is operated on a supply setpoint and reheat is incorporated, the figures show that energy saving may be possible by changing the cooling control.

RETROFIT OPTIONS

A number of retrofit options and combinations thereof were investigated through simulation. These options consist of different coil control, new setpoints, economiser control, new time schedules, and addition of evaporative coolers. Although these retrofits were discussed in general in Chapter 1, the manner in which they relate to this building are discussed below.

- Coil control. In the current building, the coils are controlled to deliver a set supply temperature of 15°C. This results in energy wastage if this is more than required for the heating load of the zone. By controlling the off coil temperature, in relation to the zone internal temperature, energy could be saved. The exact amount of cooling would then be delivered to the zone, relieving load on the chillers.
- New setpoints. The current cooling setpoint of the building is 22°C. This is at the lower range of the comfort band. For the retrofit, the cooling setpoints were raised to 23°C, which is still in the comfort band [1]. This will also relieve load from the chillers.
- Economiser control. The fresh air dampers of the building were set to deliver a constant supply of 20% fresh air. This was changed to operate on an economiser control as discussed in Chapter 1. With this control, the outdoor air will be used for cooling if it is possible and required.
- New time schedules. From the HVAC energy breakdown figures, it was evident that the fans were the largest consumer of energy of the HVAC system. For the retrofit the time schedules of the fans were changed, to operate only when cooling and heating are required.
- Evaporative coolers. If evaporative coolers are fitted to the system, it will ease the load of the chillers, maybe to such an extent that the chillers need not operate for a large part of the year. The evaporative coolers will be used in conjunction with conventional cooling, although the setpoint for evaporative cooling will be lower than the cooling coils.

5.5. Retrofit results

The retrofit options named above, and combinations thereof were investigated through simulation during the project. The most important financial results are displayed in the following tables:

Electricity cost savings			
Descripton	**Cost (R)**	**Cost savings (R)**	**% savings**
Base year	2101488	-	-
Economiser	2013746	87741	4
New Setpoints	2084303	17184	1
Schedule	1914419	187068	9
Coil control	2015528	85959	4
Evaporative cooler	1795732	305755	15

Table 5-7: Electricity cost savings

Financial analysis					
Description	**Project cost (R)**	**Direct Payback Period (months)**	**Discounted Payback Period (months)**	**Loan rate (%/year)**	**Net Present Value (R)**
					Year 3
Economiser	10000.00	2	2	18.00	180773
New Setpoints	12000.00	9	9	18.00	25365
Schedule	14000.00	1	1	18.00	394737
Coil control	17000.00	3	3	18.00	174899
Evaporative cooler	170000.00	7	8	18.00	493975

Table 5-8: Financial analysis

From the table it can be seen that the combination of economiser, new setpoints, changing of the ventilation schedule, changing of coil control and addition of evaporative coolers have a combined savings effect of a little over 14%, which amounts to over R 300 000.00 per annum. This combination of the retrofits also has the longest payback period (seven months), due to the high capital cost of installation of the evaporative coolers.

5.6. Conclusion

The program was successfully used for a theoretical energy savings potential study. This included all the project steps from data acquisition, set up, verification, and calibration of the simulation model, simulation of retrofit options, economic analysis of the results and the writing of the report of the findings.

The use of the program validated the belief that a diplomate engineer could use the tool for a retrofit study, and that such a study could be completed within a two-week period. However, certain limitations and restrictions were found that could affect certain projects adversely. These are discussed in the concluding chapter. Also, that the proposed retrofits have not been implemented, which means that the results of the saving study must still be verified.

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6

CONCLUSION

In this chapter, the objectives of the study are repeated. During the use of the program in the case study, certain limitations were observed. These limitations are discussed, as well as the need for further work.

6. CONCLUSION

6.1. Summary

It is important for any research and development project that the main objectives be satisfied. Following is a discussion of the main inventions and findings that resulted from this thesis.

Firstly, the literature survey established that a rise in energy consumption of the world is expected. In South Africa, this increase is reaching dramatic proportions, and the electricity demand may exceed supply by 2007. Building, and air-conditioning systems in particular, consume a large portion of the world energy. However, definite potential exists for energy savings in this area. Such studies are typically done by an Energy Service Company (ESCO), and the optimal way to predict electricity saving is by using a building simulation tool. Such studies are normally a very time-consuming process.

Various building simulation tools exist, but none is principally geared towards the building retrofit project. Therefore, the objective of this study was to establish a building retrofit audit procedure embodied in a software program that would enable the consultant to complete an entire audit in an integrated fashion.

A typical, commonly used simulation program was used in a retrofit project in order to evaluate it. This program also incorporates various measures that are aimed at increasing its usefulness in the retrofit audit area. The simulation also shed light on the effectiveness of these measures.

Specific requirements were identified for a holistic retrofit procedure. The procedure should form part of an integrated program, designed specifically for the building retrofit audit. This was done with the input of various individuals and companies, as well as the authors' past experience.

With this in mind, a new procedure, incorporated in a software program called *ETB*, was developed. The main aim of this tool is to allow a diplomate engineer to complete a building retrofit audit within a period of 10 workdays. The scope of the audit must include all aspects of a typical audit, from data acquisition to the compiling of the project report.

This program was then used in an actual retrofit study. The results were favourable, but certain limitations were found. In addition, the requirement for additional work was established. These are described in this chapter.

The result of the study is a software program and protocol that enables the consultant to accomplish a retrofit audit in an integrated fashion in a greatly reduced timeframe. The program is especially useful in a fast, preliminary study to determine areas in the building and HVAC system which are most suited for energy saving retrofits, as well as obtaining an estimate of possible cost and energy savings which might be realised.

6.2. Limitations of the program

In order to design a program that will allow a technician to carry out a full building retrofit audit in a short timeframe, one is forced to make certain assumptions, and also attempt to simplify the entire audit structure. Such simplifications then limit the program to certain operational conditions and constraints. Some of the very assumptions adopted to enable the program to meet the time requirements, may impact the project negatively in some conditions. Some of these are discussed below.

- The set templates and components, component connections and component control, could limit the range of building and system types that can be audited with the tool. It is obvious that the more templates that are supplied with the program, the less is the chance that an unspecified building type will be encountered. However, it is impossible to supply a template for every system type found in industry.
- Although the results of the program are mostly satisfactory from the viewpoint of a retrofit audit, the results are not available outside of the program for post-processing in another program. Therefore, no manipulation of the results can be done for reporting or testing purposes in a spreadsheet program.
- The very short timeframe proposed by the protocol does not leave much room for debugging, if it is required. Therefore, when one cannot calibrate the building after the

measurements were taken, the specified timeframe of the protocol would most likely be exceeded.

- The skill-level specification of a diplomate engineer may not be sufficient, since he/she may not have the required qualification or experience to explain calibration problems when they arise. Deeper insight into the building and HVAC system may be required when calibration of the model proves difficult.
- The measurements required by the program do not include the logging of detailed demand loads for any equipment units. Experience has shown that the system components do not always operate on the schedule or control that is obtained from the building maintenance officer. By not measuring the equipment units in detail, one could make mistakes in simulating the realistic operation of the system. This could lead to calibration and verification problems.
- In order to fully evaluate the retrofit, or understand the building operation, it may be useful to see a graphical representation of the load over 24 hours. However, no post-retrofit load graphs are displayed. Such graphs are needed especially for the DSM initiative in South Africa.
- The energy and comfort audits of the project have been simplified, and this results in a limited amount of measurements required. Although this is a positive input to the project, it also has a negative implication. By reducing the number of measurements, the consultant may miss a certain operating condition or fault of the system. For example, if one measures the airflow in the air handler, but not at the zone, on could miss a possible leak in a broken air duct.

6.3. Need for further work

Certain requirements that should be added to the program became known during the use of the program for the building audit. These requirements are:

- Because the procedure is designed specifically for South African conditions, more emphasis should be placed on load shifting and energy efficiency during the so-called peak demand periods of the day. These periods are between six and nine AM and between six and eight PM.

- No software program can be fully trusted if it is not verified. Therefore, it is very important that the simulation section of the program be verified to establish its accuracy. The most efficient way to achieve this would be to compare it to the BESTEST verification platform.
- The main result of the program is the potential for energy saving by the implementation of certain retrofit options. However, the savings predicted by the program must be verified by the implementation of such measures in an actual building.

Appendix A

Comfort Measurements

The measured zone temperature data that was taken during the week of 26th August 1999 to 1st September 1999 is shown in this section.

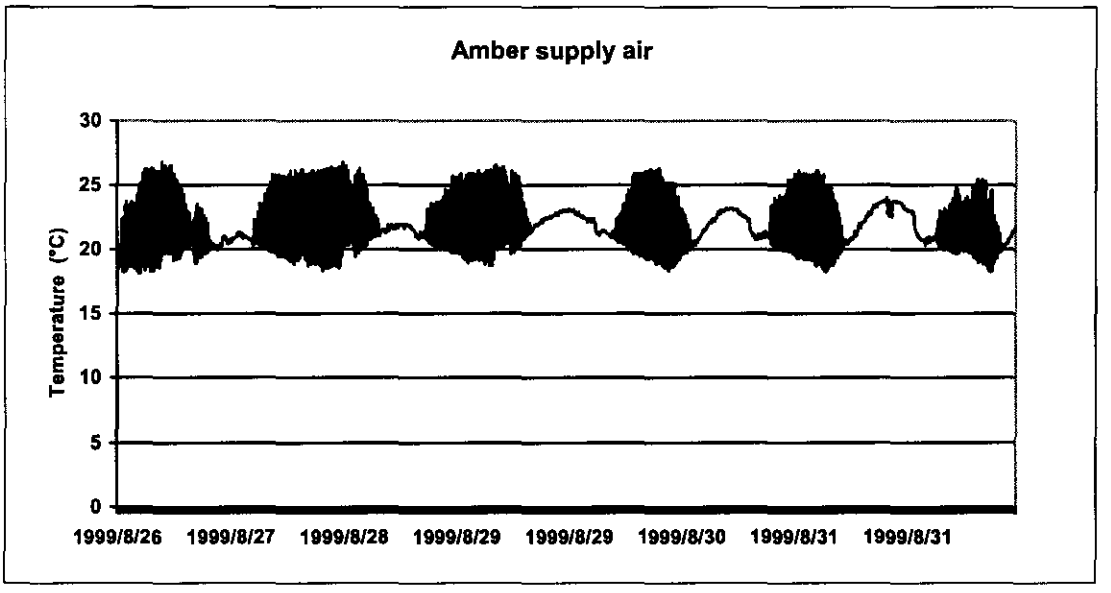


Figure 1: Amber measured supply air

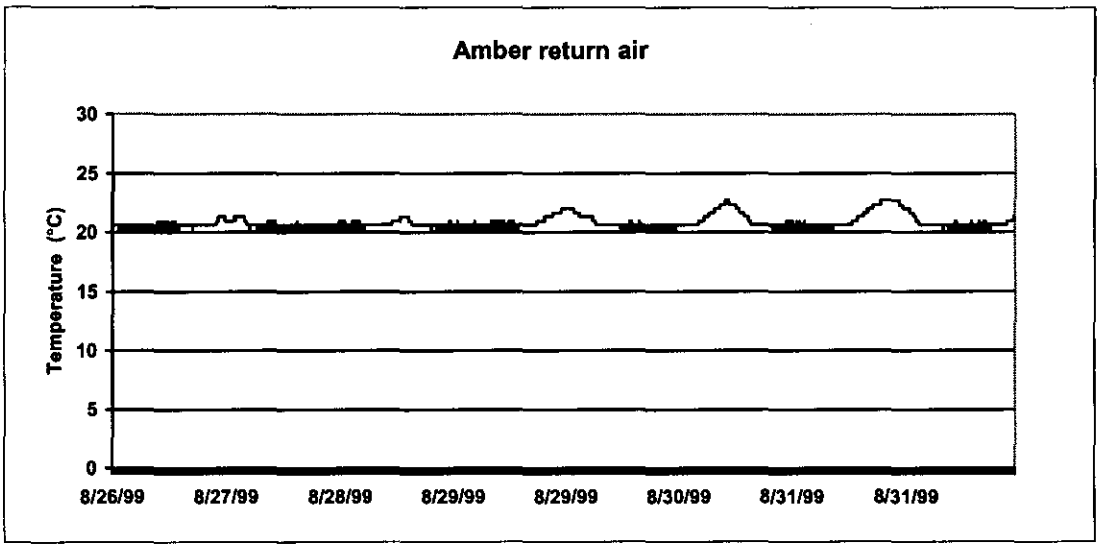


Figure 2: Amber measured return air

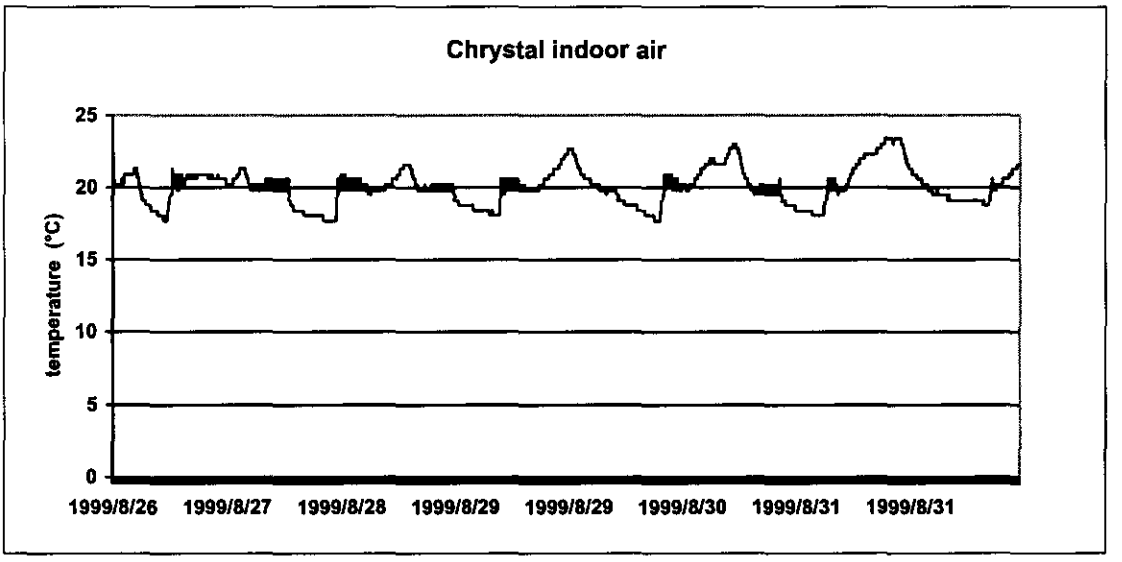


Figure 3: Chrystal measured indoor air

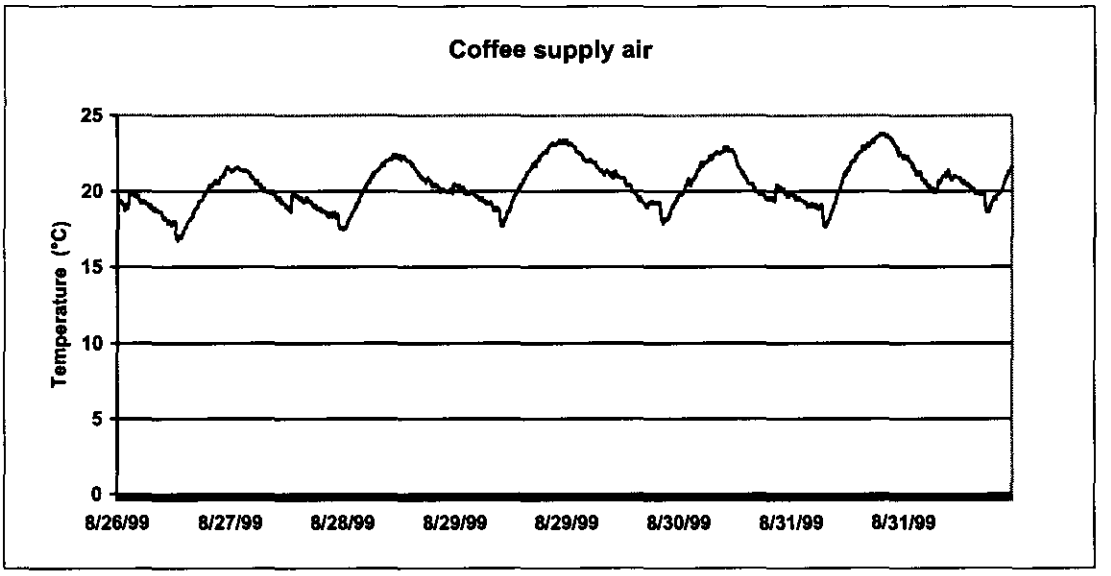


Figure 4: Coffee measured supply air

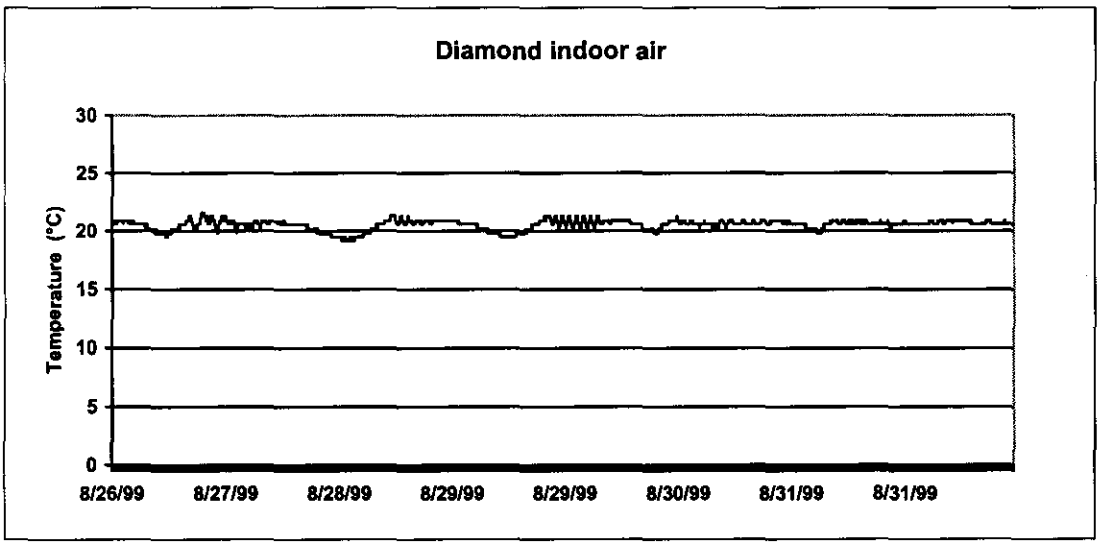


Figure 5: Diamond measured indoor air

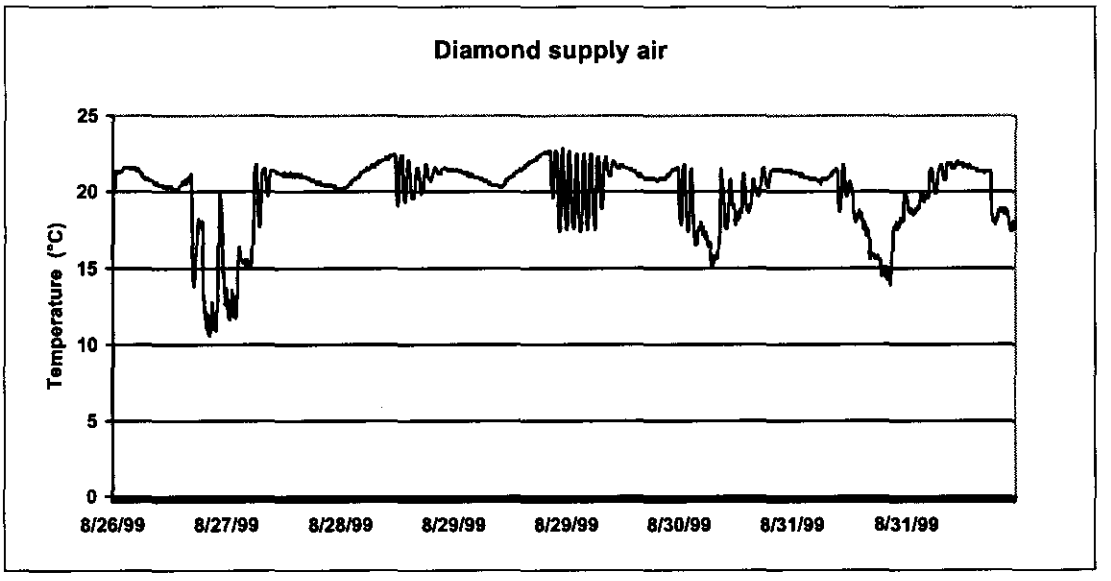


Figure 6: Diamond measured supply air

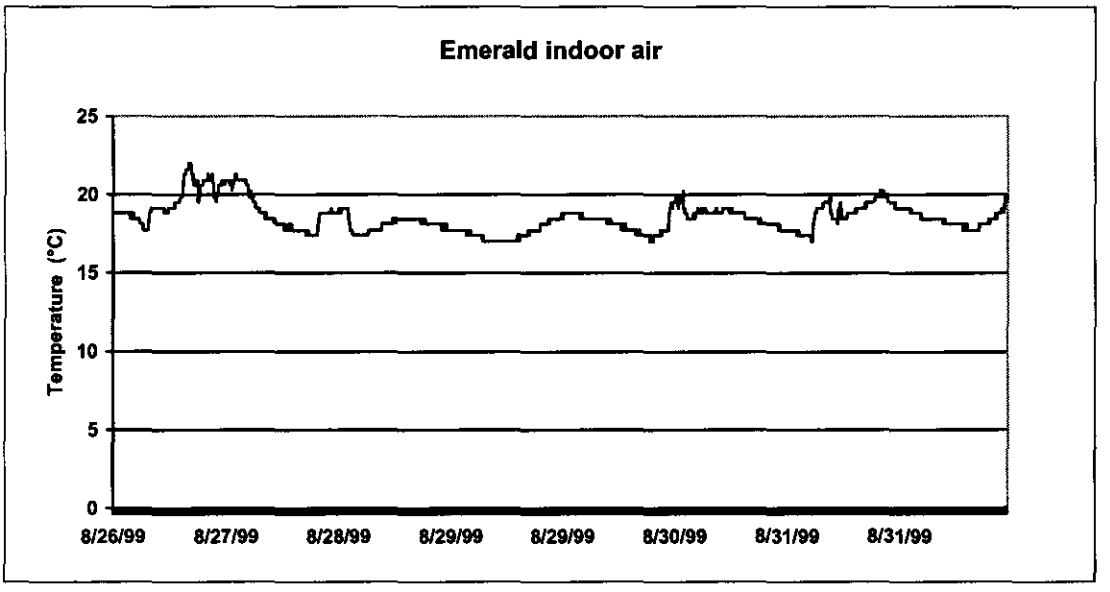


Figure 7: Emerald measured indoor air

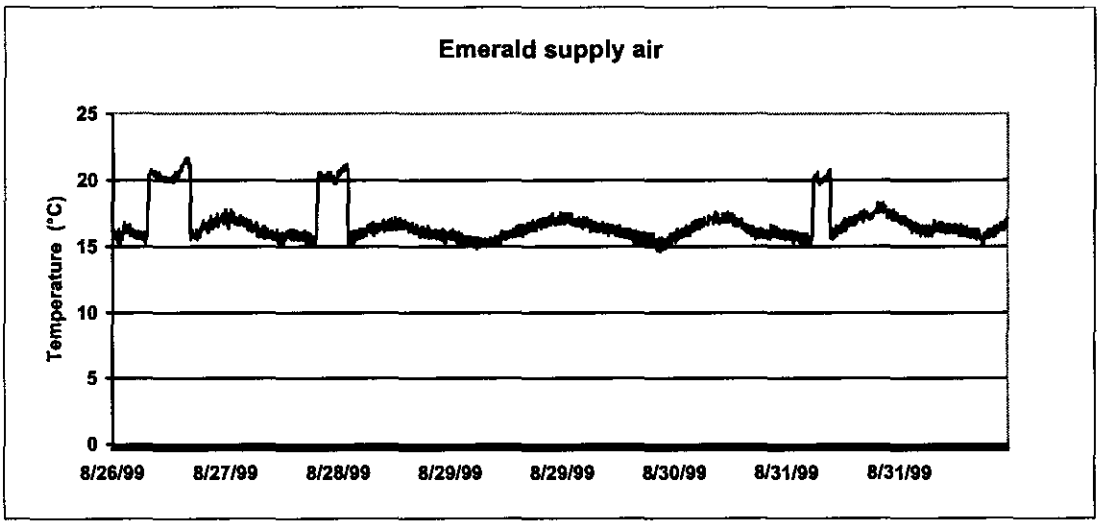


Figure 8: Emerald measured supply air

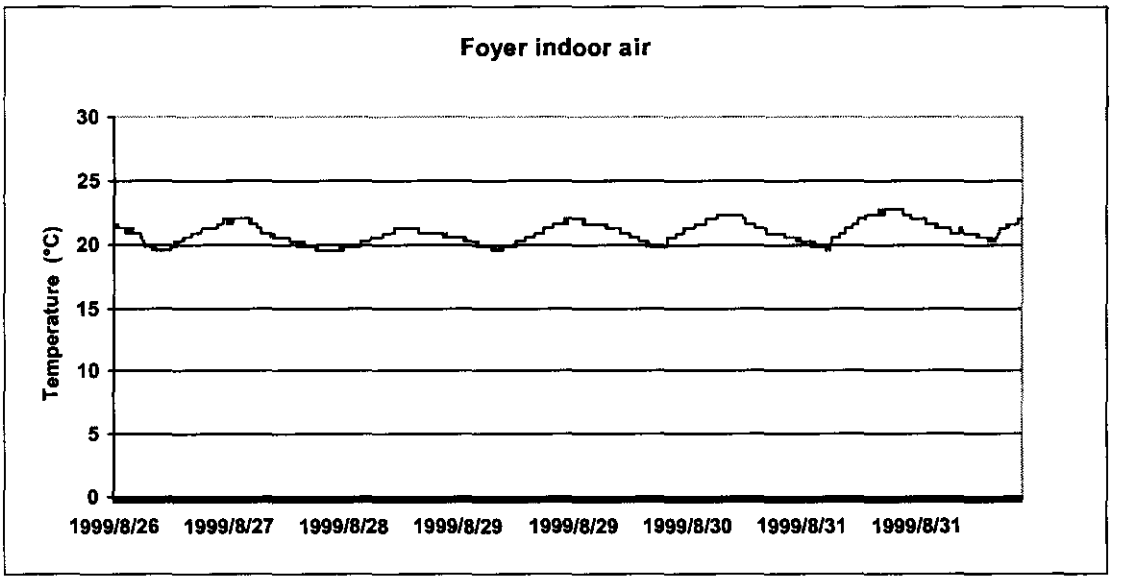


Figure 9: Foyer measured return air

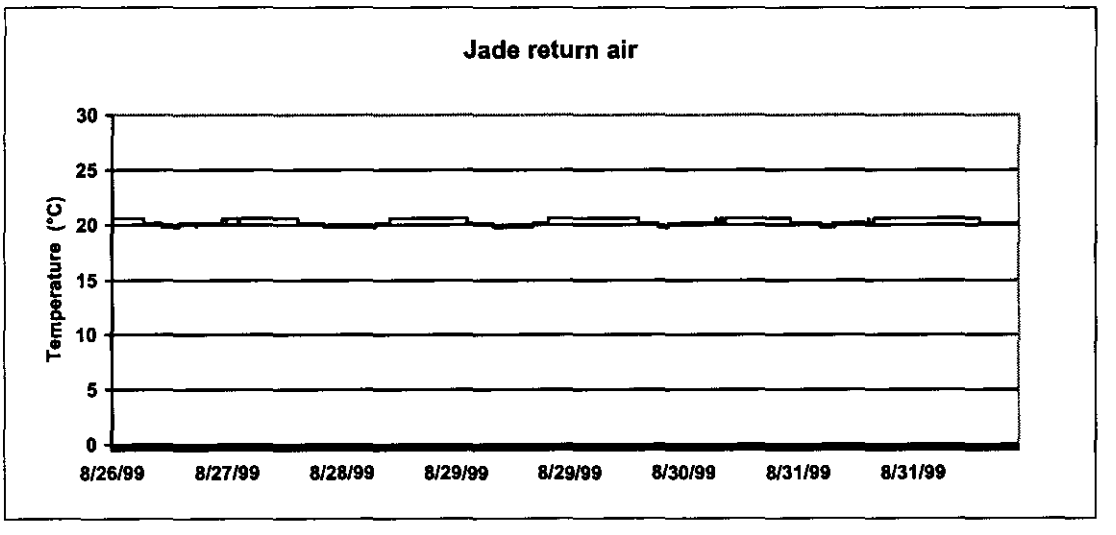


Figure 10: Jade measured return air

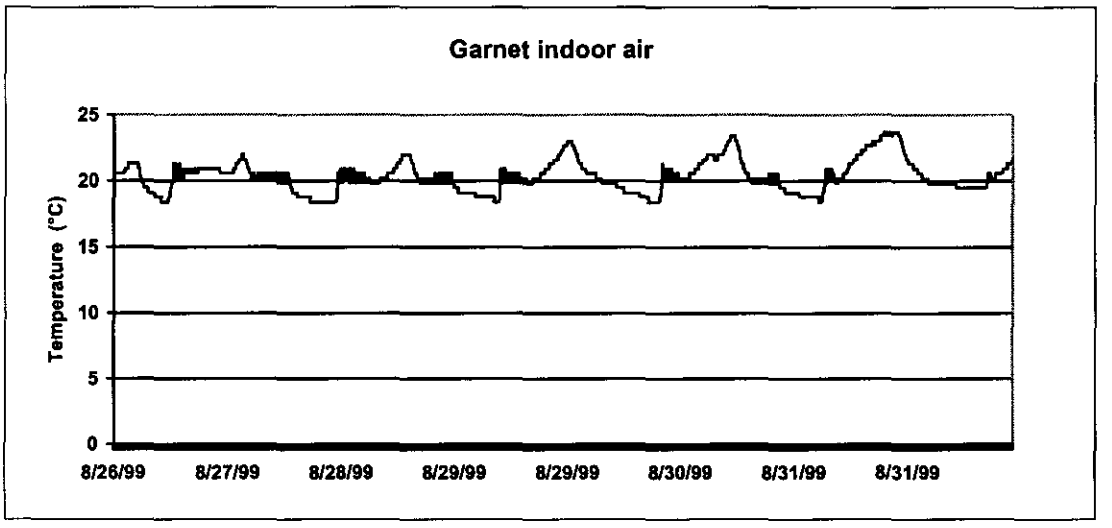


Figure 11: Garnet measured indoor air

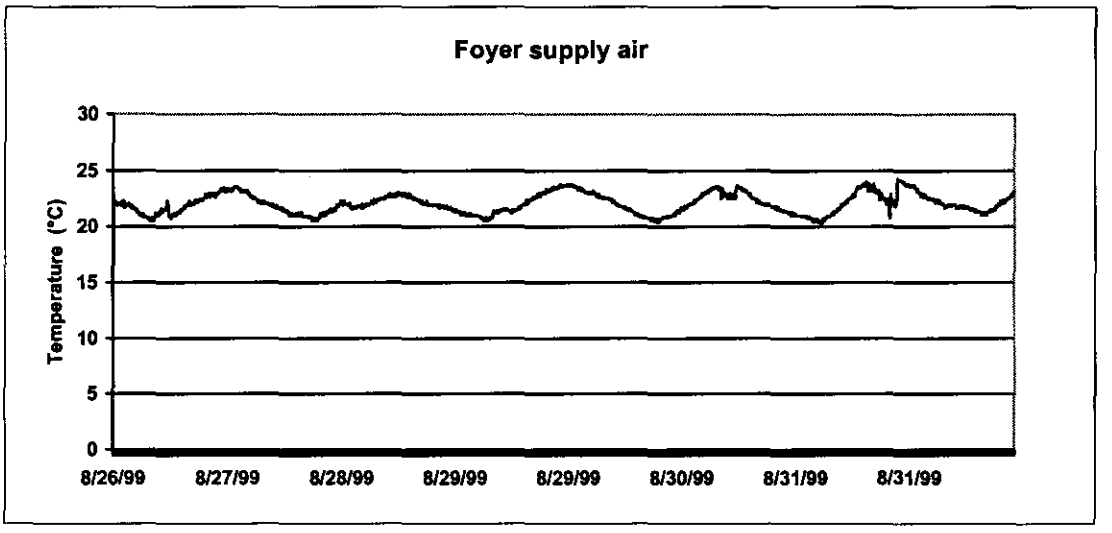


Figure 12: Foyer measured supply air

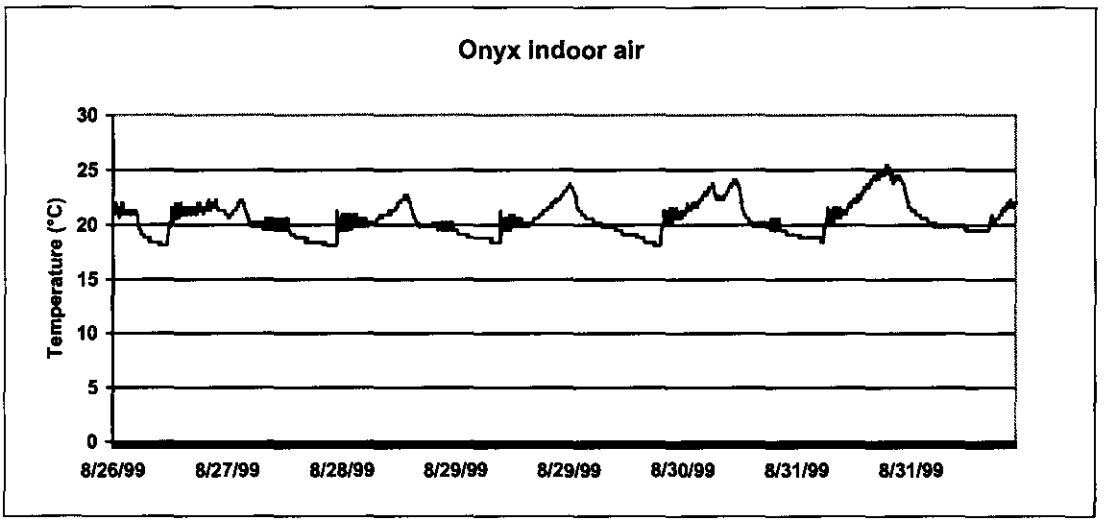


Figure 13: Onyx measured indoor air

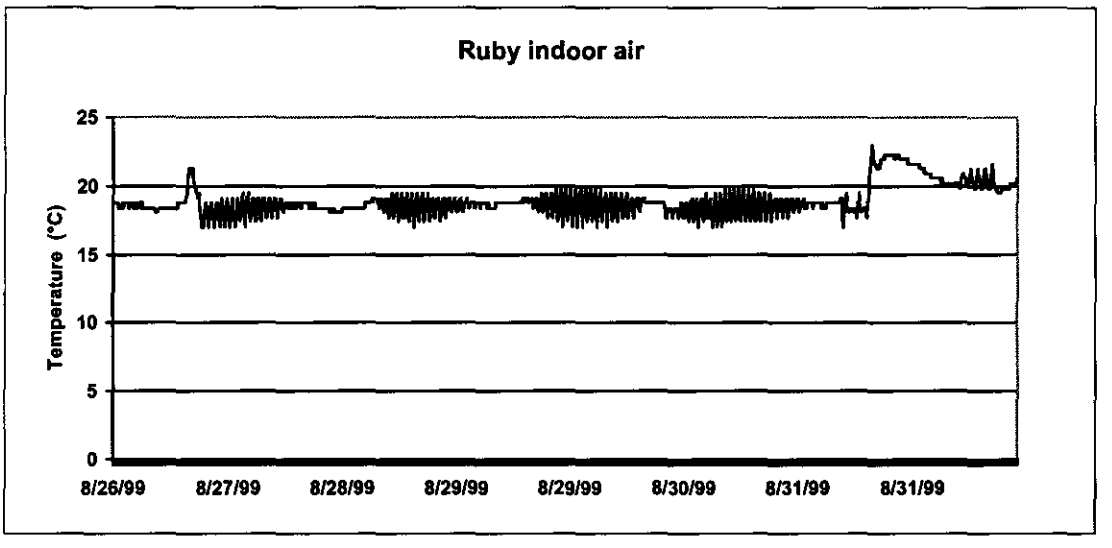


Figure 14: Ruby measured indoor air

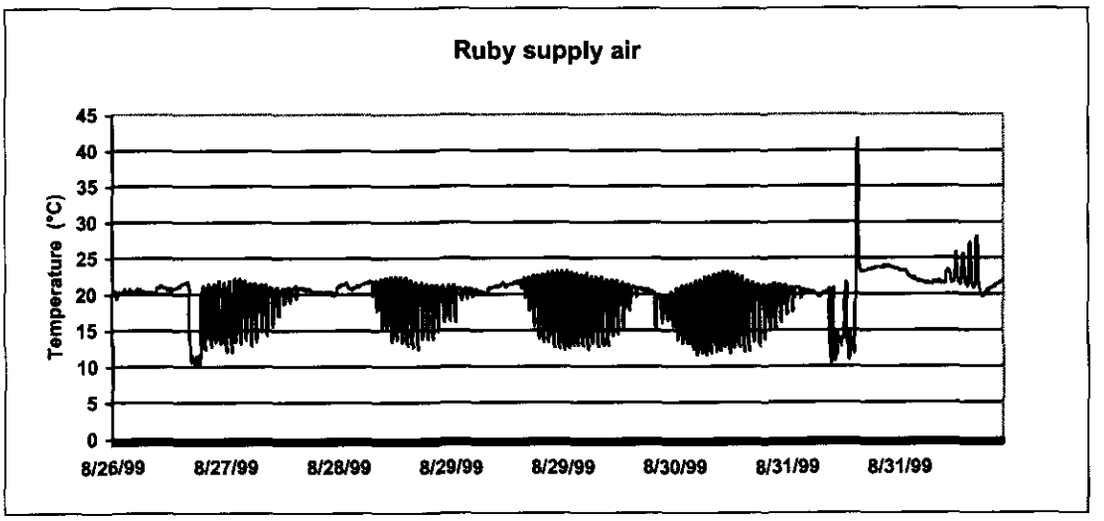


Figure 15: Ruby measured supply air

Appendix B

Energy Measurements

The electrical measurements were taken for the week of 26th August 1999 to 1st September 1999. This section shows the weeks electrical measured data.

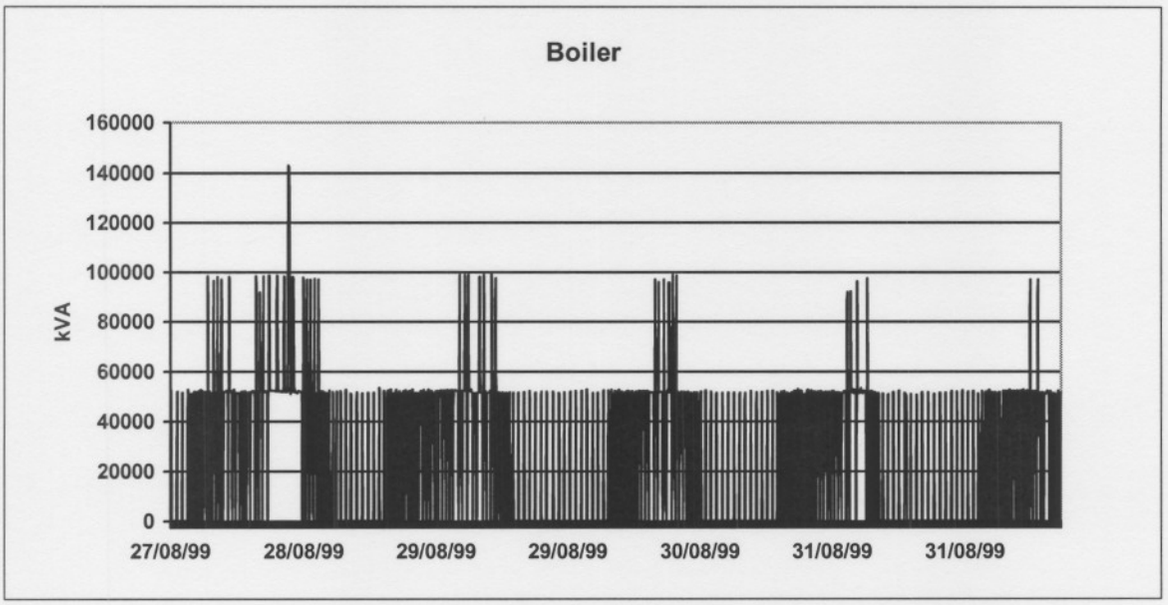


Figure 1: Boiler measured kVA

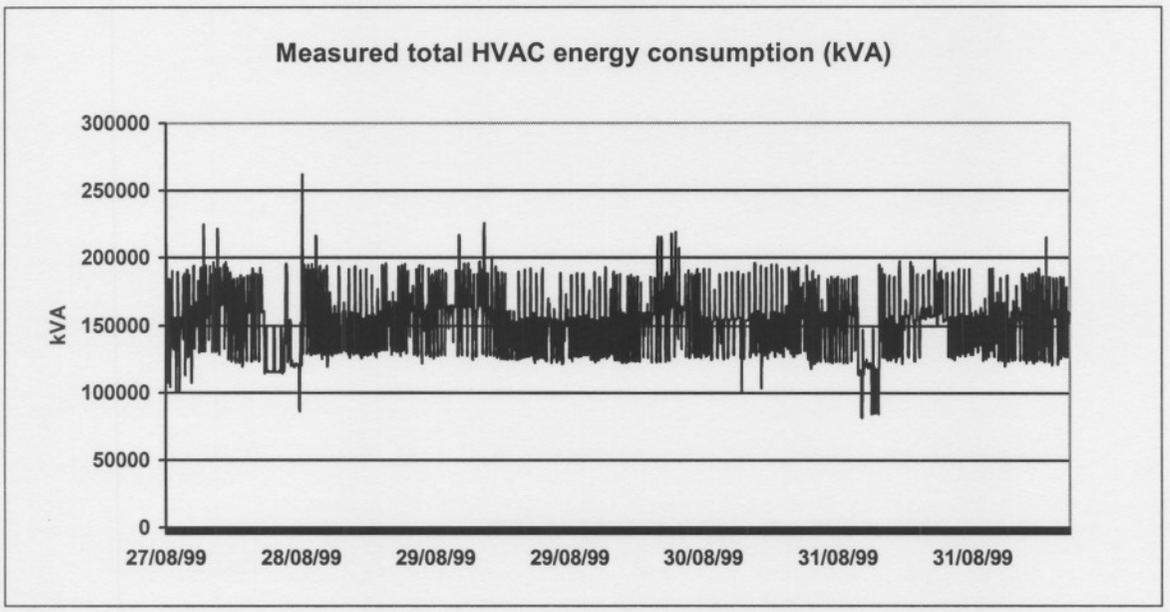


Figure 2: Total measured HVAC system kVA

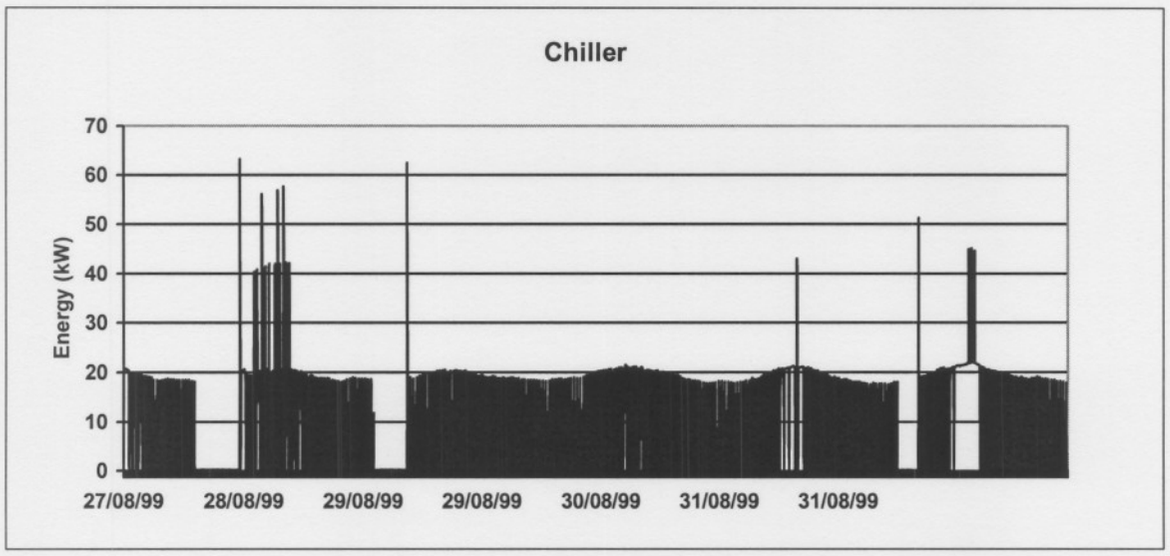


Figure 3: Measured chiller power consumption

Appendix C

Verification Results

The graphs of the verification study of QUICKcontrol are shown in this section. The output from QUICKcontrol is shown together with the measured data. Included is a summary of the supply and return temperatures of each zone, given in terms of the maximum error, average error and percentage of time that QUICKcontrol simulated the daily trend within 2 % of the measure data.

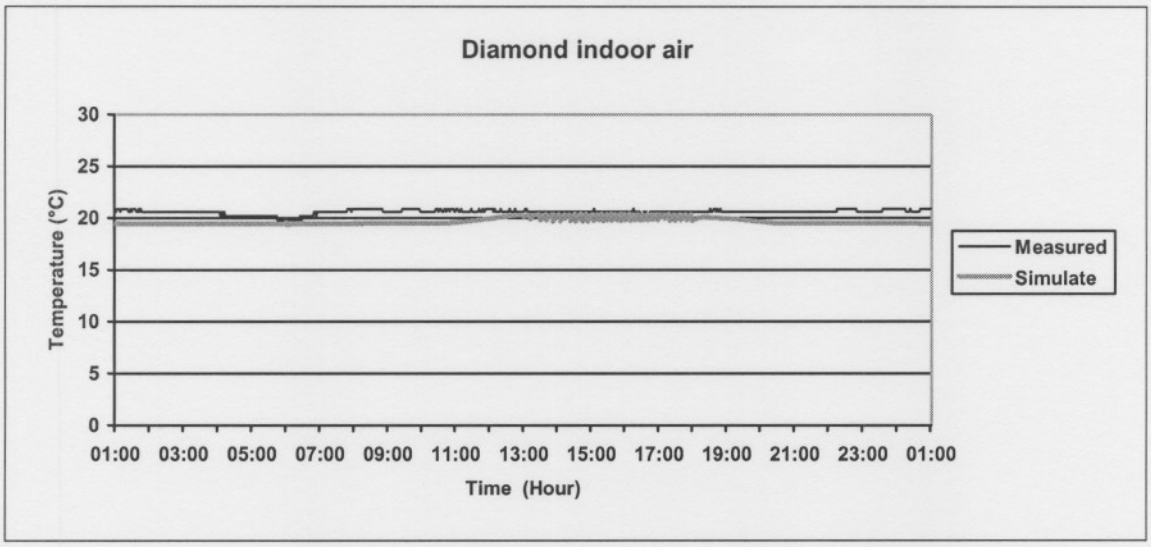


Figure 1: Diamond indoor air verification study

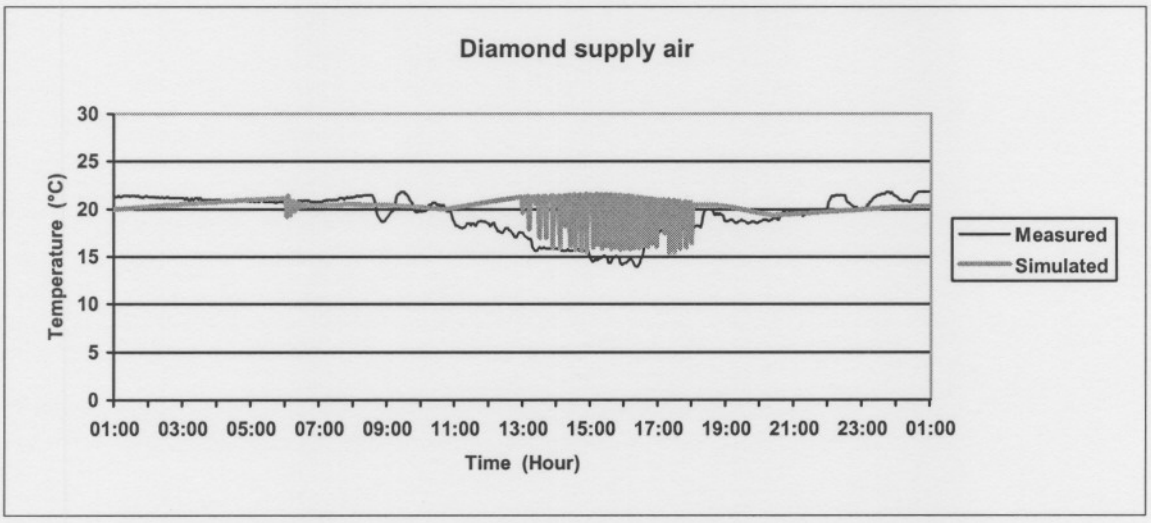


Figure 2: Diamond supply air verification study

	Max error (°C)	Average Error (°C)	% of time within 2 °C
Supply air	6.8	1.5	75
Indoor air	1.4	0.9	100

Table 1: Summary of Diamond verification results

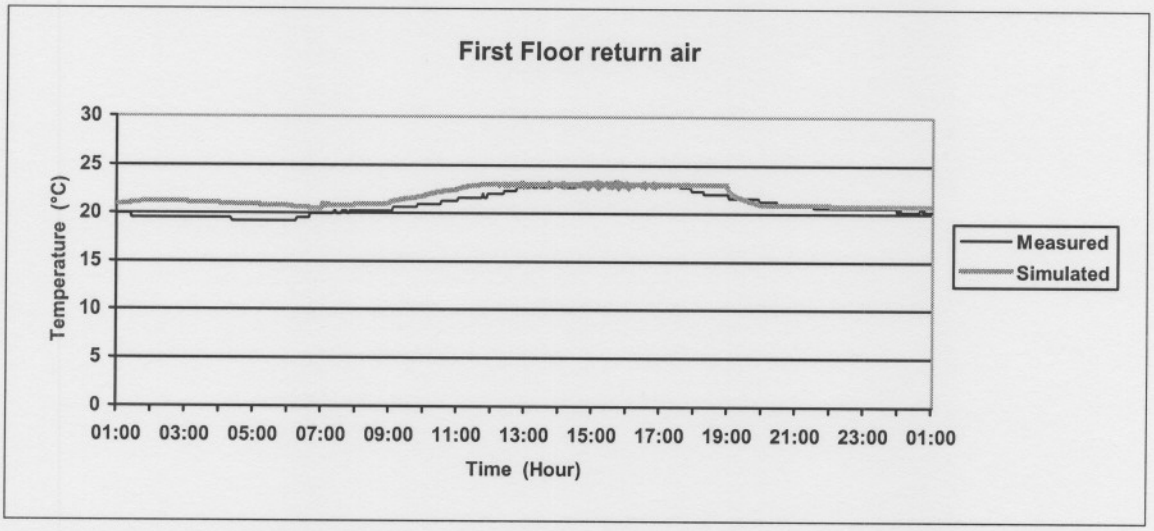


Figure 3: First Floor return air verification study

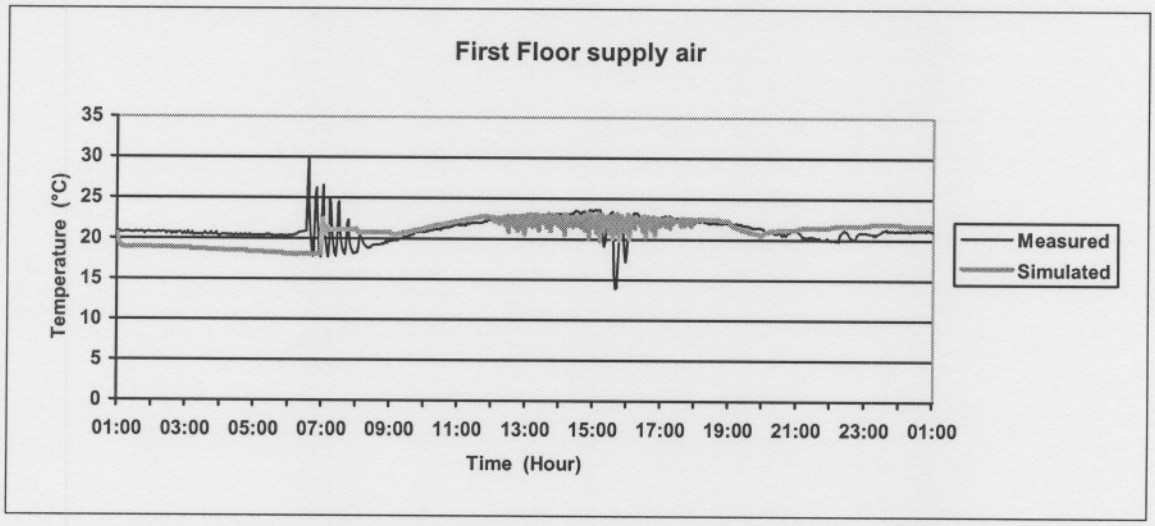


Figure 4: First Floor supply air verification study

	Max error (°C)	Average error (°C)	% of time within 2 °C
Supply air	15	1.4	81
Return air	2.4	0.6	100

Table 2: Summary of First floor verification results

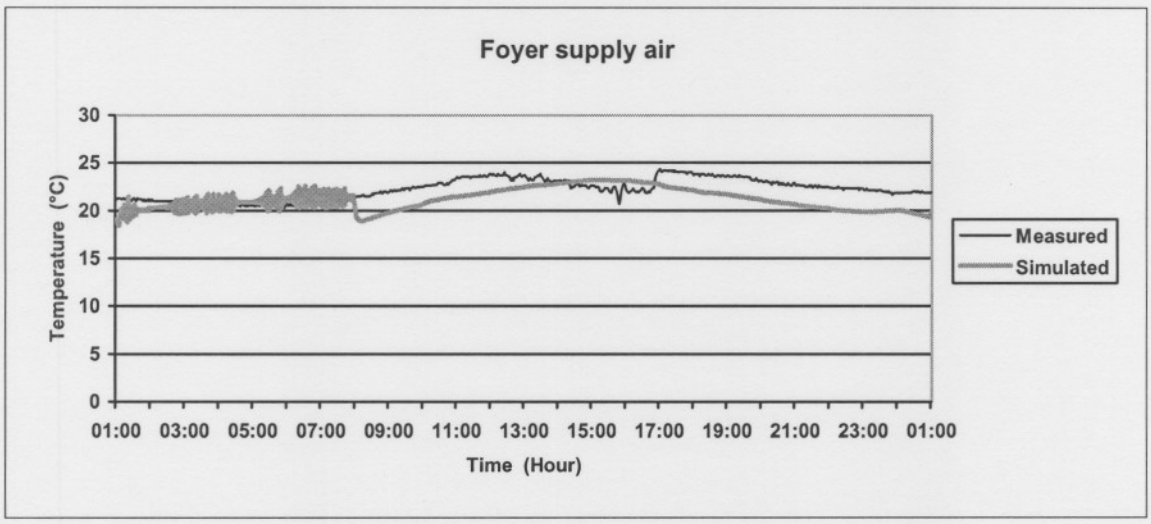


Figure 5: Foyer supply air verification study

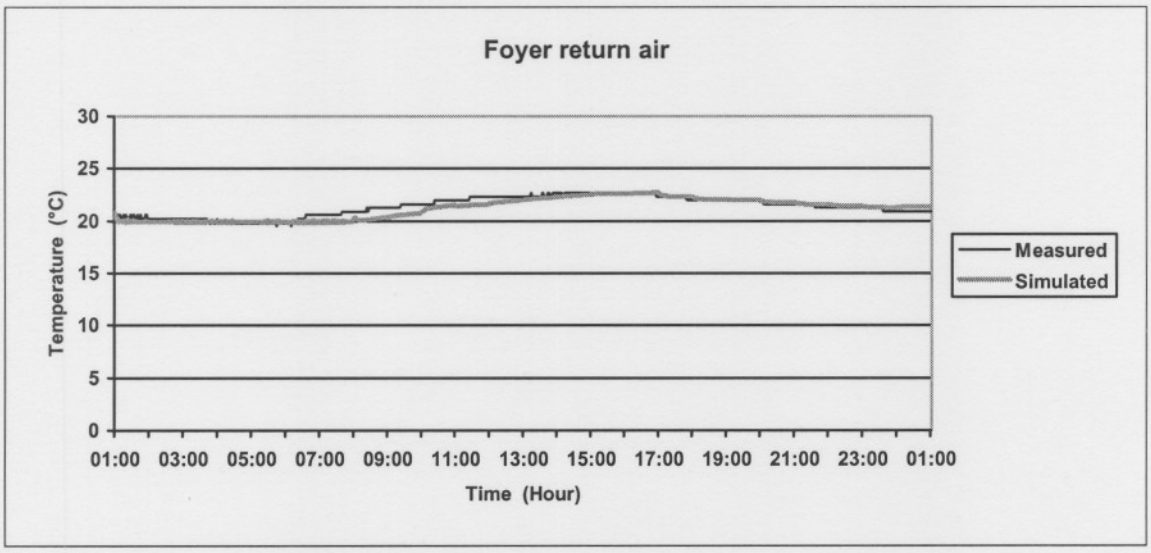


Figure 6: Foyer return air verification study

	Max error (°C)	Average error (°C)	% of time within 2 °C
Supply air	3.4	1.3	72
Return air	4.9	0.2	100

Table 3: Summary of First floor verification results

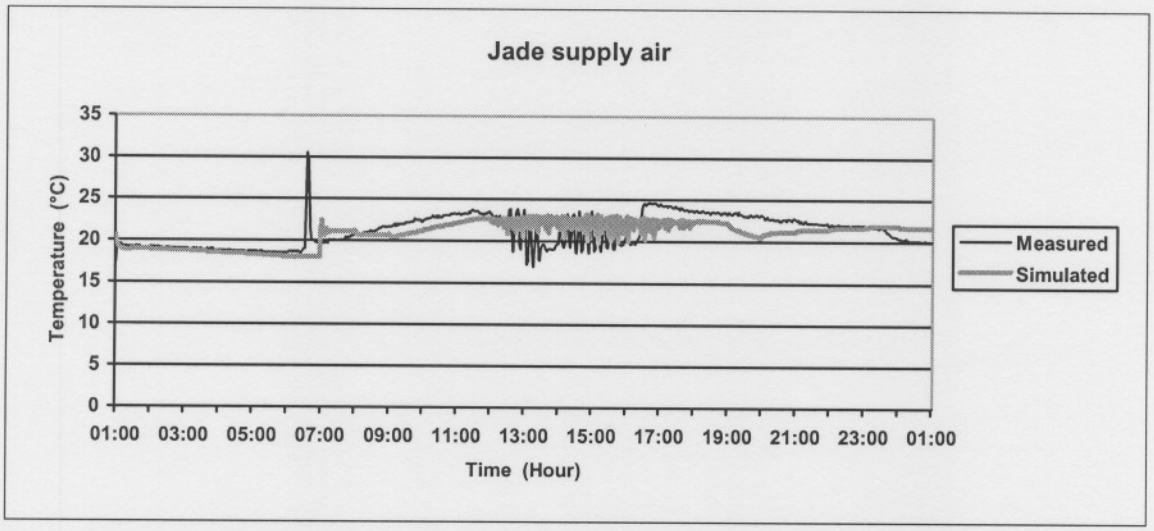


Figure 7: Jade supply air verification study

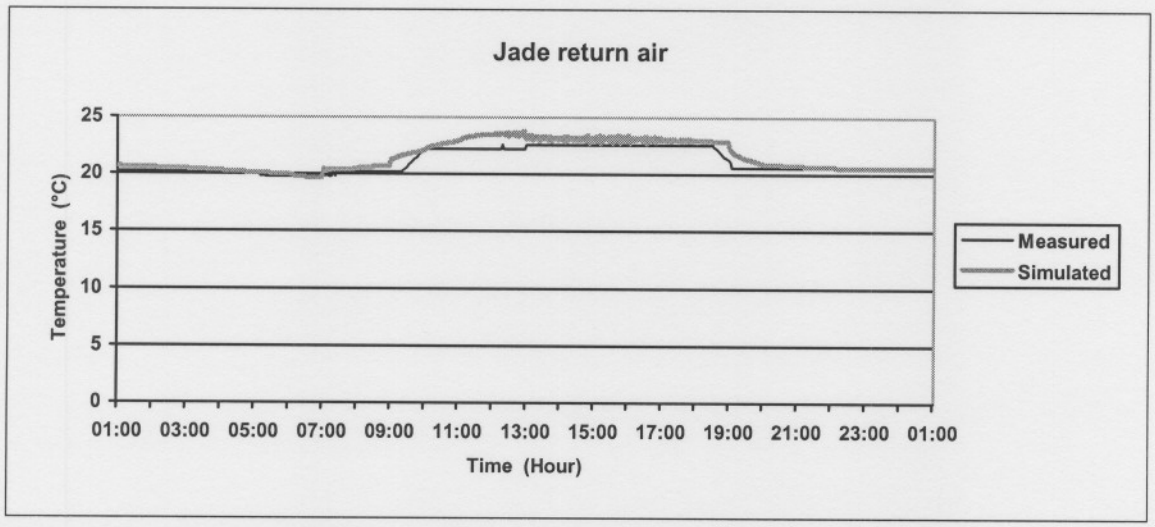


Figure 8: Jade return air verification study

	Max error (°C)	Average error (°C)	% of time within 2 °C
Supply air	12	1.7	88
Return air	1.5	0.4	100

Table 4: Summary of Jade verification results

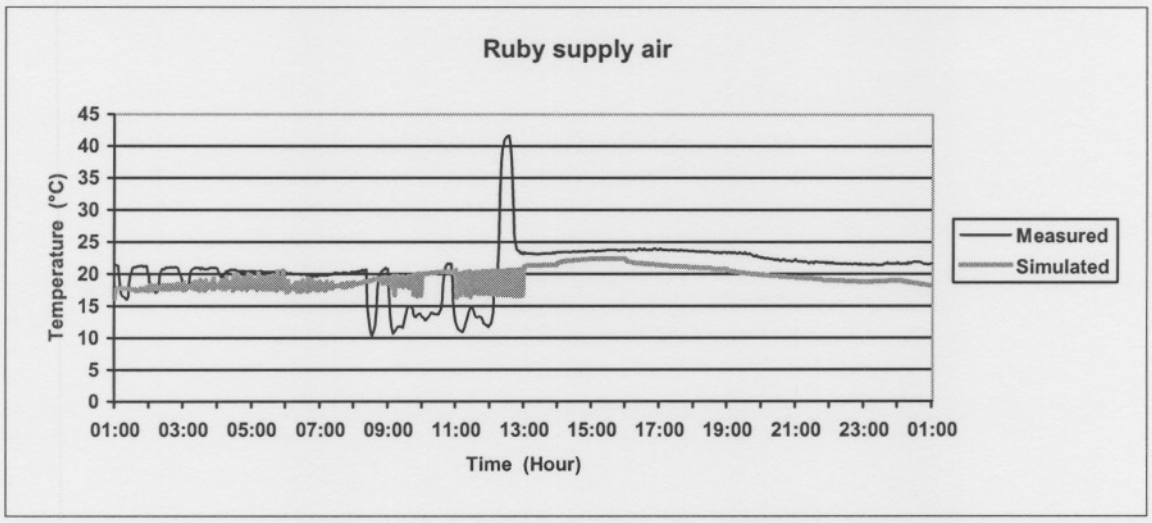


Figure 9: Ruby supply air verification study

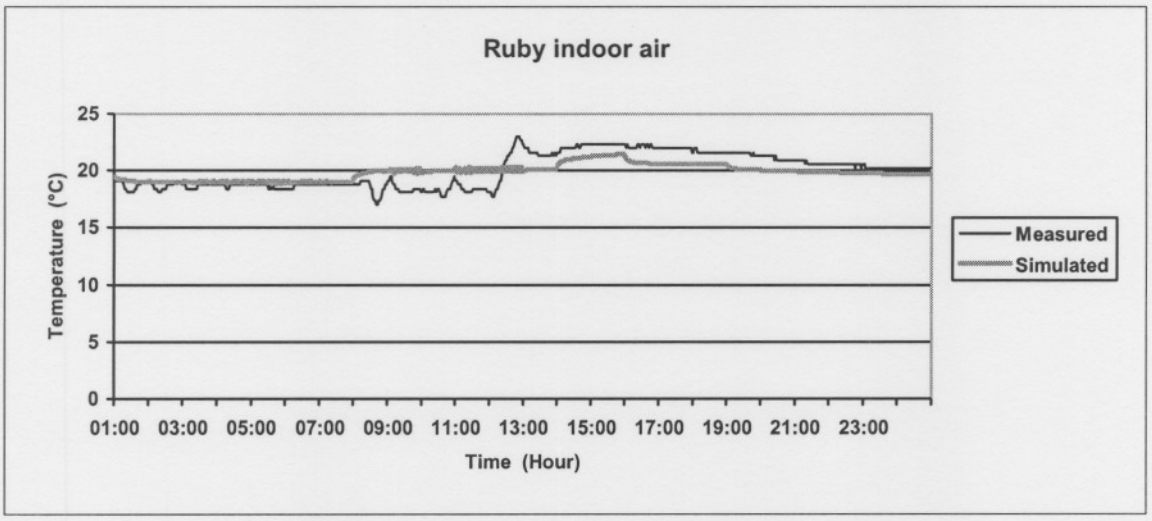


Figure 10: Ruby indoor air verification study

	Max error (°C)	Average error (°C)	% of time within 2 °C
Supply air	20	3.1	97
Return air	3	1	100

Table 5: Summary of Ruby verification results

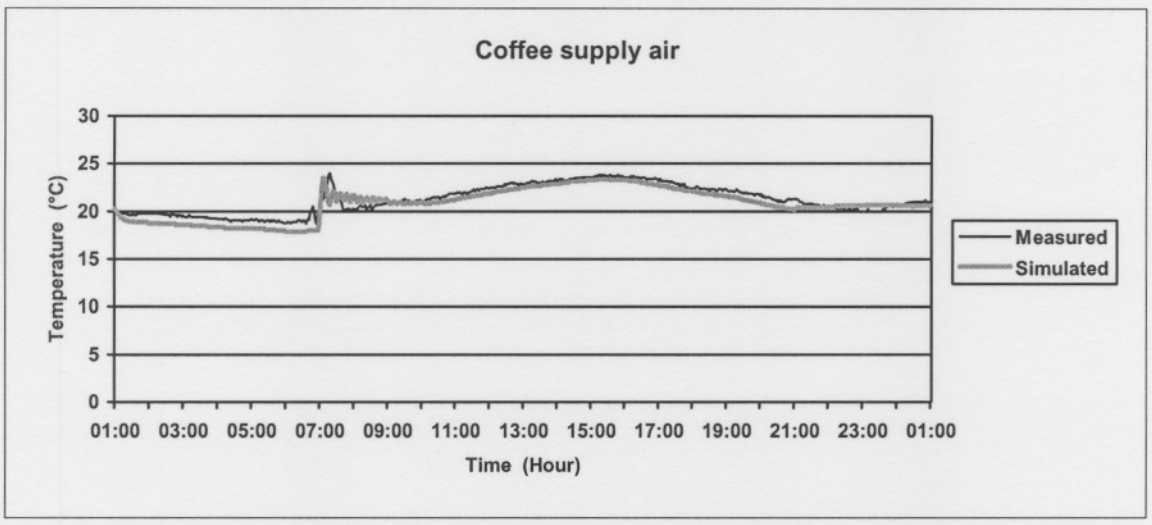


Figure 11: Coffee supply air verification study

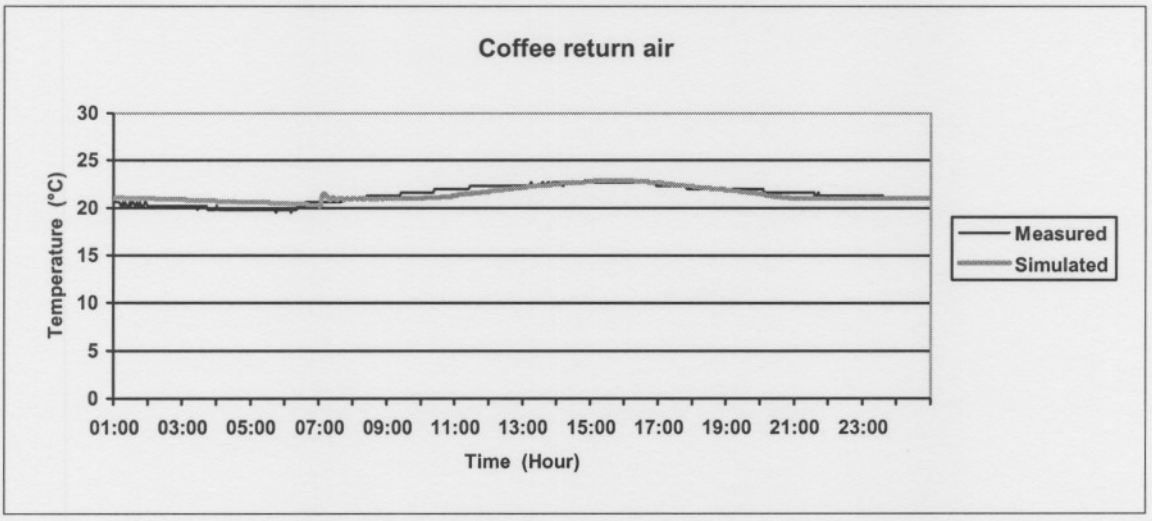


Figure 12: Coffee return air verification study

	Max error (°C)	Average error (°C)	% of time within 2 °C
Supply air	3	0.6	99
Return air	1	0.4	100

Table 6: Summary of Coffee verification results

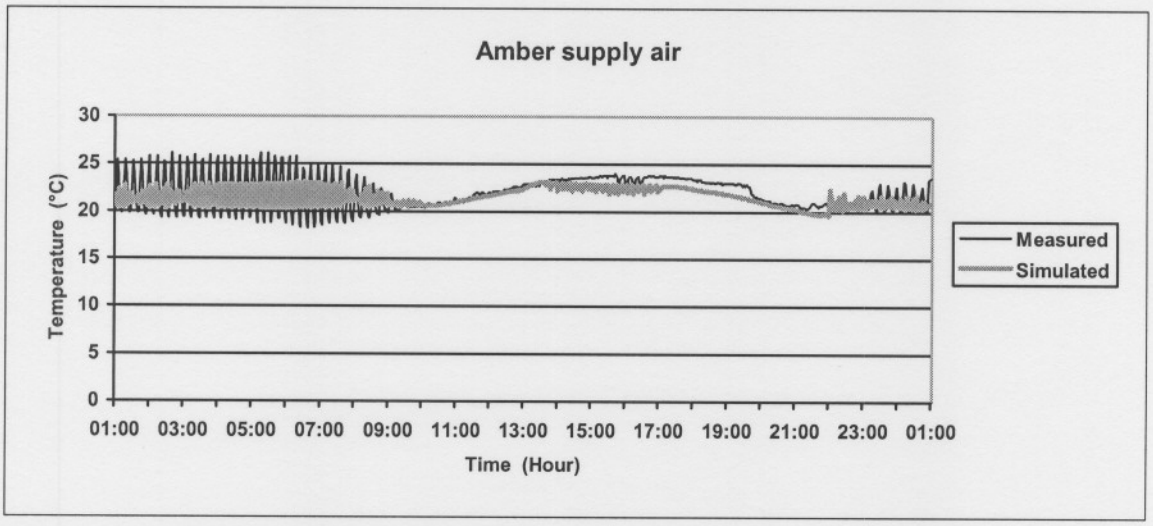


Figure 13: Amber supply air verification study

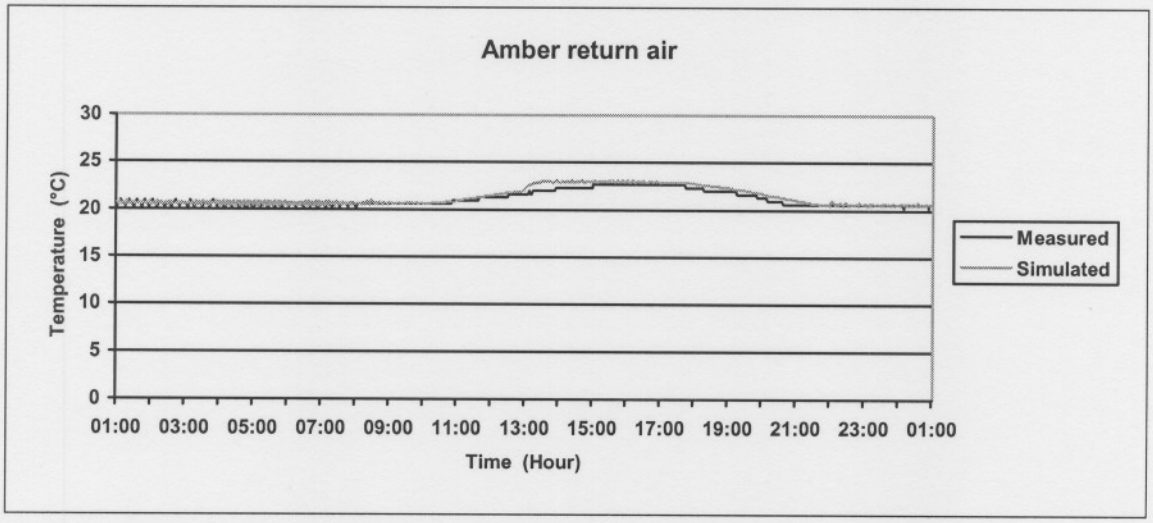


Figure 14: Amber return air verification study

	Max error (°C)	Average error (°C)	% of time within 2 °C
Supply air	6.3	1.6	75
Return air	1.8	0.6	100

Table 7: Summary of Amber verification results

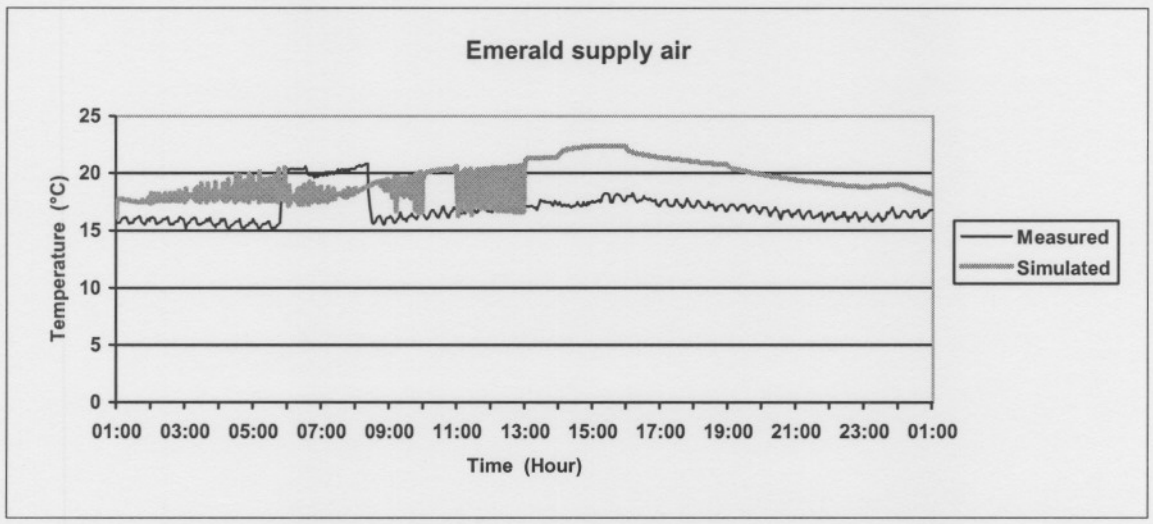


Figure 15: Emerald supply air verification study

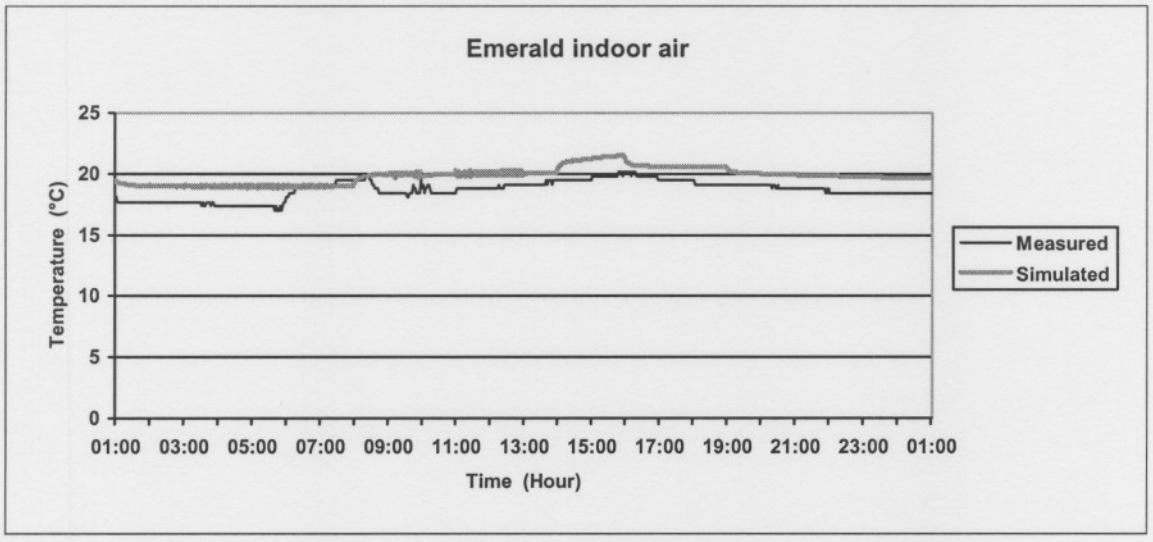


Figure 16: Emerald indoor air verification study

	Max error (°C)	Average error (°C)	% of time within 2 °C
Supply air	5.4	2.8	27
Return air	2.1	1.1	100

Table 8: Summary of Emerald verification results

Appendix D

QEC verification results

In this appendix the temperature output of the new tool is displayed with the weighted measured data and QUICKcontrol output, in order to present the verification study of the new program.

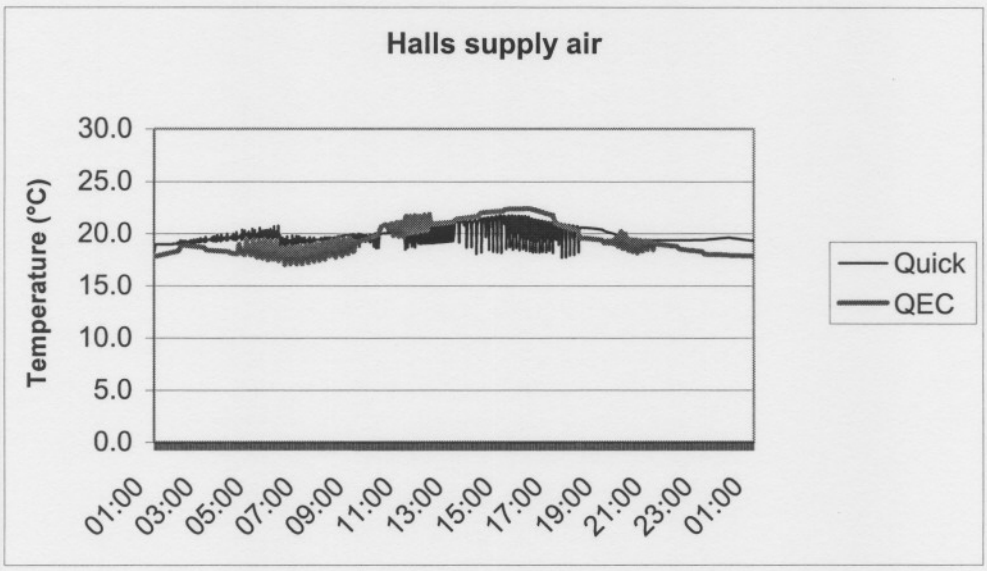


Figure 1: Halls supply air, QEC vs. QUICKcontrol

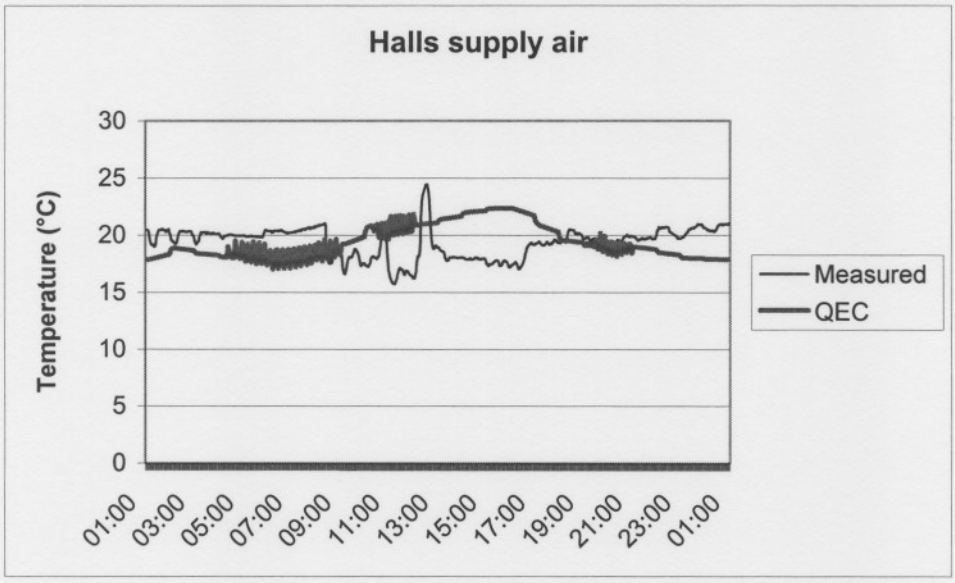


Figure 2: Halls supply air, QEC vs. measured data

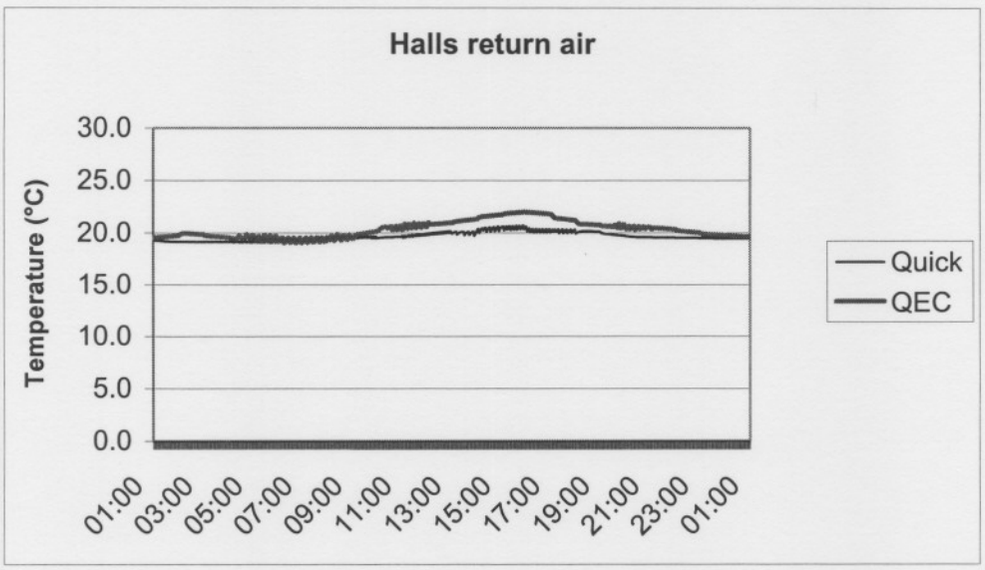


Figure 3: Halls return air, QEC vs. QUICKcontrol

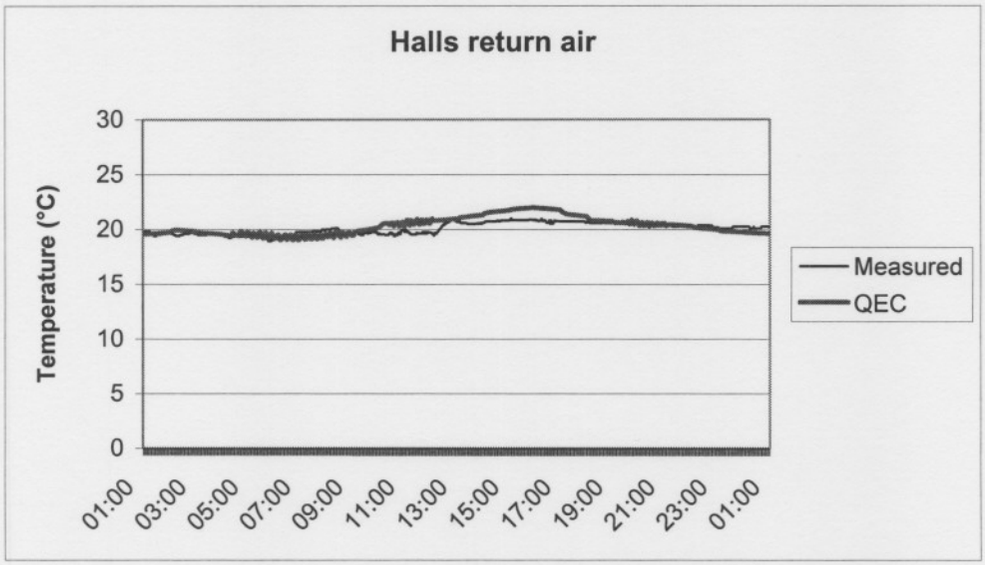


Figure 4: Halls return air, QEC vs. measured data

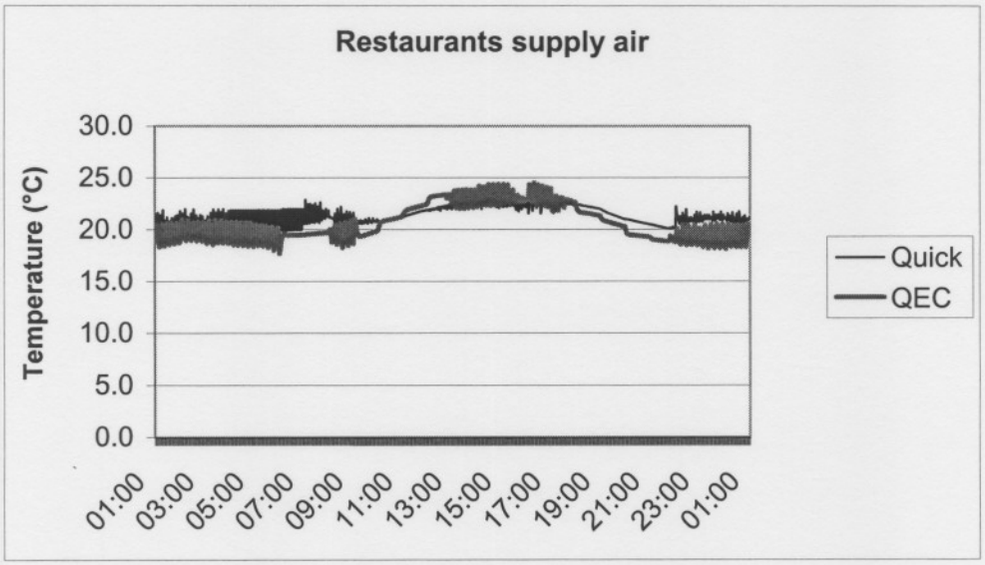


Figure 5: Restaurants supply air, QEC vs. QUICKcontrol

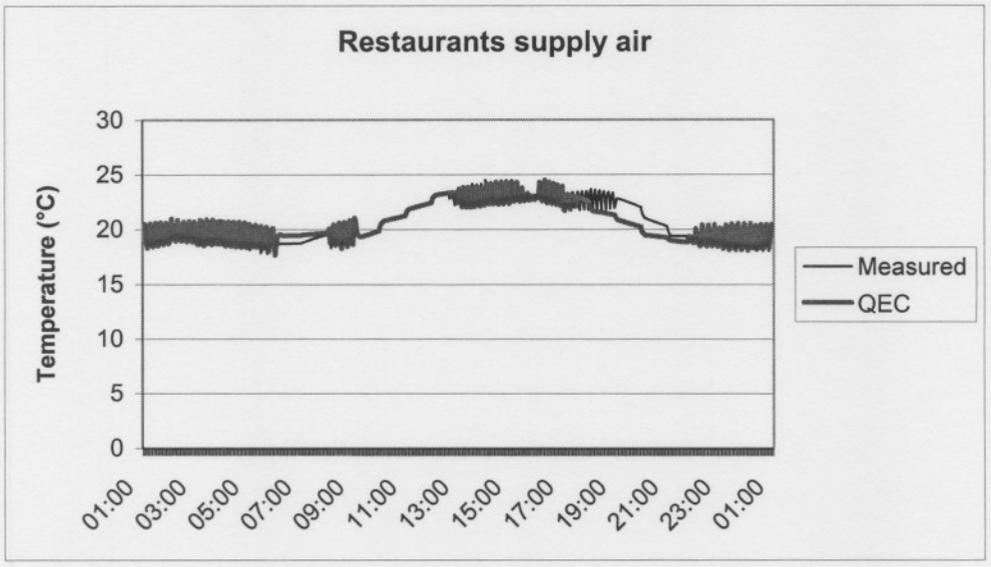


Figure 6: Restaurants supply air, QEC vs. measured data

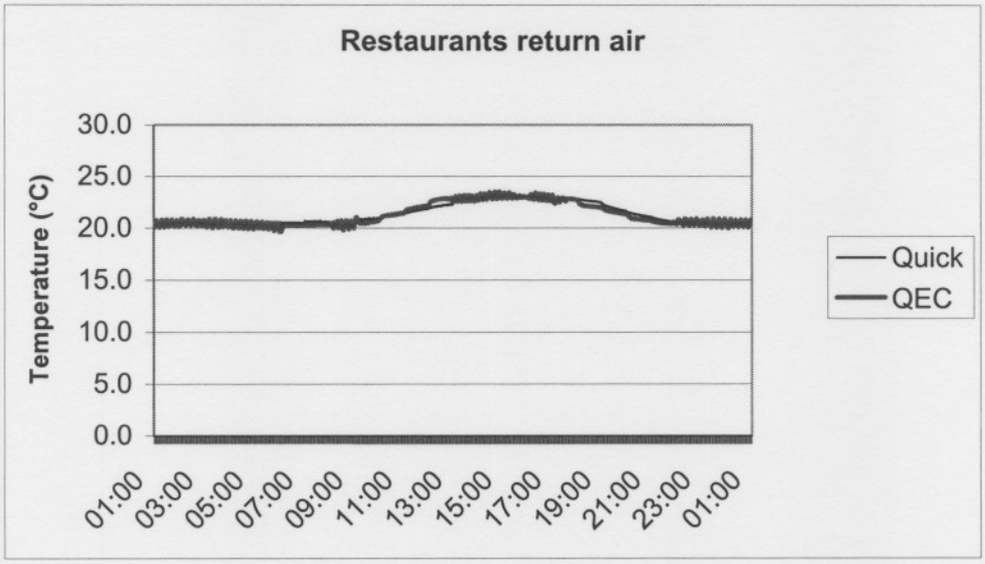


Figure 7: Restaurants return air, QEC vs. QUICKcontrol

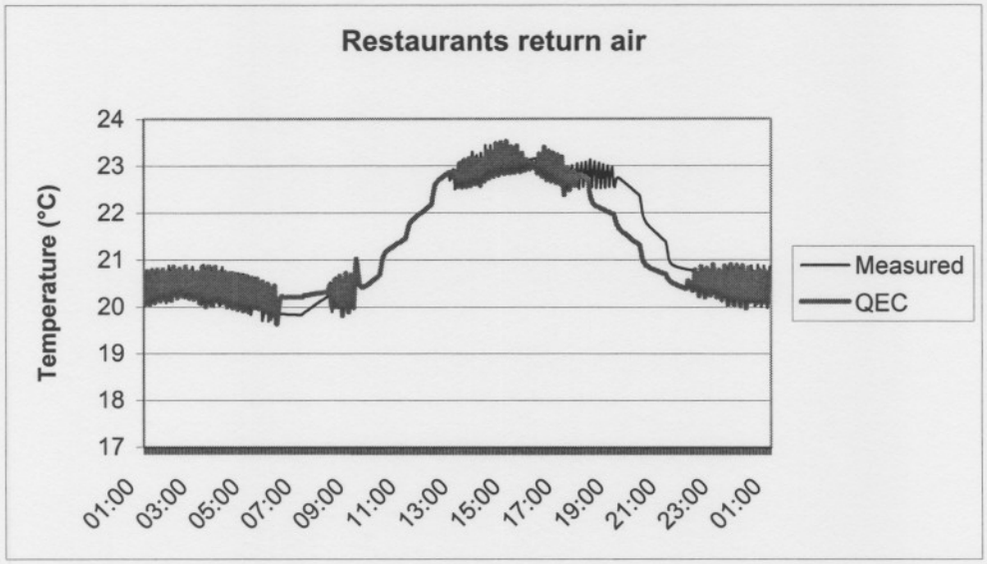


Figure 8: Restaurants return air, QEC vs. measured data

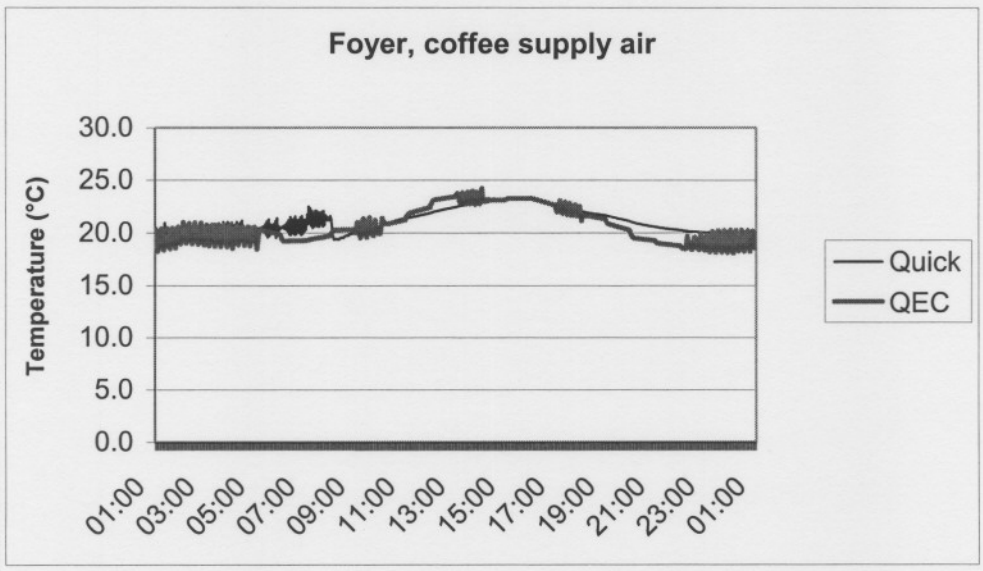


Figure 9: Foyer, coffee supply, QEC vs. QUICKcontrol

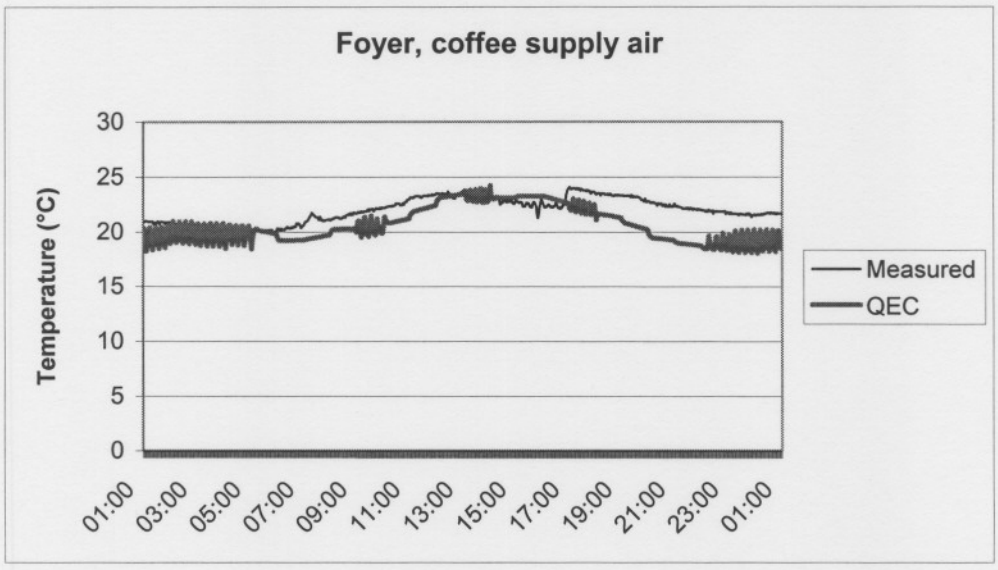


Figure 10: Foyer, coffee supply, QEC vs. measured data

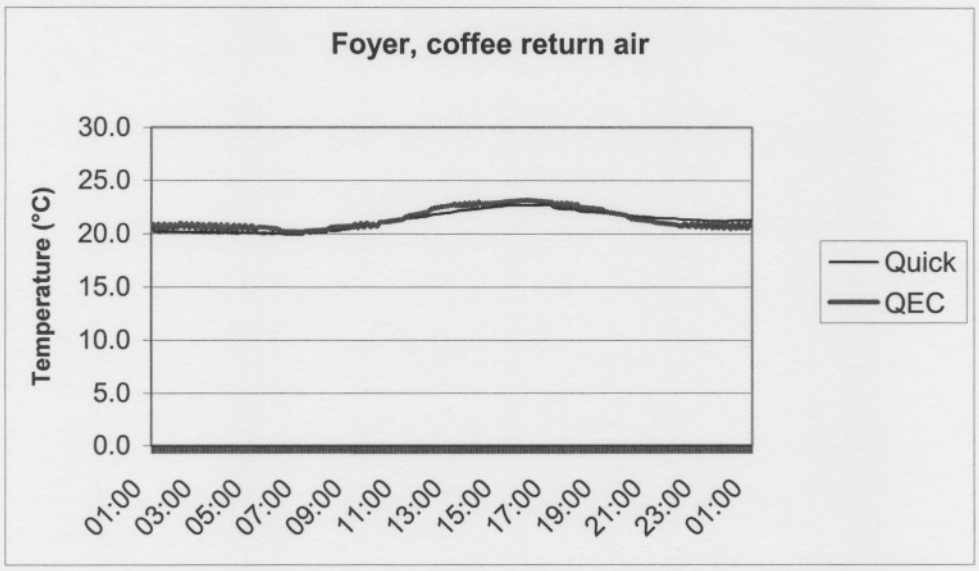


Figure 11: Foyer, coffee return, QEC vs. QUICKcontrol

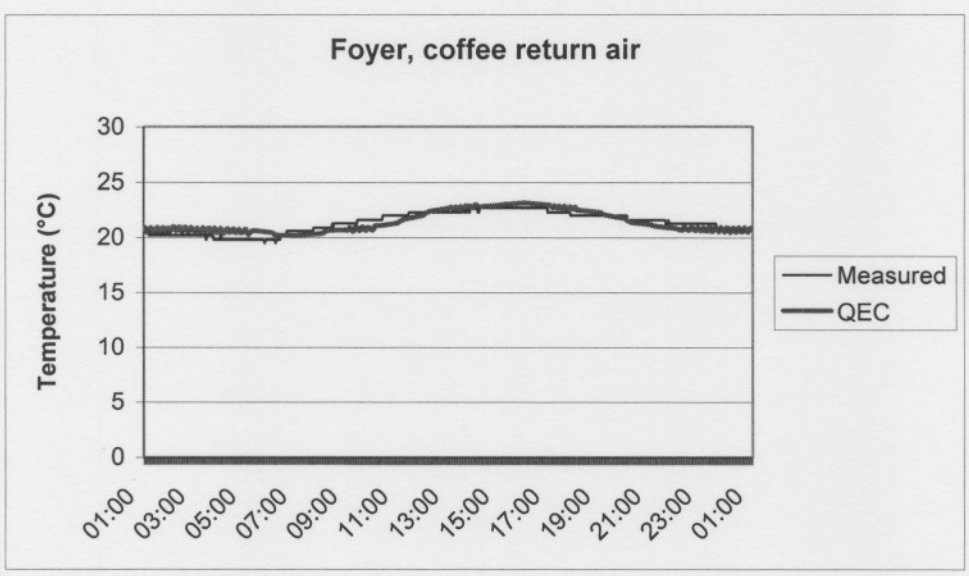


Figure 12: Foyer, coffee return, QEC vs. measured data

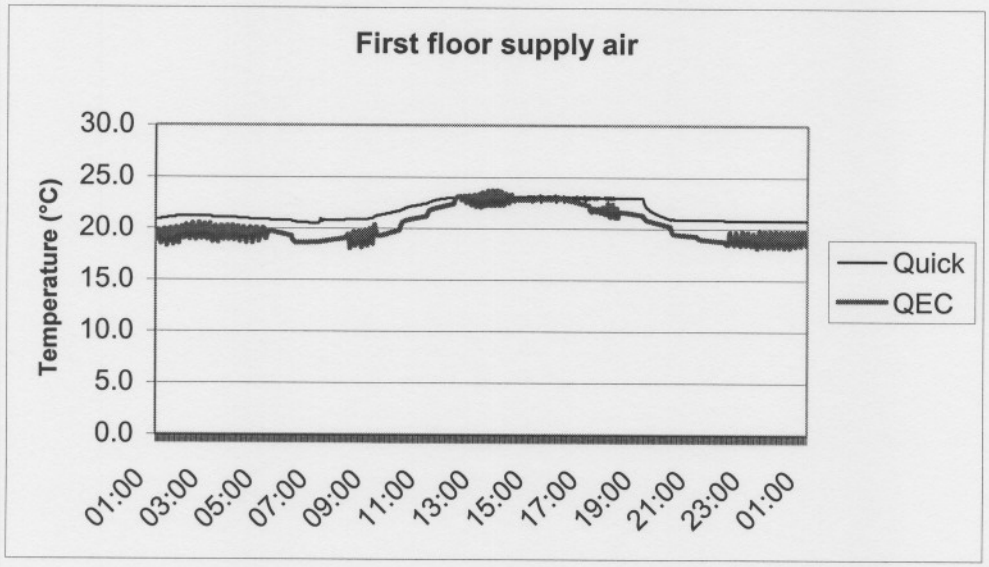


Figure 13: First floor supply air, QEC vs. QUICKcontrol

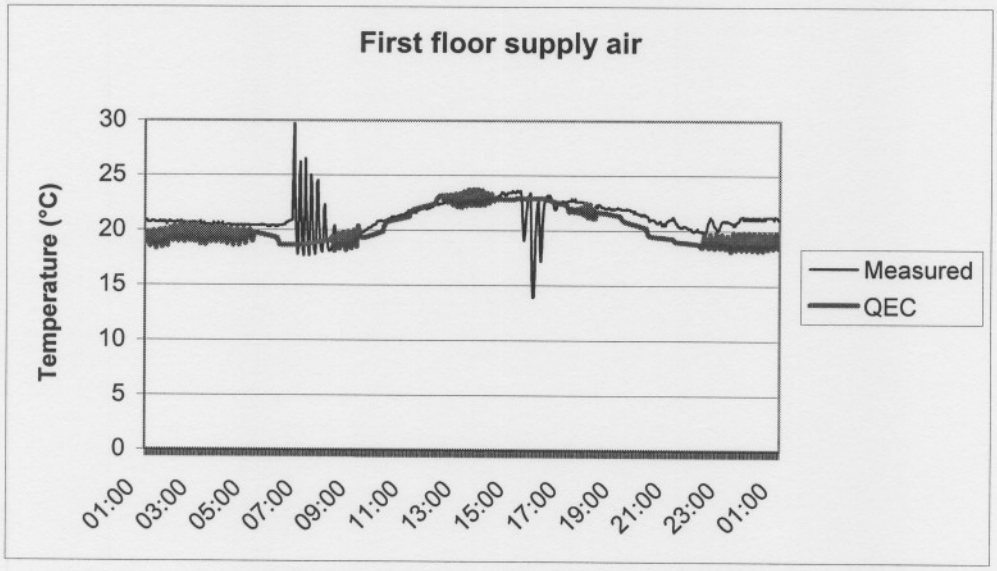


Figure 14: First floor supply air, QEC vs. measured data

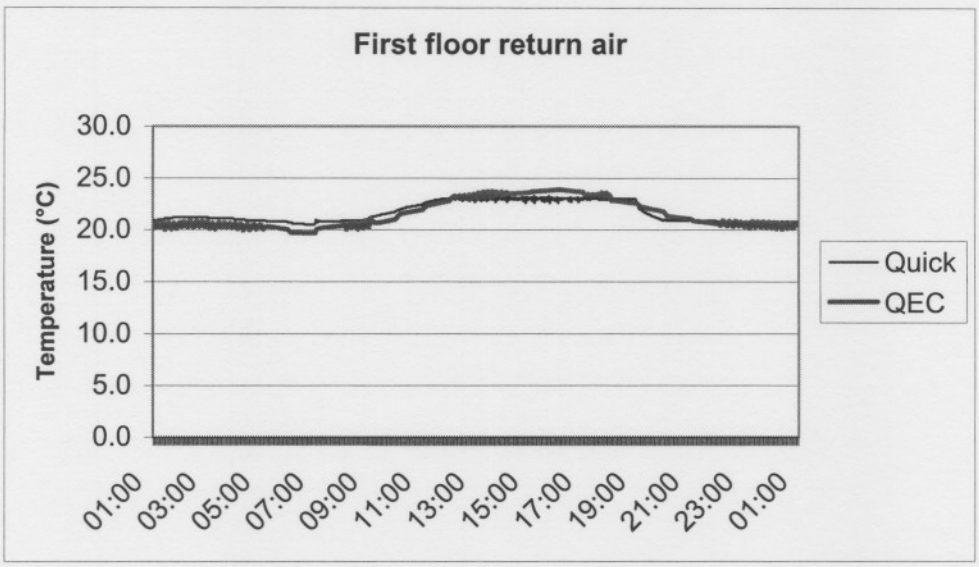


Figure 15: First floor return air, QEC vs. QUICKcontrol

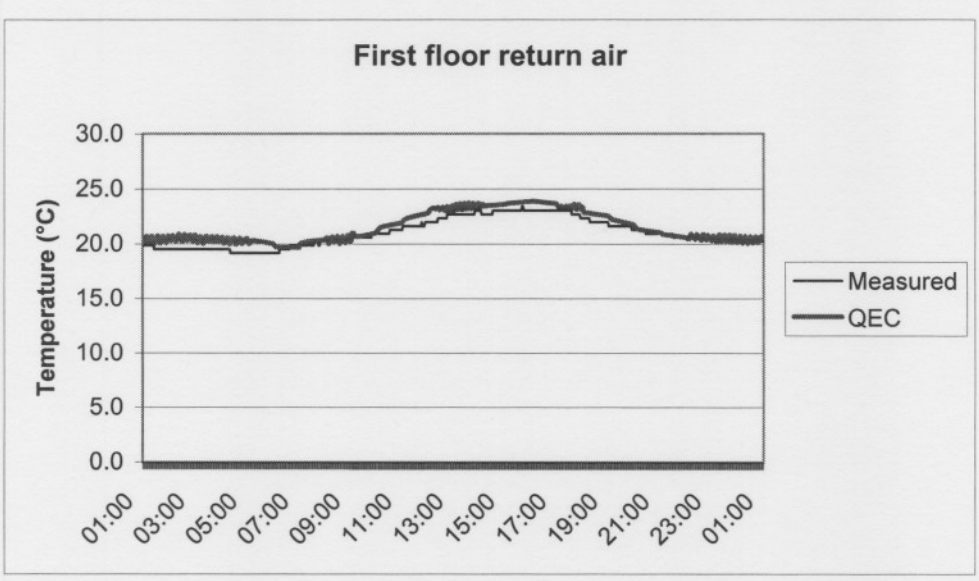


Figure 16: First floor return air, QEC vs. measured data

Appendix E

ETB Input screen prints

In this appendix the screen prints of ETB-Input is shown.

The figure below is the first screen of *ETB-Input*. A user has a choice of three options, namely to start a new project, to enter the zone data, or to enter the HVAC system information.

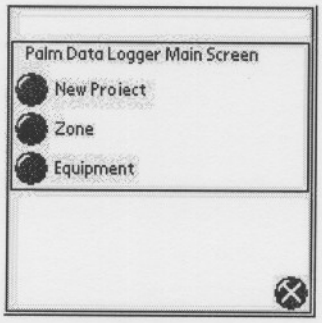


Figure 1: ETB-Input main interface

By starting a project all the components that has been logged in *ETB-Input* are deleted and the components of a new project can then be added.

To add an HVAC component the EQUIPMENT button is selected. The user must then select between the water circuit components and the air circuit component. When a specific component is selected from the list, all of the components of this type are show in another list. The user can also add, edit, copy, or delete a component of the chosen type.

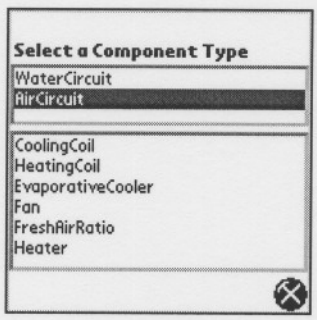


Figure 2: HVAC system group selection



Figure 3: Add, edit, delete, copy component interface

HVAC SYSTEM COMPONENTS

All of the HVAC system components available in *ETB-Input* is shown in this section.

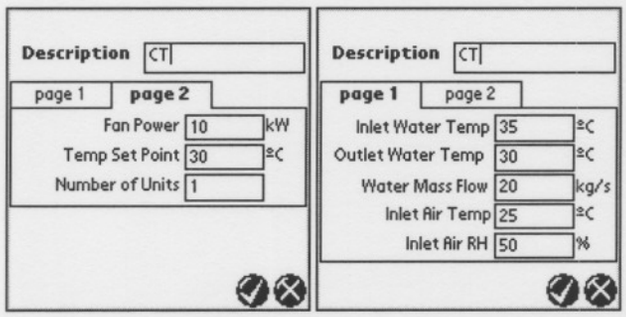


Figure 4: Cooling tower

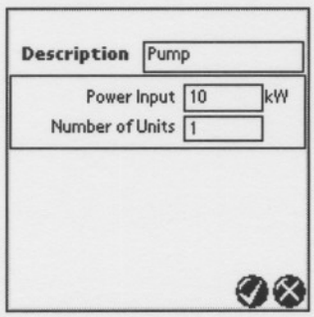


Figure 5: Pump

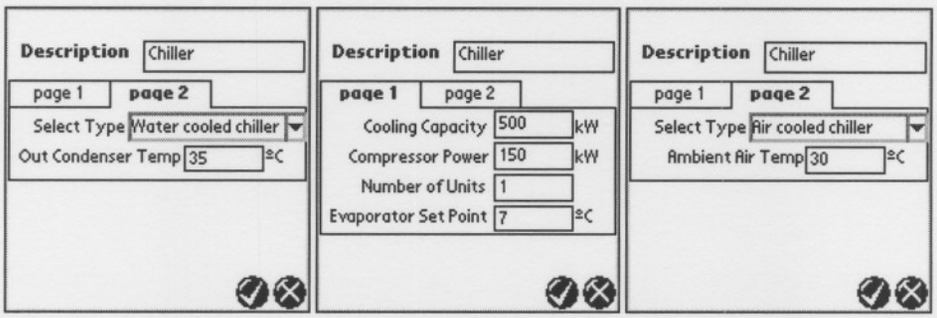


Figure 6: Chiller

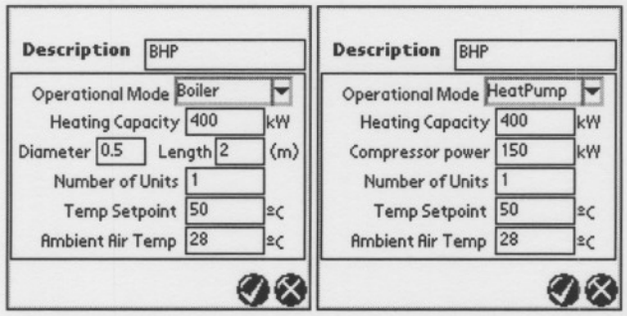


Figure 7: Heat pump/Boiler

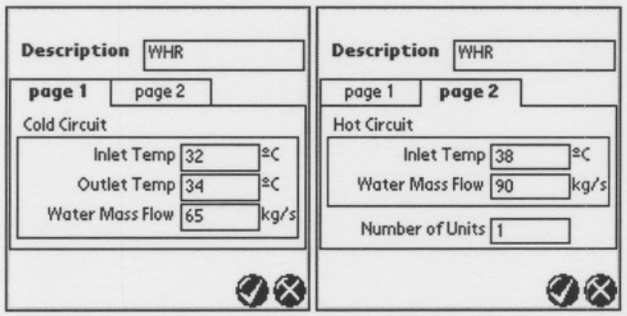


Figure 8: Water heat recovery

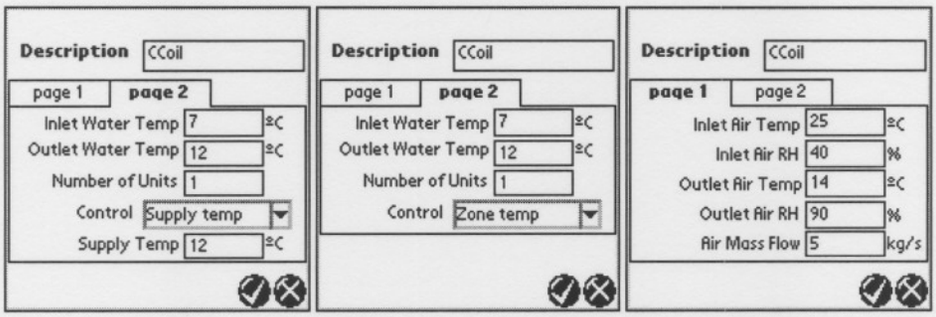


Figure 9: Cooling coil

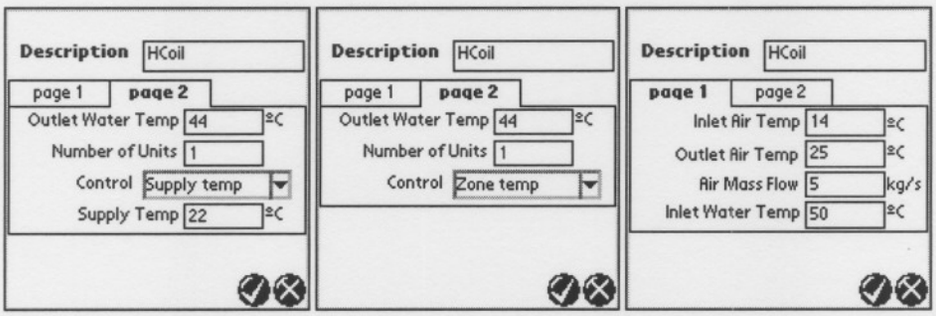


Figure 10: Heating coil

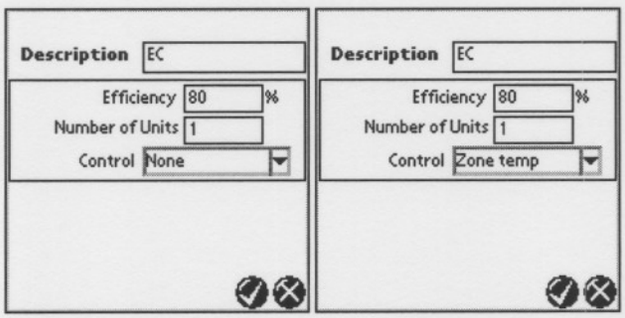


Figure 11: Evaporative cooler

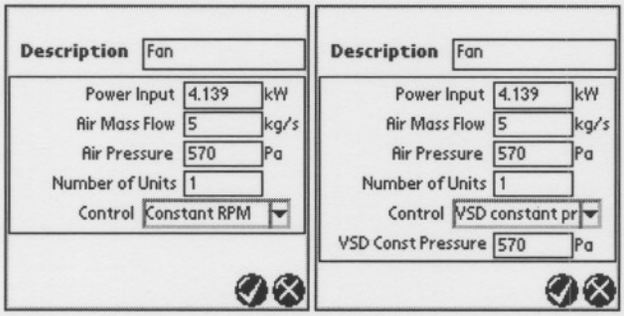


Figure 12: Fan

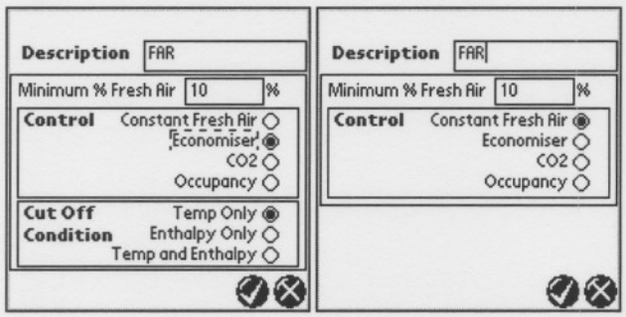


Figure 13: Fresh air ratio

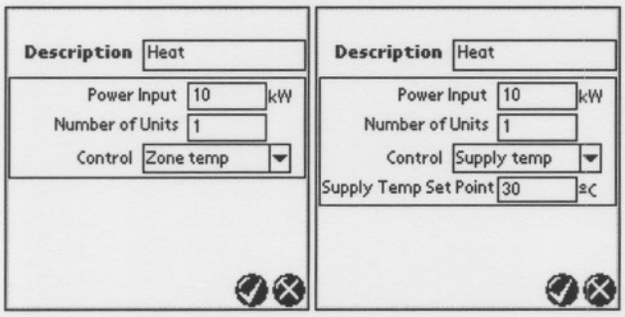


Figure 14: Heater

Zone

If the user selects the zone input option from the main selection screen, a list of all the zones in the project is displayed. The user then has the option to add a new zone, or edit, delete or copy an existing zone. These screen prints are shown below. The information required for a zone can is divided into five groups, namely Description, Dimensions, Structure, Internal heat generation and Control.

The zone main selection and management interfaces are shown below.



Figure 15: Zone management interface

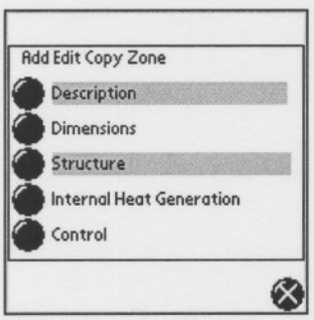


Figure 16: Zone information selection interface



Figure 17: Zone dimenstions input

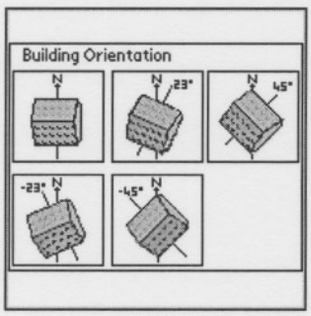


Figure 18: Zone orientation selection

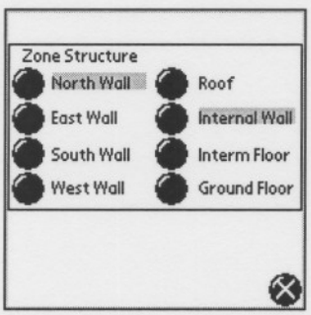


Figure 19: Zone structural element input selection

For each structural element, the user must enter certain information. Some of the information that is required is dependant on other information. For example, if no window is present in the wall, then the window type option is not given. An example for the north wall is shown below.

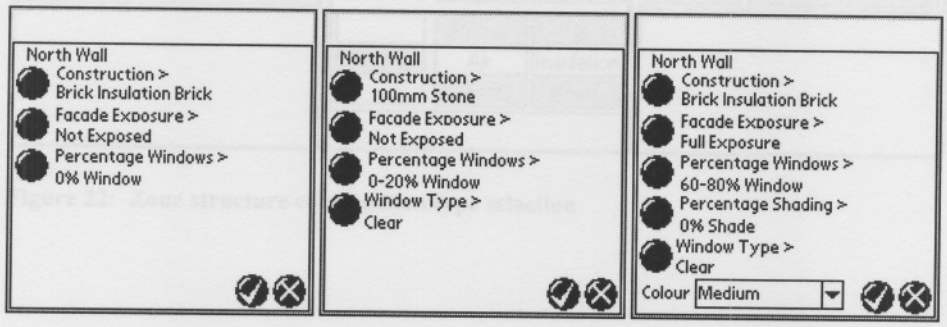


Figure 20: North wall information input

Many of the inputs required from the user are shown as a graphical list from which the correct option must be chosen. These are shown below.

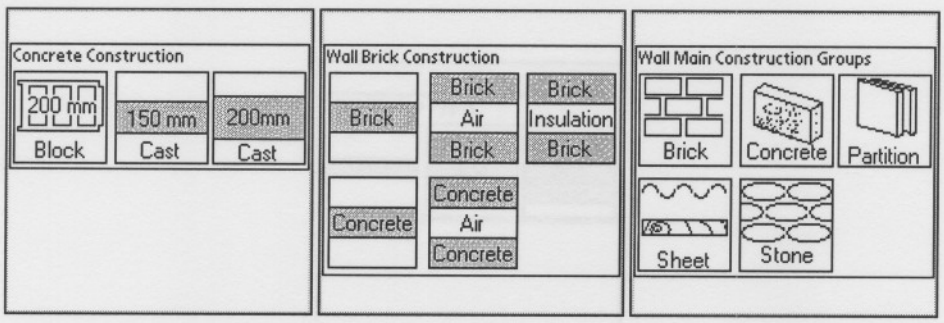


Figure 21: Zone structure construction type selection

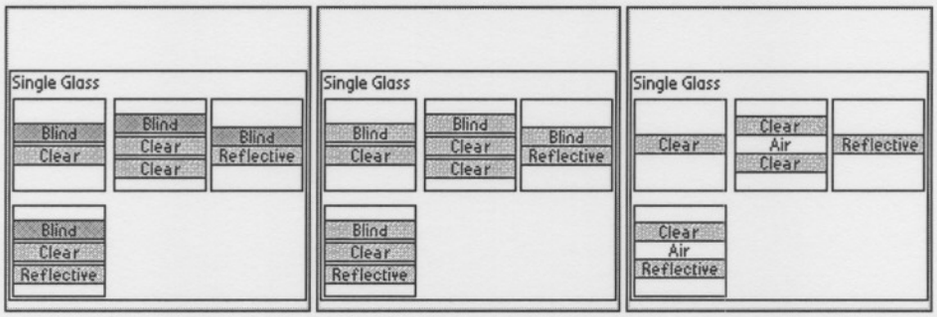


Figure 25: Window construction selection

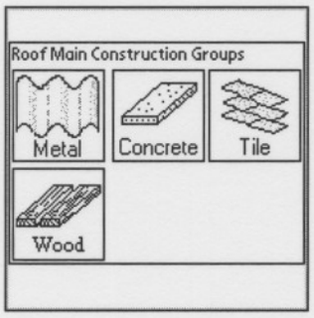


Figure 26: Roof main construction type

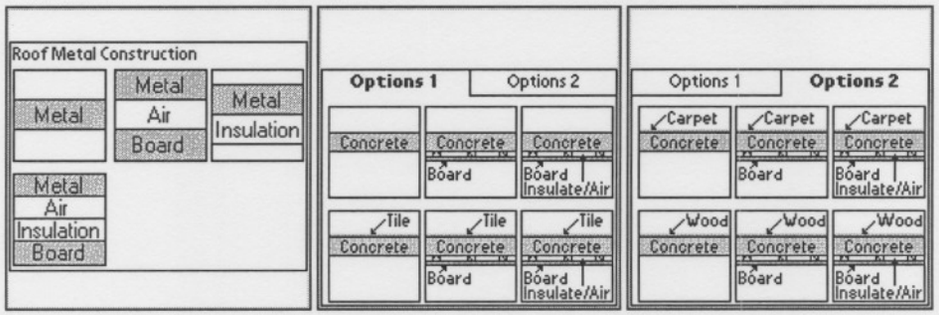


Figure 27: Roof metal and concrete construction selection

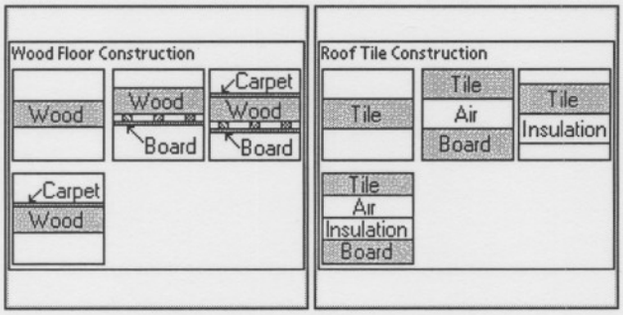


Figure 28: Roof wood and tile construction selection

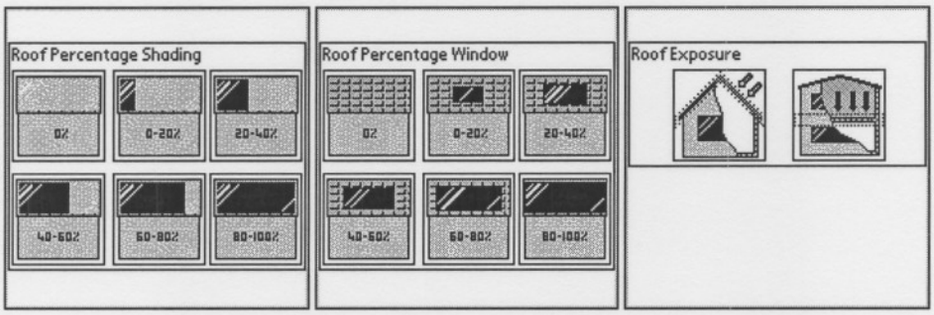


Figure 29: Roof shading, percentage window and exposure selection



Figure 30: Ground floor exposure selection

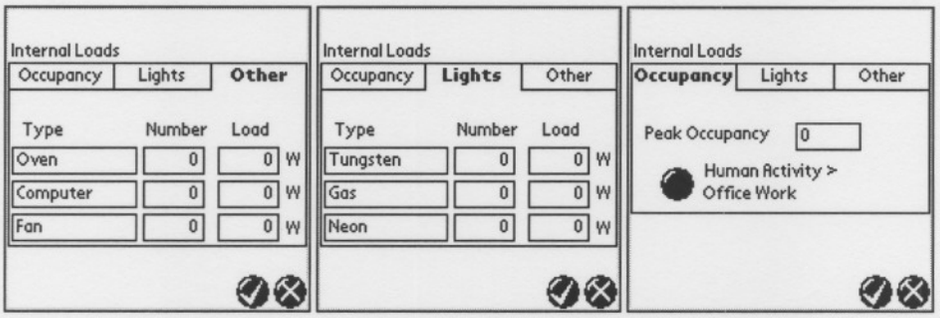


Figure 31: Internal heat generation input interface



Figure 32: Zone control input interface

Appendix F

ETB-Simulate screen prints

The screen prints of ETB-Simulate are shown in this appendix. A brief description of the various interfaces is also given.

Introduction

To execute the simulation tool click on the BUILDING SIMULATION button on the *ETB* main interface. The main *ETB* interface can be seen in the following figure:

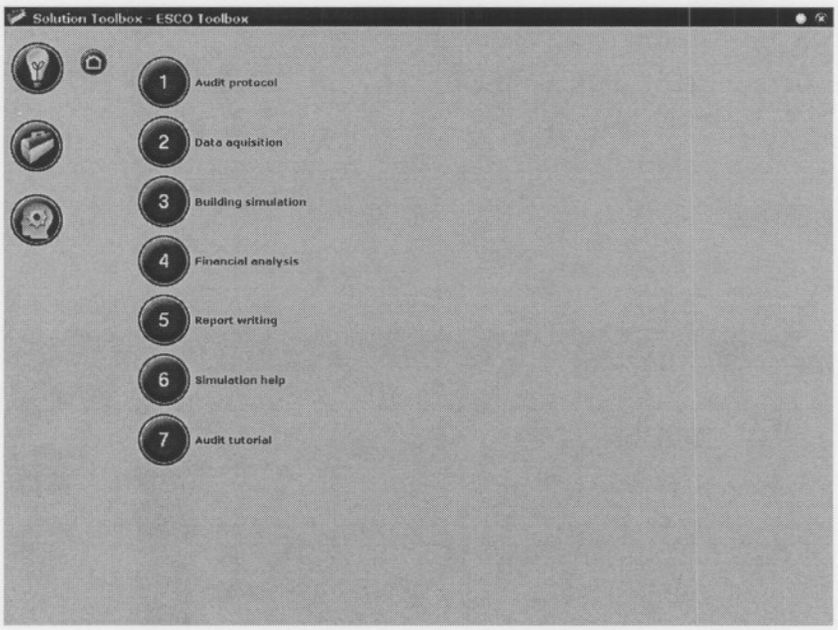


Figure 1: ESCO Toolbox main interface

The main screen of *ETB-Simulate* is shown below. This screen is activated when the user selects the BUILDING SIMULATION BUTTON.

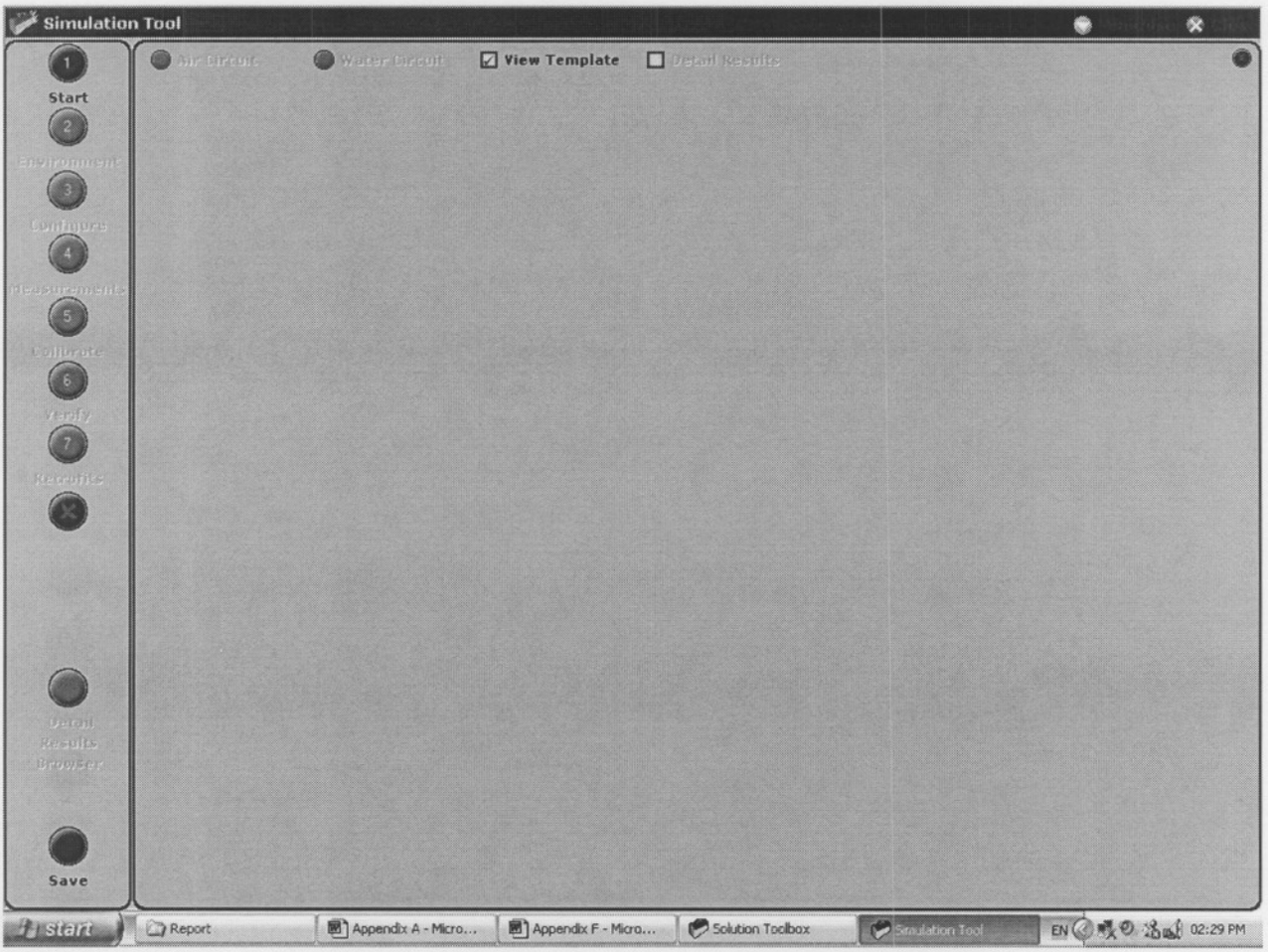


Figure 2: ETB-Simulate main screen

Start

To start a new project, or work on an existing project, click on the START button on the main simulation interface. The following figure displays the start interface of the simulation tool:

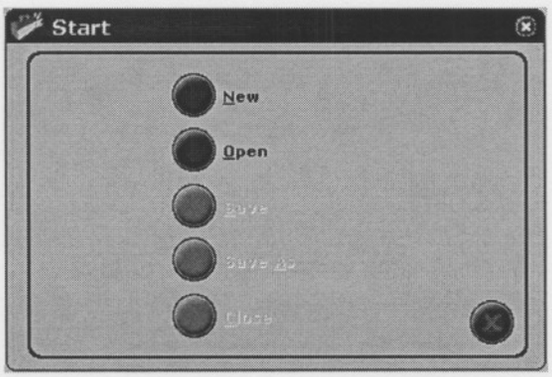


Figure 3: Start interface

New: To start a new project, click on the NEW button and select one of the default templates.

Open: To work on an existing project, click on the OPEN button and select the project file.

Save: To save the current project file, click on the SAVE button.

Save As: To save the current project file under another file name, click on the SAVE AS button.

Close: To close the current project, click on the CLOSE button.

Environment

To set up the environmental parameters of the project, click on the ENVIRONMENTAL button on the main simulation interface. The following figure displays the environmental interface of the simulation tool:

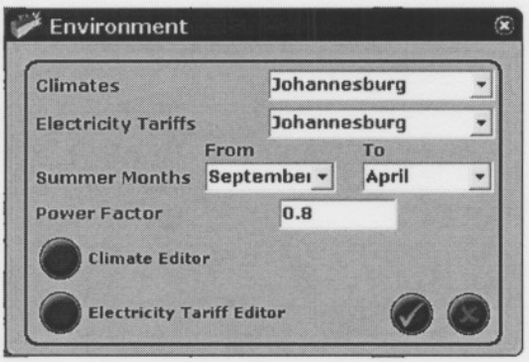


Figure 4: Environment selection interface

Climates: To select a project climate, click on the climate drop down list box and select a climate. The selected climate will be used as climate inputs during the verification and retrofit simulations.

Electricity tariffs: To select a project electricity tariff, click on the tariff drop down list box and select a tariff. The selected tariff will be used for all electricity cost calculations.

Summer months: To select the summer months, click on the "from" and "to" list boxes and specify the summer season. The selected months will be used as the summer season and the other months as the winter season during all the simulation calculations.

Power factor: This is the average power factor (PF) of the building total electricity load.

Climate editor: To add, edit or delete climates, click on the CLIMATE EDIT button. Here the user must enter hourly temperatures, RHs, Global radiation and diffuse radiation for each month of the year. The following figure displays the climate input interface:

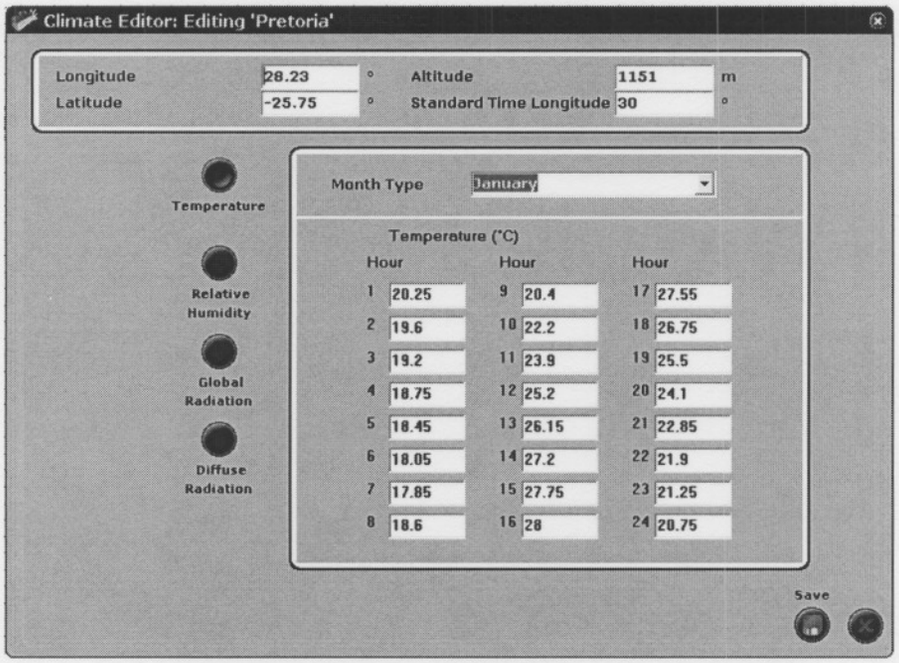


Figure 5: Climate editor interface

Electricity tariff editor: To add, edit or delete tariffs, click on the ELECTRICITY TARIFF EDIT button. Here the user will enter hourly active energy, reactive energy and Maximum Demand (MD) rates for each day type and season. The following figure displays the climate input interface:

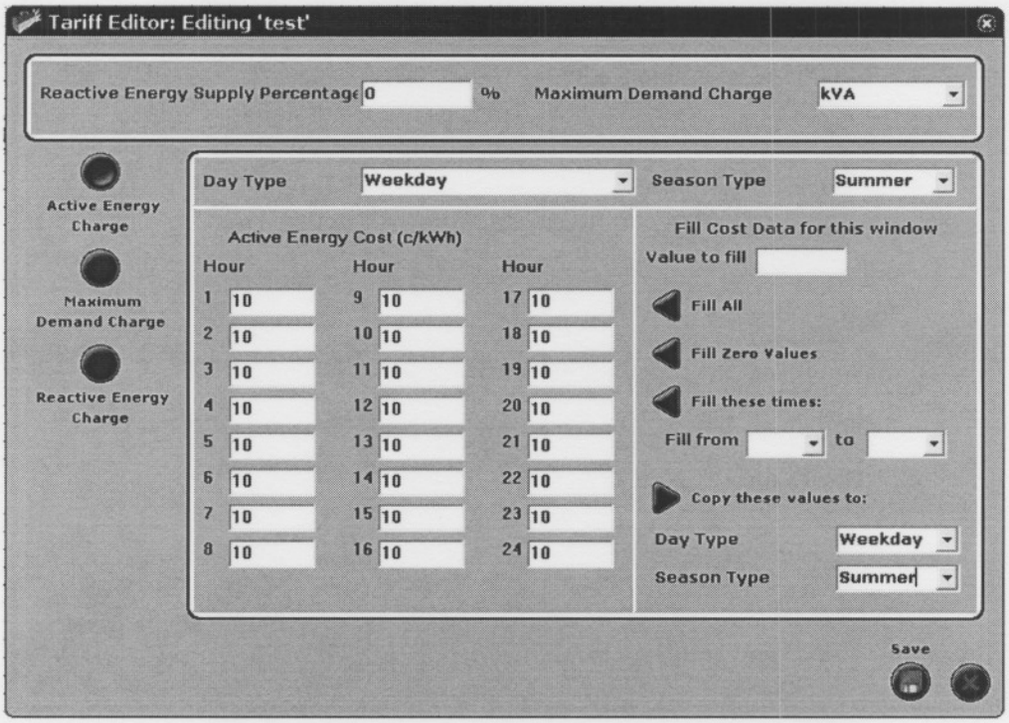


Figure 6: Tariff editor interface

Reactive energy supply %: All reactive energy (KVarh) used in excess of this entered percentage of the active energy (kWh) will be charged against the reactive energy charge.

Maximum Demand charge: Either select KVA of KW from the drop down menu.

CONFIGURE

Download palm components

When the CONFIGURE button is pressed the user will be prompted to download the palm data logger components on to the simulation tool. To download the PDA components connect the PDA to the PC and press the "hotsync" button on the cradle. All the palm components will now be available in the component list under downloaded components in the simulation tool. The configure simulation interface can be seen in the following figure:

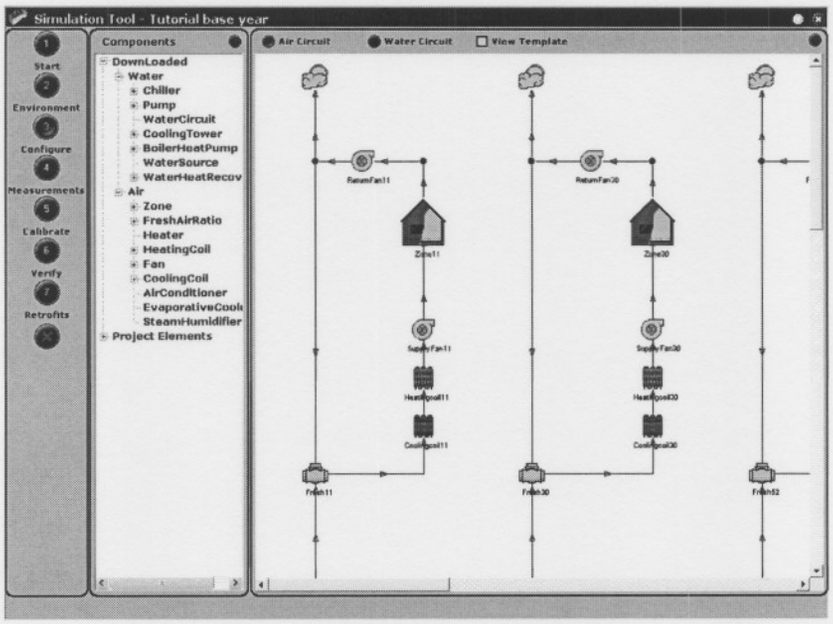


Figure 7: ETB-Simulate screen showing downloaded components

Customise air and water circuits

To customise the template, click on the components with the RIGHT MOUSE BUTTON to be included in the simulation. The selected (active) components will be display in colour, and the inactive components are displayed in black and white. The components can be deactivated by another RIGHT MOUSE click. The following figure displays the template view mode:

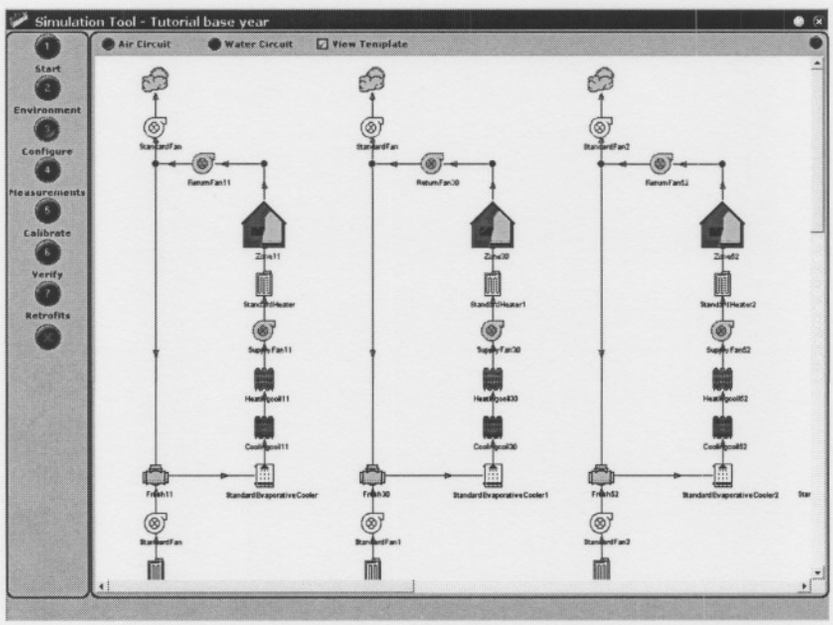


Figure 8: ETB-Simulate template view

Insert palm components

All the palm components will be displayed under the downloaded list. The user can now drag and drop the components on their respective template positions.

Air circuit components

The air circuit screen is displayed in the following figure:

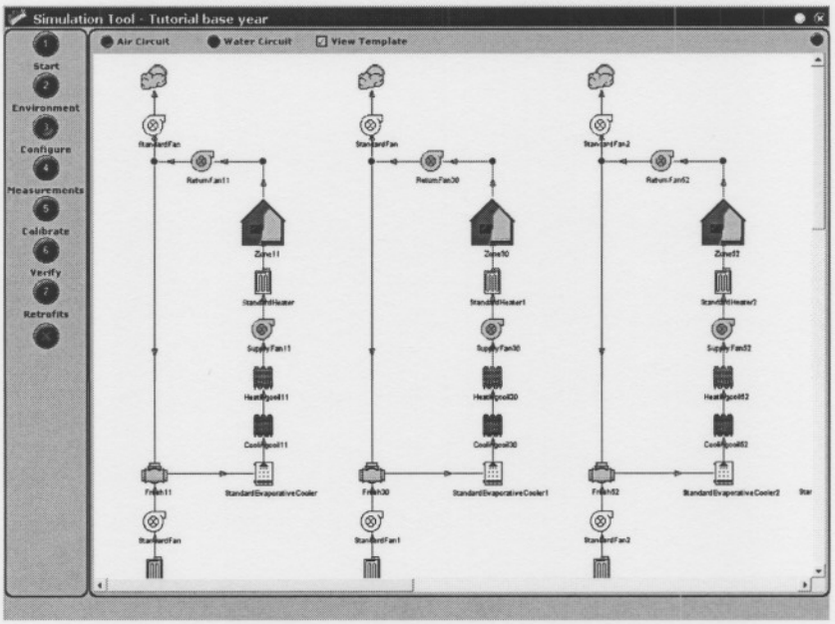


Figure 9: ETB-Simulate air circuit

Air circuit: To add or edit a component on the air circuit, click on the AIR CIRCUIT button. The user can now select the components by a single right mouse click on the icon. To edit the selected component inputs, double click on the component icon.

Building zone

The information required for the building zone is divided into the following:

Description: To enter a descriptive zone name enter a name in the text box.

Dimensions: To enter all the important building dimensions click on the DIMENSIONS button and complete the zone dimensions input interface.

Structure: To enter the building construction click on the STRUCTURE button and complete all the zone structure input interfaces.

Internal heat generation: To enter internal heat sources (lights, computers, people, etc.) into the building zone click on the INTERNAL HEAT GENERATION BUTTON and complete the input interface.

Control: To specify the zone control, setpoints (Temperature, RH, air flow) and air-conditioning schedules click on the CONTROL button and complete the interfaces.

Output: To view the hourly zone air temperatures and relative humidity's, click on the OUTPUT button.

Dimensions

The building zone dimensions screen is displayed in the following figure:

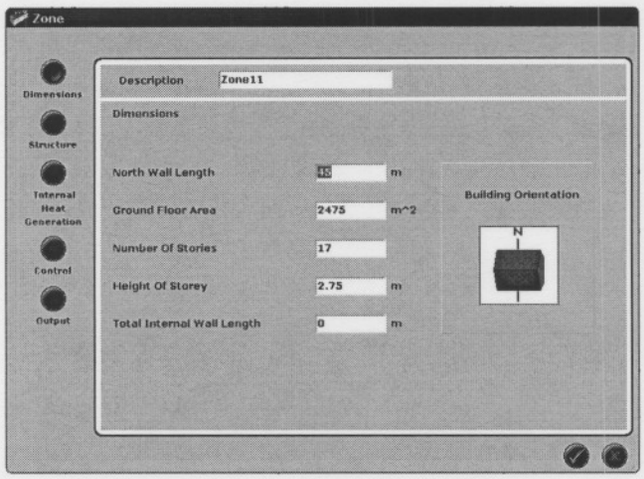


Figure 10: Zone dimensions input screen

North wall length: This is the length of the wall facing north. This is the total zone north wall length.

Internal floor area: This is the internal floor area of the zone. The internal floor area per storey (one level) for building zones, with more than one storey, is required.

Number of storeys: This is the number of floor levels per building zone.

Height of storey: This is the height of one storey from the floor to the ceiling

Total internal wall length: This is the total length of all the walls inside the zone that do not form part of the zone boundaries (North, East, South, West wall

Building orientation: This information can be entered in two ways. Firstly as a positive value, measured clockwise from north, zero at north, to +45°. Alternatively as a negative value, measured anti-clockwise from north, zero at north, to -45°. The information is usually obtained from building plans, but can also be measured on site.

Structure

The building zone structure screen is displayed in the following figure:

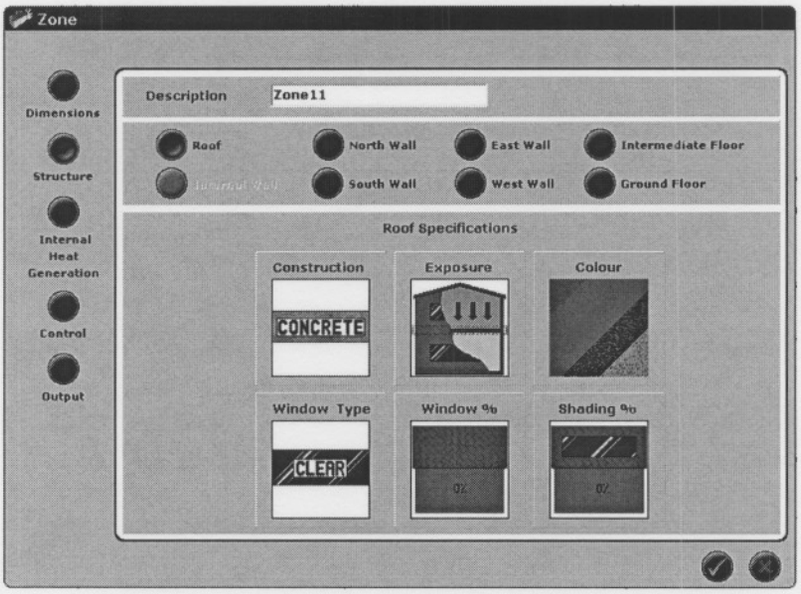


Figure 11: Structure input screen for the roof

Zone structure: To specify the construction of each surface type displayed on the interface, click on the respective surface type (North wall, East wall, etc) button and complete the inputs.

Construction: The user can choose a surface construction from a pre-defined surface database. To select a construction type, click on the CONSTRUCTION icon and select a type from the menu.

Exposure: To specify the exterior exposure of the surface, click on the EXPOSURE icon and select a type from the menu.

Window %: This is the window area as a percentage of the total surface area. To specify the percentage, click on the WINDOW % icon and select one of the options from the menu.

Shading %: This is the shaded area as a percentage of the total window area. To specify this percentage, click on the SHADING % icon and select one of the options from the menu.

Window type: The user can choose a window type from a pre-defined database. To select a type, click on the WINDOW TYPE icon and select a type from the menu.

Colour: This is the exterior colour of the surface. To select a colour, click on the COLOUR icon and select a colour from the menu.

Internal heat generation

The building internal heat generation screens are displayed in the following figures:

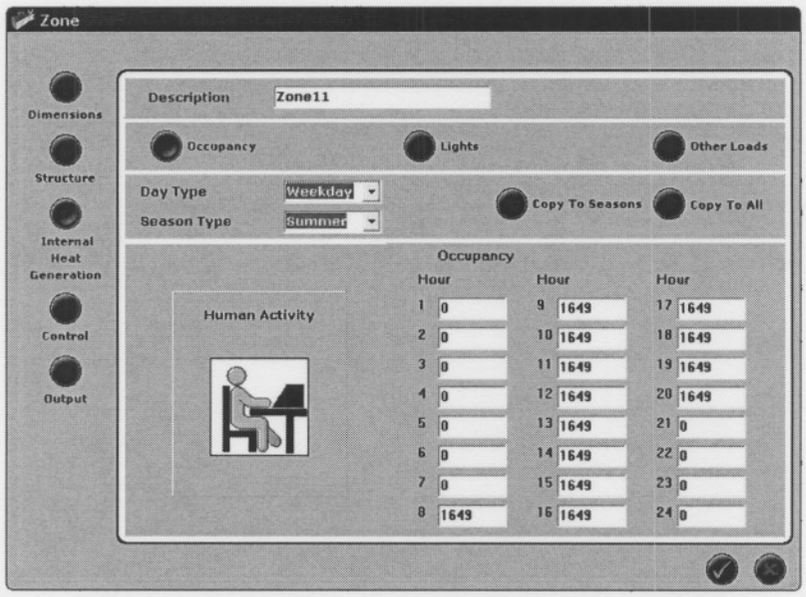


Figure 12: Internal heat generation input screen for occupancy

Occupancy: This is the typical number of people inside the building zone at the same time. The user can enter a value for each hour, day type and season. To specify the number of people enter the value into the text box.

Human activity: This is the typical activity of the people inside the building zone. Specify the activity by selecting one form the menu.

The figure below shows the lights input page.

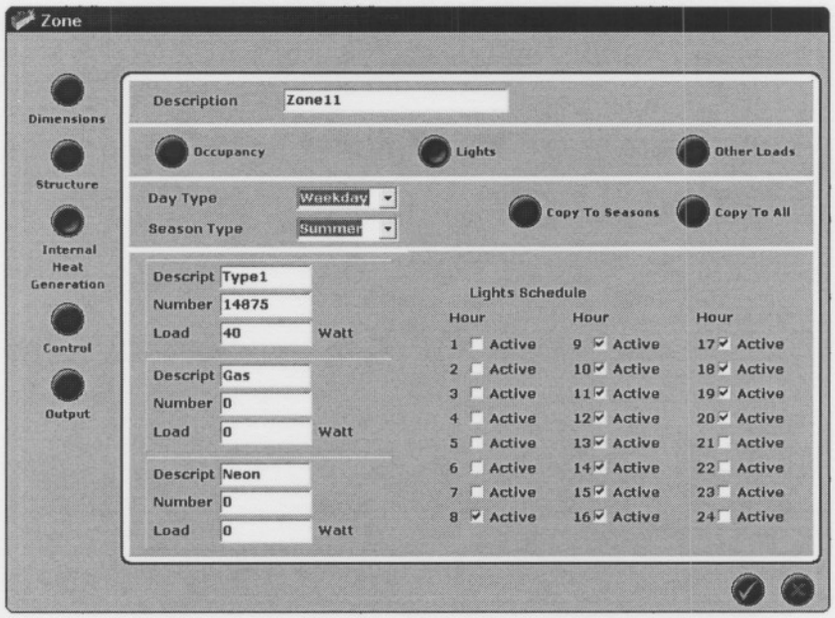


Figure 13: Internal heat generation input screen for lights

Lights: Here the user can specify three types of lighting fixtures. Enter the type, load and number of each fixture. A lighting schedule for each day type and season can be specified.

The figure below displays the input interface for additional loads.

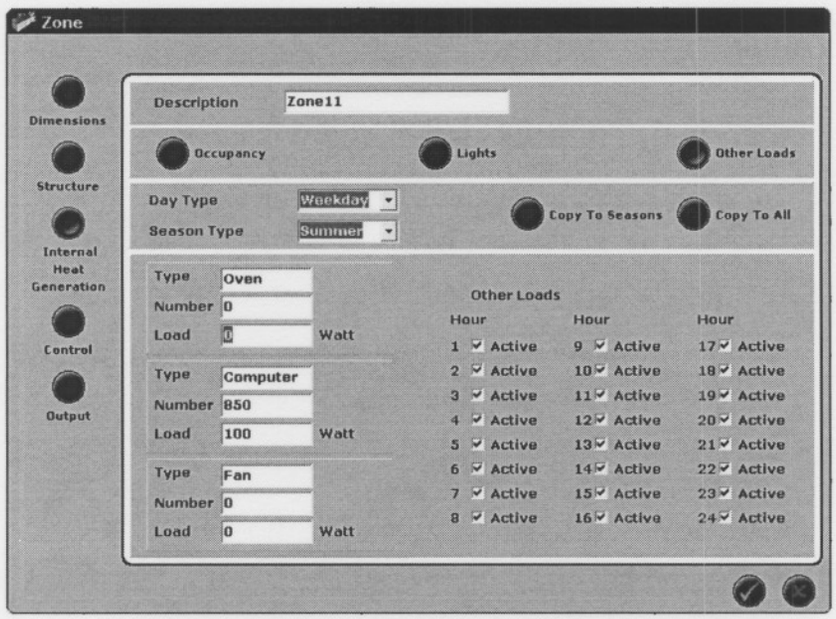


Figure 14: Internal heat generation input screen for other loads

Other loads: Here the user can specify three types of other internal loads (computers, lifts, etc.). Enter a description, load and number of each type. A load schedule for each day type and season can be specified.

Control

The building zone control screen is displayed in the following figure:

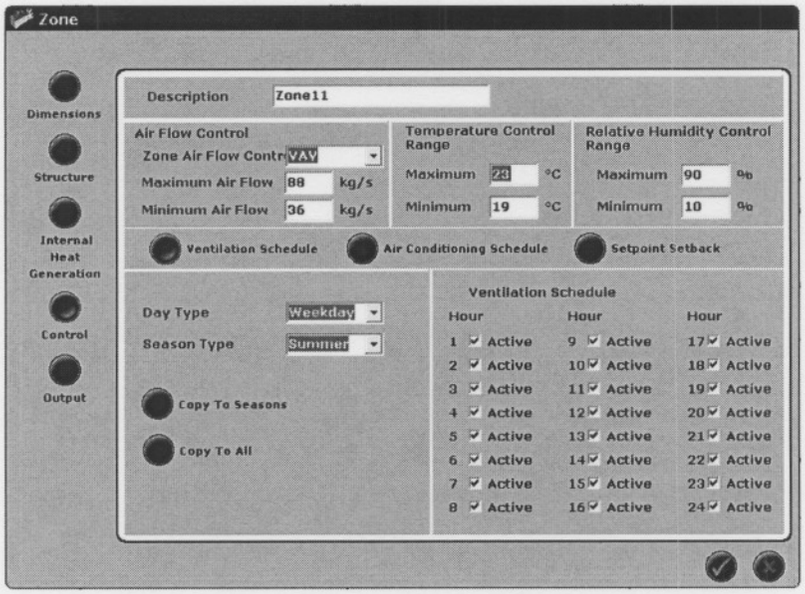


Figure 15: Control input screen for ventilation schedule

Temperature control: This is the zone temperature control range. The system will control (when cooling and heating schedule is active) the zone temperature between the entered minimum and maximum temperature inputs.

RH control: This is the zone relative humidity (RH) control range. The system will control (when cooling and heating schedule is active) the zone RH between the entered minimum and maximum RH inputs.

Volume flow: The user can either select constant air volume, or variable air volume. In a variable air volume system the indoor temperature is controlled by the supply more or less air to the zone. The user must specify the minimum and maximum air flow to the building zone.

Maximum flow: This is the air flow rate to the building zone measured at 100% cooling load. This means all the supply air control dampers must be 100% open.

Minimum flow: This is the air flow rate to the building zone measured at 100% heating load. This means all the supply air control dampers must be at their minimum flow position.

Ventilation schedule: This is the operating schedule of all the fans (fresh air, supply air, return air and exhaust air fan) of the building zone. The user can specify a schedule for each day type and season.

Air-conditioning schedule: This is the operating schedule of all the heating and cooling elements (coils, heaters, and evaporative coolers) of the building zone. The user can specify a schedule for each day type and season.

Setpoint setback: This is a specified setpoint setback temperature for each hour. For example, if 2°C is entered at a specific hour, 2°C will be added too the maximum and minimum temperature control range for that hour. The user can specify setbacks values for each day type and season.

Cooling coil

The cooling coil screen is displayed in the following figure:

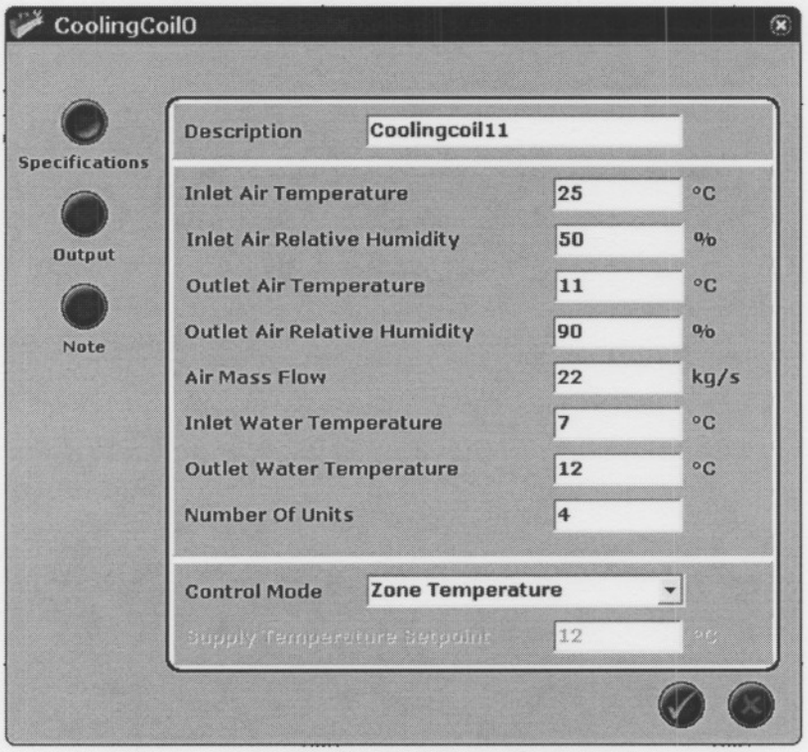


Figure 16: Cooling coil input screen

All the cooling coil inputs must be given at 100% cooling load. This means no water must by-pass the coil. Remember all the inputs are for one unit only (per unit if more than one unit).

Inlet air temperature: This is the inlet air temperature of the cooling coil at 100% cooling load.

Inlet air RH: This is the inlet air RH of the cooling coil at 100% cooling load.

Outlet air temperature: This is the outlet air temperature of the cooling coil at 100% cooling load.

Outlet air RH: This is the outlet air RH of the cooling coil at 100% cooling load.

Air mass flow: This is the air mass flow through the cooling coil at 100% cooling load.

Inlet water temperature: This is the inlet water temperature of the cooling coil at 100% cooling load.

Outlet water temperature: This is the outlet water temperature of the cooling coil at 100% cooling load.

Number of units: This is the number of coils with the same thermal characteristics and control strategy configured in parallel.

Control: This is the control strategy of the cooling coil. Here the user can either select zone temperature or supply temperature. Zone temperature means the coil capacity will be controlled to maintain the zone indoor air temperature at the maximum temperature control range value. The supply temperature option will imply that the coil capacity is controlled to maintain a constant coil leaving air temperature.

Heating coil

The heating coil screen is displayed in the following figure:

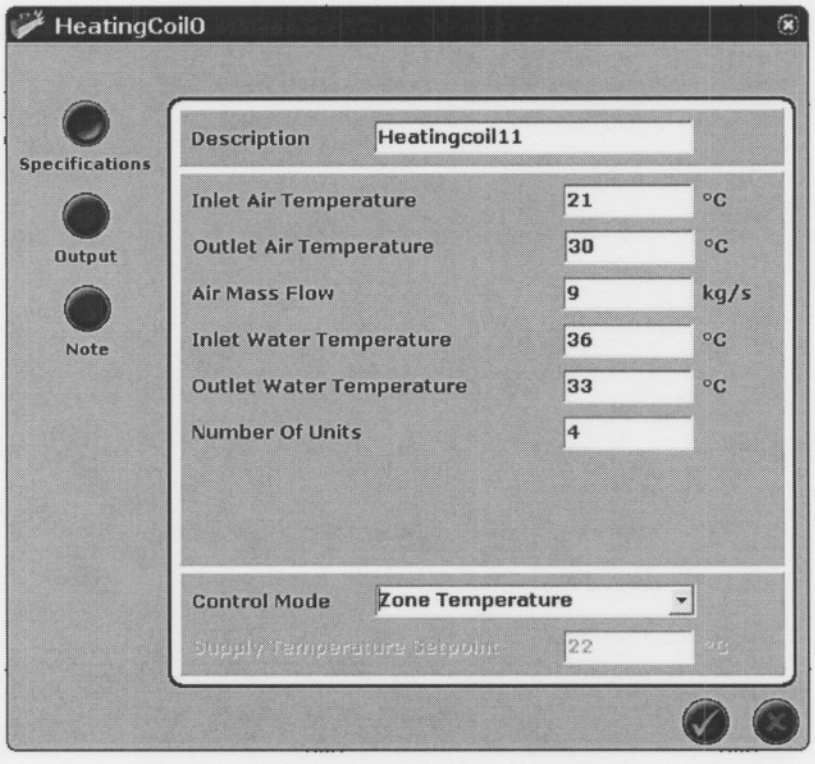


Figure 17: Heating coil input screen

All the heating coil inputs must be given at 100% heating load. This means no water must by-pass the coil. Remember all the inputs are for one unit only (per unit if more than one unit).

Inlet air temperature: This is the inlet air temperature of the heating coil at 100% heat load.

Outlet air temperature: This is the outlet air temperature of the heating coil at 100% heat load.

Air mass flow: This is the air mass flow through the heating coil at 100% cooling load.

Inlet water temperature: This is the inlet water temperature of the heating coil at 100% heat load.

Outlet water temperature: This is the outlet water temperature of the heating coil at 100% heat load.

Number of units: This is the number of coils with the same thermal characteristics and control strategy configured in parallel.

Control: This is the control strategy of the heating coil. Here the user can either select zone temperature or supply temperature. Zone temperature means the coil capacity will be controlled to maintain the zone indoor air temperature at the minimum temperature control range value. If the supply temperature option is selected, the coil capacity is controlled to maintain a constant coil leaving air temperature.

Evaporative cooler

The evaporative cooler screen is displayed in the following figure:

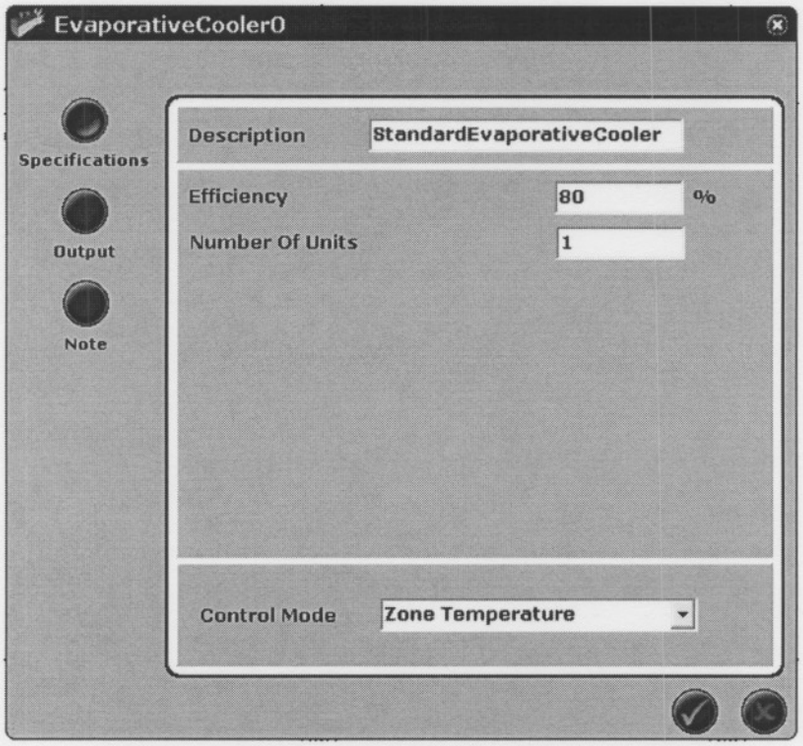


Figure 18: Evaporative cooler input screen

Efficiency: Evaporative cooler efficiencies range typically between 75% and 85%.

$$Efficiency = (Tdb,in-Tdb,out)/(Tdb,in-Twb,in)*100$$

Tdb - Dry bulb temperature (°C)

Twb - Wet bulb temperature (°C)

in - Inlet air condition

out - outlet air condition

Number of units: This is the number of coolers with the same thermal characteristics and control strategy configured in parallel.

Control: This is the control strategy of the evaporative cooler. Here the user can either select zone temperature or none. The zone temperature option means the cooler capacity will be controlled to maintain a constant zone air leaving temperature at 1°C below than the maximum temperature control range value. If the none option is selected, the cooler is always delivers 100% load when active.

Fan

The fan screen is displayed in the following figure:

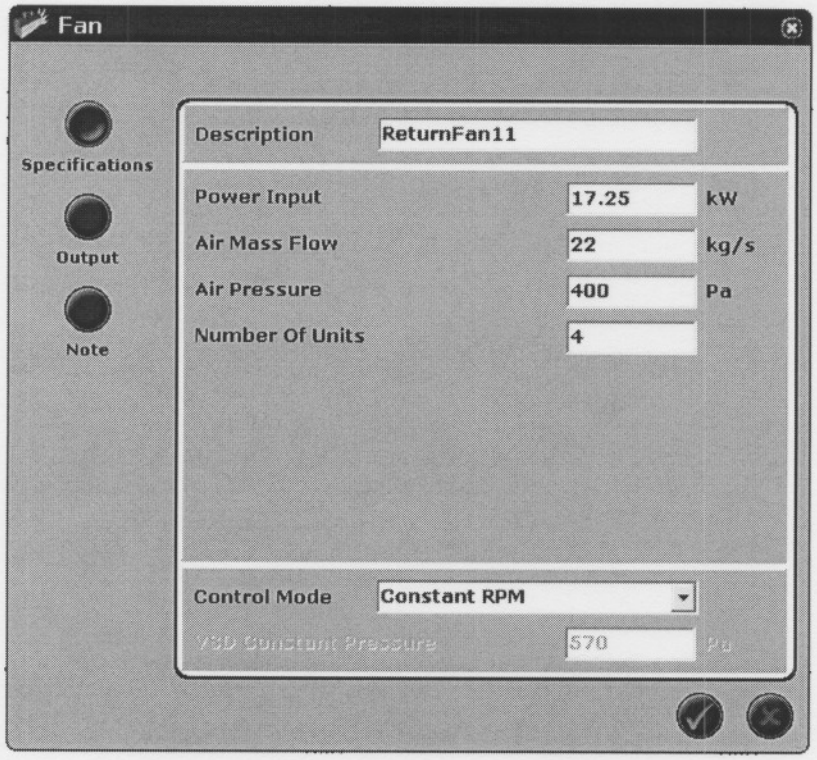


Figure 19: Fan input screen

All the fan inputs must be given at maximum air flow. This means all the supply air control dampers must be 100% open. Remember all the inputs are for one unit only (per unit if more than one unit).

Power input: This is the electrical power input of the fan, at maximum air flow.

Air mass flow: This is the air flow through the fan, at maximum air flow.

Air pressure: This is the total pressure difference over the fan, at maximum air flow.

$$Air\ pressure = (P + 0.5pv^2)out - (P + 0.5pv^2)in$$

P - Static air pressure (Pa)

p - Air density (kg/m^2)

v - Average air speed (m/s)

Number of units: This is the number of fans with the same thermal characteristics and control strategy configured in parallel.

Control: This is the control strategy of the fan. Here the user can either select constant RPM or VSD constant pressure. Constant RPM means the fan will always operate at a constant RPM. VSD or frequency control at a constant pressure implies that the fan's speed will be controlled to maintain a constant total pressure over the fan.

Fresh air ratio

The fresh air ratio screen is displayed in the following figure:

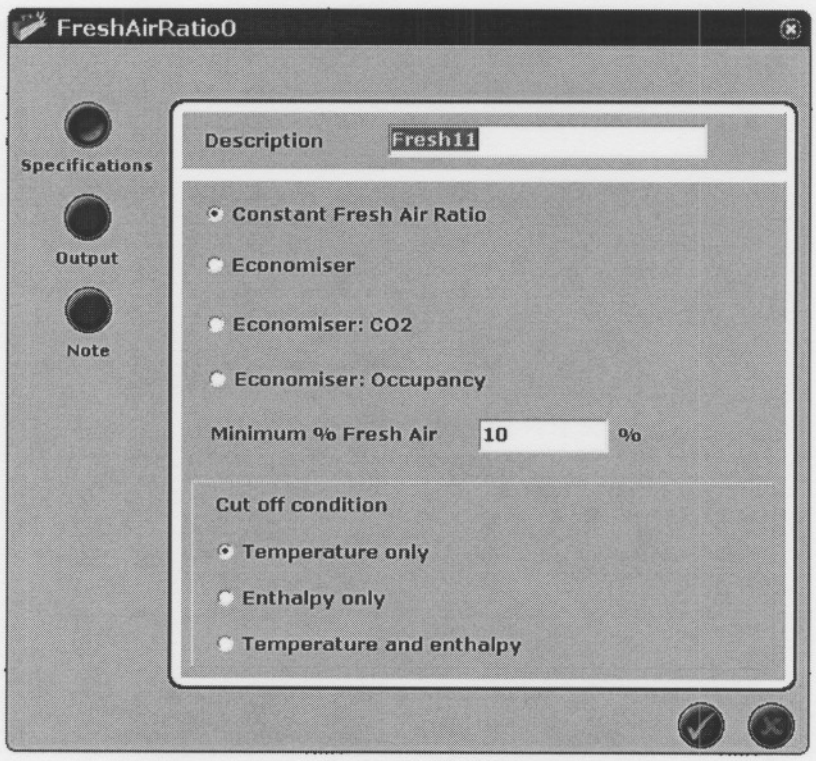


Figure 20: Fresh air ratio input screen

Minimum % fresh air: This is the minimum amount of fresh air as a percentage of the total air supplied to the building zone. This means the fresh air dampers must be at their minimum setting (economiser control).

Control: This is the control strategy of the fresh and return air dampers. The dampers will be controlled to maintain a constant zone temperature at 1°C below the maximum temperature

control range value. Here the user can either select constant fresh air, economiser, CO2, or occupancy.

- *Constant fresh air* - No damper control (no economiser).
- *Economiser* - Economiser control with a specified minimum fresh air setting.
- *Occupancy* - Economiser control with a specified minimum fresh air setting when the building zone is occupied and a zero minimum fresh air setting when the building is unoccupied.
- *CO2* - Economiser control integrated with CO2 control to keep the building zone within its CO2 levels (700 ppm CO2 above the outside CO2 level)

Cut off condition - This is the condition used to determine if outside air can be used for cooling or not. Outside air is only used for cooling when the outside air cut off condition is lower than the zone return air cut off condition.

- *Temp only* - Outside air is used for cooling when the outside air temperature is below the zone return air temperature.
- *Enthalpy only* - Outside air is used for cooling when the outside air enthalpy is below the zone return air enthalpy.
- *Temp and enthalpy* - Outside air is used for cooling when the outside air enthalpy and temperature are below the zone return air enthalpy and temperature.

Heater

The heater screen is displayed in the following figure:

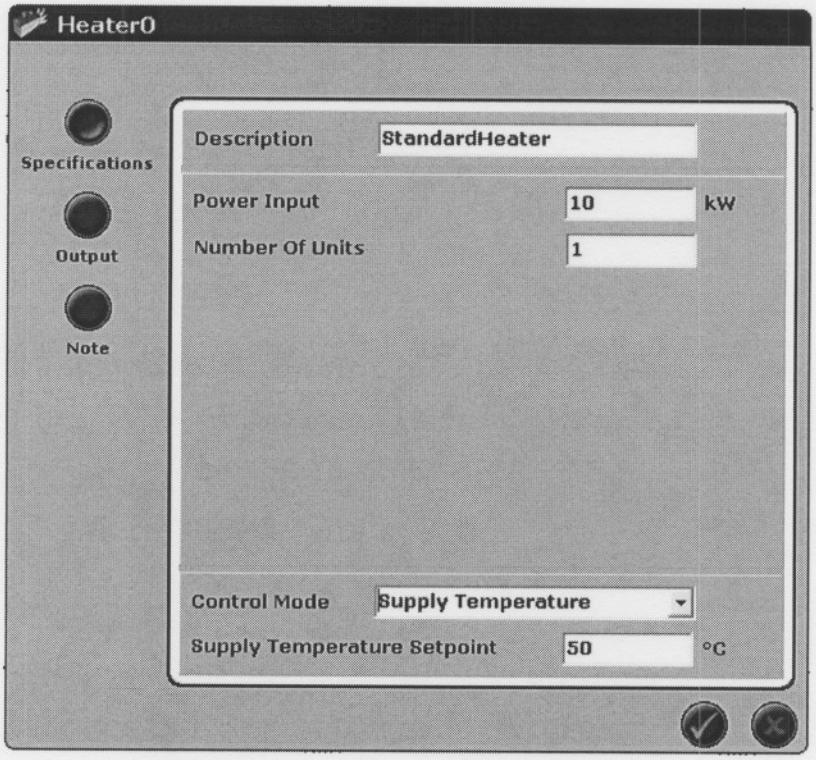


Figure 21: Heater input screen

Power input: This is the electrical power input of the heater at 100% load. This means all the heating elements must be active. Remember all the inputs are for one unit only (per unit if more than one unit).

Number of units: This is the number of heater banks with the same control strategy configured in parallel.

Control: This is the control strategy of the heater. Here the user can select zone temperature or supply temperature. When zone temperature is selected the heater capacity will be controlled to maintain a constant zone indoor air temperature at the minimum temperature control range value. The supply temperature option implies that the heater capacity is controlled to maintain a constant heater leaving air temperature.

Water circuit components

The water circuit screen is displayed in the following figure:

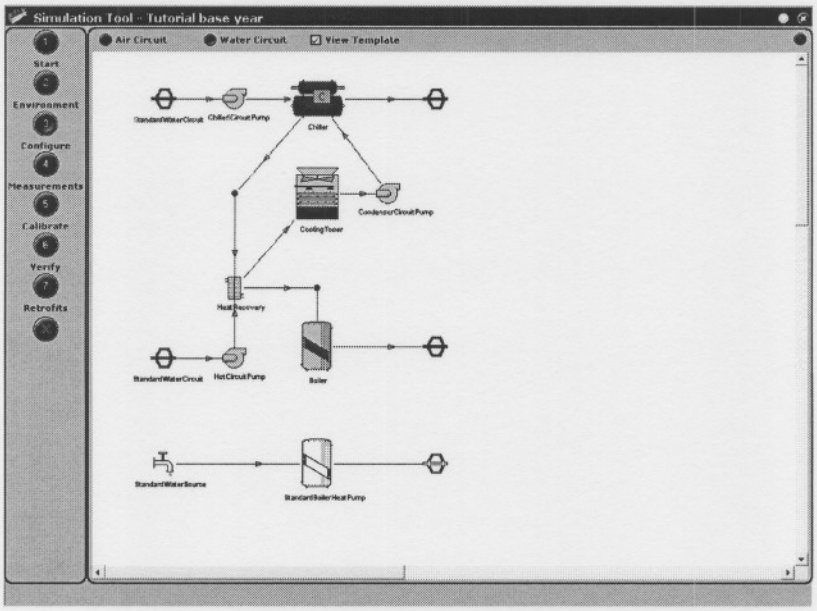


Figure 22: Water circuit

Water circuit: To add or edit a component on the water circuit, click on the WATER CIRCUIT button. The user can select the components by a single mouse click on the icon. To edit the selected component inputs, double click on the component icon.

Cooling Tower

The cooling tower screen is displayed in the following figure:

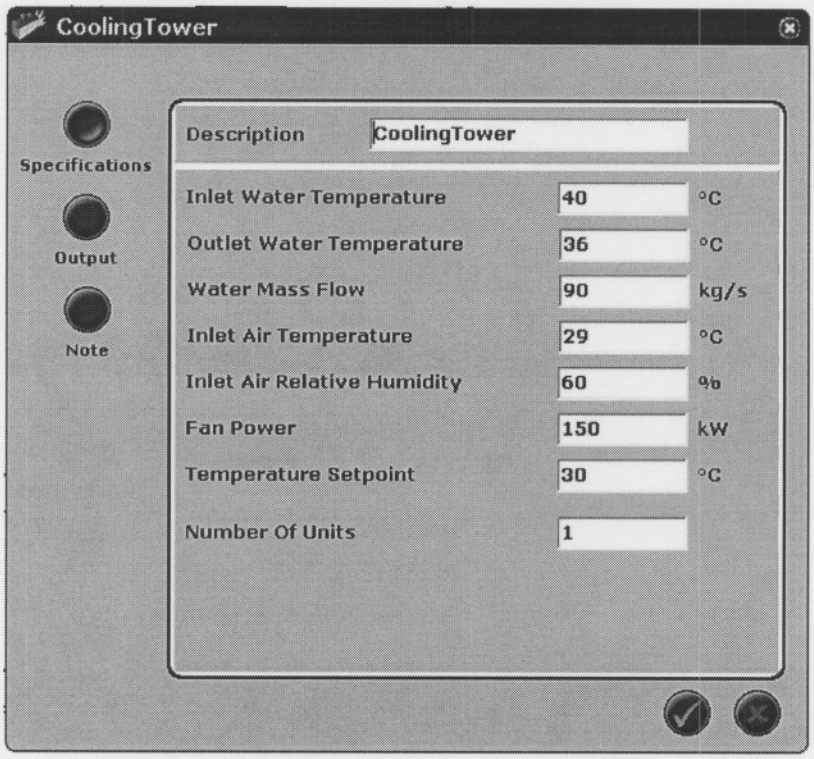


Figure 23: Cooling tower input screen

All the cooling tower inputs must be given at 100% cooling load. This means no water must by-pass the cooling tower. Remember all the inputs are for one unit only (per unit if more than one unit).

Inlet water temperature: This is the inlet water temperature of the cooling tower at 100% load.

Outlet water temperature: This is the outlet water temperature of the cooling tower at 100% load.

Water mass flow rate: This is the outlet water temperature of the cooling tower at 100% load.

Inlet air temperature: This is the inlet air temperature of the cooling tower at 100% load. This means no water must by-pass the cooling tower.

Inlet air RH: This is the inlet air relative humidity of the cooling tower at 100% load.

Power input: This is the electrical power input of the cooling tower fan at maximum air flow. This means all the fans must operate.

Temperature setpoint: This is the control setpoint of the cooling tower water leaving temperature.

Number of units: This is the number of cooling towers with the same thermal characteristics and control strategy configured in parallel.

Pump

The pump screen is displayed in the following figure:

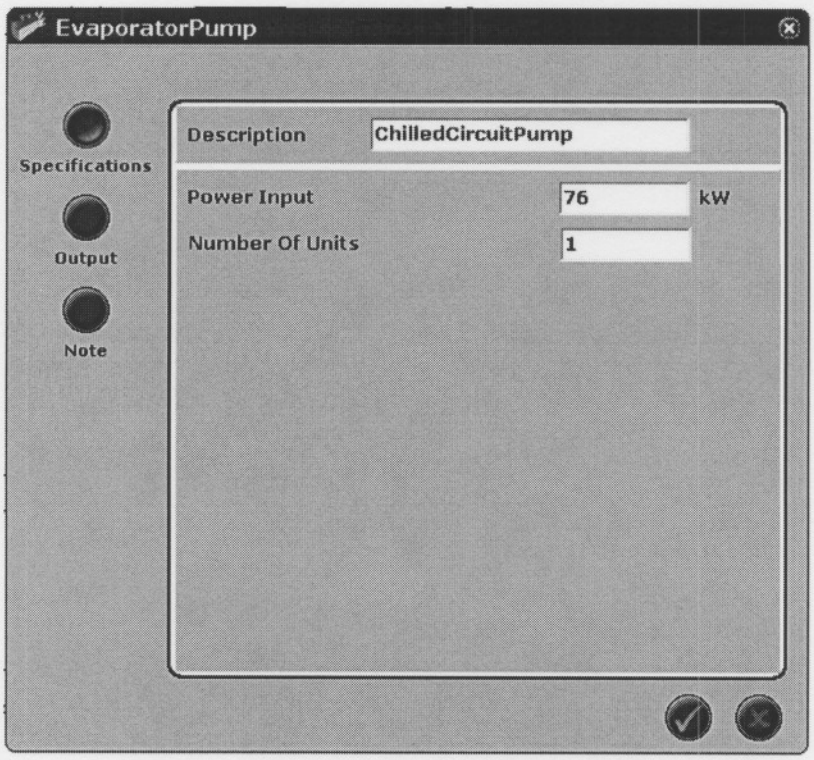


Figure 24: Evaporator pump input screen

Power input: This is the electrical power input of the pump when in operation. Remember all the inputs are for one unit only (per unit if more than one unit).

Number of units: This is the number of pumps with the same performance characteristics and control strategy configured in parallel.

Chiller

The chiller screen is displayed in the following figure:

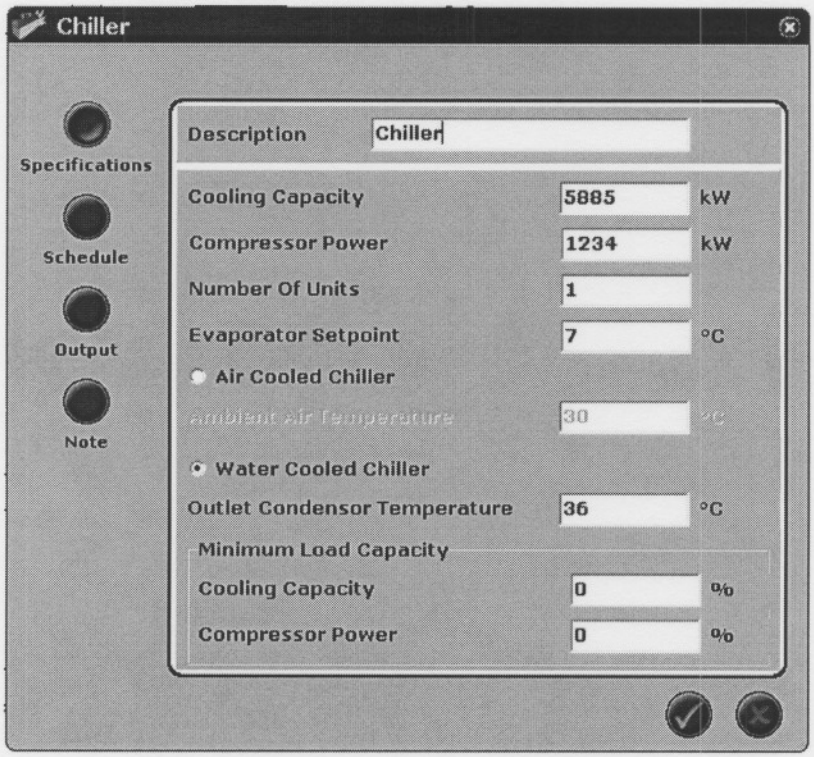


Figure 25: Chiller input screen

All the chiller inputs must be given at 100% load. Remember all the inputs are for one unit only (per unit if more than one unit).

Cooling capacity: This is the cooling capacity of the chiller at 100% load.

$$Cooling\ load\ (kW) = Mevap*(4.2)*(Tevap,in - Tevap,out)$$

Tevap,in - Evaporator inlet water temperature (°C)

T evap,out - Evaporator leaving water temperature (°C)

Mevap - Evaporator water mass flow (l/s)

Compressor power: This is the compressor power of the chiller at 100% load.

Evaporator setpoint: This is the evaporator leaving water temperature at setpoint.

Number of units: This is the number of chillers with the same performance characteristics and operating strategy configured in series or parallel.

Select type: Here the user can either specify if the component is an air cooled or water cooled type. When air cooled is selected, the ambient air temperature at the condenser must be entered, and for water cooled the condenser leaving water temperature must be entered.

Minimum load capacity: This is the minimum cooling load (first loading step) of the chiller as a percentage of 100% load and the respective compressor power percentage.

Heat pump

The heat pump screen is displayed in the following figure:

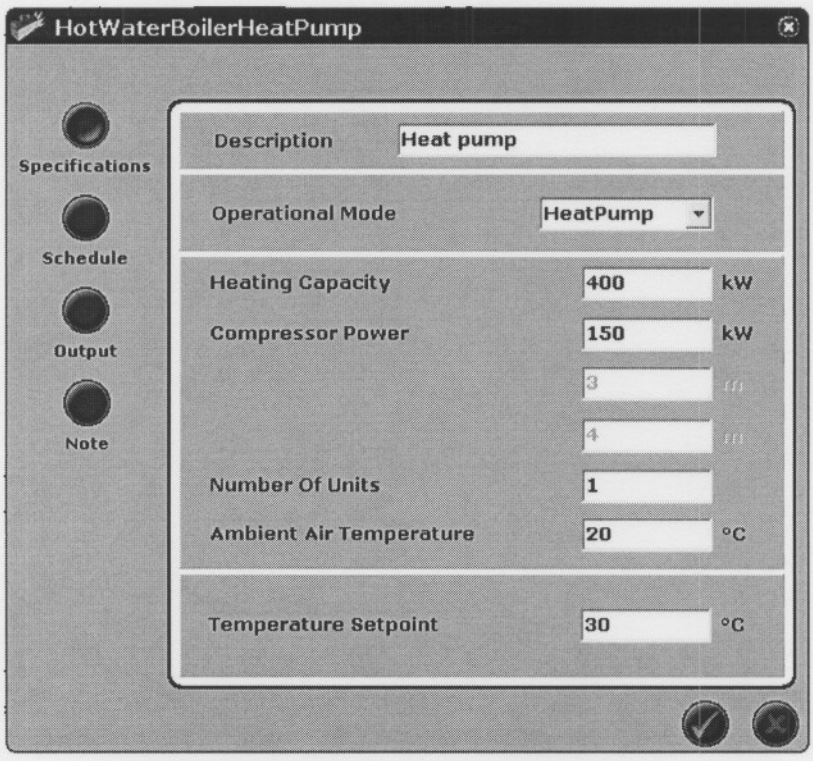


Figure 26: Heat pump input screen

All the heat pump inputs must be given at 100% load. Remember all the inputs are for one unit only (per unit if more than one unit).

Heating capacity: This is the heating capacity of the heat pump at 100% load.

$$Heating\ load\ (kW) = Mcon*(4.2)*(Tcon,out - Tcon,in)$$

Tcon,in - Condenser inlet water temperature (℃)

T con,out - Condenser leaving water temperature (℃)

Mcon - Condenser water mass flow (l/s)

Compressor power: This is the compressor power of the heat pump at 100% load.

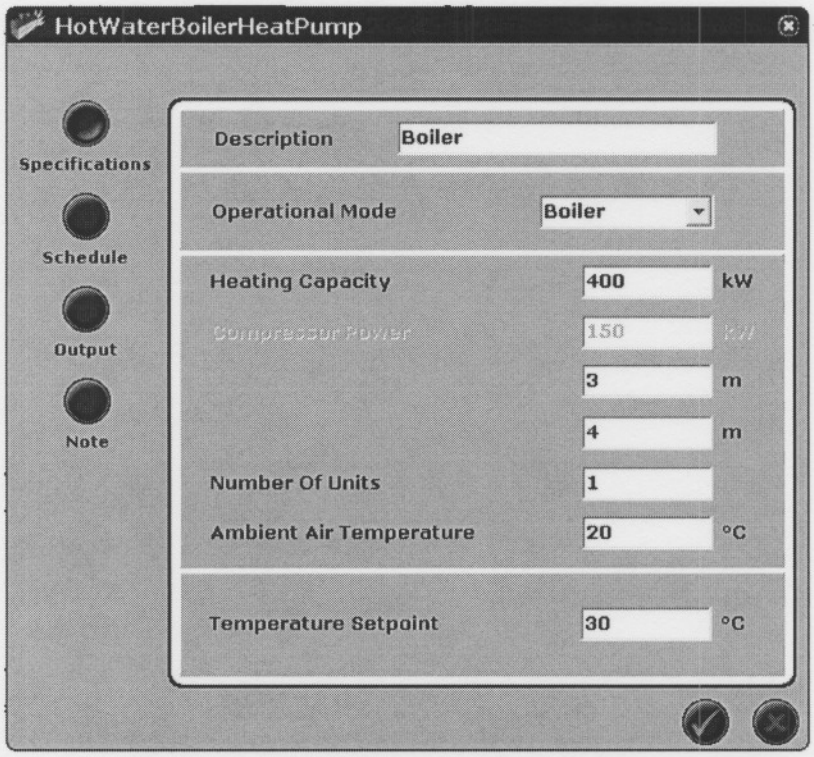
Temperature setpoint: This is the condenser leaving water temperature at setpoint.

Number of units: This is the number of heat pumps with the same performance characteristics and operating strategy configured in series or parallel.

Ambient air temperature: This is the ambient air temperature measured at the evaporator

Boiler

The boiler screen is displayed in the following figure:



F **Figure 27: Boiler input screen**

Heating capacity: This is the heating capacity of the boiler at 100% load. Remember all the inputs are for one unit only (per unit if more than one unit).

Length: This is the length of the boiler water tank.

Diameter: This is the diameter of the boiler water tank.

Temperature setpoint: This is the boiler leaving water temperature at setpoint.

Number of units: This is the number of boilers with the same performance characteristics and operating strategy configured in series or parallel.

Ambient air temperature: This is the ambient air temperature measured at the boiler tank.

Water heat recovery

The water heat recovery screen is displayed in the following figure:

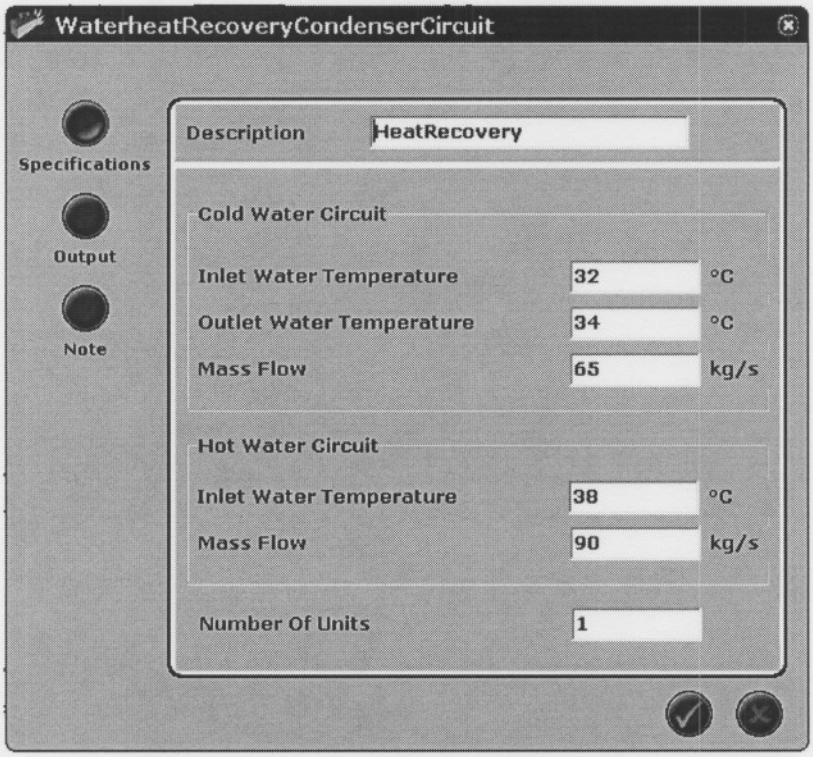


Figure 28: Water heat recovery input screen

Remember all the inputs are for one unit only (per unit if more than one unit).

Cold circuit inlet temperature: This is the inlet water temperature of the heat exchanger of the cold stream.

Cold circuit outlet temperature: This is the outlet water temperature of the heat exchanger of the cold stream.

Cold circuit water mass flow: This is the water mass flow through the exchanger of the cold stream.

Hot circuit inlet temperature: This is the inlet water temperature of the heat exchanger of the hot stream.

Hot circuit water mass flow: This is the water mass flow through the exchanger of the hot stream.

Number of units: This is the number of heat exchangers with the same thermal characteristics and control strategy configured in parallel.

MEASUREMENTS

The calibration measurement screen is displayed in the following figure:

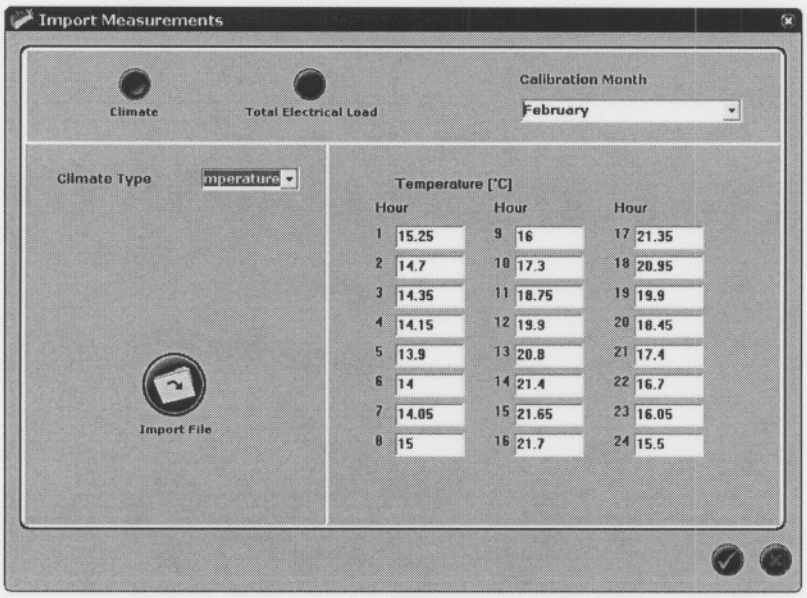


Figure 29: Measurement screen

Climate: This is the climate measurements for calibration. The user will have to enter average hourly temperature and relative humidity values for a typical weekday. The calibration simulations will use the radiation values of the selected climate under the environment option. The calibration month must be selected from the dropdown list box for the correct sun angles.

Total electrical load: This is the total building electrical load measured for calibration (active and reactive energy). The user will have to enter average hourly energy (kWh) values for all the required day types.

CALIBRATE

The calibration output screen is displayed in the following figure:

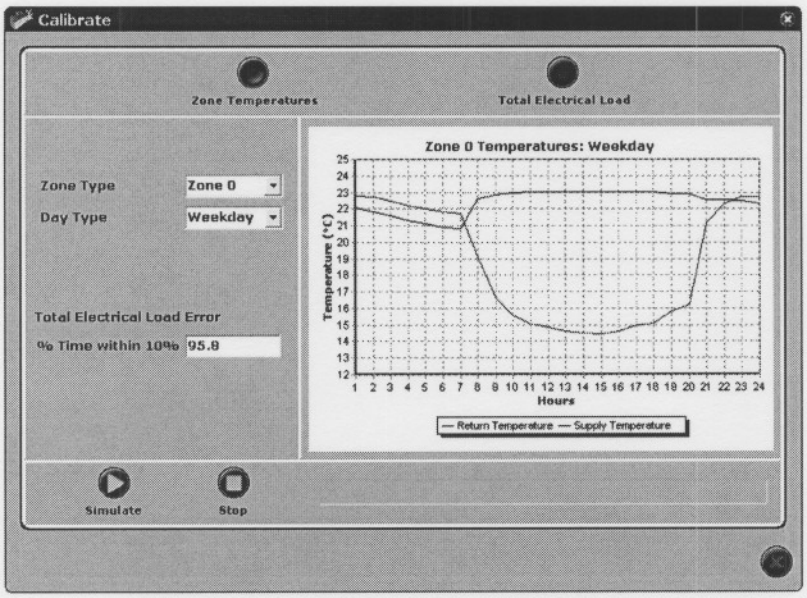


Figure 30: Calibration screen

Simulate: To execute a calibration calculation click on the SIMULATE button. The software will now execute calibration weekday, Saturday and Sunday calculations.

Zone temperatures: To view the simulated zone return and supply air temperatures trends, click on the ZONE TEMPERATURE button.

Total electrical load: To view the simulated and measured total electrical load trends, click on the TOTAL ELECTRICAL LOAD button.

Calibration error: This is the percentage of time where the simulated energy load trend is within 10% of the measured trend.

VERIFY

The verification screen is displayed in the following figure:

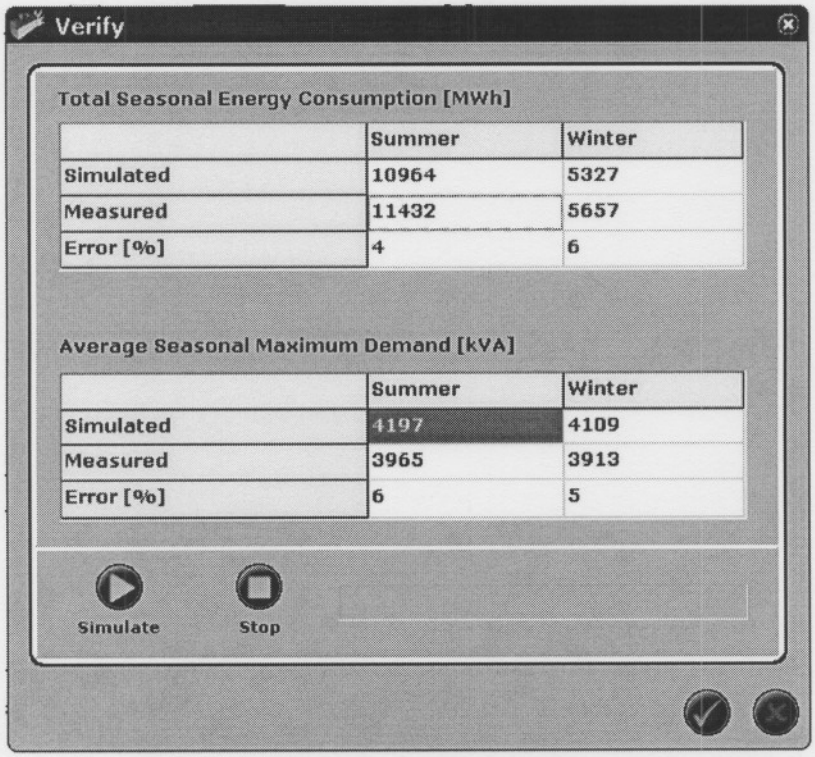


Figure 31: Verification screen

Simulate: To execute a verification calculation click on the SIMULATE button. The software will execute verification calculations for the summer and winter season.

Measured total energy consumption: Enter the measured energy consumption of the summer and winter months into the respective table cells. Remember the summer months are the months selected on the environment input interface.

Measured average Maximum Demand (MD): Enter the measured average MD of the summer and winter months into the respective table cells. Remember the summer months are the months selected on the environment input interface.

Total energy consumption % error: absolute(measured energy consumption - simulated energy consumption)/(measured energy consumption)*100.

Average Maximum Demand (MD) % error: absolute(measured MD - simulated MD)/(measured MD)*100.

RETROFIT

The retrofit screen is displayed in the following figure:

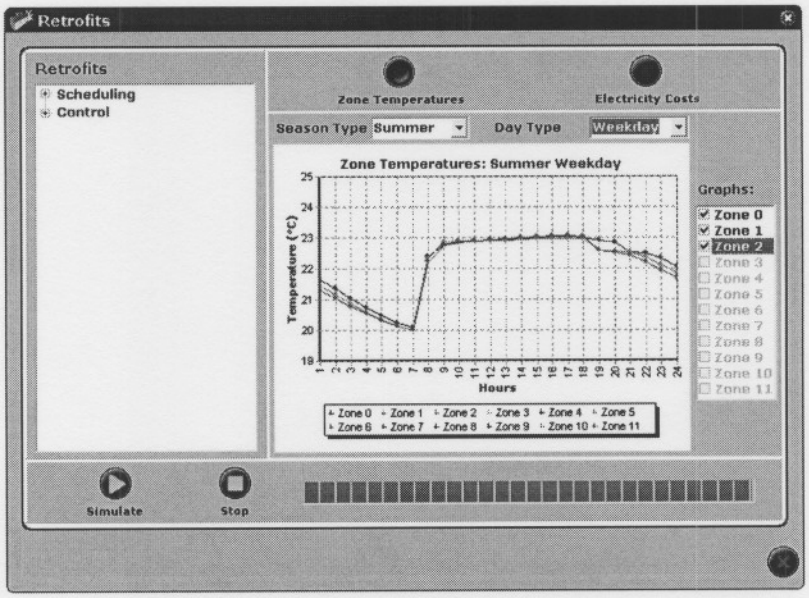


Figure 32: Retrofit simulation screen

Simulate: To execute a retrofit calculation click on the SIMULATE button. The software will then execute retrofit calculations for the summer and winter season.

Retrofits: Select typical retrofit options from the retrofit list. Click on the option of your choice and the software will take you directly to the selected component interface. The user is given a choice between Scheduling retrofits and Control retrofits.

Zone temperatures: This is the zone air temperature result of each retrofit simulation. To see the zone air temperature results, click on the ZONE TEMPERATURES button.

Electricity costs: This is the electricity cost results of each retrofit simulation. To see the electricity cost results, click on the ELECTRICITY COSTS button.

Appendix G

Screen prints of ETB-Economic analysis

This appendix shows the screen prints of ETB-Economic analysis. A brief description of the interfaces is also given.

INRODUCTION

To access the financial analysis tool, click on the FINANCIAL ANALYSIS button on the main ESCO Toolbox interface. This tool will allow the user to calculate electricity cost savings, payback periods and internal rates of return. The user has the option to select four buttons on the main screen, namely START, DESCRIPTION, CONFIGURE, RESULTS.

START

The figure below displays the START screen.

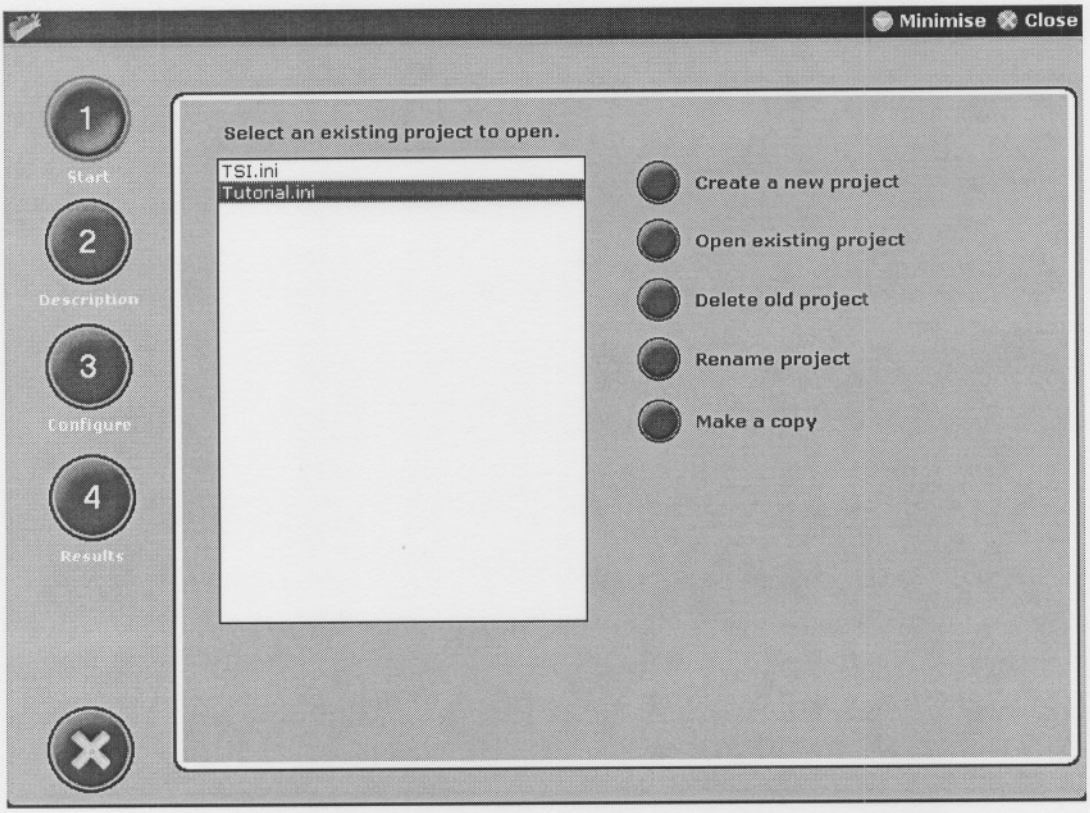


Figure 1: Economic analysis start screen

When the START button is selected, a list of all available projects is displayed. The user then has the option to open a project, create a project, delete, rename, or make a copy of a project.

DESCRIPTION

The figure below displays the DESCRIPTION screen.

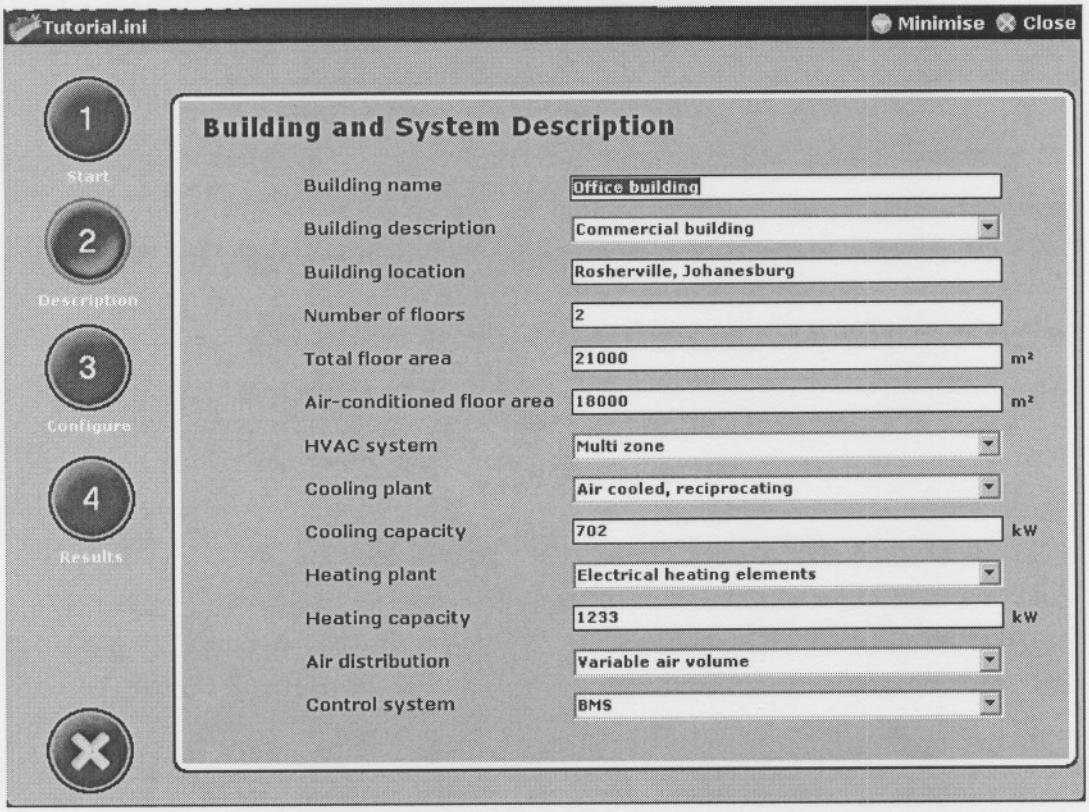


Figure 2: Economic analysis description screen

The user is required to enter all the information requested. The information entered in this area consists of general information regarding the building and is used in the report writing section.

CONFIGURE

The figure below displays the CONFIGURE interface.

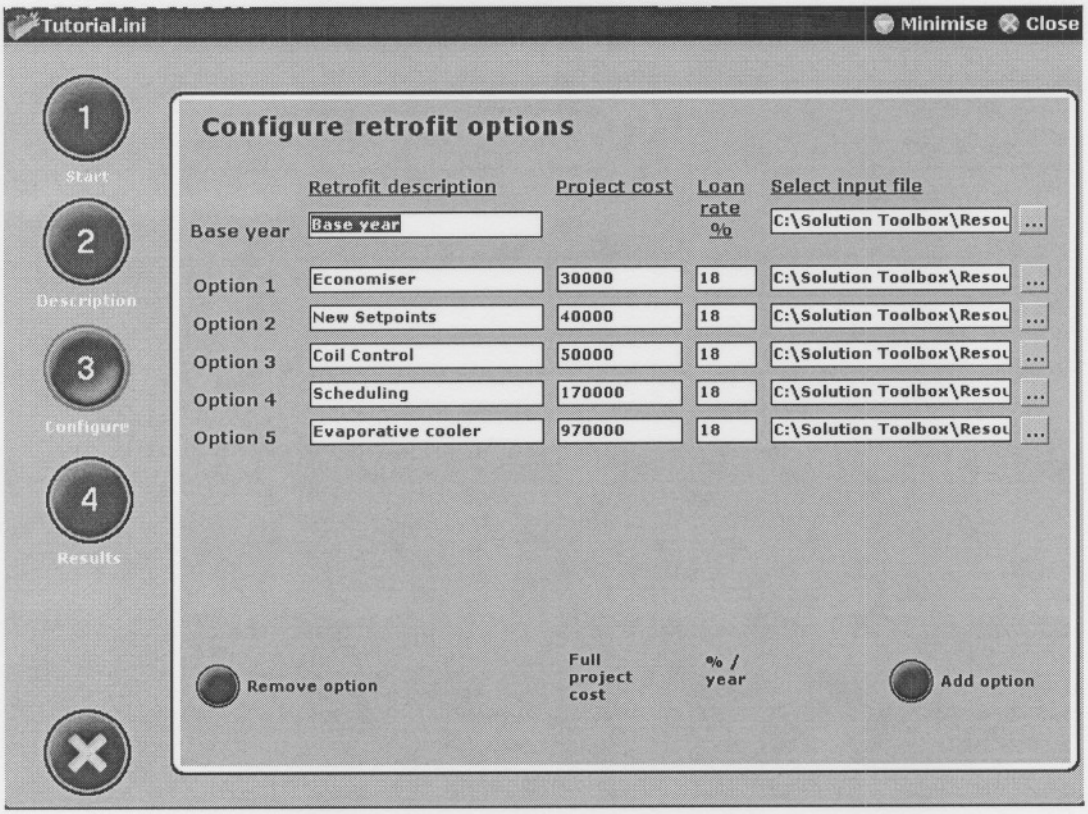


Figure 3: Economic analysis configure screen

The user must enter a descriptive name for the base year simulation project. In the *Select input file* section, the user can link the relevant file created by *ETB-Simulate* to the particular retrofit. Other retrofit options can be added to the project by pressing the ADD OPTION button. For each retrofit added the user must enter a descriptive name, as well as the cost of the project, the capital loan rate, and link the relevant file to the retrofit in the same manner as the base year simulation.

RESULTS

The results that are displayed is divided into four groups, namely Calibration and Verification, Cost breakdown, Electricity cost saving, and Financial analysis.

The CALIBRATION and VERIFICATION screen is shown below.

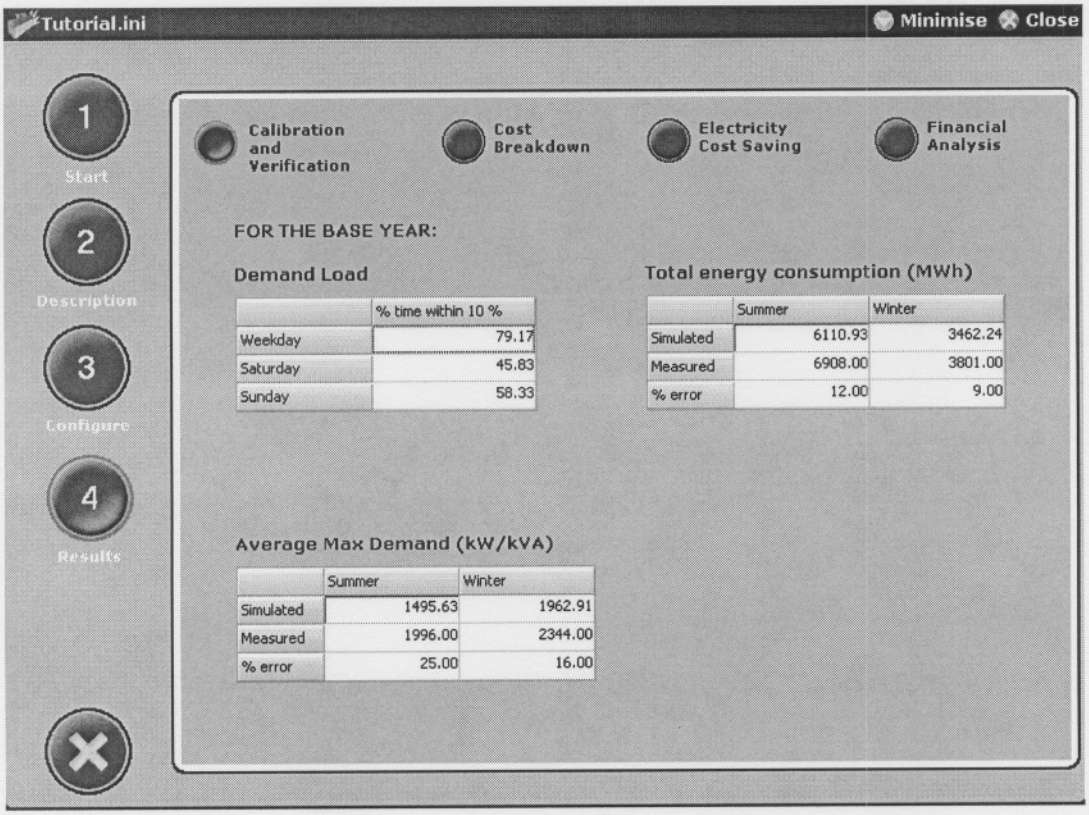


Figure 4: Calibration and verification screen

The CALIBARATION AND VERIFICATION screen gives a summary of the results obtained from *ETB-Simulate.*

The figure below displays the COST BREAKDOWN interface.

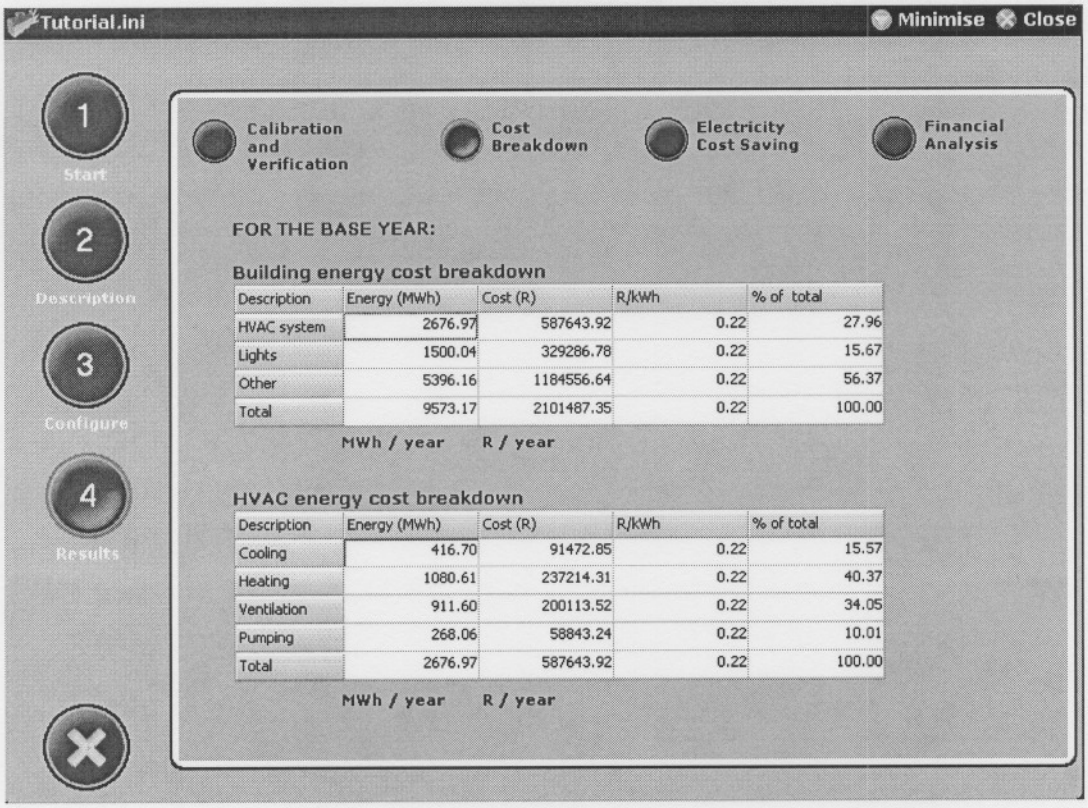


Figure 5: Cost breakdown screen

This interface displays the building energy cost breakdown and the HVAC system energy cost breakdown. The building energy cost breakdown is broken down in the subsections of HVAC system, lights, other and total. The HVAC energy cost breakdown is divided into cooling, heating, ventilation, pumping and total. The energy, cost, cost per energy and the percentage of the total are given for each of these sections.

The ELECTRICITY COST BREAKDOWN interface is shown below.

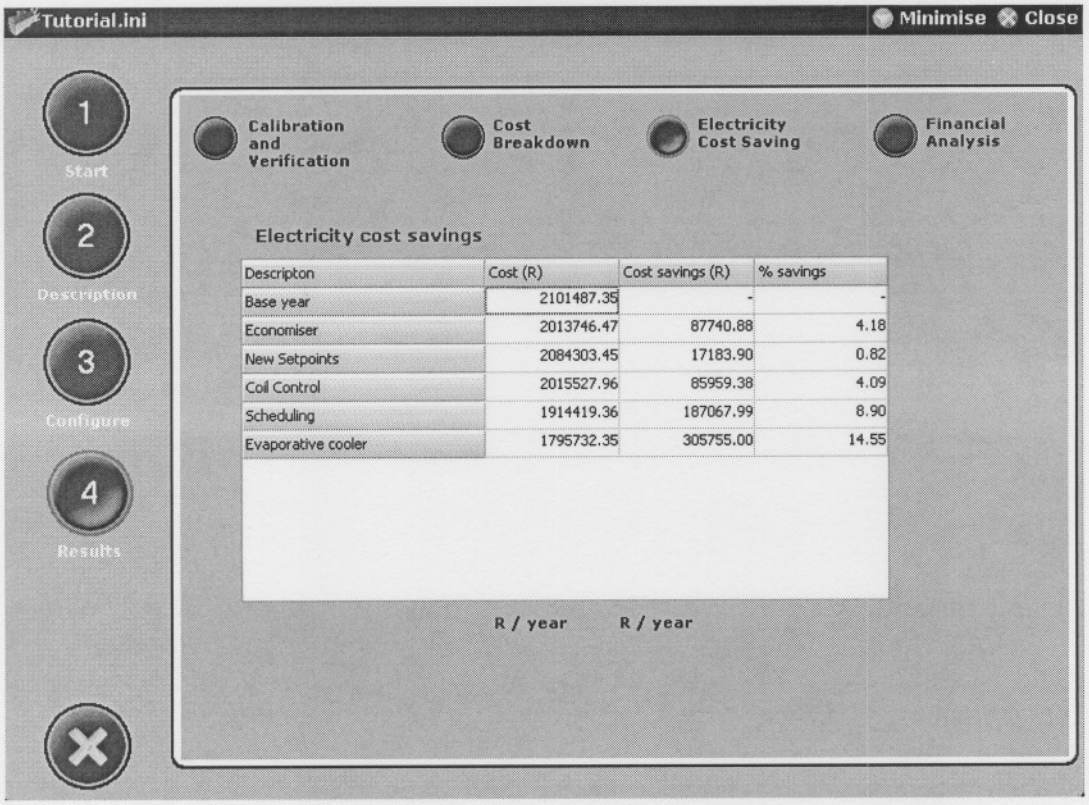


Figure 6: Electricity cost saving screen

This interface displays the cost, cost saving and percentage saving for each of the retrofits specified in the CONFIGURE section.

The interface of the FINANCIAL ANALYSIS interface is shown below

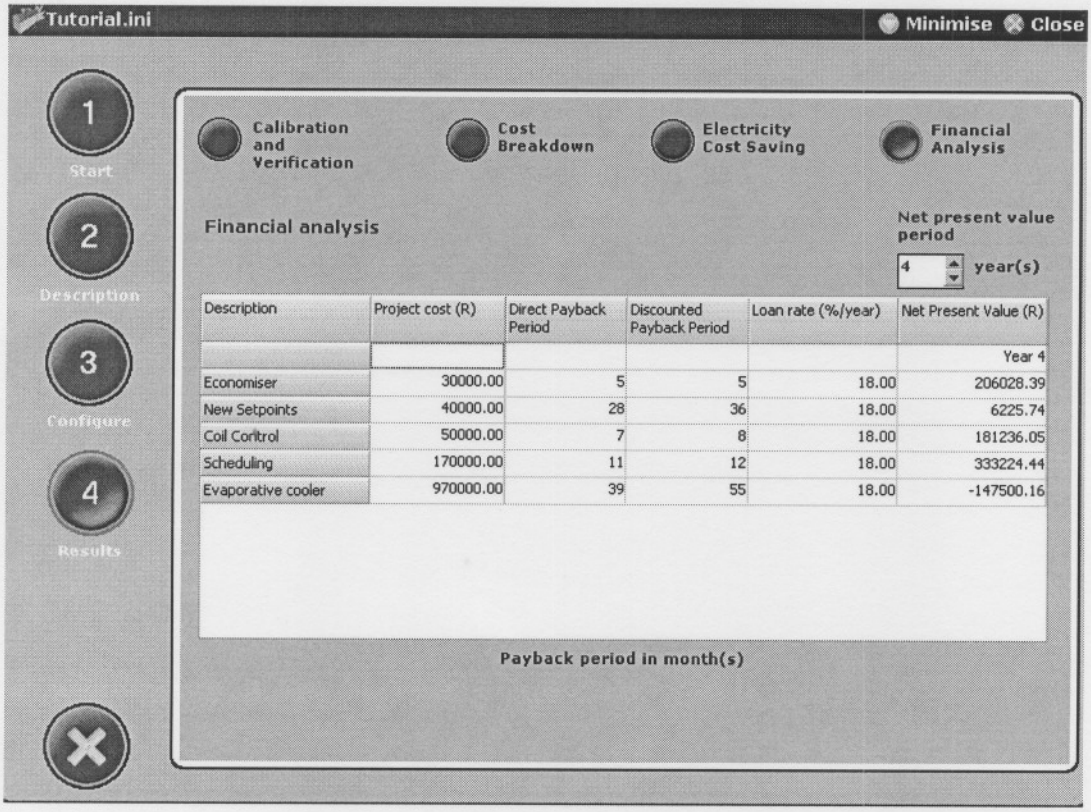


Figure 7: Financial analysis screen

This interface displays the most important information required to compare the various retrofits and to make a recommendation for energy saving in the building. For each retrofit the total project cost, the direct and discounted payback periods, the loan rate and the net present value over a user specified time is show.