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A FRAMEWORK FOR HVAC CONTROL AT A TERTIARY INSTITUTION

by

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ABSTRACT

Most utility's and electricity resellers stimulate changes in their load shape through various demand side management activities. The most common way of altering their load shape is through the implementation of different tariff structures. The thesis investigates the effect of combining hot water load control with heating ventilation and air-conditioning load control to reduce the electricity costs due to a demand tariff that is a direct result of demand side management. The entire study is focused on the demand tariff of the University of Pretoria. Although the study was done on the University of Pretoria the methods developed are universal and can be implemented in any situation where hot water load control and heating ventilation and air-conditioning load control are to be combined.

The study presents a detailed literature study on the current developments in the field of hot water and heating ventilation and air-conditioning load control. No current work could be found in which the two control methods are combined. Models were developed for controlling the electricity load and for determining the savings. The heating ventilation and air-conditioning load's and the hot water load's uncontrolled load models respectively had a mean absolute percentage errors of 3.83% and 3.2%. The forecasting method used to determine the available energy for pre-cooling and the start time of shedding had a mean absolute error of 3.2%.

A case study of the University of Pretoria was done. The effect of using only hot water load control is presented. The case study was expanded to include structural thermal energy storage and then water thermal energy storage. This expansion was done using the HVAC system in combination with the hot water load control system. With an only 10.3% contribution to the university's maximum demand, the hot water load control reduced the university's electricity account (energy + demand) by 5.44%. The heating ventilation and air conditioning load contribute to 6% of the university's maximum demand. With the structural thermal energy storage using the heating ventilation and air conditioning system, the savings increased to 6.12%. With the addition of a 750m^3 water thermal energy storage tank to the heating ventilation and air-conditioning system, the savings increased to 7.14%.

Keywords: heating ventilation and air-conditioning, load management, electrical load control, hot water load control, thermal energy storage

OPSOMMING

Meeste elektrisiteitsvoorsieners en herverkopers van elektrisiteit stimuleer veranderinge in die vorm van hul verbruikspatrone deur van verskillende soorte aanvraag-bestuursmetodes gebruik te maak. Die algemeenste manier om die veranderinge te veroorsaak is deur die implementering van verskillende tarief-strukture. Die verhandeling ondersoek die effek van die kombinering van warm-water-lasbeheer met lugversorger-lasbeheer om aanvraagkostes te verminder. Die aanvraagkostes is 'n direkte gevolg van aanvraagsbestuur deur die elektrisiteitsvoorsieners of die herverkopers van elektrisiteit. Die verhandeling is toegespits op die aanvraagtarief van die Universiteit van Pretoria. Die modelle wat ontwikkel is, is universeel en kan enige plek toegepas word waar warm-water-lasbeheer en lugversorger-lasbeheer gekombineer word.

Die verhandeling lewer 'n gedetailleerde litratuurstudie waarin die huidige ontwikkelinge in die veld van warm-water-lasbeheer en lugversorger-lasbeheer bespreek word. Geen werk kon gevind word waarin die twee tipes beheer gekombineer word nie. Modelle is ontwikkel om die elektrisiteitslas te beheer en om die besparings as gevolg van die lasbeheer te bereken. Die warm-water-beheer en lugversorger-beheer se onbeheerde lasmodelle het gemiddelde persentasie-foute van 3.83% en 3.2% respektiewelik, gehad. Die voorspellingsmetode wat gebruik is om die beskikbare energie vir vooraf-verkoelling en die aanvangstyd van die lasverskuiwing te bepaal, het 'n gemiddelde persentasie-fout van 3.2% gehad.

'n Gevallestudie is van die Universiteit van Pretoria gedoen waarin die effek van die warm-water-lasbeheer voorgelê is. Hierdie studie is uitgebrei om strukturele-termiese-energie-stoor en water-termiese-energie-stoor met die gebruik van die lugversorgers in te sluit. Met slegs 'n 10.3% bydrae tot die universiteit se maksimum verbruik, het die warm-water-lasbeheer die universiteit se rekening (energie + aanvraag) met 5.44% verminder. Die lugversorgers vorm 6% van die universiteit se maksimum verbuik. Met die byvoeging van die strukturele-termiese-energie-stoor deur middel van die lugversorgersisteem is die besparing verbeter na 6.12%. Deur die byvoeging van 750m^3 water-termiese-energie-stoor tot die lugversorgersisteem is die besparing na 7.14% verbeter.

Sleutelwoorde: elektrisiteitslasbeheer, lugversorger-beheer, warm-water-lasbeheer, elektrisiteitsvoorspelling, termiese-energie-stoor

LIST OF ABBREVIATIONS

IF	Interface
LF	Load factor
HVAC	Heating ventilation and air-conditioning
DSM	Demand side management
RDSM	Residential demand side management
CDSM	Commercial demand side management
TES	Thermal energy storage
COP	Coefficient of performance
MAPE	Mean absolute percentage error

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1 INTRODUCTION

This chapter is initiated with a background consisting of the reasons for the current energy management as well as the desired position of energy management at the University of Pretoria, which motivated this study. The background is followed with a literature overview of the university's energy management problems. Due to the lack of solutions found in the literature for the university's energy management problems, a problem statement and main and specific objectives were formulated.

1.1 Background

The uncoordinated use of electricity can add up to extremely high electricity bills. These bills push up the running cost of the company or institution. The controlling of electricity consumption is therefore solely done for the purpose of reducing electricity cost, which in return lower running costs. It is thus important to control based on the billing tariff. These billing tariffs are set by the supply utility to stimulate the demand side in order to reduce their peaks to save money. If the peaks are not reduced the supply side will have to use expensive peak demand power stations. This process is known as demand side management (DSM) because the utility indirectly stimulates activities such as load shedding, strategic conservation, peak clipping and valley filling through the different tariff structures [1]. When billed based on a time-of-use tariff, the emphasis will be on the shifting of the energy to the cheaper energy periods of the time-of-use tariff. When billed on a demand tariff, the emphasis will be on peak reduction [2]. For example, take the University of Pretoria. The university is billed on a two-part tariff (energy + demand) over half an hour integration periods. This means that for the university the emphasis is placed on obtaining a unity load factor through peak reduction and valley filling. The first step that the university took towards reaching a unity load factor was to control the hot water cylinders on Main and Lynnwood campuses. This was done because the two campuses are fed from the same substation, and billed together, they form the largest part of the university's electricity bill. The largest part of the residences and student communes that contain 2,8MW of hot water cylinders with a controllable load of 1.3MW, are also situated on these two campuses. Utilising the controllable load through the installation of radio controlled load switches for the switching of the hot water cylinders, the university has managed to save an average of 5,5% per month on their electricity cost during the year 2000. With the control in place, the average cost of 22 c/kWh for electricity has been reduced to less than 20 c/kWh. This is still far away from the desired marginal cost of 16.14 c/kWh per unity load factor. The current load factor, with the hot water control in place, is between 0.6 and 0.7. To obtain load factors of 0.7 with the hot water control of the university, the hot water cylinders have to be switched off for long periods without any cycling. This will result in unwanted cold water. A load factor of about 0.65 is more realistic with the hot water control. To further improve the load factor without providing the hostel students with cold water, another energy consumer that has a storage capacity like a capacitor, had to be found. The other major consumer of electricity on campus, with energy storing capacity, was identified as the heating ventilation and air-conditioning (HVAC) systems located in the lecture halls, library and office buildings. In conjunction with the hot water cylinders it was decided to target some of the larger air-conditioners on campus to further improve the load factor of the university. By targeting the air-conditioners and hot water cylinders, the university is acting as an experimental DSM town with residential (RDSM) and commercial (CDSM) loads being controlled. From a single user point of view, the controlling methods implemented at the university are also applicable to commercial buildings with large amounts of hot water heating like shopping centres and offices that has residential living units, hotels, etc.

1.2 Literature study

To do the scheduling of the HVAC and hot water load control the literature research can be divided into the following five topics.

- ☐ *DSM and tariffs*: DSM and tariffs is the first to be covered in the literature study. This is because DSM, through tariffs, forms the motivation behind the energy management process at the university.
- ☐ *Control of HVAC's using thermal energy storage (TES)*: One of the energy management elements is the centralised HVAC. This section covers the research and experiments done on HVAC control for peak clipping. This will give an indication of what is possible, what works and what still needs to be done to implement HVAC load control at the university.
- ☐ *Control of hot water cylinders using TES*: This section will help to understand the process of hot water load control currently implemented at the university.
- ☐ *HVAC models*: This section covers the HVAC models that were developed for the HVAC units at the university during the research. These models could be useful in the understanding and modelling of the HVAC processes at the university.
- ☐ *HVAC constraints*: International health and safety regulations related to HVAC's exist that have to be adhered to. The control of the HVAC's must take place within these constraints. This section gives a brief overview of the constraints.

1.2.1 DSM and tariffs

According to Gellings [5] DSM activities are those activities that involve actions on the demand or customer side of the electricity meter, either directly caused or indirectly stimulated by the utility. These activities include load management, strategic conservation, increased market share and other behind-the-meter actions. This study focuses on the load management part of DSM. Load management encompasses the following categories: peak clipping, valley filling, load shifting and strategic conservation.

The billing tariff will steer the way in which the load management is going to take place. There are 7 basic tariff structures [6]: flat rate, single energy tariff, two-part tariff, demand tariff, time-of-use tariff, real-time pricing tariff, special deals tariff and commodity pricing [7]. Variations on these tariff structures exist. The university is billed according to a demand tariff from the City Council of Tswane. The City Council is a reseller of electricity that they buy from Eskom. Eskom is South Africa's national electricity generator and grid operator. The load management strategies in this thesis are therefore going to be done for a demand tariff. The building owners that can gain from this study are mostly on this tariff. The demand tariff of the university consists of two parts: the energy charge and the maximum demand charge. This means the university pays R/kVA + c/kWh. The energy cost is calculated from the number of consumed energy units during the billing month. The maximum demand cost is calculated taking the highest kVA half hour integrated demand period for the billing month. It is thus advantageous for the customer to clip his peaks by filling the valleys to keep his monthly peak as low as possible. This is done to avoid a high cost for the demand part of the electricity cost. The following example will best illustrate the cost of creating a peak. The university currently (July 2001) pays R 46.88 / kVA and 9.98 c/kWh.

In the example's calculations it is assumed that the university has a power factor (pf) = 1. If the university switches on a 100 kW electrical motor in the mechanical or electrical laboratories during a non-peak demand half hour it would cost the university an extra:

$$\begin{aligned}
&Cost = Energy * Cost\ \ For\ \ Energy \\
&Cost = 50kWh * R0.0988 / kWh \\
&Cost = R4.94
\end{aligned}$$

Only the energy part is considered in the calculation because it is outside the maximum demand half hour. If the same motor was switched on during the maximum demand half hour it would cost the University an extra:

$$\begin{aligned}
&Cost = Energy * Cost\ \ For\ \ Energy + Demand\ \ Added * Cost\ \ For\ \ Demand \\
&Cost = 50kWh * R0.0988 / kWh + 100kVA * R46.60 / kVA \\
&Cost = R4.94 + R4{,}660 \\
&Cost = R4{,}664.94
\end{aligned}$$

From the above example the benefit to rather switch on the electrical motor outside the maximum peak demand period than during the maximum peak demand period is clear. Reducing peak without creating a new peak would have the opposite effect in terms of savings.

Gellings [5, pp.17-32] suggested four types of logic for controlling demand.

Ideal rate accumulates and compares the actual rate of energy used during the demand interval with a predetermined ideal rate of use. As the consumption reaches the ideal rate, load is shed.

Converging rate is the same as the ideal rate except that the ideal rate's shed rate and restore rate converge at the end of the demand interval. In this way a finer control is established as the end of the interval comes nearer.

Instantaneous demand control continuously monitors and compares the usage to the desired maximum demand. At the desired point, load is shed. The load is then restored when a lower offset is reached. With this method cycling throughout the interval is easily obtained.

Forecast type control continuously monitors the consumption during the integration period. Using the already measured consumption, the consumption at the end of the integration period is forecasted. If the forecasted value is larger than the set point, load is shed and visa versa for restoring.

1.2.2 Control of HVAC's using TES

Morris et al. [8] conducted experiments to compare night setback control with dynamic building control. The building's thermal energy storage was used with the dynamic building control. In the experiments Morris recorded that a 7 cm thick concrete slab sub-cooled to 6°C has 254 Wh/m^2, this is about a ¼ of a building's cooling load for a twelve-hour day. A 7 cm concrete slab is regarded as light concrete. The buildings at the university with heavy concrete slabs could store more energy. Morris recorded peak reductions of up to 40% and energy reductions of up to 15% with dynamic control. The energy reduction was due to the low outside temperature experienced during the night, which improved the system efficiency. Morris concluded that night setback control may minimise energy consumption but does not minimise cost due to peak demand tariffs. Dynamic control minimises cost if billed on a demand or time of use tariff.

Using dynamic control in his simulations, Braun [9,10] published two papers on the use of TES to reduce electricity costs of cooling. His first paper focused on building TES and the second paper incorporated ice storage. He developed building, cooling system and weather models to do the dynamic control. His dynamic control took into account demand and time of use tariffs. Braun optimised either to energy or to peak reduction and not to both. Braun ignored the HVAC components' dynamics due to his 24 step discrete optimisation. Braun recorded savings of 0% – 50% using the dynamic control. The savings varied depending on the case examined.

Kintner-Meyer et al. [11] did experiments on building TES. The experimental building was a lightweight building and had additional water storage. The dynamics of the HVAC components were taken into account. Kintner-Meyer's paper included a comprehensive explanation of the mathematics used to do the control. Savings of ± 10% were recorded using the building TES and dynamic control. Savings increased to ± 52 % when the water storage tanks were included.

Using predictive control Henze et al. [12] developed an optimal predictive control algorithm to use with real time pricing that does not have a demand charge. The predictions were done using auto-regression formulas. Henze included a comprehensive explanation of the prediction mathematics. The HVAC system's imperfections were also taken into account with the predictions. Henze concluded that in the presents of complex rates the predictive controller performed better than conventional systems. Savings of 31% were recorded with the optimal control and 18% with priority control.

Snyder et al. [13] found cost savings of 18% and Andresen et al. [14] found peak reductions of as much as 50% with dynamic control over setback control. The simulations were applied to lightweight buildings.

Experiments conducted by Ruud et al. [15] were done on an in-use building in Jacksonville, Florida, USA. The building employed was of a lightweight construction. A simple pre-cooling strategy was used. The maximum pre-cooling was done during unoccupied times. Due to the high humidity of Florida no night ventilation was possible. The pre-cooling maximised the load shifting possibilities, but increased the overall energy consumption of the building. If no high peak charges are applicable this method could become more costly than setback control.

Conniff [16] built an office room replica at a testing facility. Simple control strategies were employed and compared against night setback control. By pre-cooling the room to the daytime set point 6 hours in advance, the peak-cooling load was reduced by 28% more than in the case of night setback control. Conniff then experimented with letting the temperature set point drift upwards toward the end of the working day. This resulted in a 10% reduction in peak. Conniff concluded that combining pre-cooling with set point drift could greatly reduce peak cooling loads.

Spratt et al. [17] described the implementation of an optimal control system at a Canadian university. Part of the optimal control was done using a load predictor. The predictions were done using weather forecasts. Spratt did not do cost analysis, but found that the perceived thermal comfort of the building improved.

Using linear difference equations to describe the system and its reactions, Daryanian et al. [18] experimented with the development of an optimal control model to use with TES. He concluded that more work needed to be done in characterising the linear differential equation models in the case of TES and complex building processes.

Diana et al. [19] from the University of Natal is working on HVAC load shifting. This is the only South African tertiary institution that has energy management equipment installed to reduce their peak-cooling load. Their main energy storage is a large TES tank that is connected to the HVAC cooling plants. The TES tank gives them the ability to shift 24% of their total load of 5,5 MVA to off-peak times. This is currently their only exploited load shifting opportunity.

The following are published case studies using TES. Akbari et al. [20] did studies on two buildings with ice storage and found a reduction of 55% on peak demand. Abouzelof [21] is the chief engineer at a large office complex with a newly built shopping mall next door. The shopping mall's cooling load is supplied from a 10500 ton-hrs water TES tank. The

TES water is cooled during the office complex's off-peak periods using its HVAC plant. The peak electricity cost is therefore reduced with the equivalent energy consumption of a 448 ton-hrs HVAC system that would have been installed in the shopping mall. Texas instruments [22] installed TES tanks at two of their plants. The two plants recorded peak reductions of around 12 %. Williams [23] initiated the installation of a TES system at Pomerado hospital during major renovations to the hospital. The TES system had a payback period of 4.2 years, with savings of $27,000 per annum. Milton Meckler [24] integrated the fire sprinkling system with the HVAC system. The thermal energy storage obtained with the sprinkler system resulted in annual savings of 25%.

1.2.3 Control of hot water cylinders using TES

Delport [2] developed a simplified load model for a single hot water cylinder. This model is of a generic nature and can be applied to any energy storage hot water cylinder. The single cylinder model is expandable for the modelling of a group of cylinders. Delport also described the factors that affect the control of the university residences' hot water load.

Wilken et al. [25] discussed the differences between centralised and decentralised hot water load control. Centralised gives optimum benefit to the supplier and decentralised gives optimum benefit to the end-user. Wilken explained the effect of holidays on the hot water load control. The process of notch testing to determine the load consumption of the end-users is explained. The consumption is calculated using the ADMD (after diversity maximum demand) graphs obtained through the notch tests. Wilken discussed the process of configuring the end-user groups used in the shedding control algorithm.

Van Harmelen et al. [26] looked at the effect that optimal control of hot water load would have on Eskom's load profile. Van Harmelen also stated that better tariff signals would stimulate optimal control of the utilities' load profile. Jooste et al. [27] did statistical analysis to formulate models for centralised utility control. Beute [28-29] researched the effect of hot water load control on the national grid. Forlee [30] calculated and stated the cost benefits of hot water load control for the electricity utility.

1.2.4 HVAC models.

This section gives a short literature overview of models developed for the simulation of the HVAC's at the University of Pretoria or generic HVAC models that was tested on university buildings.

Arndt [31] developed detail models for three of the air-conditioners situated on the University of Pretoria campus. This was done to study retrofit options and their payback periods. The models for the HVAC's of the Engineering Tower, Chancellors Building and Education Building included models for the chillers, cooling towers, cooling coils, air supply fans, condenser water pumps and chilled water pumps. Arndt concluded that the models were accurate and retrofitting could save large amounts of money.

As one of his case studies Grobler [32] targeted the Merensky Library's HVAC system for his holistic approach to retrofitting. For the retrofitting study he developed detail models to use in simulations of the HVAC system. In the modelling he included models for the indirect evaporative cooler that was installed on his recommendation. Changes made to the control system by Grobler after simulations, improved the HVAC's operating efficiency and indoor comfort. A detailed description of the Merensky HVAC system was included.

Piani [33] developed models to evaluate HVAC retrofitting benefits for buildings. The Merensky Library was one of the buildings the models were tested on. Detailed descriptions of the HVAC parameters were included in the thesis. Piani concluded that retrofitting the Merensky would improve comfort and lower the energy bill. Piani also stated that the chillers in the Merensky Library was only utilised to half of its capacity on a very hot day.

In developing models to simulate the thermal performance of a building, Van Heerden [34], in one of his case studies, tested his thermal model on the Engineering Tower. An office on the ninth level was turned into an experimental room. A description was given of the construction material parameters of the Engineering Tower that were used as inputs to the thermal models.

1.2.5 Air conditioning constraints

In controlling and shifting the energy consumption of the air-conditioners adherence must be given to the limitations and constraints set by international standards to ensure indoor comfort and prevent sick building syndrome. Sick building syndrome [32, pp. 4] is the ailments that people have when they are inside the building but which stop when they leave the building. The following are symptoms of sick building syndrome:

- ☐ Headache,
- ☐ Runny nose,
- ☐ Fatigue,
- ☐ Eye irritation,
- ☐ Difficulty breathing,
- ☐ Sinus problems,
- ☐ Congestion,
- ☐ Sneezing,
- ☐ Nausea,
- ☐ Sore throat, and
- ☐ Stuffy smells.

Grobler [32, pp. 4 and appendix CIII] defined the following constraints to ensure indoor quality.

1.2.5.1 Indoor temperature

There are two internationally accepted standards for the indoor temperature of a conditioned building.

ISO standard 7730: The summer temperature must range between 23-26 °C.

ASHREA-standard 55-1981: The summer temperature must range between 22.8-26.1 °C.

The higher temperatures can still cause sick building syndrome even though the temperatures are within indoor temperature specifications.

1.2.5.2 Relative humidity

The relative humidity must be between 40% and 60% the whole year. This specification is set because below a 40% relative humidity bacteria growth, respiratory infections and allergic reactions increase; and if the relative humidity exceeds 60% mould, dust mites, allergic reactions and chemical interactions escalate.

1.2.5.3 Indoor air quality

Fresh Air supply: The ASHRAE specification requires a minimum of 10 l/s of fresh air for a non-smoking area and 20 l/s for a smoking area. The recommended air supply to avoid sick building syndrome is at least 15 l/s.

Air movement: The specification for the air movement in a specified space is 4,5-6 $l/s/m^2$.

CO_2: In the case of a lack of fresh air-supply to a conditioned space the amounts of CO_2 may increase. The specified amount of CO_2 is 600 ppm.

CO: In the case of a lack of fresh air-supply to a conditioned space the amounts of CO may increase. The specified amount of CO is 9 ppm, but 2 ppm is recommended.

SO_2: In the case of a lack of fresh air-supply to a conditioned space the amounts of SO_2 may increase. The specified amount of SO_2 is 0.02 ppm but 0.3 ppm is allowable for a maximum of 1 hour.

NO_2: In the case of a lack of fresh air-supply to a conditioned space the amounts of NO_2 may increase. The specified amount of NO_2 is 0.05 ppm but 0.2 ppm is allowable for a maximum of 1 hour.

Dust particles: There are currently no specifications available with regard to dust particles in the air.

1.3 Problem situation

In order to get the maximum benefit of the two-part tariff, the largest amount of movable peak energy has to be shifted to off-peak times without creating a new peak. This means that proper combined scheduling of the HVAC load and hot water load load shedding has to take place. No current literature could be found where this kind of combined scheduling had been done. It would also be very time-consuming and costly for an operator to do the scheduling every day. The operator would also not be able to do the scheduling real-time, which means that the control might not be optimal. A method has to be developed that will enable load controllers to automatically do the scheduling in real-time. With the real-time scheduling the controllers would also have to be in constant communication, thus a communication protocol needs to be clearly defined to ensure that the controllers know what to do and when to do it.

The reduction in the utility's peak as a result of load shifting through the end-user not only provide capital savings but also a solution to the following situations.
Unemployment: A five percent increase in electrical energy efficiency in South Africa by the year 2001 would lead to a net increase in jobs of 39 000 [3].
New power station: If enough people apply the load shifting opportunities presented to them, it will delay or stop Eskom from having to build a new power station that could cost millions and increase electricity prices [4].

It is therefore crucial to develop a cost effective and easy to use system for property owners to do load shifting with their HVAC's and hot water cylinders.

1.4 Objectives

The main and specific objectives of this research project are as follows.

1.4.1 Main Objective

To develop a framework for a load controller that integrates HVAC control with hot water load control, to reduce peak demands. With the addition of the HVAC control the peak demand must further be decreased and consequently help to take some pressure of the hot water load control system, resulting in higher end-user comfort for the hot water users. The implementation of the HVAC control at the university must improve the university's load factor to more than 0.7.

1.4.2 Specific objectives

In order to obtain the main objective the following specific objectives need to be satisfied.

Uncontrolled load: Developing a model to determine the uncontrolled load of the university to be used in the control calculations and load forecasting. The uncontrolled load must be a true reconstruction of the load profile, as if there were no hot water load shifting and HVAC load shifting done. This reconstruction must include the load shifted through the hot water cylinders and HVAC's. The HVAC and hot water load uncontrolled load constructions must have a smaller than 5% mean absolute percentage error (MAPE).

Forecasted profile: Developing a model to forecast the next day's load profile with a smaller than 5% MAPE. The forecasted profile is used to determine the schedule for the hot water load and HVAC load shedding. The amount of energy to be shifted and the available system energy for the HVAC pre-cooling are calculated from the forecast. Pre-heating of the hot water load is naturally part of the uncontrolled load profile and does not have to be calculated. The forecasting is done with the uncontrolled load data so that a true reflection of the load that must be shifted can be found.

HVAC models: Developing thermal models for the HVAC systems and the buildings under control. These models are going to be used with the forecasted profile to calculate the start of pre-cooling and the amount of pre-cooling necessary. The pre-cooling has to be done as close as possible to the start of shedding to minimise thermal losses. The HVAC models must have a MAPE smaller than 5%.

Load Controller: Developing a communication system between the controllers so that the controllers always know what they must do and when they must do it.

1.5 Conclusion

From the literature it is clear that the utilities aim to enforce DSM through the structuring of tariffs. Gellings [5] suggested different techniques to control demand during the integration period. These techniques can be applied to any type of tariff.

Morris et al. [8], Braun [9-10], Kintner-Meyer et al. [11], Henze et al. [12], Snyder et al. [13], Andresen et al [14], Ruud et al. [15], Conniff [16], Spratt et al. [17], Daryanian et al. [18] and Diana et al. [19] developed models for building, water, ice or eutectic salt thermal storage or their integration to do load shifting. Savings of 0%-55% were recorded.

Akbari et al. [20], Abouzelof [21], Fiorino [22], Williams [23] and Meckler [24] reported on practical installations where TES is in use and on its advantages to the owners. The savings ranged from 12%-55%.

Delport [2] developed models to use in the control of hot water. Wilken et al. [25] discussed the process of load shifting and end-user group configurations.
Van Harmelen et al [26], Jooste et al [27], Beute [28-29] and Forlee [30] described load control as seen from the utility.

Arndt [31], Grobler [32], Piani [33] and Van Heerden [34] developed different HVAC component models, which were tested on buildings at the university.

Grobler [32] gave a detailed analysis of the indoor air quality that has to be maintained in a building. The control of the HVAC's must be done within these constraints.

No literature references could be found where RDSM using energy storage of hot water cylinders and CDSM using energy storage of HVAC's were integrated to improve end-user comfort and load shedding. Models have to be developed where this kind of control is used to do load shifting. Load shifting using this type of control must have a financial benefit to the property owners.

2 MODELLING METHODOLOGY

In the previous chapter the main and specific objectives were discussed. This chapter explains the thinking process of solving the objectives and the reasons why they need to be solved. To get a clear perspective of the problem solution this chapter is divided into the following two main sections and subsections.

- Current load shedding
    - Working of the hot water load control
    - Consumption patterns
- New load shedding system
    - Hot water uncontrolled load
    - Forecasting
    - Available energy
    - Pre-cooling
    - HVAC control
    - HVAC uncontrolled load
    - HVAC load controller

The energy management described in this thesis only applies to Main and Lynnwood campus, which are billed together as one. This is because they are supplied from the same substation. Their combined consumption forms the larges part of the university's electricity bill.

2.1 Current load shedding

As stated in the previous chapter the university is billed according to a two-part demand and energy tariff. With an average load factor smaller than 0.6, the university was heavily penalized by the demand part of the tariff. Some way had to be found to improve the load factor. One of the easiest solutions was to control the maximum demand through the hot water cylinders on campus. The largest portion of the hot water electricity consumption is found in the hostels. The hostels have an installed capacity in the order of 2.8 MW. This made the installation of a hot water load control system an obvious choice.

2.1.1 Working of hot water load control

Figure 2.1 illustrates the working of the hot water load control system for a single hot water cylinder.

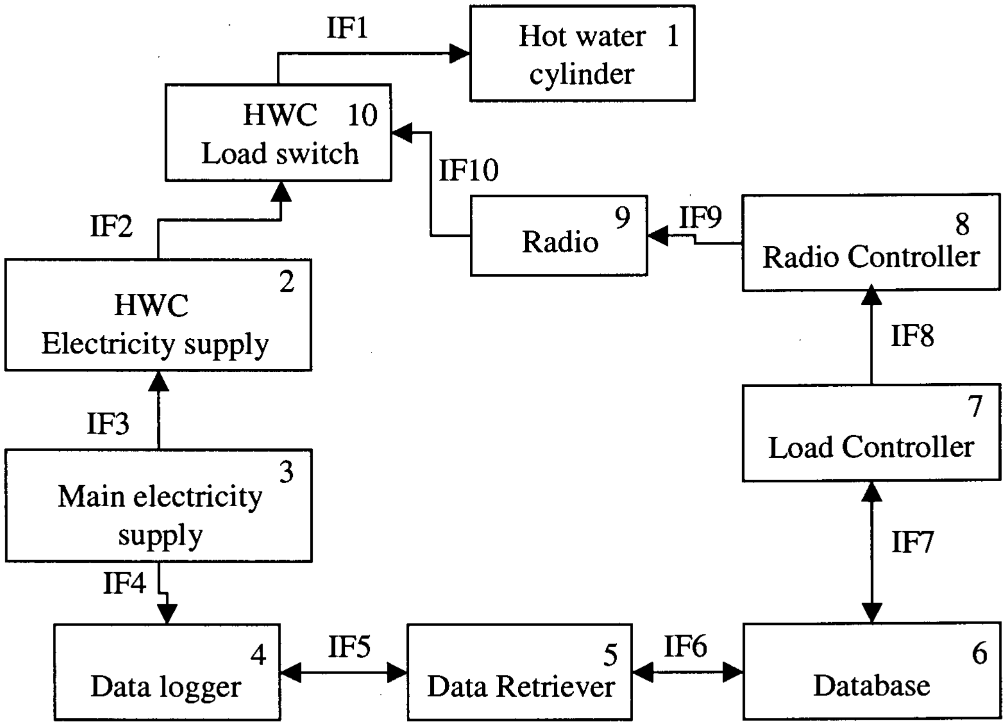

Figure 2.1. This figure illustrates the hot water load control at the university.

The component functions are as follow.

1 Hot water cylinder: The hot water cylinder is an insulated water storage tank with an electrical heating element to heat the stored water. The heated water supplies the end-users with hot water. The insulation around the storage tank and the water's thermal capacity enables the hot water cylinder to retain the heat transferred from the heating element. The heat is retained with minimal losses. This storage of the heat energy makes the hot water cylinders an ideal element for energy shifting.

2 Hot water electricity supply: The cylinders on campus are either supplied from single-phase 220V or from a three-phase 380V supply. The larger boilers (1000 litres and larger) have three phase elements. The smaller boilers have single-phase elements.

3 Main electricity supply: The university buy's 11kV three-phase electricity from the City Council. The 11kV is transformed to 380 V.

4 Data logger: Three phase energy meters measure the energy consumption. The energy consumption is averaged and logged on a one-minute interval.

5 Data retriever: The data retriever retrieves the measured data minutely from the data loggers.

6 Database: The retrieved data is stored inside the database for use by other applications.

7 Load Controller: The load controller monitors the measured energy consumption entered into the database. Using a forecasting method [5, pp. 23] the load controller predicts the half-hourly integrated consumption. The hot water cylinders are divided into groups of equal electrical capacity. If the predicted consumption is larger than the maximum preset consumption the groups are shed one by one on a rotation basis. If the predicted consumption overshoot is larger than one groups shedding capacity, multiple groups are shed at a time. Once the predicted consumption falls below the preset consumption, the groups with the longest off time is switched back on.

8 Radio Controller: The radio controller receives the information on which groups are to be shed or restored. The information is converted for transmission via radio signal.

9 Radio: The radio transmits the shedding and restoring commands to the load switches. Two repeaters located around the university strengthen the signal to improve coverage.

10 Hot water cylinder load switch: The load switch, switches the electricity supply to the hot water element on or off. This enables the load controller to remotely control the consumption of the hot water cylinder.

The different components are connected via the following interfaces (IF).

IF1: Electricity supply from the load management switch to the hot water cylinder.

IF2: Electricity supply for the hot water cylinder via the load switch.

IF3: The 11kV three-phase supply reduced to 380V three-phase.

IF4: The measured current and voltage.

IF5: The University's computer network or radio communication. An IPX protocol is used as communication base on the network.

IF6 & IF7 & IF8: The database, data retriever, load controller and radio controller communicate via the university's network, using TCP/IP network protocol.

IF9: The radio receives data using a RS232 protocol.

IF10: The radio signals send to the load switches.

2.1.2 Consumption patterns

The hot water cylinders installed capacity is not always equal to their electricity consumption at any specific time of the day. For determining the consumption pattern of a group of hot water cylinder that are not individually measured an ADMD profile needs to be generated [25]. From the ADMD profile the consumption can be calculated. Figure 2.2 shows the hot water consumption of the university.

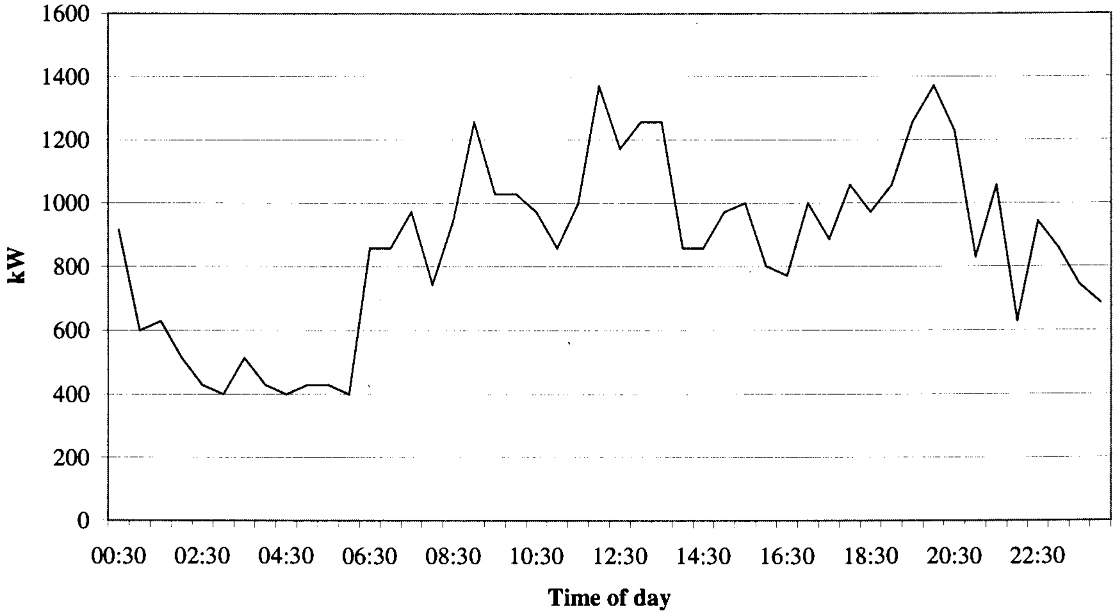

Figure 2.2. This Figure shows the university's hot water load consumption.

From Figure 2.2 three substantial peaks can be seen. These peaks occur around 8 in the morning, around twelve in the afternoon and around eight at night. The first two peaks usually occur during the university's peak period. If most of the first peaks energy is removed with shedding, the energy removed is too much to be put back before the occurrence of the second peak. This results in cold water. Currently the only way to overcome the second peak is to increase the set point. Less energy is then removed, giving the system enough time to put back sufficient heat energy to overcome the second peak without leaving the end-user with cold water.

2.2 New load shedding system

In overcoming the problematic second peak, the HVAC system, another major electricity consumer with storage capacity is going to be targeted. With the inclusion of the HVAC, hot water load will be given more recovery time, while still limiting the load at a lower set point. The hot water pre-heating, already included in the university's load profile, is done during the night until the morning's high consumption starts. The hot water load's energy consumption can thus only be moved forward as shown in Figure 2.3.

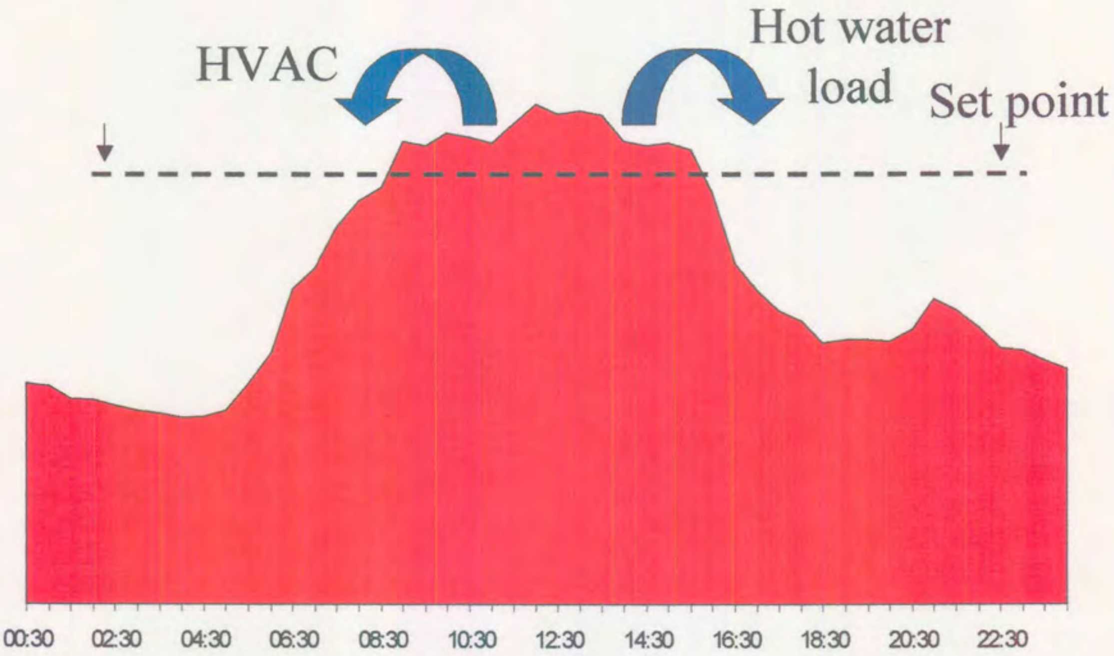

Figure 2.3. This figure shows the energy shifting done on the university's load profile.

The HVAC's is currently running on night setback control. From Figure 2.3 a large valley exists during the night and early in the mornings, creating non-demand energy consumption space for pre-cooling. The pre-cooling energy will be stored in the building envelope and system coolant. Energy will be lost due to building heat losses such as fenestration, conduction, etc [35]. The pre-cooling has to take place as close as possible to the time of shedding to minimise losses [36]. In order to determine the time that shedding has to start, the day's profile has to be known in advance. Forecasting the day's profile does this. Forecasting the profile requires the historical uncontrolled load of the university. If the forecasting were done with controlled historical data, a controlled profile would be forecasted. Therefore a wrong start time will be calculated. The profile of the university is constantly changing. Up to the previous day's uncontrolled load has to be known for an accurate forecast. The controlled load has to be reconstructed to represent the university's load without any control. The construction must be done in real-time for the forecasting to use the newest uncontrolled load data. The uncontrolled load's reconstruction has to include the hot water and HVAC control.

2.2.1 Hot water uncontrolled load

Knowing the amount of energy shed during a group's off period requires knowledge of the group's individual consumption pattern. The group's consumption patterns are constructed using notch-tests [25]. According to the first law of thermodynamics [37] the amount of energy added to the system equals the energy change of the system plus losses. Losses are included in the notch tests results. The shed energy has to be put back into the system to restore hot water's temperature. The restored energy, in a system without losses, must be equal the shed energy. The restorable energy is the difference between the installed capacity and the group's consumption pattern. The energy is restored at a rate equal to the restorable energy, until it is equal to the amount of energy shed. Figure 2.3 illustrates the construction of the hot water uncontrolled load.

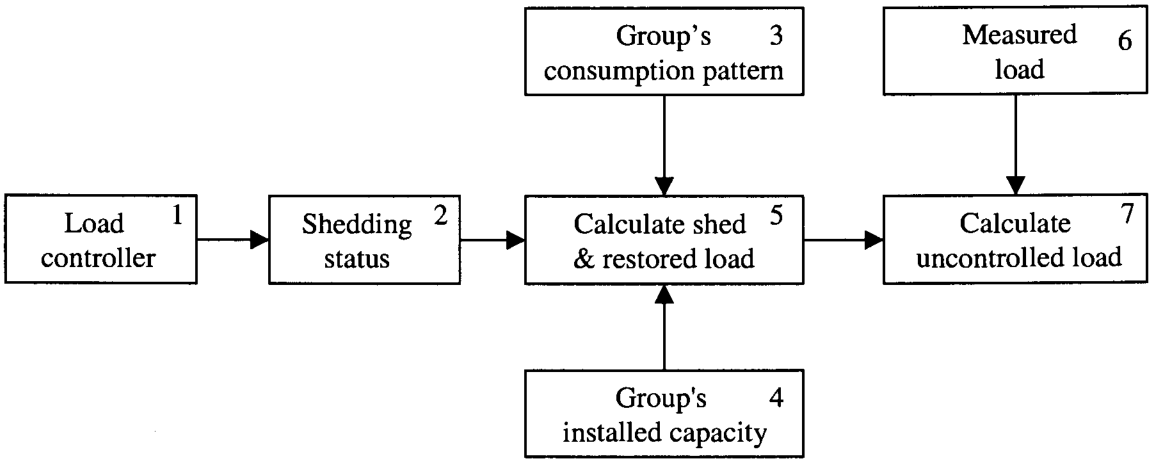

Figure 2.3. This figure illustrates the process of constructing the uncontrolled load.

The uncontrolled load construction's functions are as follow.

1. Load controller: The load controller represented in Figure 2.1.

2. *Shedding Status*: Every minute the load controller decides whether a group has to be shed or restored. The controller constructs a binary string that represents the status for each minute. A one for shed and zero for restored. This binary string is stored in the database of Figure 2.1.

3. *Group's consumption pattern*: Each group's consumption pattern is stored in the database of Figure 2.1.

4. *Groups installed capacity*: Each group's installed capacity (maximum energy consumption) is stored in the database of Figure 2.1.

5. *Calculate shed & restored load*: From the status string, if a group is shed during the minute, the energy switched off is calculated using the consumption profile. The shed energy is equal to the consumption load shed. In calculating the restored load, the shed energy is accumulated for every minute the group is shed. If the load switch status is restored, the accumulated shed energy is decreased in magnitude equal to the restorable energy. The restorable energy is the installed capacity minus the consumption load. This process continues until the accumulated energy is equal to zero.

6. *Measured load*: This is the measured load from the data loggers stored in the database of Figure 2.1.

7. *Uncontrolled load*: The uncontrolled load calculations are done through the addition of the shed load to the measured load and the subtraction of the restored load.

2.2.2 Forecasting

Determining the time when shedding has to start and the available pre-cooling energy requires the day's load profile to be known in advance. Different forecasting techniques are available for use in load forecasting. Bunn et al. [38] showed various techniques where weather and other influential factors were combined with regression models to do load forecasting. The kind of regression used differed according to the load situation.

Dillon et al. [39] suggested using neural networks to do load forecasting.

Rahman et al. [40] developed a priority vector based forecasting technique in order to do load forecasting. Makridakis et al. [41] wrote a book on economic forecasting. The book included various exponential forecasting techniques that can easily be adapted for load forecasting.

The method of using neural networks was discarded due to the long training period of the network and the number of different inputs needed for a high accuracy. The priority vector based method required to many different inputs.

For the university, the Winters exponential smoothing method described by Makridakis was selected. The temperature component like suggested by Bunn was added to the Winters method to improve accuracy. The Winters method takes into account a seasonal effect. The smallest season for the university, which is one day, was selected. This method is easy to implement, fast to train and quickly adapts to changes in the university's profile. The quick adaptation is needed due to the sudden changes that student activity can have on the university's profile.

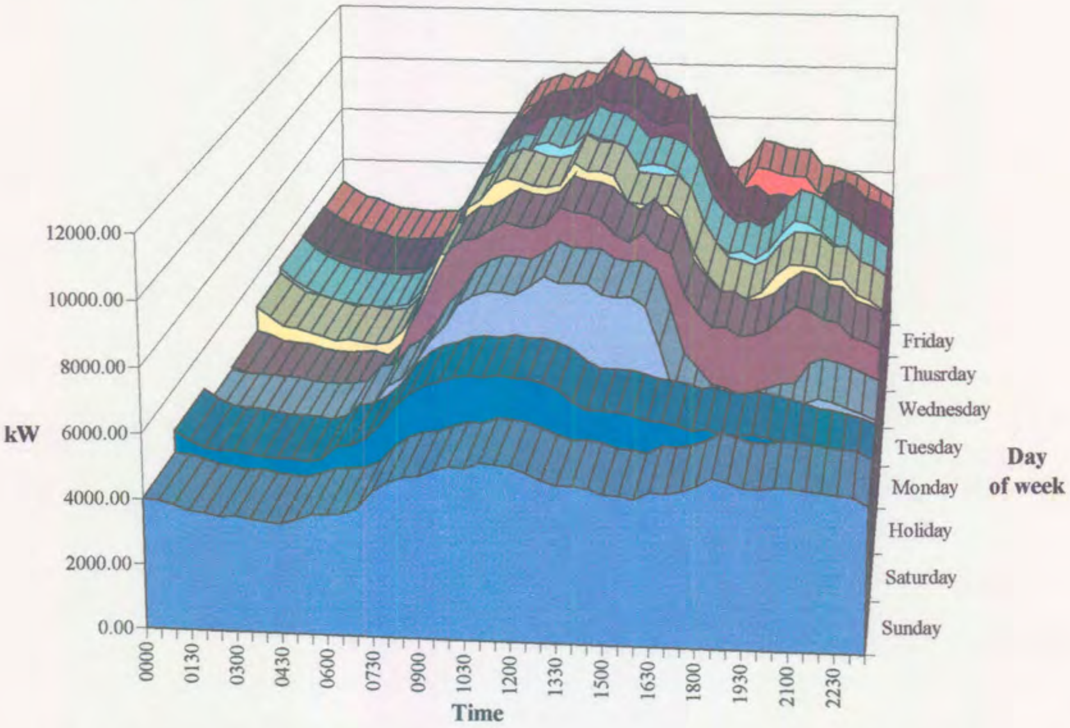

Figure 2.4. This figure shows the shape of the university's load profile for the days of the week.

Figure 2.4 was constructed for days with similar weather patterns. The maximum temperature was ± 30°C. From the Figure it can clearly be seen that each day has its own little peaks at different times. On a Monday the first peak is later than on a Tuesday, etc. These variations in the peaks are due to student activity related to their timetables and the organized social life of the residences. To over come these peaks and getting a more accurate forecast the training data set used to forecast a specific day would only consist of that day type. During student holiday's weekday are all regarded as holiday's, no distinguish is made between a Monday, Tuesday etc. This is done because the rest of the university operates as a business with fixed working hours. During public holidays and university closures the days are regarded as Sundays.

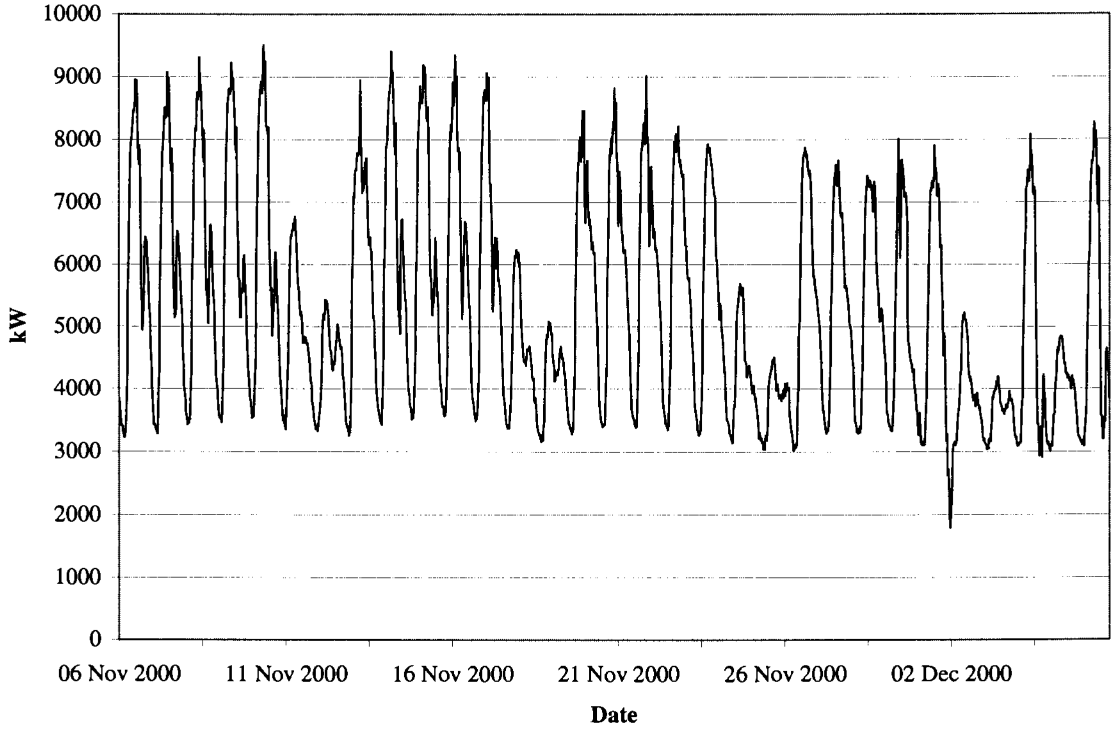

Figure 2.5. This figure shows the effect of the examination on the university's load profile.

The first two weeks of the examination is regarded as normal days. After the first two weeks and during the re-examination the weekdays are regarded as student holidays. Most students finish their examination during the first two weeks and go home. The effect can clearly be seen in Figure 2.5. The Figure includes the examination (6 Nov – 25 Nov) and re-examination (29 Nov – 6 Dec) at the end of the year (2000). The third week is usually higher but is still included with the holiday period. If shedding were necessary during the third week the hot water load and HVAC's load would be able to shed enough energy to over come peaks without wasting energy on pre-cooling.

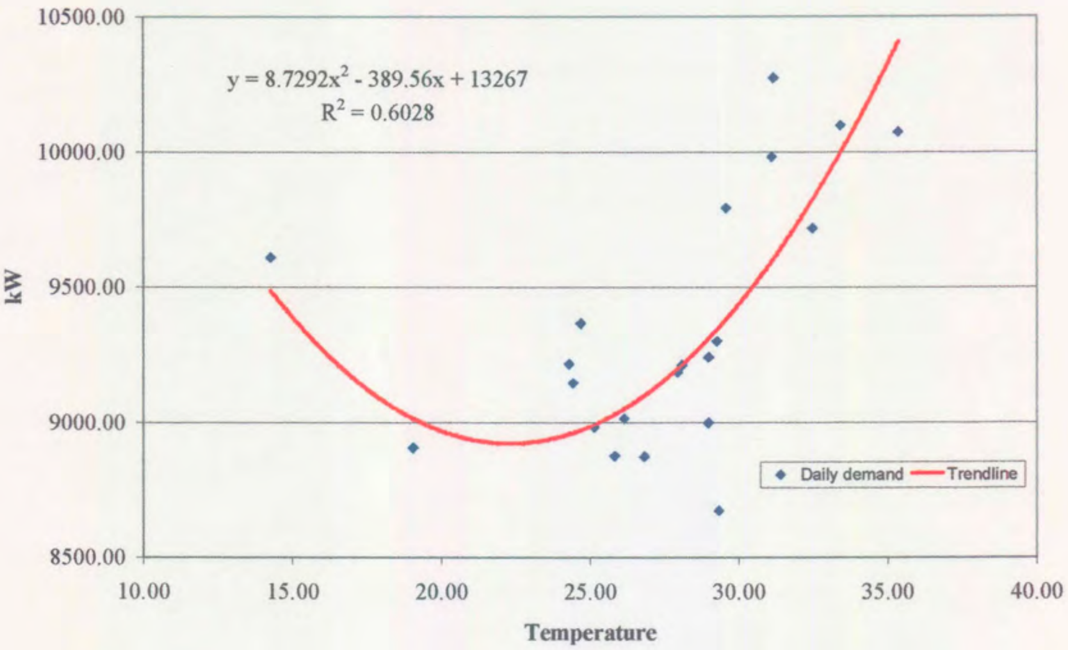

Figure 2.6. This figure shows the effect of temperature against daily demand.

Figure 2.6 shows a series of Wednesday demands against their maximum temperatures. A second order trend line is fitted to the demand series. The same effect is seen for the other weekdays. From the fitted trend line it can be seen that the university's daily demand is quadrilateral related to temperature. In improving the accuracy of the forecasted profile, the forecasted profile is scaled according to the temperature demand curve. The day's maximum temperature used for scaling is automatically obtained from the South African weather bureau's website [42]. The forecasting and scaling process described above is illustrated in Figure 2.7 on the following page.

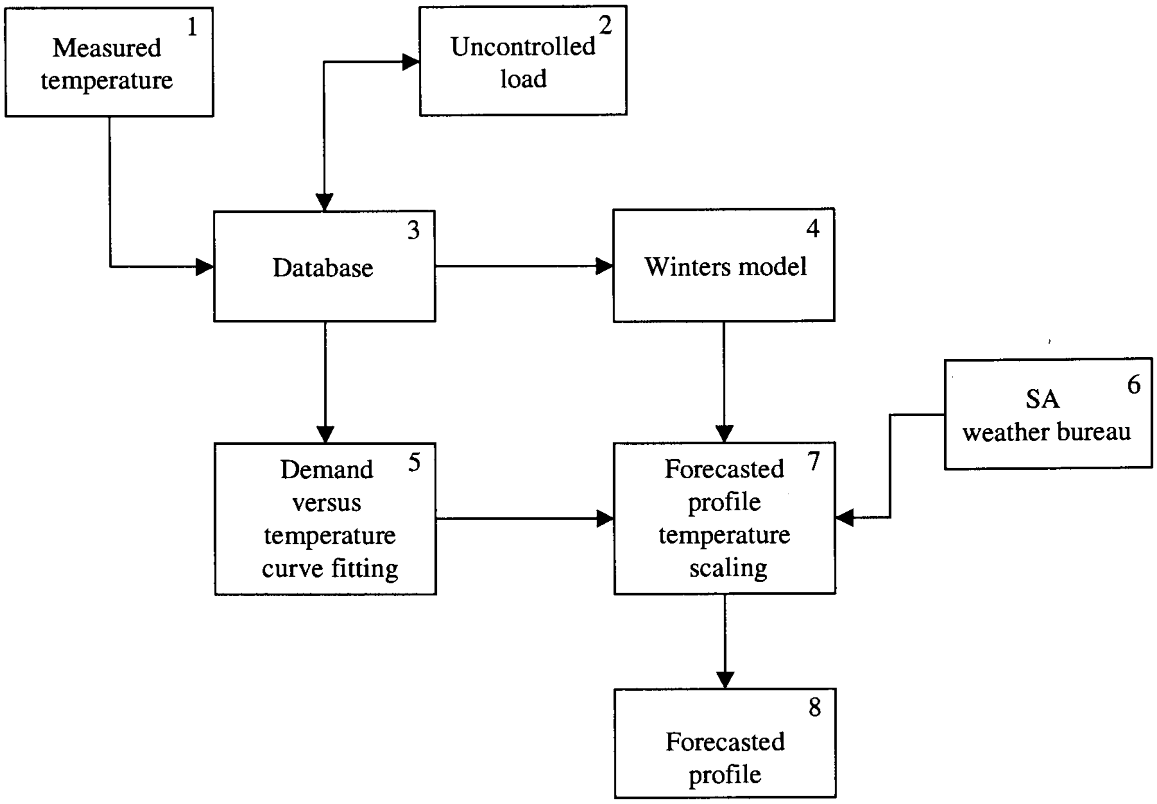

Figure 2.7. This figure shows the forecasting process.

1 Measured temperature: The externally measured temperature retrieved from the data logger by data retriever from Figure 2.1.

2 Uncontrolled load: The uncontrolled load calculated as shown in Figure 2.3.

3 Database: The database from Figure 2.1 that stores al the university's measured data.

4 Winters model: The historical data required to do the forecasting is selected from the database. The selected data is used by the Winters model to learn the university's load profile shape. The day's profile is forecasted after the shape has been learned.

5 Demand versus temperature curve fitting: Historical data from the database is used to fit a second order polynomial curve to the data. The curve represents the temperature effect on the demand of the university. The curve is constructed using data from only similar days as the one to be forecasted.

6 SA weather bureau: The maximum temperature for the day forecasted is automatically obtained from the South African weather bureau's website [42].

7 Forecasted profile temperature scaling: The forecasted profile from block 4 is scaled in relation to the curve of block 5 and the temperature forecast from the weather bureau represented by block 6.

8 Forecasted profile: The forecasted profile.

2.2.3 Available energy

Before the pre-cooling of the buildings can be done, the amount of energy available for pre-cooling needs to be known. The amount of available energy is calculated by subtracting the forecasted profile from the set point value. The positive resultant profile is the available energy.

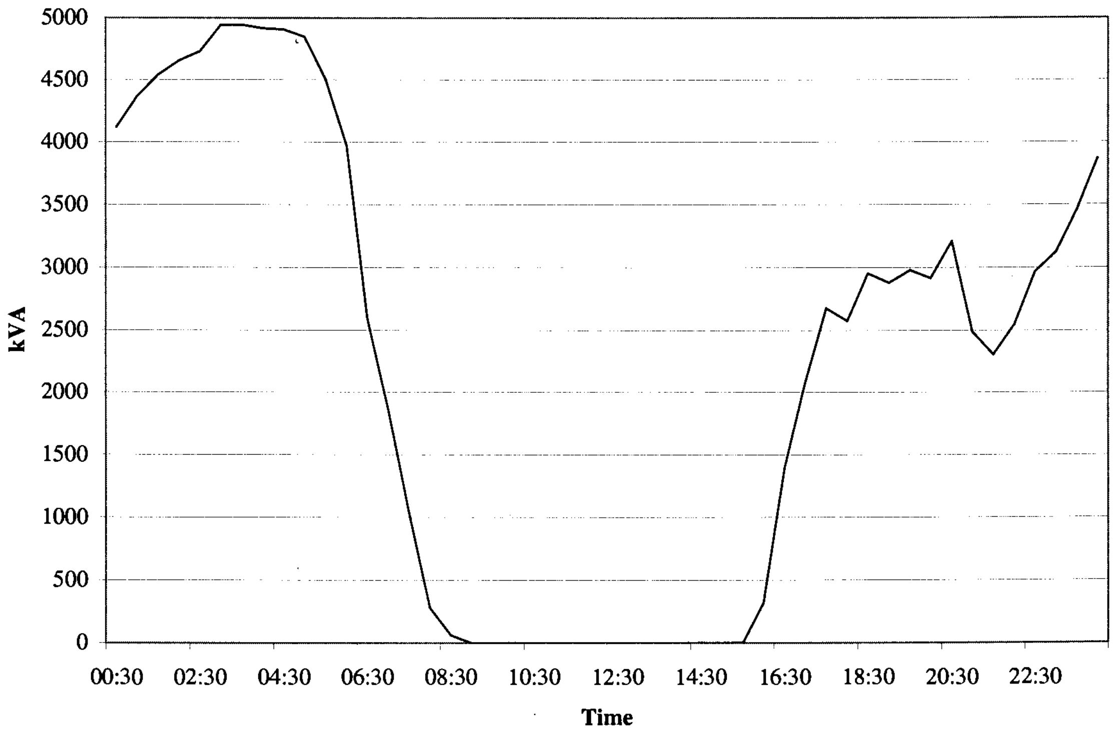

Figure 2.8. This figure shows the available energy profile.

From the available energy profile shown in Figure 2.8 two-energy blocks can be seen. The afternoon block is used for pre-heating of the controlled hot water cylinders. The block in the morning is open for pre-cooling with the HVAC system. The pre-cooling must be done within the limits of the available energy. The pre-cooling has to take place as close as possible to the shed time to minimise losses. The pre-cooling therefore has to be an accurately calculated process to keep within the above-mentioned constraints.

2.2.4 Pre-cooling

Most compressors have more than one cooling stage. The amount of cooling required determines the number of stages used. The HVAC's electrical consumption is directly proportional to the number of stages in use. For the pre-cooling calculations the assumption is made that the maximum cooling capacity of the compressor is used. This is because the cooling has to be as close as possible to the start of shedding. The pre-cooling therefore has to be done as fast as possible.

In calculating the electrical energy required for the pre-cooling, the pre-cooling load of the building is required. The electrical equivalent of the cooling load is determined by dividing the COP (coefficient of performance) of the HVAC chiller into the cooling load [43]. The available energy is known from the previous sections calculations. The pre-cooling is done through the filling of the available energy with the pre-cooling energy. This is done from the time shedding has to start back into the early mornings and late night until all the required pre-cooling energy is inserted. The backwards filling of the available energy bock will yield the start time for the pre-cooling.

The amount of cooling energy required to pre-cooling is calculated through the specific amount of energy required to reduce the building internal and external mass to the desired temperature from its current steady state temperature. The energy losses in the building must be added to the temperature reduction energy to give the cooling energy required. The losses are directly proportional to the required cooling load of the building. The cooling load is calculated by adding together the following internal and external heating sources. The sources are as follow [43, pp 95].

- External
    - Solar infiltration through glass windows.
    - Conduction through glass windows.
    - Infiltration through cracks and openings.
    - Conduction through the external walls.
    - Conduction through the roof.
    - Conduction through the floor.
- Internal

- Heat given of by the interior lights.
- Heat given of by people.
- Heat given of by equipment.
- Conduction from the other rooms.

2.2.5 HVAC control

The controlling of the HVAC system is done through the manipulation of the set point or control temperatures. If the building has to be pre-cooled the set point or control temperatures of the HVAC is decreased up to where all the compressor stages will be on. Vice versa is done when the HVAC has to be switched of to reduce demand. When pre-cooling the set point must not be to low, otherwise the chillers will trip to avoid freezing. Manufacturer data sheets have to be consulted for the lowest set point where the chillers will not trip.

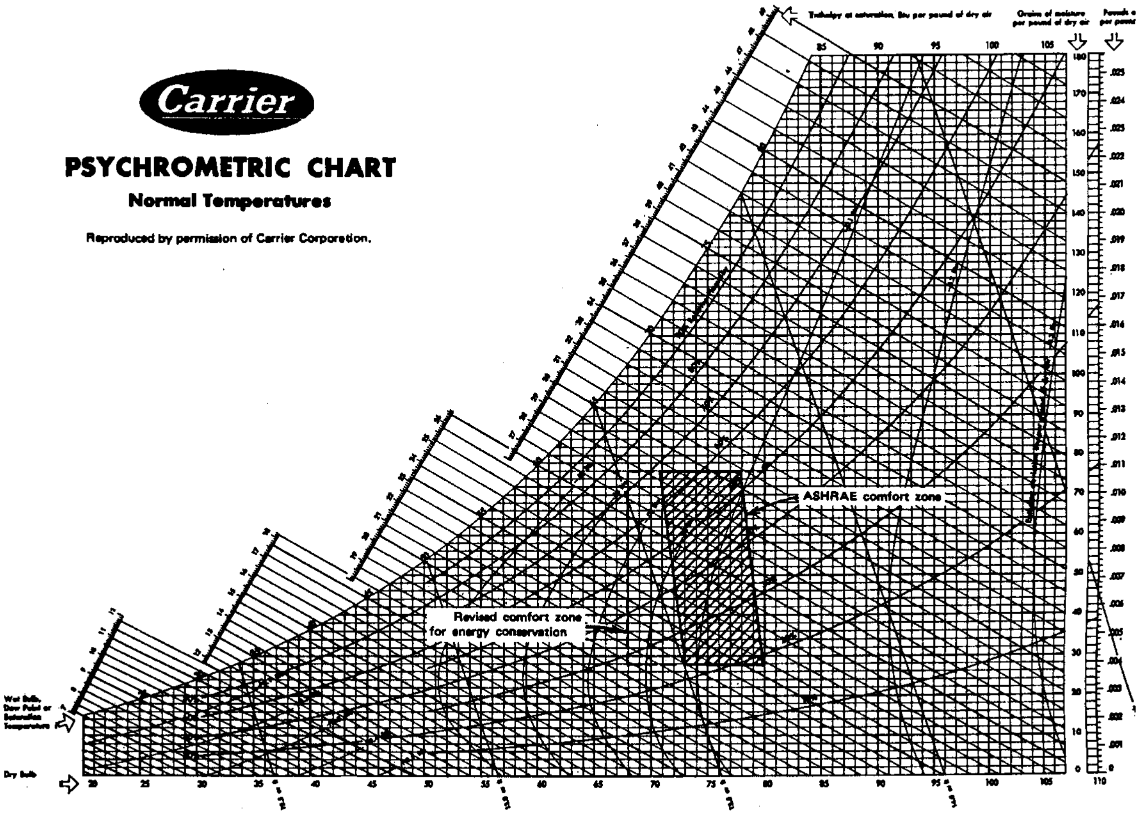

Figure 2.9. This Figure shows the extended ASHRAE comfort zone for energy conservation [43, pp. 138].

Using Figure 2.9 and the average relative humidity for the month of controlling, the minimum and maximum internationally accepted pre-cooled indoor temperature can be obtained. The average relative humidity is captured form the South African weather bureau's web site [42]. As the end of the working day comes closer and more shedding is required in overcoming demand or in helping the reheating of the hot water cylinders, set point temperature drift can be implemented [16]. The internal set point is gradually increased to reduce energy consumption.

2.2.6 HVAC uncontrolled load

The same as with the hot water load control, the HVAC control alters the university's load profile's shape. This will results in an inaccurate forecasted profile. The uncontrolled load of the HVAC control also has to be constructed. The energy consumption of the controlled HVAC's is measured. The HVAC's usually have a constant consumption 24 hour a day except for the chillers. Due to the health and safety act air supply must be maintained in a building, therefore only the chillers are switched off with night setback control. The chillers consumption can therefore easily be identified. The uncontrolled load is calculated by removing the entire chiller consumption. The correct chiller consumption is then added through the use of the cooling model described in section (2.2.4) on pre-cooling. If night setback control is in use, energy builds up during the night off times. When the uncontrolled load for night setback control is constructed the energy build up must be added to the cooling model of section (2.2.4). When the system starts up, all the compressors are maximally switched on to bring the chilled water back to the set point temperature. This immediately reflects on the energy consumption profile. Using the specific heat equation to change water temperature and dividing it with the COP of the chillers calculate the energy required to change the temperature of the cooling water. The energy build up of the building structure reflects slower on the system. The buildings energy build up is modelled using an exponential decrease in the energy build up. The energy required for the decreasing is then added to the cooling load. The energy that has to be added to the cooling load with the exponential trend line fitted to it is shown in Figure 2.10.

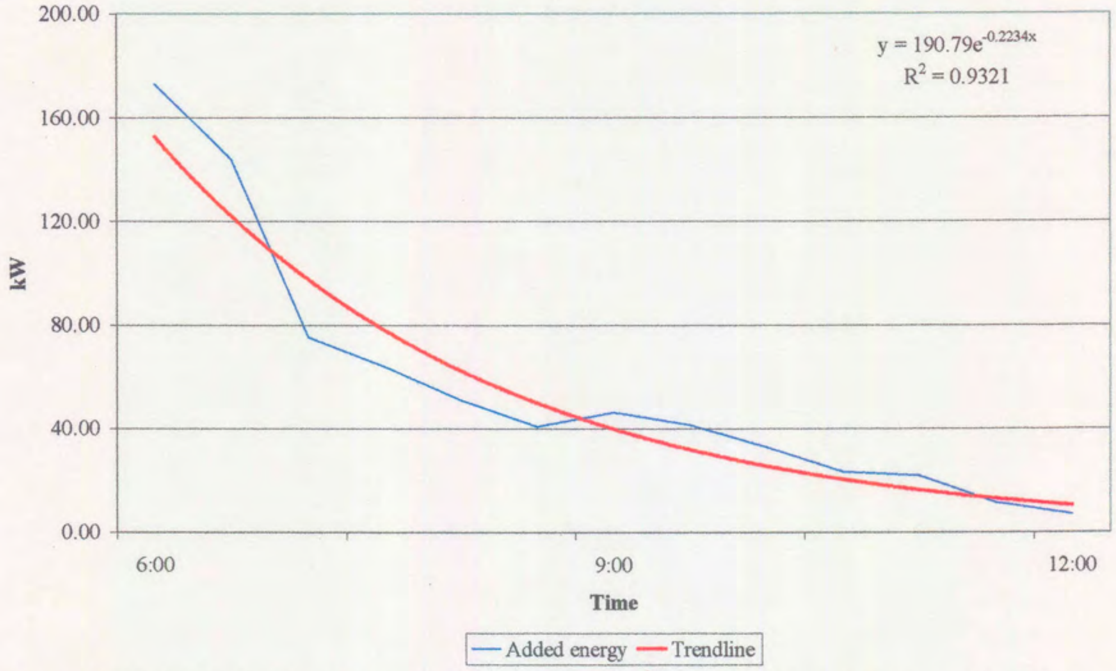

Figure 2.10. This figure shows the energy that has to be added to the cooling load and the modelled trend line fitted to it.

Figure shows the period between 6 and 12 when the addition of the energy takes place after the cooling water has been brought back to its set point temperature. From Figure 2.10 it can be seen that the energy has to be put back exponentially. The process of calculating the uncontrolled load is shown in Figure 2.11.

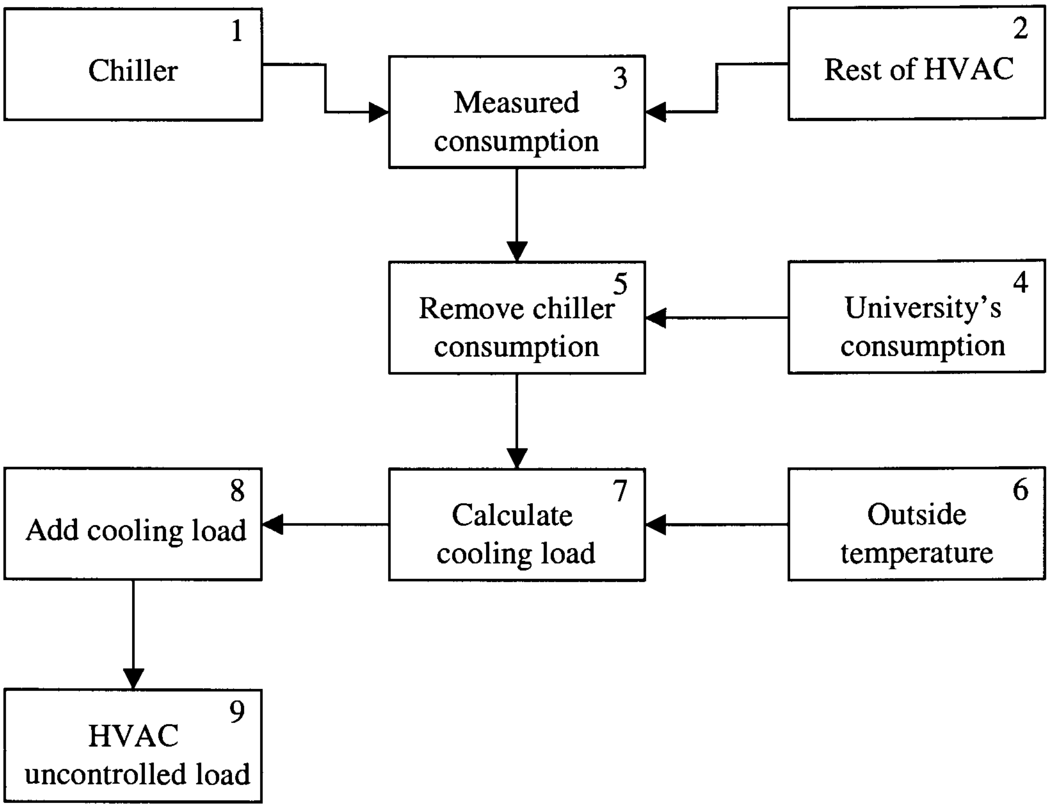

Figure 2.11. This figure shows the process of calculating the HVAC uncontrolled load.

1 Chiller: Represents the energy consumption of the chillers.

2 Rest of HVAC: Represents the energy consumption of the rest of the HVAC. This includes the air-handling units, cooling towers etc.

3 Measured consumption: The energy consumption is measured and retrieved with the data loggers and retriever shown in Figure 2.1. The data is the stored in the database of Figure 2.1.

4 University's consumption: Is the measured consumption of the university as shown in Figure 2.1.

5 Remove chiller consumption: The chiller consumption is removed from the university's measured load. This leaves the university's profile without the chiller consumption.

6 Outside temperature: The measured outside temperature shown in Figure 2.7 and stored in the database of Figure 2.1.

7 Calculate cooling load: The cooling load is calculated using the model described in section 2.2.4. The model requires the outside temperature for the load calculations. The cooling load divided by the COP, this gives the energy consumption of the chillers.

8 Add cooling load: The calculated cooling load is what the HVAC would have consumed if no control were done.

9 HVAC uncontrolled load: The university's load with normal setback control operation.

2.2.7 HVAC load controller

The HVAC load controller executes al the processes described in sections (2.2.1-2.2.6). From the forecasted profile if the energy to be shifted at any given time is more than half of the hot water load consumption, the HVAC control will be included in the university's demand control. If the energy is less than half the consumption enough cycling is possible to ensure hot water. The HVAC load controller will pre-cool the buildings and their coolant. If the pre-cooling is successful, the hot water load controller will be notified. The hot water load controller will not control until the HVAC controller notifies it. The HVAC load controller, like the hot water load controller, uses a forecasting method [5, pp 17 – 32] to determine if shedding has to take place within a specific integration period. If the HVAC load controller has to bring back load, it first notifies the hot water load controller. The hot water load controller then sheds load in equal amount to that what the HVAC load controller is going to bring back. Once the hot water load is shed the HVAC controller is notified. After the notification the HVAC controller restores the cooling load. The HVAC controller monitors the inside temperature to determine when to restore the HVAC system. If the inside temperature cannot be monitored or if it is too expensive the return water from the building is used as an indication. If the hot water load controller's off time becomes to long as the end of the working day comes closer the HVAC load controller is notified. The inside temperature set point is gradually increased. The temperature drift reduces energy consumption giving the hot water load controller space to restore load.

The university's demand charge is taken over a whole month; it is therefore critical that the controllers must function properly. In the case of no communication being established between one another a warning e-mail and sms (short message service) is send to the operator of the system. During this no-communication period both systems will try to control the load to the best of their ability until the problem is fixed or the operator manually takes over control. If no communication can be established between the load controller and its controllable load, warnings are generated and the other controller is given full control.

The two controllers communicate via their local area network. They use TCP/IP protocol for the communication. The HVAC load controller communicates with the HVAC's via the data loggers shown in Figure 2.1. The protocol is thus IPX up to the data logger and RS 485 from the logger to the HVAC's temperature measurement equipment.

3 MODEL MATHEMATICS

The section describes the mathematical models used in the calculations of the modelling methodology described in section (2.2). The models will be covered in the same order as presented in section (2.2).

3.1 Hot water uncontrolled load

The hot water uncontrolled load is constructed using the shedding status from the hot water load controller and the consumption patterns from the notch-tests. As explained in the previous section the consumption from the notch-tests represents the shed energy and the installed capacity minus the consumption represents the restore capacity. According to the first law of thermodynamics [37, pp. 1-26] for each individual group

$$\sum P_{shed} = \sum P_{restore} \tag{3.1}$$

applies, where:

P_{shed}	the energy shed	[kWh]
$P_{restore}$	the energy restored	[kWh]

For the total system

$$P_{shed,all} = P_{shed,group1} + \ldots + P_{shed,groupN}, \tag{3.2}$$

$$P_{restore,all} = P_{restore,group1} + \ldots + P_{restore,groupN} \tag{3.3}$$

apply, where:

$P_{shed,all}$	the total shed load of the university	[kWh]
$P_{shed,group}$	the individual group's shed load	[kWh]
groupN	number of groups	
$P_{restore,all}$	the total restored load of the university	[kWh]
$P_{restore,group}$	the individual group's restored load	[kWh]

At the end of each half hour the system calculates the amount of energy shed and the energy restored. This is done from the switch status recorded every minute during the half hour. The shed energy for the specific half hour is equal to the calculated shed energy from the consumption profile and switch statuses. For a half hour, if the restored energy according to the switch statuses is larger than the shed energy, the restore energy is equal to the shed energy from equation (3.1). If the shed energy is larger than the restored energy the restored energy for the half hour is equal to the calculated restored energy. To satisfy equation (3.1) the shed energy not restored during a half hour is carried over to the next half hour and added to $\mathbf{P_{shed}}$. The process repeats every half hour until equation (3.1) is satisfied. The restore and shed energy now remain zero until load is again shed. After each half hour the energy shed during the half hour is added to the measured load profile using equation (3.2), the restored energy is subtracted using equation (3.3).

3.2 Forecasting

The forecasting is done to know the shape and size of the next day's load profile. The forecasting is divided into two sections. The first part of the forecasting process uses the Winters method. The method calculates the shape and size of the forecasted profile from previous trends. The method has three smoothing parameters; an overall smoothing, a trend smoothing that determines the speed at which the method reacts to changes in historical data and a seasonal soothing which determines the speed of reaction towards seasonal changes. The Winters method's formulas are as follow [41]:

$$S_t = \alpha \frac{X_t}{I_{t-L}} + (1-\alpha)(S_{t-1} + b_{t-1}), \tag{3.4}$$

$$b_t = \gamma (S_t - S_{t-1}) + (1-\gamma) b_{t-1}, \tag{3.5}$$

$$I_t = \beta \frac{X_t}{S_t} + (1-\beta) I_{t-L}, \tag{3.6}$$

$$F_{t+m} = (S_t + b_t m) I_{t-L+m}, \tag{3.7}$$

where:

S_t	first smoothing (overall smoothing)	
Bt	second smoothing (trend smoothing)	
I_t	third smoothing (seasonal smoothing)	
X_t	data point at sample position t or at time t	[kW]
α, β, γ	the smoothing constants that determine the weight of each one of the three different smoothing types.	
F_{t+m}	the forecasted value m steps ahead form the position t.	[kW]
L	the lengths of a season for the university's load profile.	

The length of a season is taken as 24 hours (one day), which is the smallest seasonal component found in the profile of the university's consumption. The university's billing data is sampled on half-hourly intervals therefore the value of **L** is 48.

The second part of the forecasting is to scale the forecasted profile according to the South African weather bureau's temperature forecast for the next day. This is done because the university's consumption is quadratic related to temperature change. Scaling the Winters forecasted profile a temperature against demand curve needs to be known. From Figure 2.6 in the previous section one can clearly see that a quadratic fit is required. The regression formulas to calculate the quadratic fit are as follow [45]:

$$\sum_{k=1}^{N} x_k^4 A + \sum_{k=1}^{N} x_k^3 B + \sum_{k=1}^{N} x_k^2 C = \sum_{k=1}^{N} y_k x_k^2, \tag{3.8}$$

$$\sum_{k=1}^{N} x_k^3 A + \sum_{k=1}^{N} x_k^2 B + \sum_{k=1}^{N} x_k C = \sum_{k=1}^{N} y_k x_k, \tag{3.9}$$

$$\sum_{k=1}^{N} x_k^2 A + \sum_{k=1}^{N} x_k B + \sum_{k=1}^{N} NC = \sum_{k=1}^{N} y_k, \tag{3.10}$$

$$y = Ax^2 + Bx + C, \tag{3.11}$$

where:

x	the maximum temperature values	[°C]
y	the maximum demand values	[kW]
k	the position of the data point in the data series	
N	the number of data points	
A,B,C	the regression coefficients	

Equations (3.8-3.10) form a linear system, solving **A**, **B** and **C** of the linear system yields the values for the coefficients of the parabola. Equation (3.11) represents the effect of temperature on the day's maximum demand. Scaling the forecasted profile of equation (3.7) using the answer of equation (3.11) yields the day's forecasted profile.

3.3 Available energy

Before any pre-cooling can be done the energy available in order to do the pre-cooling needs to be known. The available energy is calculated using the forecasted profile of the previous section and the desired set point. The available energy is then calculated using the following formulas:

$$AE_t = \frac{SP - F_t}{2} \; where \; SP - F_t \geq 0, \tag{3.12}$$

$$AE_t = 0 \qquad where \; SP - F_t < 0, \tag{3.13}$$

where:

AE	available energy	[kWh]
SP	set point	[kW]
F	forecasted value	[kW]
t	time of day (1 to 48 half hours)	

3.4 Pre-cooling

The first step in the pre-cooling of a building is the calculation of the buildings temperature transition energy and its cooling load. The second step in the pre-cooling is to translate the cooling energy required into electrical energy consumption. The electrical energy consumption then has to be fit into the available energy as close as possible to the start of shedding. The energy required to change the building mass temperature is calculated by using the following formula [44].

$$Q = mc\Delta T \tag{3.14}$$

where:

Q	heat flow	[BTU/hr]
m	mass of material	[lb]
c	specific heat capacity of material	[BTU/lb·K]
ΔT	temperature change	

The cooling load is calculated adding together all the components that add heat to the building. These components have to be overcome to cool down the building. The different cooling load components are added together and scaled using the following formula [43, pp. 96 - 134].

$$\begin{aligned} P_{cool} = (&Q_{conduction,ext} + Q_{conduction,\text{int}} + Q_{solar,glass} + Q_{lightning} \\ &+ Q_{people} + Q_{equipment} + Q_{\text{inf}\,iltration}) \times Q_{\text{heat, surroundings}} \end{aligned} \tag{3.15}$$

where:

P_{cool}	total cooling load	[BTU/hr]
$Q_{conduction,ext}$	conduction through exterior surfaces	[BTU/hr]
$Q_{conduction,int}$	conduction through interior surfaces	[BTU/hr]
$Q_{solar,glass}$	radiation through glass	[BTU/hr]

$Q_{lightning}$	heat gains from lightning sources	[BTU/hr]
Q_{people}	heat gains from people inside the building	[BTU/hr]
$Q_{equipment}$	heat gains from equipment	[BTU/hr]
$Q_{infiltration}$	heat gains from infiltration through crack, etc.	[BTU/hr]
$Q_{heat,surroundings}$	heat transfer to surroundings	[BTU/hr]

For the ease of using the ASHRAE tables the formulas are kept in the metric system.

The electrical energy required is calculated using the following translation relationship:

$$E = \frac{hrs * P_{cool}}{COP}, \tag{3.16}$$

where:

E	energy	[kWh]
hrs	hours	[hr]
P_{cool}	total cooling load	[BTU/hr]
COP	coefficient of performance of the chillers	

The different components of the total cooling load found in equation (3.14) is calculated as follow:

3.4.1 Conduction through external surfaces

The conduction through the external surfaces is the heat transferred through the walls, roof and floor that cause heat gain inside the building. The formula to calculate the conduction through external surfaces is [43, pp. 96-101]:

$$Q_{conduction,ext} = U \times A \times CLTD_c \tag{3.17}$$

$$where,$$

$$CLTD_c = [(CLTD + LM) \times K + (78 - t_R) + (t_0 - 85)] \times f, \tag{3.18}$$

where:

$Q_{conduction,ext}$	net heat gain through roof, wall or glass	[BTU/hr]
U	overall heat transfer coefficient for roof wall, or glass	[BTU/hr]
A	area of roof, wall or glass	[ft^2]
$CLTD_c$	corrected cooling load temperature difference	[F]
CLTD	cooling load difference	[F]
LM	correction for latitude and month	
K	correction for colour of surface	

t_r	room temperature	[F]
t_o	average outside design temperature	[F]
f	correction for ceiling ventilation	

The **CLTD$_c$** value is calculated using ASHRAE tables. The ASHRAE table are given only for northern latitudes. The north latitude values form the ASHRAE table are converted to south latitude values. Rotating the position of the sun lit areas and months relative to the suns position in the southern latitudes, changes the values.

3.4.2 Conduction through interior structure

The conduction through interior structure is the heat flow from unconditioned spaces to conditioned spaces. The flow can be through partitions, floors or ceilings. The formula to calculate the conduction through the interior structures is [43, pp. 101]:

$$Q_{conduction,\text{int}} = U \times A \times TD \tag{3.19}$$

where:

$Q_{\text{conduction,int}}$	heat transfer rate through partition, floor or ceiling	[BTU/hr]
U	overall heat transfer coefficient	[BTU/hr-ft^2-F]
A	area	[ft^2]
TD	temperature difference	[F]

3.4.3 Solar radiation through glass

Solar radiation through glass is the radiant energy from the sun that passes through transparent material and become heat gains to the room. Transparent material is material like glass, etc. The formula to calculate the heat gain from solar radiation through glass is as follow [43, pp.102-108]:

$$Q_{solar} = SHGF \times A \times SC \times CLF, \tag{3.20}$$

where:

Q_{solar}	net solar radiation heat gain through glass	[BTU/hr]
SHGF	solar heat gain factor	[BTU/hr-ft^2]
A	area of glass	[ft^2]
SC	shade coefficient	
CLF	cooling load factor for glass	

3.4.4 Lighting

In the generation of light for the interior of a room heat is given off by the lighting equipment. This results in a heat gain inside the room. The formula to determine the heat gain from the lighting is as follow [43, pp. 108-111]:

$$Q_{lighting} = 3.4 \times W \times BF \times CLF, \qquad (3.21)$$

where:

$Q_{lighting}$	net heat gain from lighting	[BTU/hr]
W	lighting capacity	[W]
BF	ballast factor	
CLF	cooling load factor for lighting	

3.4.5 People

The people inside the building give off heat. The amount of heat generated by a human body depends on the body's activity level. The more active the more heat is generated. ASHRAE has averaged tables for the heat generated by different activities. The following formula calculate the heat gain as a result of people inside the building [43, pp. 111-113]:

$$Q_{people} = q \times n \times CLF, \qquad (3.22)$$

where:

Q_{people}	sensible heat gains	[BTU/hr]
q	sensible heat gain per person	[BTU/hr]
n	number of people	
CLF	cooling load factor for people	

3.4.6 Equipment

All electrical equipment such as computers, printer, etc. generates heat that causes heat gains inside a building. The heat gains from the equipment is either found on the nameplate or taken from generalized tables.

3.4.7 Infiltration

The infiltration of air through cracks, open windows, open doors, around windows and doors, etc. results in heat gains to the inside of the building. The infiltration of air into the building is calculated using the following formula [43, pp. 114-115]:

$$Q_{\mathrm{inf}\,iltration} = 1.1 \times CFM \times TC, \qquad (3.23)$$

where:

Q	sensible heat gain from infiltration	[BTU/hr]
CFM	air infiltration rate	[BTU/hr]
TC	temperature change between inside and outside air	[F]

3.4.8 Heat transfer to surroundings

Some of the heat gain inside the building is transferred through the structure to the surroundings and never appear as part of the building heat load. The heat loss is calculated and added as a correction factor to the total building heat load. The correction factor for heat gains due to heat transfer to the surroundings is calculated using the following formula [43, pp. 115]:

$$F_c = 1 - 0.02K \qquad (3.24)$$

where,

$$K = \frac{(U_w A_w + U_g A_g)}{L}, \qquad (3.25)$$

and where:

F_c	multiplier to correct each rooms sensible heat gain	
K	unit length conduction	[BTU/hr-ft-F]
L	length of exterior wall	[ft]
U_w	the walls heat transfer coefficient	[BTU/hr-ft^2-F]
U_g	the glass windows heat transfer coefficient	[BTU/hr-ft^2-F]
A_w	area of wall	[ft^2]
A_g	area of glass	[ft^2]

3.5 HVAC control

In order to do the pre-cooling the controller needs to know to what temperature the building can be pre-cooled. The temperature depends on the relative humidity of the air. A lookup table for the controller was created using Figure 2.9 obtained from ASHREA and revised for energy saving applications. The controller uses the lookup Table 3.1 to determine the maximum pre-cooling and temperature drift, temperatures. The temperature drift is implemented at the end of the working day if the system requires extra restore energy for the hot water cylinder. The relative outside humidity is obtained from the South African weather bureau. The assumption is then made, depending on the HVAC, that it causes a certain % change from the outside humidity to the inside humidity if no humidity control is installed. If humidity control is installed the relative humidity is taken as the controlled humidity set point. An air-conditioner without humidity control usually has a dehumidification effect.

Table 3.1. The table shows the pre-cooling and drift temperatures.

Relative humidity	Minimum temperature		Maximum temperature	
%	°F	°C	°F	°C
20	77	25	80	26.7
30	68	20	80	26.7
40	68	20	80	26.7
50	68	20	80	26.7
60	68	20	74	23.3
70	68	20	70	21.1

The operator can change the temperature depending on differing situations and the amount of energy needed for shedding. The set points can also be varied for indoor comfort. Great care has to be taken to avoid bacterial growth as a result of the temperature variations.

3.6 HVAC uncontrolled load

To calculate the HVAC's uncontrolled load the day's cooling load without control needs to be known. The cooling load without control is calculated using the same formulas used in the calculation of the cooling load for pre-cooling. This produces the uncontrolled cooling load. The uncontrolled load of the university is then calculated by taking away the measured HVAC load of the controlled HVAC's and adding the electrical analogy of the cooling load calculated. This is done through the use of the formulas described in section (3.4) together with,

$$P_{t,uncontrolled} = P_{t,university} - \sum_{n=1}^{k} P_{t,n,HVAC} + \sum_{n=1}^{k} \frac{P_{t,n,cool}}{COP_n}, \qquad (3.26)$$

where:

$P_{t,uncontrolled}$	the calculated uncontrolled load	[kVA]
$P_{t,university}$	the measured load of the university	[kVA]
$P_{t,n,HVAC}$	the measured load of the HVAC	[kW]
$P_{t,n,cool}$	the calculated cooling load	[BTU/hr]

COP_n	the chillers coefficient of performance
n	the nth buildings HVAC
k	the number of HVAC's used in the control
t	time of day (1 to 48 half hours)

The university has power factor correction installed; the assumption of unity power factor is made. Thus 1 kW = 1 kVA.

As stated in section 2.2.5 if night setback control is employed the energy build up has to be put back exponentially. The exponential curves equation is described as follows.

$$Q_t = (Q_{\max} - Q_{start})e^{t/\Delta T} \tag{3.27}$$

Q_t	the cooling energy added at position t	[BTU/hr]
Q_{max}	the modelled maximum cooling for the day	[BTU/hr]
Q_{start}	the modelled cooling energy at the start of the period	[BTU/hr]
ΔT	the inside temperature change	

3.7 HVAC load controller

In determining if load has to be shed, the load controller uses a forecasting method. The real time data logged during the integration half hour is fit to a straight-line curve, which is extrapolated up to the end of the half hour. The end of the half hour value determines if shedding is needed. The curve fitting is done using the following formulas [45, pp. 259 262]:

$$\sum_{k=1}^{N} x_k^2 A + \sum_{k=1}^{N} x_k B = \sum_{k=1}^{N} y_k x_k, \tag{3.28}$$

$$\sum_{k=1}^{N} x_k A + \sum_{k=1}^{N} NB = \sum_{k=1}^{N} y_k, \tag{3.29}$$

$$y = Ax + B, \tag{3.30}$$

where:

x	the time position within the integration period	
y	the measured power values	[kW]
k	the position of the data points in the data series	
N	the number of data points	
A,B	the regression coefficients	

Equations (3.28-3.29) form a linear system, solving **A** and **B** of the linear system yields the values for the coefficients of the straight line. Equation (3.30) represents the demand within the half hour.

4 MODEL VERIFICATION

Before the models described in the previous section can be used to help in the saving of money for the university they have to be verified. The verification is done to ensure that the models are working. If the models are not working properly, the wrong answers could result in large money losses. The models needing verification are going to be verified in the same order as presented in chapters two and three. They are:

- ☐ The hot water load uncontrolled load
- ☐ The forecasting method
- ☐ The HVAC cooling load

4.1 Uncontrolled load

To verify the controlled with the uncontrolled load one has to compare the measured load without control with the constructed uncontrolled load for a day with control. With the university no two-day's are the same. The only way to verify the uncontrolled load is compare the two profiles for the same day, but this is impossible. One can get a generalized view of the accuracy by selecting random controlled day's uncontrolled profile and comparing them to a measured load profile without control. This is show in Figure 4.1.

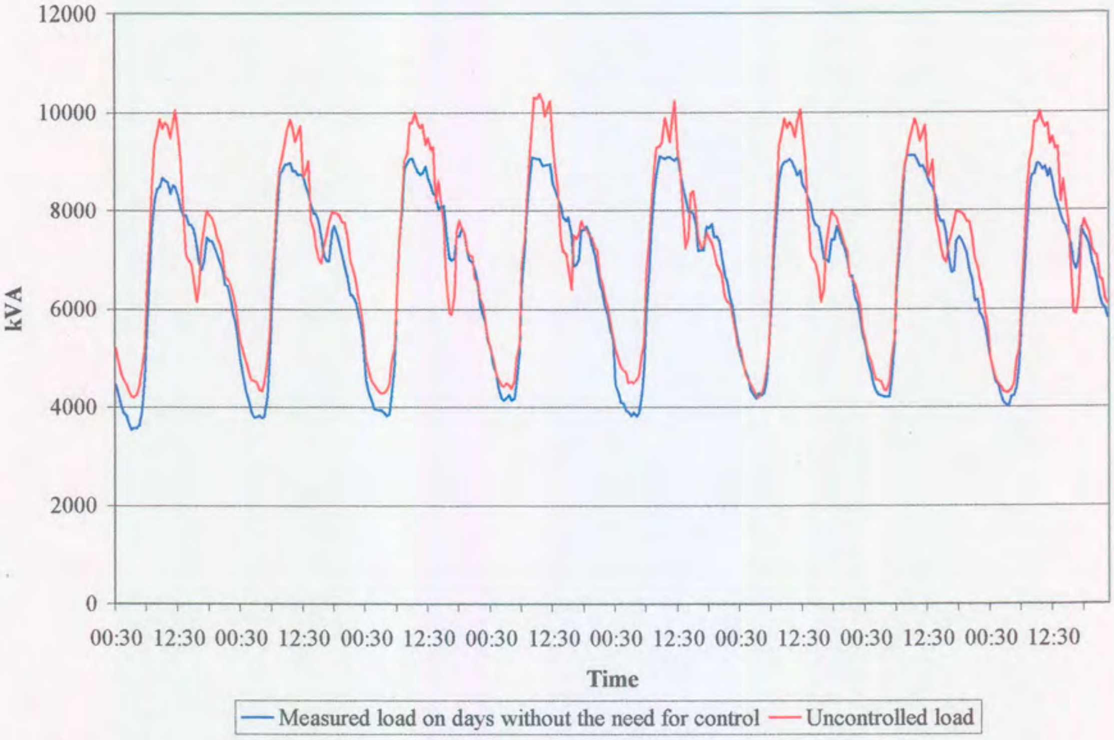

Figure 4.1. This figure shows the comparison between measured loads on days without control to the constructed uncontrolled load of days with control.

In getting a more accurate view of the accuracy of the uncontrolled load the measured load without control has to be scaled to be more or less the same size as the uncontrolled load. On high consumption days the university's profile increases between 7:00 and 14:00. This is due to the fact that most students' shower during the mornings, heaters are switched on in the offices during the winter on cold days and the air-conditioners are turned on during hot summer days. After 14:00 most classes are finished causing the people to leave, this causes a decrease in the air conditioning load. Not many students shower in the afternoon thus causes a drop in the load as the hot water cylinder reach their preset maximum temperature and switches off. The hot water cylinders now only maintain temperature, this process only use a small amount of electricity. Thus by scaling to the maximum demand difference between 7:00 and 14:00 one gets an indication of the uncontrolled loads accuracy. A scaled measured profile for a day is compared to a constructed uncontrolled load profile as show in Figure 4.2.

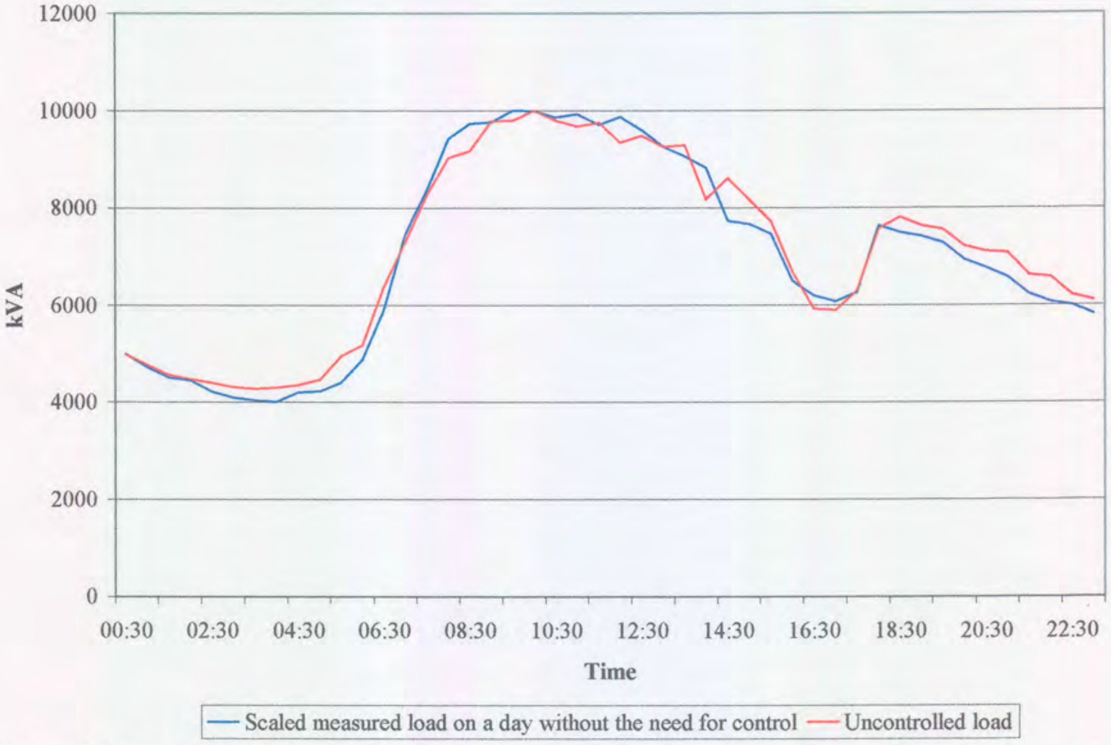

Figure 4.2. This figure shows a scaled measured load on a day without control against a day's constructed uncontrolled load.

For the scaled day shown in Figure 4.2 the energy only differed with 0.14% this means that the scaling is nearly correct. The difference between the two graph series has a mean absolute percentage error (MAPE) of 3.75%. This means that the uncontrolled model is a fairly accurate representation of the true profile without control. The HVAC controller needs to forecast the start period correctly for the pre-cooling thus the reconstruction of the period between 7:00 and 14:00 has to be correct. The MAPE between 7:00 and 14:00 was 2.4%. This is a very important period because all the control is done during this period Although the two graphs series differed before 7:00 it does not matter, because no control is done during this period therefore the measured load and the uncontrolled load would be the same. The available energy calculated from the forecasted profile before the start of shedding would thus be correctly calculated. This is because the historical data used in the forecasting for the period before 7:00 would be correct despite the difference in Figure 4.2. The difference is due to load size at the time of measuring the two-day's in question.

Repeating the process for 10 random days produces the following results shown in Table 4.1.

Table 4.1. The table shows the accuracy of ten days scaled measured load compared to the constructed uncontrolled load.

Number	**Energy difference %**	**MAPE 00:00-23:30**	**MAPE 07:00-14:00**
1	2.63	9.49	4.39
2	3.16	8.95	4.22
3	0.19	5.01	3.90
4	0.41	5.85	5.56
5	0.53	9.64	4.75
6	1.73	4.99	3.67
7	2.30	6.71	3.94
8	1.39	3.75	2.42
9	1.81	4.35	2.10
10	0.95	3.90	3.40
Average	**1.51**	**6.26**	**3.83**

From the results one can see that between 07:00 and 14:00 when the construction accuracy is important the accuracy is on average 3.83%. This is good enough to use in the HVAC control.

4.2 Forecasting

In verifying the forecasting process historical uncontrolled data is going to be used. The historical data from October 2000 up to the end of June 2001 was selected. The data before June was used to train the forecasting algorithm to forecast the first week in June. For the second week of June the first week's data was included in the training set. Figure 4.3 show the 13th of June 2001 forecasted profile versus the actual constructed uncontrolled load.

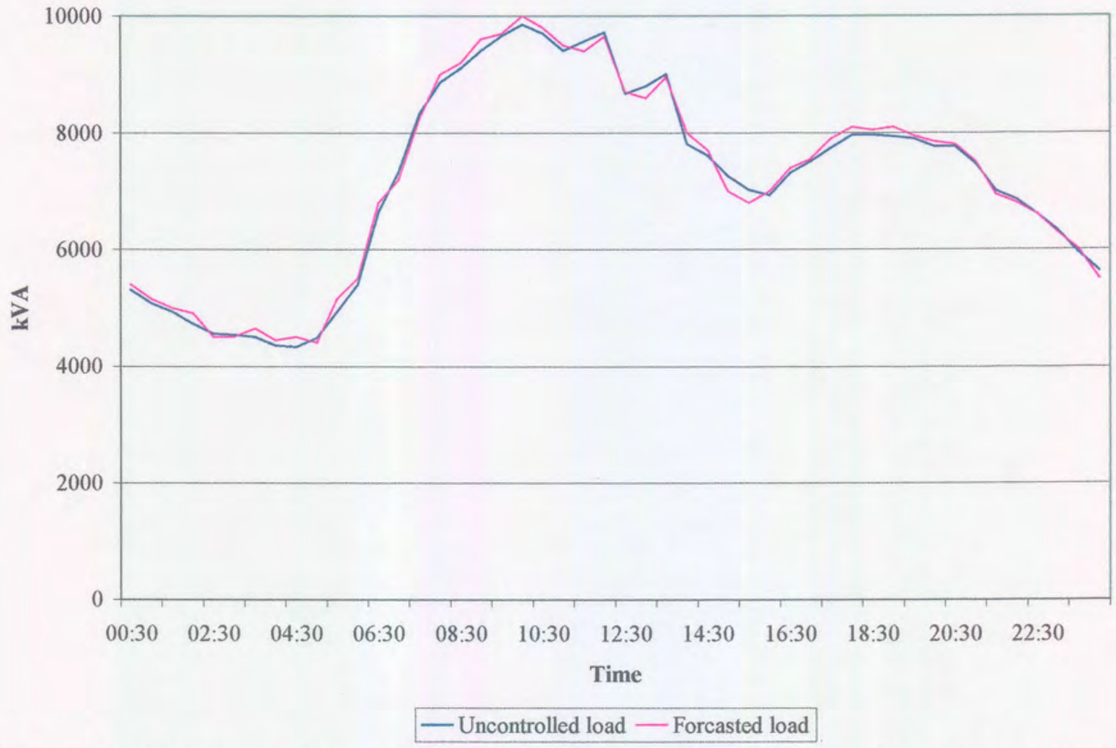

Figure 4.3. This figure shows the forecasted uncontrolled load against the constructed uncontrolled load

For the graph show in Figure 4.3 the MAPE was 1.55%, thus is within the specified criteria stipulated in the specific objectives of chapter 1. The results obtained for the entire two weeks is summarised in the following Table 4.2.

Table 4.2. The table summarizes the MAPE for two week of forecasted versus actual values.

Day of June	MAPE
1	2.3
2	3.6
3	3.1
4	3.3
5	2.5
6	1.7
7	4.5
8	3.0
9	4.2
10	1.6
11	4.7
12	3.9
13	1.6
14	4.4
Average	**3.2**

From Table 4.2 it is seen that the best was the 1.6% on the 13th and the worst was 4.7% on the 11th. The 4.7% is still lower than the prescribe 5% of chapter 1. With an average of 3.2% the forecasting method can confidently be used in the HVAC load controller's calculations.

4.3 HVAC cooling load

The Engineering Tower building situated on Main campus was used for the verification of the cooling models. The Engineering tower consists of offices on floors 6 to 15. Floors 4 and 5 are entrances. Floors 1 to 3 lead to, and form the basement. The basement consists of 9 lecture halls differing in size. Figure 4.4 shows a photo of the Engineering Tower building.

Figure 4.4. This figure shows the Engineering tower.

In verifying the cooling load the modelled cooling load is divided by the COP of the chillers and compared to their measured electrical load. The reason for the division is explained in section (2.2.4). Before the calculation can begin a walk audit of the engineering tower needs to be done to determine the patterns and number of the people inside the building, the electrical equipment generating heat that has to be cooled by the HVAC. Table 4.3 summarises the results obtained for the electrical equipment in the building.

Table 4.3. This table shows summarises the number of electrical equipment in the Engineering tower building.

Level	40 W lights	55W lights	60W lights	58W lights	65W lights	75W lights	150W lights	Computers	Laser printers	Ink Printers	Dot Matrix Printers	Kettles	Refrigerators	Photocopier	Fax Machines	Answering Machines
1	76	8	93		8	142	58									
2	8		2													
3	26		2													
4	24		4													
5	16		4	8												
6	76	48	4					6	3		2		1	2		
7	84	12	4	2	6	2		11	8		1	1	2	1	3	1
8	120		4					25	6		1					
9	116		4			4		18	8	2		1	2	1		2
10	110		4			8		43	6	4	1		1	2		2
11	113		3			8		21	12	2		1	1			
12	122		6			4		19	13	3		1	1			1
13	118		1	2				30	10	3	1	1	1	1		
14	118					6		24	15	3	1		1	2		
15	122					4		24	11	5		1	2	1		
Power (W)	40	55	60	58	65	75	150	100	14	14	14	2000	400	1500	250	10
Total (kW)	50.0	3.7	8.1	0.7	0.9	13.4	8.7	22.1	1.3	0.3	0.1	12.0	4.8	15.0	0.8	0.1

With the audit it was found that during the day (07:00-18:00) there are around 300 people in the office section of the building. During the early part of the night (18:00-21:00) there are around 20 people in the office section. In the mornings (07:00-13:00) there are around 450 people in the lecture halls. During the afternoon (13:00-18:00) there are around 200 people in the lecture halls. For the lecture halls and offices the times not mentioned, the assumption is made that they are empty. From observation made with the walk audit it seemed like around 5% of the people move around therefore generate more heat. The dimensions of the Engineering tower required in the calculations were obtained from building plans.

The gathered technical data to determine the cooling load was entered in to the cooling model formulas described in section (3.4). The COP of the chiller was assumed as a constant due to the slight variation it has under normal operation. Figure 4.5 shows the modelled power consumption versus the measured consumption for two days in March 2001.

Figure 4.5. This figure shows the simulated power consumption versus the measured power consumption.

From Figure 4.5 the first part of the simulation does not compare to the measured load. From the measured load one can see that the chillers are switched of during the night from 22:00 to 05:00. This means that the system employs night setback control. From the simulated profile it can be seen that during the night, energy build up takes place within the inside of the building that has to be overcome by the system. Calculating the energy difference between the simulated and the measured profile there is only a 4% difference. This means that the assumption of the energy build up is true. The first spike seen when the system starts up is due to the cooling of the water. The cooling of the water is firstly calculated and added to the simulated cooling load. This is done using equation (3.14) of chapter 3. Then, using equation (3.28) of chapter 3, the energy accumulated inside the building during the night is added. The simulated results versus the measured load are show in Figure 4.6.

Figure 4.6. This figure shows the simulated load versus the measured load with the corrections for setback control.

From Figure 4.6 it can clearly be seen that the model is an accurate representation of the Engineering Towers cooling load. The modelled load shown in Figure 4.5 had a MAPE of 3.5%. The same simulation was carried out for 14 different day's, the results shown in Table 4.4.

Table 4.4. This table summarizes the MAPE for 14 different days of measured versus modelled consumption values.

Day	MAPE
1	2.3
2	3.6
3	3.1
4	3.3
5	2.5
6	1.7
7	4.5
8	3.0
9	4.2
10	1.6
11	4.7
12	3.9
13	1.6
14	4.4
Average	**3.2**

From Table 4.4 it is seen that the best was the 1.6% on the 3rd day and the worst was 4.7% on the 1st day. The 4.7% is still lower than the prescribe 5% of chapter 1. With an average of 3.2% the cooling load model can confidently be used in the HVAC load controller's pre-cooling and uncontrolled load calculations.

5 CASE STUDY

In the previous chapters the modelling methodology, mathematical models and the verification of the models were discussed. In this chapter the load management process developed is going to be implemented on the University of Pretoria. This is done to determine the improvement in end user comfort and savings. From the case study it will become clear if the objectives set in chapter 1 were reached. For the first part of the case study the calculations are done for the six buildings HVAC's that are currently measured; the Engineering Tower Building, the Merensky Library, the Architectural Science Building, the Chancellors Building, the Human Science Building and the centralised air conditioning plant in the Administration Building. The case study is then expanded to include all the centralised air-conditioners on campus. This is going to be done by taking the six measured buildings' average saving as a percentage of their maximum demand on the simulated day, extrapolating the percentage to include all the centralised air-conditioners. This will give an estimated saving of including all the air-conditioners on campus for load management. For the second part of the case study structural TES is combined with storage-water TES to see the effect. This is only for the six measured buildings because their HVAC performance needs to be known for the thermal water-cooling.

5.2 Structural thermal energy storage

As stated in chapter one when billed on a demand and energy charge, the emphasis would be on peak reduction. With the hot water load control it was found that the cold-water complaints were minimised when not more than 75% of the controllable cylinders were switched off at one time. This is due to the long shedding period caused by the university's flat profile from 07:00 to 14:00. If the university had a shorter definite peak it would have been possible to switch off most of the cylinders without complaints. With the inclusion of the HVAC control the controllable peak seen by the hot water control system would be reduced. With the reduction in the hot water control shed period, more cylinders can be shed at a time. The simulations are done by taking February's uncontrolled peak day and removing the peak. The maximum amount of peak is removed. The maximum amount is determined by the no more than 75% off, criteria. The energy removed is calculated to act as a limitation for the amount of energy that can be shed with the hot water load when the HVAC control is added. This is to ensure that the comfort levels of the hot water end users are kept. Figure 5.1 shows February's peak day and the energy removed with the hot water load control.

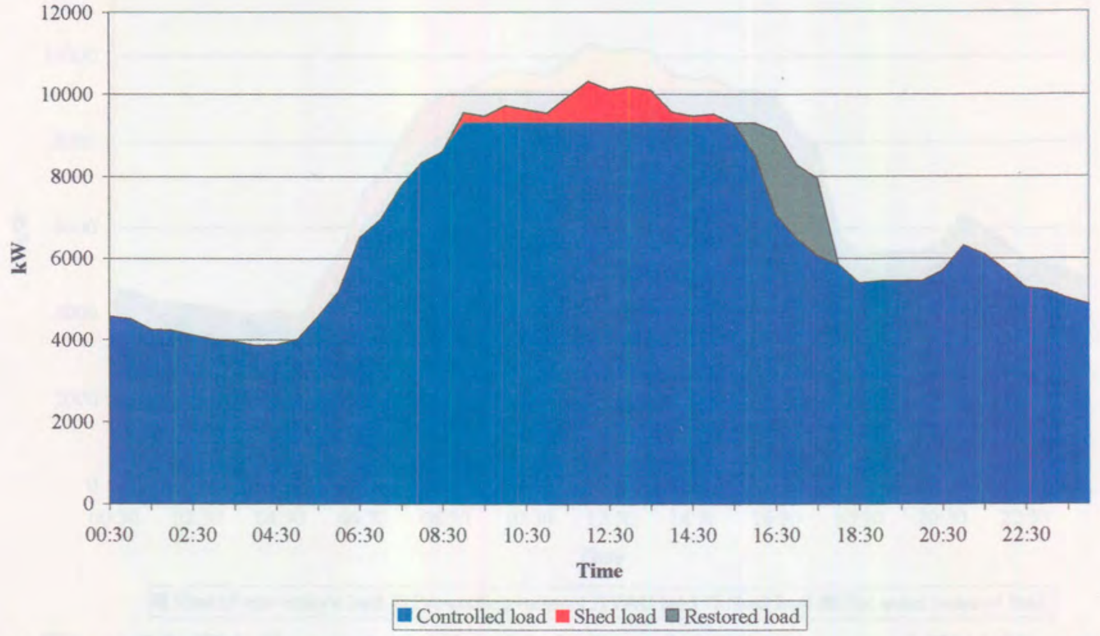

Figure 5.1. This figure shows Februaries demand day and the energy moved or shed.

The shifting of the peak energy shown in red to off peak shown in grey in Figure 5.1 resulted in a saving of R 48,000 for the month. This amounted to a 9.93% saving on demand charges and a 5.44% saving on demand and energy charges. The LF for the month with the shifting in place was 0.64 and the days LF was 0.73. The amount of energy shifted was 3,253 kWh. In the control simulation with the integration of HVAC and hot water load control not more than 3,253 kWh of hot water energy must be shed to still ensure user comfort. Figure 5.2 shows the maximum demand day of February with the inclusion of the six HVAC's in the control.

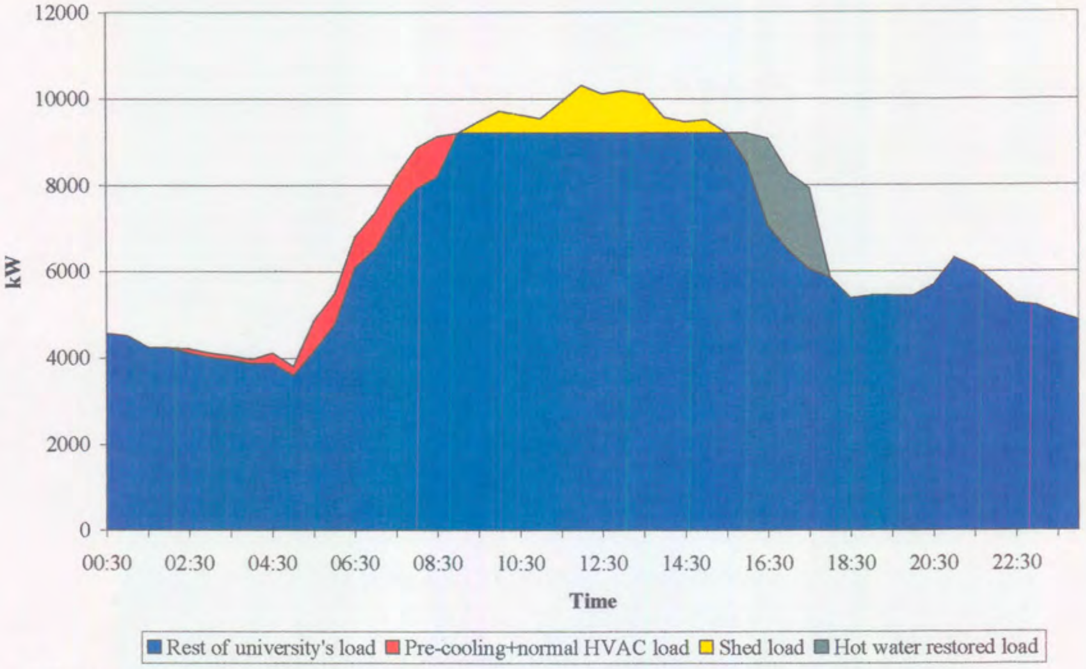

Figure 5.2. This figure shows the simulation where the measured HVAC's was included in the control.

The red part of Figure 5.2 show the pre-cool and normal operating energy up to the point where shedding starts. The yellow part of the graph represents the load shed. The blue part represents the measured load without the pre-cooling and normal operating energy of the six HVAC's up to the point of shedding. The grey part represents the hot water load restored energy. Table 5.1 summarizes the results of the simulation.

Table 5.1. This table summarizes the results of the simulation with the measured HVAC control included.

Monthly LF	0.65
Day's LF	0.74
Energy moved	3,855
kVA saving	1,115
Saving (Rand)	52,300
Pre-cooling losses (Rand)	250
Demand Saving (%)	10.82
Total Saving (%)	5.93

From Table 5.1 the monthly load and demand day's LF improved by 0.01. The energy moved increased by 458 kWh. The movement resulted in an R 52,300 saving, that is

R 4,300 more then with only the hot water load control. The losses due to pre-cooling amounted to R 250, only a saving of R 4,050 was made. With this load shifting method a 10.82% saving was made on demand charges and a 5.93% saving on demand and energy charges.

The simulation now includes the six measured buildings, the Education and Law Building, the Agricultural Science Building, the AE du Toit Auditorium, the Nature Science 1 and the Nature Science 2 Building. The same effect is seen with the inclusion of the extra three buildings as shown in Figure 5.2. Table 5.2 summarizes the results of the simulation with all the buildings included.

Table 5.2. The table summarizes the results of all the centralised HVAC's on campus.

Monthly LF	0.65
Day's LF	0.75
Energy moved	4,000
kVA saving	1,150
Saving (Rand)	54,000
Pre-cooling losses (Rand)	300
Demand Saving (%)	11.17
Total Saving (%)	6.12

With all the buildings included the monthly and maximum demand day's LF did not improve by much. The energy moved improved by 150 kWh and the savings improved by R 1,700. The losses increased by R 50, thus only an increased saving of R 1,650. With this load shifting method a 10.82% saving was made on demand charges and a 5.93% saving on demand and energy charges.

5.3 Structural and storage-water TES

In this section an insulated water storage tank is going to be added to the HVAC system to further improve their load shifting capabilities. The same principals are going to apply as with the previous simulations. The amount of pre-cooling is going to increase to cool the larger amount of storage water. The simulations are firstly going to be done with a $48m^3$ water storage tank cooled to 6°C. The result with the inclusion of the 48m3 water tank for each building is shown in Figure 5.3.

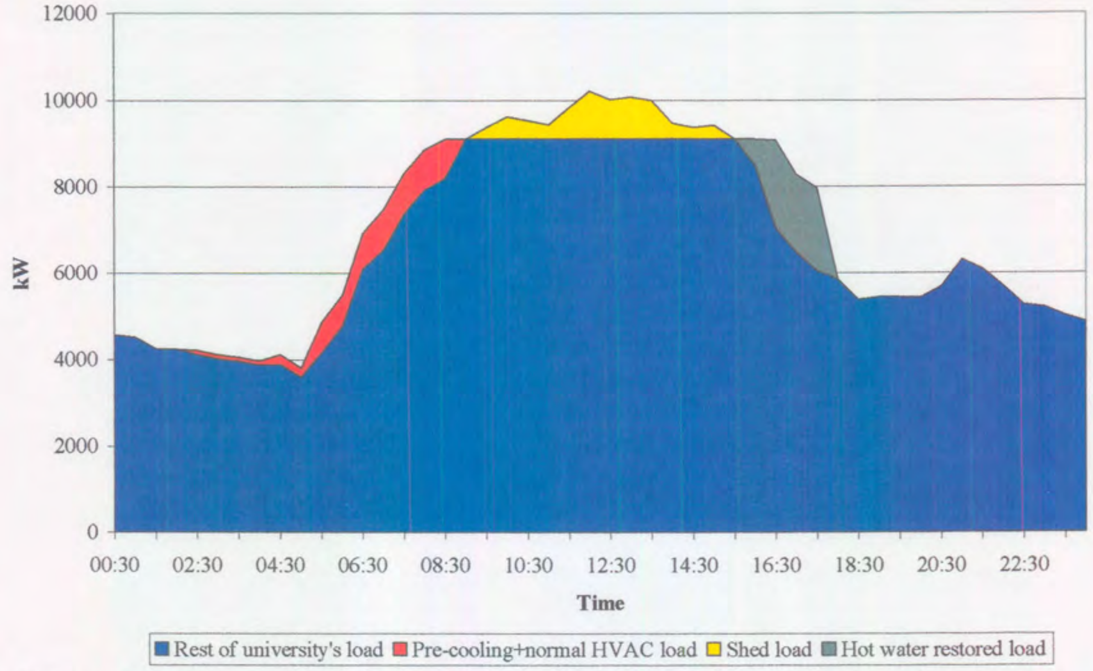

Figure 5.3. This figure shows the results with the inclusion of 48m^3 water-storage tank.

The red part of Figure 5.2 show the pre-cool and normal operating energy up to the point where shedding starts. It can be seen from the graph that the amount of pre-cooling has not increased by much due to the small losses of the storage tank. The yellow part of the graph represents the load shed. The blue part represents the measured load without the pre-cooling and normal operating energy of the six HVAC's up to the point of shedding. The grey part represents the hot water loads restored energy. Table 5.3 summarizes the results of the simulation.

Table 5.3. This table summarizes the results with the inclusion of the 48m^3 storage tanks.

Monthly LF	0.66
Day's LF	0.76
Energy moved	4,550
kVA saving	1,214
Saving (Rand)	57,000
Pre-cooling losses (Rand)	255
Demand Saving (%)	11.79
Total Saving (%)	6.46

From table it can be seen that with the structural and water-storage TES the savings are the largest. The saving increased by R 4,700 from just using the structural storage. The lost energy is very small and can be neglected. The monthly and maximum demand day's LF also increased by another 0.01. The energy moved increased by around 700kWh. With this load shifting an 11.79% saving was made on demand charges and a 6.46% saving on demand and energy charges. If the tank size is to be increased to 125m^3 1500 kWh more than with the structural TES can be moved. The increased size would result in a saving of R 63,000 this would be an improvement of R 10,700 per month, which is a 13.03% saving on demand charges and a 7.14% saving on energy and demand charges. The bigger the TES tank becomes the more space is required and the higher the cost becomes. If the TES tank is big enough the entire days HVAC load can be shifted to the off-peak night times. To shift the entire load to off-peak the size and cost of the tank has to be taken into account. From the literature the payback period for TES is around 5 years [22, pp.31, 23, pp. 37]. With the cost from the literature, the current exchange rate, inflation and the university's electricity charges the payback period for the university would be in the order of 7 years.

6 CONCLUSIONS AND RECOMMENDATIONS

6.2 Conclusions

The main objective of this thesis was to develop a framework for a load controller that integrates HVAC control with a hot water load control, to reduce peak demands. With the addition of the HVAC control, the peak demand must further be decreased and help in taking some pressure of the hot water load control system, resulting in higher end user comfort for the hot water users. In order to implement the controller a literature study was conducted into hot water load control and HVAC load control. No literature could be found where the integration of the two types of control was done. From the literature study and practical considerations the following factors were implemented to form the load controller. These factors also formed the specific objective of the load controller.

- *Uncontrolled load*: The uncontrolled load was constructed to resemble the university's load without control. The uncontrolled load is used in the calculation of the savings and the forecasting (the next factor to be discussed). The hot water uncontrolled load model produced an average MAPE of 3.83%. The HVAC model is used in the uncontrolled load calculations of the HVAC system produced an average MAPE of 3.2%. For both uncontrolled loads these Figures are within the specified 5% of the specific objectives.
- *Forecasting*: The amount of load to be shed and the available pre-cooling energy need to be know in advance in order to pre-cool with the HVAC system. The control day's profile is forecasted to do these calculations. The forecasting is done integrating the Winters forecasting method with a temperature adjustment. The forecasting combination produced an average MAPE of 3.2 %. This is within the specified 5%.
- *HVAC models*: Thermal and electrical models were developed for the HVAC. These models are use to calculated the HVAC uncontrolled load and the amount of pre-cooling required. As specified in the uncontrolled load section the HVAC models have an average MAPE of 5%, which is what was specified.
- *Load controller*: The load controller was developed to do the control. The controller integrates the above-mentioned factors to do the control. A communication basis for the control was established between the two controllers.

Implementing the above specific objectives to reach the main objective resulted in the following results. The results are for February 2001 and state the improvement over just hot water load, load control.

- *Hot water loads with the inclusion of the six measured buildings structural TES*: With this combination the savings improved by R 4,050 and the monthly LF increased from 0.64 to 0.65. The maximum demand day's LF increased from 0.73 to 0.74. With this load shifting method a 10.82% saving was made on demand charges and a 5.93% saving on demand and energy charges.
- *Hot water loads with the inclusion of the all the centralised HVAC buildings structural TES*: With this combination the savings improved by R 5,700 and the monthly LF increased from 0.64 to 0.65. The maximum demand day's LF increased from 0.73 to 0.75. With this load shifting method an 11.17% saving was made on demand charges and a 6.12% saving on demand and energy charges.
- *Hot water load with the inclusion of the six measured building structural TES and water-storage TES*: A 48m^3 water-storage was added to the six buildings. With this combination the savings improved by R 8,750 and the monthly LF increased from 0.64 to 0.66. With this load shifting method an 11.79% saving was made on demand charges and a 6.46% saving on demand and energy charges. The maximum demand day's LF increased from 0.73 to 0.76. The water storage was increased to a 125m^3 storage tank. This improved the savings to R 10,700 or 7,14% of the energy and demand charges and 13.03% of the demand charges.

From the results it is clear the desired monthly LF of 0.7 was not reached. The maximum demand day had a LF of higher than 0.7. Only a few days in February needed control. If there were more days that needed the same control as the maximum demand day the specified 0.7 LF could easily be met. The structural TES improved savings but not by much. The addition of water-storage further improved the saving. The larger the water-storage the more are the savings that can be achieved. Space and cost would mainly affect the viability of this option. The structural storage can be implemented more easily if it is possible to communicate in real time with the HVAC's control system and change set points on the chiller and inside the building remotely. Higher saving is possible with all the above systems, but end user comfort was the main objective with all the simulations.

6.3 Recommendations

This thesis has proven that more savings are possible with the inclusion of HVAC structural and water-storage TES load shifting. However there are still a few other possibilities that could be explored.

- ☐ With the university, the hot water consumption only contribute around 10.3 % and the HVAC chillers simulated contribute around 6% of the university maximum demand. In a hotel or shopping centre the contribution of the HVAC and hot water heating would dramatically increase. An investigation into this situation might result in showing large saving possibilities.
- ☐ An investigation into the university changing to a TIME-OF-USE tariff with the addition of the HVAC control might reveal larger savings.
- ☐ With the simulations only water-storage TES was taken into account with the structural TES. An investigation into the use of ice storage that would reduce the large space requirement of the water-storage could be done.

7 REFERENCES

[1] S Talukdar and CW Gellings, *Load Management*, IEEE press, New York, USA, pp. 3-7, 1987.

[2] GJ Delport, "Hot Water Load Control Models Used on Campus", *The 7th Domestic Use of Electrical Energy Conference Proceedings*, pp 15-18, 18-19 April 2000.

[3] S Latner, "Energy Efficiency Investments: A Dynamic Link Between Environmental Quality and Positive Job Benefits for South Africa", *The 8th Domestic Use of Electrical Energy Conference Proceedings*, 10-12 April 2001.

[4] C Forlee, "More for Less? ESKOM's RDSM Program", *Electron Journal of the South African Institute of Electrical Engineers*, pp.31-33, NOV/DEC 1995.

[5] CW Gellings and JH Chamberlin, *Demand-side Management: Concepts and Methods*, The Fairmont Press, Lilburn, pp. 2, 1988.

[6] A. Calitz, K. Campbell, "Consider Your Verdict: The A to T of Electricity Pricing", *Electron Journal of the South African Institute of Electrical Engineers*, pp 8-19, March 1991.

[7] ESKOM's Annual Report, pp 68, 1998.

[8] FB Morris, JE Braun and SJ Treado, "Experimental and Simulated Performance of Optimal Control of Building Thermal Storage", *ASHRAE Transactions*, Vol. 100, No. 1, pp. 402-414, 1994.

[9] JE Braun, "Reducing Energy Costs and Peak Electrical Demand Through Optimal Control of Building Thermal Storage", *ASHRAE Transactions*, Vol. 96, No. 2, pp. 876-888, 1990.

[10] JE Braun, "A Comparison of Chiller-Priority, Storage-Priority, and Optimal Control of an Ice Storage System", *ASHRAE Transactions*, Vol. 98, No. 1, pp. 893-902, 1992.

[11] M Kintner-Meyer and AF Emery, "Optimal Control of an HVAC System Using Cold Storage and Building Thermal Capacitance", *Energy and Buildings*, Vol. 23, pp. 19-31, 1995.

[12] GP Henze, Dodier and M Krarti, "Development of a Predictive Optimal Controller for Thermal Energy Storage Systems", *International Journal of HVAC&R Research*, Vol. 3, No.3, pp. 233-264, 1997.

[13] ME Snyder and TA Newell, "Cooling Cost Minimization Using Building Mass for Thermal Storage", *ASHRAE Transactions*, Vol. 96, No. 2,1990.

[14] I Andresen and MJ Brandemuehl "Heat Storage in Building Thermal Mass: A Parametric Study" *ASHRAE Transactions*, Vol. 98, no. 1, 1992.

[15] MD Ruud, JW Mitchell and SA Klein, "Use of Building Thermal Mass to Offset Cooling Loads", *ASHRAE Transactions*, Vol. 96, No. 2,1990.

[16] JP Conniff, "Strategies for Reducing Peak Air-Conditioning Loads by Using Heat Storage in the Building Structure", *ASHRAE Transactions*, Vol. 97, No. 1,1991.

[17] DK Spratt, GW Sadler and KR Moodie, "Dynamic Control – a Case Study", *ASHRAE Transactions*, Vol. 95, No. 2, pp.193-200,1989.

[18] B Daryanian and LK Norford, "Minimum Cost Control of HVAC Systems Under Real Time Prices", *Proceedings of the 3rd IEEE Conference on Control Applications August 24-26*, pp. 1855-1860, 1994.

[19] G. Diana and P. Govender, "Demand Side Management: A Case Study of a Tertiary Institution", *The 7th Domestic Use of Electrical Energy Conference Proceedings 18-19 April*, pp 25-29, 2000.

[20] H Akbari and O Sezgen, "Performance Evaluation of Thermal Energy Storage Systems", *Energy and Buildings*, Vol. 22, pp. 15-24, 1995.

[21] Y Abouzelof, "Challenges and Achievements of a Thermal Energy Storage Tank", *Energy Engineering*, Vol. 91, No. 6, pp. 6-22, 1994.

[22] PE Fiorino, "Thermal Energy Storage Program for the 1990's", *Energy Engineering*, Vol. 89, No. 4, pp. 23-33, 1992.

[23] VA Williams, "Case Study: Successful Thermal Energy Storage Applications", *Energy Engineering*, Vol. 89, No. 4, pp. 40-57, 1992.

[24] M Meckler, "Integrating Thermal Energy Storage Systems with Automatic Fire Sprinkler", *Energy Engineering*, Vol. 89, No. 4, pp. 34-39, 1992.

[25] AS Wilken, "Hot Water Load Control- A New Perspective", *The 7th Domestic Use of Electrical Energy Conference Proceedings*, pp 49-54, 18-19 April 2000.

[26] GL Van Harmelen and JC van Tonder "Hot Water Load Control in the South African Context: Where to Next?", *The 5th Domestic Use of Electrical Energy Conference Proceedings*, pp 28-32, 6 April 1998.

[27] CJ Jooste, GL Van Harmelen and GJ Delport "Modelling Load and Customer Impact of Centralised Water Heater Control to Co-ordinate and Optimise Existing Control Resources", *The 5th Domestic Use of Electrical Energy conference proceedings*, 6 April 1998.

[28] N Beute, "Domestic Utilization of Electrical Grid Energy in South Africa", PhD Thesis, Potchefstroomse Universiteit vir CHO, 1993.

[29] N Beute, "Financial Considerations for Electrical Supply Authorities in Controlling the Residential Water Heating Load", *The 2nd Domestic Use of Electrical Energy Conference Proceedings*, pp. 33-38, 3-4 April 1995.

[30] C Forlee, "Water heating in South Africa: Facts and Figures From the 1997 Notch Testing Program", *The 5th Domestic Use of Electrical Energy Conference Proceedings*, pp 265-270, 6 April 1998.

[31] DC. Arndt, "Further Extension, Verification and Application of Integrated Building, HVAC System and Control Simulation", *Masters Thesis*, University of Pretoria, 1997.

[32] LJ Grobler, "A New Holistic Approach to HVAC Retrofitting", *PhD Thesis*, University of Pretoria, 1995.

[33] CB Piani, "Establishing the Energy Savings Potential for Office Buildings in South Africa", *Masters Thesis*, University of Pretoria, November 1995.

[34] E van Heerden, "Integrated Simulation of Building Thermal Performance, HVAC System and Control", *PhD Thesis*, University of Pretoria, 1997.

[35] G Schweitzer and A Ebeling, "Basic Air-Conditioning", Volume 1, Hayden Book Company Inc, New Jersey, pp 1-51, 1971.

[36] EA Britz and GJ Delport, "HVAC Control at a Tertiary Institution", *The 8th Domestic Use of Electrical Energy Conference Proceedings*, pp 273-277, 10-12 April 2001.

[37] W. Goodman, "Air Conditioning Analysis", The Macmillan Company, New York, pp 1-26,1944.

[38] DW Bunn and ED Farmer, "Comparative Models for Electrical Load Forecasting", John Willey & Sons, New York, 1985.

[39] TS Dillon, S Sestito and S Leung, "Short Term Load Forecasting Using an Adaptive Neural Network", *Electrical Power & Energy Systems*, vol. 13, no. 4, pp 186-192, August 1991.

[40] S Rahman and G Shrestha, "A Priority Vector Based Technique for Load Forecasting", *IEEE transactions on power systems*, vol. 6, no. 4, pp 1459-1465, November 1991.

[41] S Makridakis and SC Wheelwright, "Forecasting: Methods and Applications", John Wiley & Sons, New York, 1978.

[42] South African Weather Bureau Website: www.weathersa.co.ca

[43] GP Edward, "Air-Conditioning Principals and Systems an Energy Approach", John Wiley & Sons, New York, pp.353, 1981.

[44] PM Fishbane, S Gasiorowicz and ST Thornton, "Physics for Scientists and Engineers", Extended version, Prentice Hall, New Jersey, pp. 536, 1993.

[45] JH Mathews, "Numerical Methods for Mathematics, Science, and Engineering", Second edition, Prentice Hall, New York, pp 257 – 314, 1992.