

The adaptive predictive control of an energy efficient central water heating system applied in the South African commercial sector

WC Kukard
12188778

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Promoter: Prof M van Eldik

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this thesis are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

Warren C. Kukard

Promoter: Prof. M van Eldik

April 2016

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Abstract

LANGUAGE: ENGLISH

Since the introduction of load shedding in the latter part of 2007, Eskom, the electrical utility of South Africa, have been forced to implement energy efficient and energy management measures to ensure the stability of the national grid. Solutions within the residential, commercial and industrial sectors have been implemented which specifically targeted the reduction of electrical demand during peak hours as well as methods to reduce the total electrical demand in the country. One of the target areas within the residential and commercial sectors are sanitary water heating systems due to the ease with which energy efficient technologies and energy management solutions can be implemented. Unlike some parts of the world where water heating is supplied by district water heating networks for sanitary as well as space heating purposes, South Africa predominantly utilizes decentralized water heating systems for sanitary purposes due to the annual moderate climate in South Africa.

Conventional electrical resistance heaters have been dominating the sanitary water heating market in South Africa for decades but energy efficient technologies such as solar and heat pump water heaters have recently been key attributes in the pursuit to reduce the energy demand within the residential and commercial sectors. Although water heating only accounts for 8% of the total energy demand in the commercial sector, the demand for water heating services continues to increase due to the higher demand for accommodation throughout the city centres in South Africa. In Johannesburg, the largest city in South Africa, a demographic shift developed where most of the city's population started to relocate to the city centre in an effort to move closer to the central business district. This created an opportunity where building owners started to reconstruct high rise office buildings into apartment units to fill the accommodation void.

The central water heating systems, which included heat pump water heaters, of two renovated high rise apartment buildings were evaluated between 2011 and 2014. What became evident within the measured data throughout the four years was the high hot water consumption of the respective buildings. With hot water consumption data being a crucial

component in the design of any water heating system, the measured consumption data was compared to high density population consumption profiles of research done in the commercial sector of South Africa. The substantial variance in the consumption profiles highlighted the concern in using outdated consumption data when designing a water heating system.

Various models have been developed internationally to predict hot water load profiles of district water heating systems in an effort to reduce energy costs by means of optimum control strategies. However limited research have been done on consumption profile prediction in the South African residential and commercial sectors where decentralized water heating systems reign supreme.

The purpose of this study was to develop a control algorithm to predict in-time hot water consumption profiles for commercial high rise buildings based on historic population density group classification data. The measurements of the renovated commercial high rise buildings were used as input for the developed hot water scheduler software to predict the required hot water consumption per hour of a building. This is done by optimally controlling the water heating equipment utilizing the predicted consumption profiles to optimize the energy savings potential of a building. Several simulation scenarios were compared to the actual consumption data of the two buildings which showcased the techno-economic benefit of the hot water scheduler as an energy management tool. The tool illustrated the added benefit of utilizing the simulation results to size a central water heating system based on the results provided by the hot water scheduler.

Energy savings of up to 55% are possible when controlling the operating schedule of energy efficient heating equipment such as heat pump water heaters using the developed hot water scheduler. The conclusive outcome of this study demonstrates the advantage of controlling the schedule of water heating equipment, using population density classified hot water consumption profiles, to reduce energy costs of a water heating system for high rise apartment buildings.

KEYWORDS: *High rise buildings, sanitary hot water, consumption profiles, water heating equipment, energy efficiency, heat pump, hot water scheduler, demand side management, hot water consumption forecasting.*

LANGUAGE: AFRIKAANS

Met die instelling van beurtkrag aan die einde van 2007, was die Suid Afrikaanse elektriese verskaffer, Eskom, gedwing om energie effektiewe asook energiebestuur inisiatiewe te bekragtig om stabiliteit aan die nasionale netwerk te verseker. Verskeie oplossings binne die residensiële, kommersiële en die industriële sektore is sedertdien geïmplementeer wat spesifiek die vermindering in die vraag na energie, gedurende nasionale piek energie intervalle, geteiken het asook metodes om die totale energie verbruik van die land te verminder. Een van die teiken areas binne die residensiële en kommersiële sektore was sanitêre warmwater stelsels weens die gemak waarmee energie effektiewe tegnologieë asook energiebestuur oplossings geïmplementeer kan word. In teenstelling met sekere dele van die wêreld waar warm water verskaf word met behulp van distrik waterverhitting netwerke vir sanitêre asook lugversorging doeleindes, gebruik Suid Afrika hoofsaaklik gedesentraliseerde warmwater stelsels vir sanitêre doeleindes weens die jaarlikse matige klimaat in die land.

Konvensionele elektriese weerstand waterverhitters oorheers die Suid Afrikaanse mark al vir die afgelope paar dekades, maar energie effektiewe tegnologieë soos son en hittepomp waterverhitters het groot aanspraak gemaak in die residensiële en kommersiële markte met die oog om die vraag na energie te verminder. Al beslaan waterverhitting slegs 8% van die totale energie verbruik in die kommersiële sektor bly die vraag na waterverhitting dienste toeneem weens die hoë vraag na akkommodasie in die stedelike gebiede van Suid Afrika. 'n Demografiese skuif het in die grootste stad van Suid Afrika, Johannesburg, ontstaan waar 'n groot deel van die stad se inwoners hulself begin hervestig het in die middestad in 'n poging om so na as moontlik aan die sentrale sakegebied te wees. Dit het 'n geleentheid geskep waar eienaars van meer verdieping geboue in die middestad die uitleg van hul geboue omskep het in akkommodasie eenhede om die behoefte te vervul.

Die warmwaterprofile van twee gerestoureerde meer verdieping geboue was geëvalueer tussen 2011 en 2014. Wat duidelik geword het tydens die ontleding van die gemete data wat strek oor 'n periode van vier jaar was die hoë warmwater verbruik van die onderskeie geboue. Met warmwater verbruik wat 'n kritiese komponent vir die ontwerp van enige warmwater verhitting stelsel is, was die gemete data vergelyk met hoë digtheid bevolkings verbruiksprofile van navorsing wat gedoen was tussen die twee geboue in die kommersiële sektor van Suid Afrika. Die aansienlike verskille in die verbruiksprofile het kommer gewek met betrekking tot die gebruik van verouderde profile tydens die ontwerp van 'n warmwaterstelsel.

Verskeie modelle is reeds ontwikkel om warmwater lasprofile van distrik waterverhitting stelsels te voorspel met die doel om energie kostes te verlaag deur gebruik te maak van

optimale beheer strategieë. Daar is egter beperkte navorsing beskikbaar rakende warmwater lasprofiel voorspelling in die Suid Afrikaanse residensiële en kommersiële sektore waar gedesentraliseerde warmwaterstelsels die markte oorheers.

Die doel van hierdie studie was om 'n beheer algoritme te ontwerp wat in-tyd warmwater verbruiksprofiel voorspel vir kommersiële meer verdieping geboue gebaseer op historiese bevolkings groep klassifikasie data. Die metings van die gerestoureerde geboue word dan as inset gebruik vir warmwater skeduleerder sagteware wat ontwikkel is om die verlangde warmwater verbruik per uur van 'n gebou te voorspel. Dit word verkry deur die warmwater toerusting optimaal te beheer met behulp van die voorspelde verbruiksprofiel om die energiebesparings moontlikheid van die gebou te verhoog. Verskeie simulasië scenario's word vergelyk met die werklike verbruiksprofiel van die twee meer verdieping geboue wat die techno-ekonomiese voordele van die warmwater skeduleerder as energiebestuur toestel te beskryf. Die toestel bied ook die addisionele voordeel om die grootte van 'n warmwaterstelsel te bepaal, vir 'n spesifieke instellasië, deur gebruik te maak van die simulasië resultate wat die warmwater skeduleerder produseer.

Energiebesparings van byna 55% is moontlik wanneer die operasionele skedule van energie effektiewe toerusting soos hittepompe beheer word met die ontwikkelde warmwater skeduleerder. Die finale uitkoms van die studie demonstreer die voordeel om warmwater toestelle te beheer deur gebruik te maak van bevolkingsdigtheid klassifikasie warmwaterprofiel, wat die energie kostes van warmwater verhitting stelsels vir meer verdieping akkommodasie geboue aansienlik verlaag.

SLEUTELWOORDE: *Meer verdieping geboue, sanitêre warmwater, verbruiksprofiel, warmwater toestelle, energie effektiwiteit, hittepomp, warmwater skeduleerder, aanvraagkantbestuur, warmwaterverbruik voorspelling.*

List of Acronyms

ASHRAE American Society of Heating, Refrigerating, and Air-Conditioning Engineers

Capex Capital expenditure

CBD Central business district

CFL Compact Fluorescent light

CPF Central processing facility

CPI Consumer price index

CSV Comma seperated values

DLL Dynamic link library

EE Energy efficiency

DSM Demand side management

EEDSM Energy efficiency demand side management

GDP Gross domestic product

GW gigawatt

HPWH Heat pump water heater

kWe kilowatt electrical

kWh-e kilowatt hour electrical

kWt kilowatt thermal

LCC Life cycle cost

MW Megawatt

Opex Operational expenditure

PLC Programmable logic controller

ppph per person per hour

ROI Return on investment

SCADA Supervisory control and data acquisition

SHW Sanitary hot water

TOU Time of use

tvph Total volume per hour

ZAR South African Rand

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Chapter 1

Introduction

Sanitary water heating system design has long been a challenging exercise for engineers throughout the world due to the uniqueness of every system. Research, whether it being on small scale domestic systems or large district water heating systems, has focused on methods of design and control to optimally improve the cost and energy efficiencies of each system. With hot water consumption profiles the catalyst of any water heating system design a discussion concerning the importance of continued profile data collection is presented in this chapter. The profiles will be utilized within this study to improve water heating system control.

1.1 Problem statement

With sustained infrastructure development in South Africa since the inception of a democratic republic in 1994, more people have periodically gained access to the national electrical grid and the available water resources within the country. Various households then had the opportunity to utilize electrical appliances such as hot water heating systems which were not available in the past. Most of these hot water heating installations as well as other electrical appliances were not energy efficient because of the low electrical tariffs and high capital costs of energy efficient equipment at that time.

For decades South Africa had the privilege of excess electrical supply which limited the potential for energy efficient solutions in the residential, commercial and industrial sectors. In 2008, the luxury of excess electrical supply came to an end when the demand for electricity outstretched the national supply and forced the government owned utility, Eskom, to introduce the load shedding initiative. This solution was implemented to ensure grid stability and to eliminate the possibility of a national electrical blackout in South Africa. The need for energy efficient solutions were however identified long before load shedding materialized as research predicted the risk of a shortage in electrical supply by 2007. Energy efficiency and demand side management (EEDSM) were introduced in 2004 [1] in aid of reducing the required demand within all the sectors. Both the initiatives had acclaimed successes but the continued economic growth added too much pressure on the grid.

The residential and commercial sectors accounts for nearly 25% [2] of the total electrical energy demand of South Africa and plays a pivotal part in the pursuit of reducing the national demand. If one looks at the energy distribution within the two sectors, water heating accounts for the bulk of the total energy consumption in the residential sector with a share of nearly 40% [3] for a typical domestic household. Heating, ventilation and air conditioning (HVAC) systems are however the commercial sector's largest energy consumer with a 23% sharehold and water heating systems representing 8% of the total energy distribution [4]. The obvious approach of the EEDSM initiative within the two sectors was to implement efficient design methodologies as replacement to existing inefficient HVAC and water heating systems and to ensure efficient design methodologies for future developments. Certain rebate incentives were implemented by the utility to advance energy efficient practices as well as peak load control initiatives which ultimately created an energy conscious environment.

An influx of efficient technologies were introduced in the residential and commercial sectors which included technologies like heat pump and solar water heating systems. Even though a large majority of these installation did contribute to the reduction of the total energy demand in South Africa, numerous other installation did not add any value due to inefficient design and installation practices. Research on water heating design methodologies in the

South African context are limited to a few guidelines on system sizing and optimization as presented in Chapter 2. The research was mainly based on hot water consumption profiles obtained in the residential, commercial and industrial sectors. Some of the studies aimed at utilizing the measured consumption profiles as input to determine the optimal design criteria. All the research did however confirm the importance of consumption data in the various sectors for accurate and efficient water heating system design. Unfortunately design engineers rarely have the privilege of site specific data and usually select available profile data similar to their design criteria.

The efficiencies of a design can therefore be related to the accuracy of measured consumption profiles utilized as input to a design. To improve the design approach one requires a dynamic adaptive consumption profile with regards to a specified system. The design engineer must be able to determine the system specifications by actually simulating the system with the minimum amount of effort to acquire the most cost effective and energy efficient water heating system. After the design selection has been made, the ability to control the system by means of a water heating scheduler would be an additional benefit to maintain and improve the required efficiencies of the system.

1.2 Purpose of the study

The purpose of this study is to develop an algorithm that predicts the required hot water consumption profiles for specific water heating system configurations. The algorithm will be utilized within a newly developed water heating system scheduler to predicted consumption profiles used as input to determine optimum operational efficiency of a water heating system.

Designing a water heating system requires a combination of input variables with the fundamental input variable the actual hot water consumption per person. The hot water consumption profile is influenced by a number of elements including the daily ambient temperature variances which can restrain the design process. The ability to adapt to the dynamic operation based on the required hot water consumption of the system can ultimately improve the operating cost and energy savings potential of a water heating system.

A cost effective water heating system design methodology for multiple system configurations combined with an energy efficient operating system approach, are the intended goals of this study. These outcomes will benefit the consumer, the water heating system supplier and the electrical utility. The study will utilize newly measured consumption profile data to validate the accuracy of the developed simulation models. This study will aim to reach the following objectives:

- Develop an adaptive predictive hot water consumption profile based algorithm.

- Develop a hot water scheduler to control the operating schedule of a water heating system utilizing predicted hot water consumption profiles.
- Evaluate the techno-economic impact of the hot water scheduler on the consumer, building owner and the electrical utility.
- Determine the feasibility of a hot water scheduler as a solution to rising energy costs.

1.3 Investigative measures of the research

The objectives as listed in section 1.2 will be initiated by means of a literature survey to express the importance of this study. An in depth investigation on available hot water consumption profiles will follow the literature survey and will be compared with newly measured consumption data of two high rise buildings in Chapter 3. The hot water consumption profile predictive model will also be presented in Chapter 3 followed by a detailed design layout of the hot water scheduler in Chapter 4. Simulation results will be validated in Chapter 5 by comparing the prediction model outputs to the measured consumption data of Chapter 3. An economic feasibility study of the proposed hot water scheduler will be covered in Chapter 6. A final summary of the contributions made by this study will be discussed in Chapter 7 along with recommendations for future research. The investigative measures in each chapter are summarised in the following paragraphs:

1. Chapter 2: Literature survey

An initial summary on the state of the energy supply in South Africa will be discussed as well as typical solutions implemented to reduce the growing energy demand. The focus will then shift to the impact of increased electrical tariffs on the consumer. A detailed layout of the energy distribution of the residential and commercial sectors will highlight the energy saving potential of water heating systems within these sectors. Current energy efficient water heating solutions within South Africa will be presented and linked to the optimal design considerations of each solution. A brief introduction on the role of hot water consumption profiles in water heating system design will be introduced with a more detailed discussion in Chapter 3. The chapter will be concluded with a discussion on hot water optimization and modelling methods available in the market to promote the necessity of a hot water scheduler.

2. Chapter 3: Consumption Profiles as Input to Sanitary Hot Water System Design

Detailed information concerning available hot water consumption profiles in the residential, commercial and industrial sectors of South Africa are presented in the beginning of this chapter. The discussion is then directed to the classification of the respective end users in the market to be able to differentiate between various available consumption profiles. The focus will then shift to the profiles in the commercial sector before the hot water layout and configurations of the two measured high rise apartment buildings are introduced. Measured consumption profiles of each building will be shown and compared to the commercial profiles presented in the beginning of the chapter. The latter part of the chapter will introduce the consumption profile predictive model along with the methodology used to incorporate the model in the hot water scheduler described in Chapter 4.

3. Chapter 4: Hot Water System Scheduler Using Predicted Consumption Profiles

This chapter will start off by underlining the significance of a scheduler to effectively control a water heating system at the maximum efficiency point. The required input variables for the scheduler will be introduced and the software design and architecture will be discussed in detail, along with the control philosophy. At the end of the chapter a section will be dedicated to the operating principles of the hot water scheduler. This will include the specifications on how to determine the system size as well as how to determine the maximum efficient operating point of the system.

4. Chapter 5: Hot Water System Scheduler Simulation Results

Simulation results will be generated by the hot water scheduler using the consumption data of the two measured high rise buildings as input. The results will be evaluated and compared to validate the accuracy of the predictive consumption profiles produced by the hot water scheduler. The actual sizes of the installed water heating equipment of the two buildings will be compared with the proposed system sizing of the scheduler to establish any deficiencies. To conclude the chapter a summary will be given on the scheduled operating intervals as well as the daily predicted switching cycles of the heating equipment.

5. Chapter 6: Economic Feasibility of the Sanitary Hot Water System Scheduler

The simulation results of chapter 5 will be used as part of the economic feasibility study in this chapter. An initial assessment will be introduced to evaluate the installation and operating costs of the original hot water system designs concerning the apartment building case studies. A cost analysis of the proposed design specifications by the

hot water heating scheduler will follow the initial evaluation. The chapter will be concluded with a comparison between the existing water heating systems of the two case studies as well as the proposed system designs to establish the most cost effective and energy efficient solutions.

6. Chapter 7: Closure and future recommendations

An overview of the hot water profile prediction results and the hot water scheduler control outputs will be summarised in this chapter. The final summary of results obtained throughout the thesis will be aligned against the stated objectives of section 1.2 to confirm the validity of the anticipated goals for this study. Detail on recommended future research opportunities concerning hot water system design, control and optimization will conclude the content of this study.

1.4 Statement of originality

The original contributions of this research can be summarised by the following:

- The study will present a developed hot water consumption profile forecasting methodology which incorporates existing consumption profiles.
- A newly developed hot water system scheduling algorithm will be introduced that utilizes the forecasting consumption profiles to improve hot water system sizing and real time hot water system control.
- The study will further quantify the cogency of the hot water scheduler as sizing tool and control system to reduce capital, operational and energy costs of commercial water heating systems.

Chapter 2

Literature Survey

Eskom, the public electrical utility of South Africa, have been struggling to effectively manage the national electrical demand since the introduction of load shedding in 2008. With continued pressure of reducing the electrical energy demand, various efforts have been implemented to stabilize the national grid. A successful exertion to date was the partly Eskom funded energy efficiency and demand side management initiatives. These initiatives were implemented throughout South Africa since 2004 in aid of reducing the base load of the national grid. Sanitary hot water heating systems in the residential, commercial and industrial sectors have been a target area due to the ease with which existing technologies can be implemented to reduce the desired electrical load. Sufficient design methodologies are imperative to ensure energy efficient operation of any sanitary hot water heating system. This chapter will introduce the influential features behind the design of an energy efficient sanitary hot water heating system.

2.1 Electrical energy supply in South Africa

South Africa is currently in the midst of an energy crisis due to the limited availability of electrical generation capacity. The government owned electrical utility, Eskom, is in a relentless scuffle to effectively manage the national electrical energy demand without affecting the economic growth of the country. Low electrical tariffs combined with the continued economic growth rate, reaching levels of 5.6% in 2007 [5], were the main contributors for the accelerated growth in electrical demand in South Africa. Eskom had to introduce load shedding in January 2008 [6] due to a 16% reduction of the national electricity reserve margin from 2002 to 2007 [7]. The continued decrease in the available reserve margin was mainly due to the lack of an investment in new generation capacity.

Energy efficiency and demand side management initiatives were introduced in 2004 [1] as interim catalyst to stabilise the continued growth in electrical demand in support of the available 40GW [7] generation capacity. The Energy efficiency demand side management (EEDSM) programmes, managed by Eskom, had an enormous impact on the reduction of South Africa's electrical demand. The combined verified demand saving between the 2004/2005 and 2012/2013 financial years were 3587 MW [8] for both demand management and energy efficiency initiatives. Most of the programmes were however placed on hold during the latter part of 2013 due to a revenue shortfall of R 7,900M (US\$ 720M) compared to the R 13,900M required [9].

The financial constraints [10] within the utility effectively halted the progress for continued energy efficient initiatives. It became crucial that the utility successfully managed its 95% stake hold [10] in the South African electrical generation capacity. Unfortunately the projected completion date of the newly built coal fired power stations have been surpassed [11] which might once again trigger the load shedding phenomena. This will diminish the economic growth of the country and South Africa will be faced with a further downfall of the projected weak 3% average growth over the next 10 years [12].

The implementation of sustained energy efficient strategies are thus imperative to stabilize the national grid until the newly built generation capacity comes online. Several proven energy efficient solutions are available but the financial responsibility will rest with the consumer to ensure the aspiring outcome of a load shedding free South Africa.

2.2 Demand management and energy efficiency solutions

To date various energy efficient (EE) and demand side management (DSM) solutions have been introduced to the residential, commercial and industrial sectors of South Africa. Most of

these solutions were mainly directed at load shifting and load reduction initiatives to support the national grid. The load shifting initiatives focus on moving a portion of the electrical demand in a system to lower demand daily timeslots which are divided into standard, peak and off-peak intervals. During the peak intervals, the national electrical demand reaches the maximum available generation capacity of Eskom and requires a reduction in demand to maintain the stability of the grid. This is where the high end consumers usually introduces strategies to move some of their load requirements to the standard or off-peak intervals. Not only does the load shifting initiative benefit the utility but the time-of-use (TOU) consumer saves on electrical costs due to the high peak interval tariffs. Energy efficiency initiatives are mainly new technologies introduced to the market in an effort to replace inefficient and outdated electrical devices or equipment [13]. These technologies aim at reducing the total load requirements of the consumer indefinitely which improves the overall efficiency of the consumer and contributes to the reduction of the national demand.

Two more recent initiatives that were introduced to the market is the demand response and residential roll-out programmes [10]. The demand response programme is an initiative where high end commercial and industrial energy consumers reduce a percentage of their total load upon request from the utility. It spontaneously reduces the national base load when required as a combined effort from the major electrical consumers.

In the residential sector 47 million compact fluorescent lights were distributed throughout South Africa between 2007 and 2010 [14] as part of a mass-roll out programme. The ease with which the technology was introduced was an effective solution for the demand crises. Similar to the efficient lighting roll-out programme, nearly 394,993 [15] solar water heaters were installed throughout South Africa between 2009 and 2014. Although a large portion of the installations were implemented at households without water heating facilities, the rebate initiative offered by Eskom encouraged further installations of this technology.

In the commercial sector government buildings were retrofitted to raise energy efficient awareness [16, 17] which was initiated and approved by the South African government. Building energy management systems and lighting were some of the technologies introduced to nearly 4000 buildings [18] across the country. Energy savings were achieved since 1997 and directly contributed to the reduction of the Eskom demand but the substantial increase in savings initiated in 2004, as illustrated in Figure 2.1, where the verified demand savings surpassed the original targets set by Eskom.

The main goal of the EE and DSM initiatives are ultimately to manage the demand profiles of Eskom in such a way that the national demand never outstretches the available electrical supply of the utility. Synergy between the electrical demand of the consumer and the supply capability of the utility is however required to ensure that the productivity of the

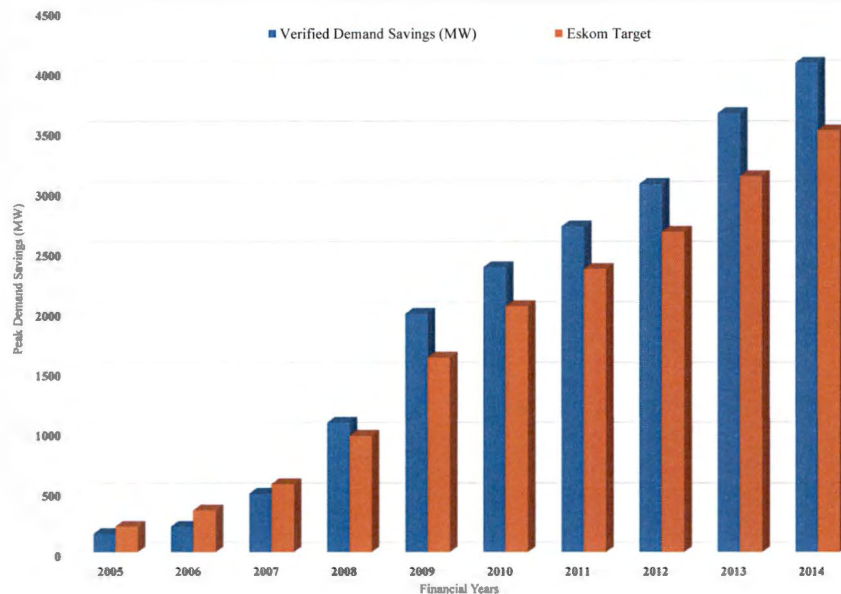


Fig. 2.1 Eskom verified vs target demand savings [10]

consumer is not affected by load shedding or the unavailability of electrical supply. Energy efficiency and demand management are therefore solutions that empower the consumer and assist the utility during the current energy crisis which rely on the development of new energy initiatives and technologies for a sustainable energy future in South Africa.

2.3 Electrical tariffs and the consumer

Between 2008 and 2014 the electrical tariffs in South Africa increased by 141.4% and further increases of 8% per annum [19] is projected from April 2013 to March 2018. These tariffs are approved by the National Energy Regulator of South Africa to equip Eskom with the necessary shortfall in funding to complete two newly built coal fired power stations. The historical electrical tariff and the consumer price index increases shown in Figure 2.2 indicate the low electrical increases throughout the past that might have contributed to the lack of generation capacity investments from Eskom which led to the current energy shortage.

At present the main priority for Eskom is the completion of the new built power stations which caused the temporary dismantling of the EE and DSM programmes due to the funding constraints. The burden of the escalating electrical tariffs are now left in the hands of the consumer which will alter the progress of continued EE and DSM initiatives. With nearly 67% of the 13.65 million [7] residential households in South Africa classified as lower

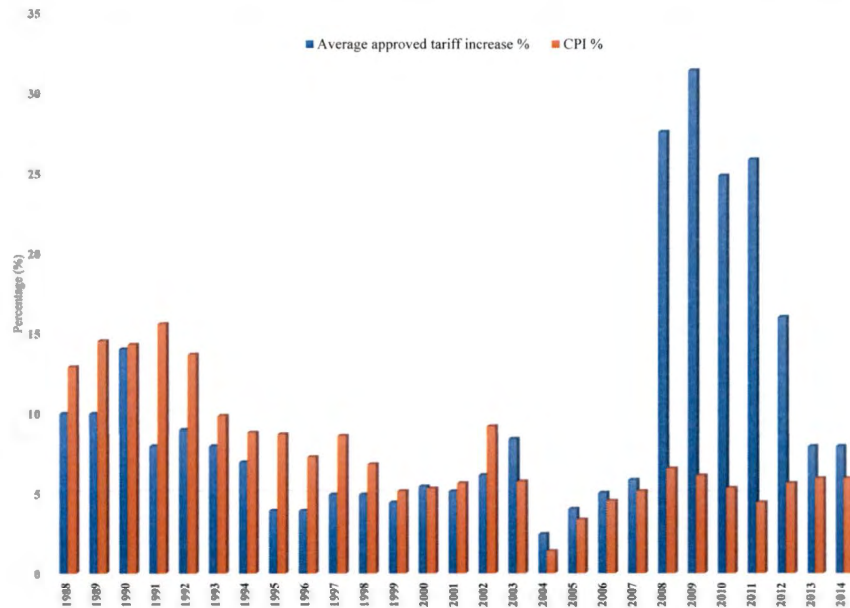


Fig. 2.2 Historical average electrical price increase in South Africa [20]

income groups, the high investment costs of energy efficient of energy reduction technologies will not be within their reach.

The responsibility therefore rests with the high-end electrical consumers to reduce their personal electrical demand with EE initiatives to achieve potential financial gains. Commercial or industrial businesses with sufficient capital expenditure might be the only entities in the position to introduce efficient technologies without the aid of EE and DSM funding programmes. The status quo for the South African public is therefore an enforced financial burden for an undisclosed period due to restricted or unavailable generation capacity of Eskom.

2.4 Energy distribution in the South African residential and commercial sectors

2.4.1 Residential Sector

Several types of energy sources are utilized throughout South Africa to fulfil the energy requirements of the consumer. Gas, wood, paraffin and coal are among the fundamental energy sources being used by a majority of South Africans but the continued expansion of

Table 2.1 Number of households per energy source in South Africa [21]

	<i>Number of households</i>		
	<i>Cooking</i>	<i>Heating</i>	<i>Lighting</i>
Electricity from mains	11,837,000	5,440,000	13,418,000
Electricity from generator	7000	5000	14,000
Gas	481,000	350,000	3000
Paraffin	1,029,000	1,155,000	373,000
Wood	1,581,000	1,838,000	8000
Coal	64,000	229,000	0

the electrical network since the start of democracy in 1994 increased the need for electricity as primary energy source.

Table 2.1 shows a list of the typical energy sources currently in use throughout South Africa. The list provides a summary on the number of households per energy source for cooking, heating or lighting purposes. Although wood and paraffin are still preferred as energy source by various domestic groups, the use of electricity remain the primary source of energy in South Africa. Due to the high volume of households dependant on their electrical connection, the need for energy efficient initiatives are a necessity rather than a luxury.

When looking at possible areas for EE solutions within the residential sector, Table 2.2 illustrate a breakdown of areas with the highest electrical consumption levels for three housing types. Cooking, space heating and refrigeration are high on the consumption list but the most energy intensive component in the upmarket and townhouse categories is water heating which accounts for nearly 40% [22] of the total electrical requirements of these households. For the informal settlements, the larger consumption type is lighting and due to the introduction of solar water heaters as part of the mass roll out programme described in section 2.2 the water heating component remains low in comparison to the other electrical equipment types. Although various EE models have targeted most of the areas in the list shown in Table 2.2 throughout the past decade, the need to manage the nearly 20% [23] contribution of the the residential sector to the total electrical demand in South Africa remain a concern if not addressed on a continuous basis.

2.4.2 Commercial Sector

The commercial sector of South Africa have a similar electrical consumption profiles compared to other parts of the world which includes office buildings, shopping centres, hotels, hospitals, restaurants and schools to name a few [4]. An end use electrical analysis of the various building types show that the total electrical consumption of the typical commercial

Table 2.2 A breakdown of domestic electricity consumption for South Africa [7]

<i>Types</i>	<i>Domestic electrical consumption</i>		
	<i>Upmarket kWh/annum</i>	<i>Townships kWh/annum</i>	<i>Informal settlements kWh/annum</i>
Water heating	2867	1345	373
Cooking	897	1260	290
Space heating	240	73	91
Refrigeration	895	429	505
Lighting	677	504	585
Other Appliances	358	183	225
Total	5934	3794	2069

buildings are distributed between fans, pumps, compressors, lighting, heating ventilation and air-conditioning (HVAC), motors and water heating geysers. HVAC and lighting respectively makes up about 26% and 18% of the total electrical load in the commercial buildings with sanitary water heating solutions [4] consuming nearly 8% of the total load. Electrical costs can be reduced by addressing the inefficiencies within the prescribed subdivision electrical loads if the correct energy measures and strategies are implemented.

Improving the efficiency of these buildings requires a durable legal and institutional framework. A model described by Winkler *et al.* suggests that EE savings of up to ZAR 13 Billion is achievable in this sector over a period of 25 years if the investment costs of the EE solutions are reasonable [24]. With the investment costs of energy savings initiatives at nearly 5% of the total project costs as illustrated by Spalding *et al.*, an intervention of the South African government is required to assist with these high EE investment costs [25]. Eskom, a government owned utility, currently absorbs a large portion of the government's guarantees [26] which places the commercial client in a similar position as the domestic client. All costs related to EE investments are currently compulsory for commercial clients which forms part of capital expenditure (Capex) budgets to manage the growing operational expenditure (Opex) costs of the buildings due to the ever increasing electrical tariffs in support of the national utility.

2.5 Commercial building water heating solutions

With the limited amount of residential consumers able to invest in new energy efficient technologies, the attention is drawn in this study to a subsystem in commercial buildings which enables commercial clients to reduce energy costs with relative ease. This subsystem is based on technologies used to heat sanitary water for typical commercial consumers like

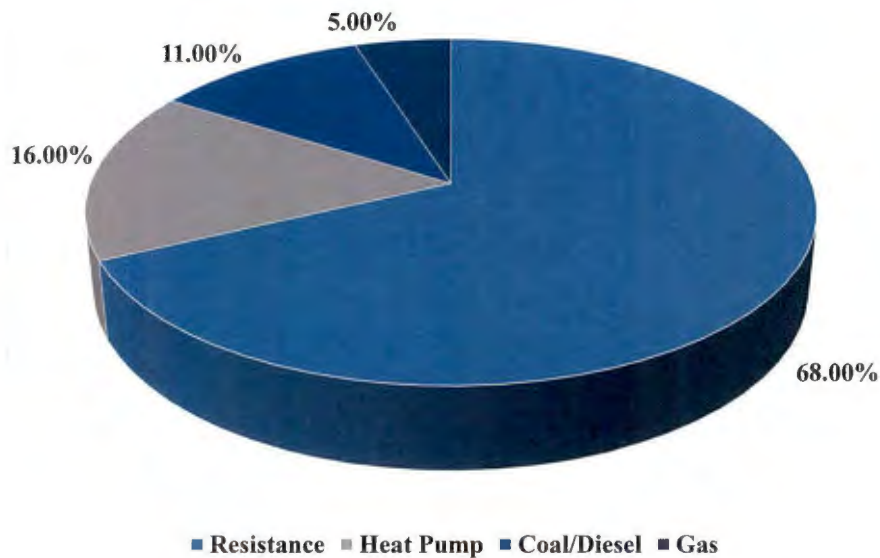


Fig. 2.3 Percentage occupants per water heating configuration in commercial buildings [27]

hotels, university dormitories, correctional services and hospitals. The implementation of energy efficient water heating technologies requires low capex in comparison to HVAC and lighting solutions within commercial buildings and make it an attractive option to reduce the energy costs for commercial clients.

The demography of the water heating sources utilized in the commercial sector of South Africa are shown in Figure 2.3 which demonstrates the dominance of electrical resistance heaters in the market. Only 21% of the total sources utilized are energy efficient technologies and highlights the energy savings potential within this subsystem. Electrical resistance heaters have been the preferred choice for more than 50 years [7] for water heating practices throughout South Africa due to the conventionally low electrical tariffs, capex requirements and the high availability of generation capacity in the past. Other advantages of the resistance heaters was the relatively high quality of the products as well as the known reliability of the technology.

In-line electrical resistance heaters and air source heat pump water heaters are other technologies that were gradually introduced to the commercial sector of South Africa since 1998. These technologies were mainly utilized for load shifting and energy reduction purposes and the benefits thereof were extensively illustrated within research done by Greyvenstein and Rousseau [27]. The research was based on an improved installation design methodology to replace the more conventional method of electrical resistance heaters located within the hot

water storage vessels. This methodology was used in a simulation environment to determine the required sizes of the heating equipment in a system. A life cycle cost (LCC) analysis of a water heating system at a prison in South Africa showed that a smaller heat pump water heater and in-line electrical resistance heater configuration can reduce the LCC of the water heating system by nearly 2.4 times compared to the actual installation.

A more recent study based on the improved installation methodology of the heat pump and in-line heater combination was conducted by Rankin et al [28] which further highlighted the compatibility of these technologies in other commercial buildings. Three different water heating installations of three different buildings were presented within this study which produced an average cost per kilowatt-hour (*kWh*) thermal saving of between 76% and 80%. Both these studies proved that by utilizing heat pump and the in-line water heaters in the South African commercial sector, one can reduce the installed electrical capacity by two thirds [29] as well as manage the thermal load of a water heating system.

The major drawback of these systems are the initial capital investment cost of the heating equipment compared to traditional electrical resistance heater solutions. A typical 65kWt heat pump unit in 2015 cost around ZAR 140,000 and a basic annual service of the unit nearly ZAR 5000, without the replacement of any major parts, based on a requested quotation from a local South African heat pump supplier. The initial cost does not include the required hot water storage vessel of a newly designed system. The costs of a similar sized in-tank electrical resistance heater which includes an average sized hot water storage vessel, is less than the cost of the heat pump unit itself. It should however be stated that the 42 month predicted payback period of the energy efficient system integration calculated by Rankin *et al.* [30], have reduced substantially over the past few years due to the high tariff increases described in section 2.3. A return on investment (ROI) of between 12 and 24 months is now possible when replacing an inefficient water heating system in the commercial sector subject to the correct design configuration.

Solar water heating solutions for the commercial sector have not been fully utilized in South Africa to date. This is mainly due to investment costs that exceeds the cost of heat pump installations and the high probability of operational problems as explained by Winkler [24] due to the complexity of intergrating the solar water heating systems in high volume applications. With limited available research on solar water heating in commercial applications, the content within this study will only focus on the integration and optimization of water heating systems that uses heat pump water heaters as energy efficient source and in-line water heaters as backup heating equipment within the design configurations.

Table 2.3 Fundamental water heating system design requirements [31]

<i>Description</i>	<i>Design constraint</i>
Water heating equipment design	Energy source type Application of developed energy to heat water Control method to deliver hot water at required temperature
Water heating equipment application	Location of equipment in system Required water temperature of building Volume of water utilized by building Flow rate requirement

2.6 Water heating system design objectives

The main objective when designing a water heating system is to accurately size the system based on the demand requirements of the consumer without negatively influencing the overall efficiency of the system. This can only be achieved by properly integrating water heating equipment, hot water storage vessels and the required piping distribution within a proposed building layout and configuration. As described in the preceding section, the combination of energy efficient water heating equipment along with a sufficient design configuration may improve system efficiencies but an undefined control methodology for the system would potentially alter the efficiency of the system. It is therefore imperative to address all the necessary input requirements to ensure the efficient operation of a water heating system for a particular application. The fundamental requirements to be addressed in a water heating system design for commercial buildings are fully described in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) which is summarized in Table 2.3.

By incorporating the respective design and application constraints within a specific design will ultimately minimize the potential of an over or under utilized water heating system. It should however be noted that external design constraints such as the peak tariff intervals of Eskom will have a substantial impact on the design process if not taken into account. Proper knowledge of the consumer requirements as well as external factors that might influence the performance of the system design are therefore crucial in an effort to lower both operational and energy costs.

2.7 Hot water consumption profiles in the residential, commercial and industrial sectors

The primary aim of any water heating system design is to ensure the sufficient delivery of the hot water to the consumer based on the water temperature and volume requirements. It is therefore essential to have proper water temperature and volume measurements as input variables for a design. These are usually in the form of actual measured hot water consumption profiles for different types of consumers within the domestic, commercial and industrial environments. These profiles offer the water heating system design engineer a platform to initiate the design process.

When looking at the available hot water consumption data of typical multifamily apartment buildings described by Goldner *et al.* [32], the dynamic behaviour in consumer demand can be seen in the presented data of the five and six storey apartment buildings. The study divided the consumption results between low, medium and high user classifications which were aligned with the income levels, the ethnic outlook as well as the localities of the various sized buildings across the United States of America and Canada that were measured. Average daily hot water consumption results for the low, medium and high user categories were measured at 53, 114 and 205 litres per person per day respectively and are still utilized today by many design engineers throughout the world.

In a South African context, the availability of hot water consumption data have gradually increased during the past two decades and similarly to the data measured by Goldner *et al.* showcases the high variance in consumption values. Early research done by Basson [33] for developed communities within the residential sector in South Africa proposed a daily consumption value of 50 litres per person which is substantially lower than the low user category of Goldner *et al.*. An estimated 35 litres per person per day proposed by Beute [34] in a study conducted nearly a decade after the proposed value by Basson indicated an uncertainty concerning actual measured data in South Africa.

The first extensive study completed in South Africa on hot water consumption profiles was published by Meyer and Tshimankinda [35–37]. These profiles were measured in both the residential and commercial sectors over the course of a year for different households in Johannesburg, South Africa. Traditional houses, townhouses and apartment units were among the households measured in this study. The daily average hot water consumption values varied between 3 litres per person for the more traditional households without electrical connections and 92 litres per person for the more developed communities. This study introduced a more complete set of consumption data that are used today by many South African engineers as input to their water heating system designs.

A more recent study on measured consumption data conducted by Rankin [38] indicated a variance in consumption values compared to the Meyer and Tshimankinda profiles for the commercial and mining sectors. The hot water consumption of two hotels in South Africa as well as six mining residences were collected within this study. The one hotel situated in Johannesburg, measured daily average consumption values between 78 and 109 litres per person and the other hotel situated in Cape Town had consumption values between 64 and 84 litres per person. Similar to the measured values of the hotels the mining residences produced average consumption values between 68 and 96 litres per person per day. The minimum and maximum values obtained within all the case studies were mainly due to seasonal variations. This study highlighted the importance of accurate consumption data as well as the impact of seasonal consumption data on a system design. A study completed by Delport [39] had a mutual outlook concerning the influence of summer and winter conditions on hot water consumption profiles which suggests that ambient annual temperatures be incorporated within the hot water system design process of a specific water heating application for more accurate results.

Figure 2.4 illustrates a typical daily hot water consumption profile measured by Meyer et al [3] against the mining and hotel profiles measured by Rankin [38]. A clear variance can be seen within all three profiles with unique demand requirements throughout a 24 hour day. The mining profile reaches a steady consumption condition at 06:00 with a slight peak in the afternoon between 14:00 and 16:00, with the consumption decreasing after the last working shift of the day at 19:00. Hotels tend to have their peak consumption during the morning hours from 06:00 to 10:00 with a slight increase during the evening. This is in contrast to the Meyer and Tshimankinda profiles that have distinct morning and evening peak intervals and are referred to as the "twin-peak" profiles. The dynamic features of these profiles complicates any water heating design process which requires accurate consumption data as input. Worldwide, various hot water load modelling methodologies have been developed to overcome this problem which are mainly directed at designing water heating systems for specific system configuration. The models aim to predict load profiles based on certain input criteria to either size a system or control a system more efficiently. Some of these models will be discussed in the following section.

2.8 Water heating system modelling

As described in the preceding sections the design of a water heating system is dependant on several input variables to accurately determine the specifications. The typical variations in hot water load requirements between the residential, commercial and industrial consumers

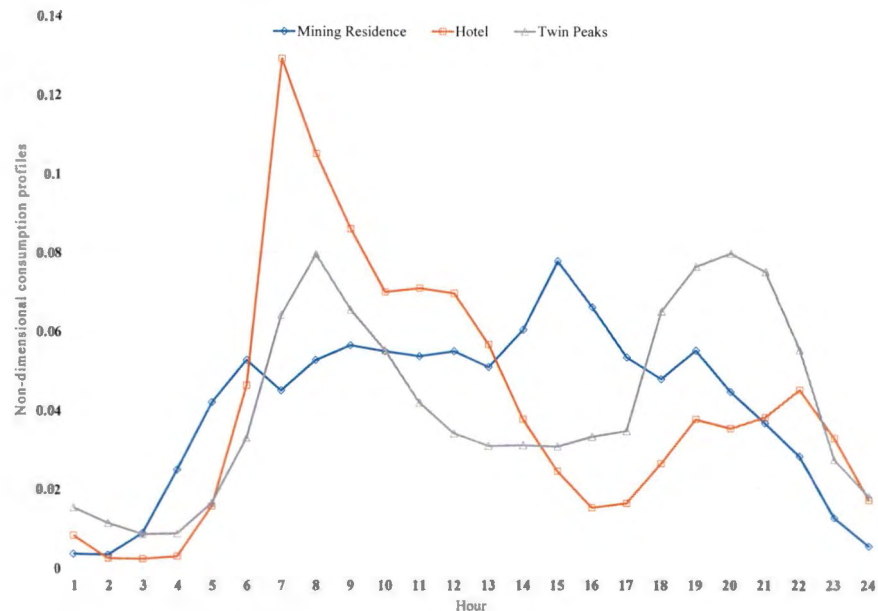


Fig. 2.4 Documented SHW consumption profiles in South Africa

in South Africa are shown in Figure 2.4. These variations in profiles are the force behind the development of water heating system design models that can predict load profiles for control purposes. Most of the models developed have the ability to determine outlet water temperatures as well as electrical demand profiles of water heating systems.

A model developed by Allard *et al.* [40] focused on the temperatures within a hot water storage vessel by using TRNSYS software which includes certain input parameters of an electric water heater. The aim of this study was to improve the accuracy of vertical stratification modelling for a water heating system by utilizing a one nodal model as part of the prediction of outlet water temperatures. Rankin [41] similarly developed a prediction model based on the internal stratification of the storage vessel. This model predicts the heating demand and hot water availability of the water heating system by utilizing the thermostatic control, outdoor temperatures and hot water consumption profiles as input to the model. Both these models focused on the performance characteristics within water heating equipment to predict certain load models.

Moreau [42] used a different approach by modelling the activation and reactivation process of several water heating systems to minimize the peak demand of the electrical grid in Canada. This model activates water heating equipment on a delayed sequence after load shifting intervals to reduce the total effect of simultaneous activation of the heaters on the grid. The ripple control model illustrated by Beute and Delport [43] assisted a municipality

in South Africa in a similar manner, by not exceeding their maximum demand, utilizing load switches for hot water heaters at random locations in residential households. A selection of control groups were structured to manage the switching cycles of the hot water heaters at high demand intervals without affecting the hot water demand of the consumer. This control algorithm included a strategy to avoid exceeding the maximum demand of the municipal load during activation of the water heaters at regular intervals.

A comparable model developed by Dolan *et al.* [44] used the associated details of a water heating system to analyse the energy flow of a storage vessel in an effort to assess the model as a DSM load management solution. Standard input variables required for the Moreau, Beute and Delport as well as the Dolan load management models are usually the electrical tariff structures and the hot water demand profiles within a system. A typical example of a model that controls the water and space heating of a large building based on tariff structures were presented by Gustafsson and Rönqvist [45]. This model avoids district heating during winter periods when the demand part of tariff structures become too expensive, to effectively minimize the costs of a system without affecting the consumer demand. It is however reiterated within this study that the costs are dependant on the heat requirements of a building and should be measured to ensure accurate input data for the model.

One feature according to Dotzauer [46], that remains essential as input to water heating system modelling, is the social behaviour of the hot water consumer. This model manages to overcome the practical challenges experienced with many complex load prediction models, by only concentrating on the ambient conditions and the behavioural profiles of the consumer to predict the required heat demand of a district heating system. It therefore proves that the absence of measured hot water consumption data greatly influences the accuracy of water heating load prediction models.

2.9 Summary

The first part of this chapter emphasized the importance of sustainable energy solutions in the South African market due to uncertainties in terms of the availability of electrical generation capacity in the country. Water heating systems within the residential, commercial and industrial sectors were identified as a market where energy efficient technologies and strategies can be implemented in an effort to help reduce the current national electrical demand in South Africa. The efficient design methods of water heating systems were addressed which highlighted the influence of hot water consumption profiles as primary input to a water heating system design. Due to the high variances in available consumption data

found in literature, simulation models are continually developed to increase predictability of hot water demand in various applications for improved system design and control.

In conclusion, without the availability of actual measured hot water consumption data for every water heating design application, the likelihood of producing accurate load prediction models will decrease due to the unique consumption behaviour of each design. Simulation models are therefore required, especially in South Africa, that can accurately predict the hot water requirements of the residential, commercial or industrial consumer by improving water heating system design and control strategies. The following chapter will introduce a method to predict the hot water consumption profiles for a specific application which will then be utilized within the newly developed hot water scheduler to be discussed in Chapter 4.

Chapter 3

Consumption Profiles as Input to Sanitary Hot Water System Design

Hot water consumption profiles play an integral part as input to the design of a hot water heating system. Without accurate hot water consumption data it becomes challenging to determine the sufficient size of a system which can ultimately influence the performance and efficiency of that particular system. The availability of recorded consumption data within the residential, commercial and industrial sectors of South Africa are limited. This chapter presents newly captured data of two renovated high rise buildings in the city centre of Johannesburg, South Africa. The data for these high density apartments were collectively measured between 2011 and 2014 and compared with the existing domestic hot water consumption profiles found in literature. A detailed analysis of the existing and new profiles will be presented as well as a method on how to predict a daily consumption profile which can be utilized as part of the hot water system design.

3.1 Housing demographics in Johannesburg, South Africa

The city of Johannesburg, situated in the province of Gauteng, is the largest city in South Africa covering 1645km² with a population density of 2,346/km² according to the latest census of 2011 [21]. Close to 4.4 million people reside in Johannesburg which accounts for nearly 36% of Gauteng and 8% of the South African population. The population growth of Johannesburg between 2001 and 2011 [47] was 37% which increased the demand for accommodation in and around the city centre. Initiatives like the state-subsidised housing scheme have provided some relief to the 15.1 million [21] households in South Africa but the negative growth in affordable accommodation remains a concern for the continued population growth.

Within the population density as depicted in Figure 3.1, the household demographics of Johannesburg have changed considerably since the start of democracy in 1994. Of the average households in the metropolitan area of the city, most are categorized as either formal or informal dwellings. Looking at the different type of households within the Gauteng area shown in Table 3.1, the majority are defined as block structure dwellings which includes the state-subsidised houses. The 19.8% informal dwellings [21] are however situated in the outskirts of the Johannesburg metropole which makes commuting between the dwellings and the central business district (CBD) a tedious and costly exercise. With most of the business activities in and around the CBD of Johannesburg, the demand for accommodation within the city centre have increased. Owners of high rise buildings have started to revamp old office buildings into living quarters to fill the accommodation void. This created a demographic shift where informal settlement residents now have access to affordable accommodation in established buildings with the added benefit of existing electrical, sanitary and water supply connections.

Although basic service delivery, especially with regards to electrical and water connections, have improved throughout the years in the underdeveloped informal settlement areas, the advantage of upgrading under utilized infrastructure in the Central Business District (CBD) of Johannesburg can assist with the high accommodation demand. The problem however exists in understanding the electrical and water consumption profiles of buildings that have already been refurbished for accommodation purposes. Behavioural variances have been noted in this study of two high rise buildings that differ from existing consumption profiles for high density population group classifications found in literature. These new profiles were obtained from the actual hot water consumption of each building measured over a period of four years and a summary of the results as well as a comparison with existing profiles are presented in the sections to follow. The emphasis is placed on the importance of up to date consumption data as part of system design and energy management initiatives. A

definitions with regards to apartment group profile classifications to assist with the water heating design process. User demand categories are defined and utilized by both sources as input to determine the heating capacity and storage volumes of the centralised water heating system.

Low, medium and high user defined categories presented in the ASHRAE guidelines are based on the hot water consumers within certain predefined demographic groups. The typical low user defined profile included consumers of middle income and of higher density populations. In contrast, the typical high user profile is defined as a low income user, on public assistance or a single parent household. These profile classifications guidelines are related to the research done by Goldner [32, 49] and Becker *et al.* [50] who all measured apartment buildings at various locations within the United States and Canada. These profiles are still used today as reference for apartment building water heating designs in various parts of the world.

With regards to the South African hot water user profiles, the research done by Meyer and Tshimankinda [36] defined the consumer profiles in the similar low, medium and high categories but instead of using demographic user content the categories were defined by the population density. These density profiles were categorized by the number of dwellings per squared kilometer as well as the number of occupants per dwelling. For a low density group a 3.1 average number of occupant per dwelling was defined irrespective of any age group, and the high density group had an average of 6.2 occupants per dwelling. In retrospect, the user profiles of Meyer and Tshimankinda [36] in comparison to the ASHRAE guidelines are inversely proportional with regards to the actual hot water consumption per person. The low user hot water consumption of the ASHRAE guidelines for example is similar in principle to the high density profiles presented by Meyer and Tshimankinda [36]. The only major difference is the value of measured hot water consumption per person per day.

The main objective of the aforementioned strategies are to obtain an average hot water consumption per person per day value which will assist the system designer to effectively size the water heating system. Incorrect consumption data may lead to under or oversized water heating and storage volume equipment. To establish a unified classification concerning the input profiles within this study the user category defined in Table 3.2 will be used. It is however not defined according to the demographic classifications of the ASHRAE guidelines but rather the density categories provided by Meyer [3]. The categories are also divided into three groups which include houses [35], apartments [36] and townhouses [37]. The predominant focus of this chapter will be to evaluate the newly measured data obtained for two high rise apartment buildings in Johannesburg Central business district (CBD) and compare it to the apartment profiles measured by Meyer and Tshimankinda [36].

Table 3.2 Demographic and user defined categories for different dwellings

<i>Group</i>	<i>Population Density Category</i>	<i>User Category</i>	<i>Density (dwellings / km²)</i>
Houses	Low density	High user	845
	Medium density	Medium user	2029
	High density	Low user	3857
Apartments	Low density	High user	4960
	Medium density	Medium user	8734
	High density	Low user	26874
Townhouses	Low density	High user	3810
	Medium density	Medium user	8116
	High density	Low user	25195

3.3 Refurbished high rise apartment buildings

The water heating systems for the two high rise office buildings mentioned earlier formed part of the refurbishment process of each building. Both apartment buildings required centralised water heating systems which included the distributed piping layout connected to each floor. The original designs were based on values specified by the client concerning the maximum projected occupants per apartment unit. With no user consumption data available as input, the design process simply aimed at supplying sufficient hot water to the occupants of the respective buildings using energy efficient hot water heaters.

Detailed descriptions of the water heating system design specifications for both apartments buildings are presented in the following sections but due to a confidentiality agreement with the building owner, the location and names of the buildings will not be disclosed within the content of this study. From here on the buildings will be referred to as *Building A* and *Building B*, respectively.

3.3.1 High rise apartment Building A

In 2011, the installation and commissioning of the water heating system of Building A was completed. This seven (7) storey building has 131 apartment units in total as well as one (1) rooftop and three (3) basement apartments including a laundromat. The layout of all the apartment units are generic in design which are similar in size and includes a kitchenette and bathroom per unit. As depicted in Appendix A, the bathroom is equipped with a bathtub, washing basin and toilet which are isolated from the open plan configuration of the apartment. The physical layout drawings presented in Appendix A assisted with the design of the cold and hot water distribution network of the building but the water heating system design required the projected occupant specification of the building. An average of 2.5 occupants per

apartment were specified as input to the design along with a speculative average occupancy level of 100%. This information was used as input to the sizing calculations for the water heating equipment and will be presented in the following sections.

Building A water heating system design

- Storage vessel volume:

The first step in the original design process was to determine the hot water storage capacity of the system. This required the maximum occupancy specification along with the seasonal hot water consumption per person per day. An average daily hot water consumption of 60 litres per person were chosen for the 39 weeks of summer between September and May with an average consumption of 80 litres per person for the remaining winter months. The consumption values were based on experience with regards to commercial accommodation units and not according to a density group classification. To determine the minimum storage capacity requirement the estimated winter consumption was used as reference along with a maximum consumption sizing factor. With a sizing factor of 100% for example, all the occupants in the building required a continuous supply of 80 litres hot water per person per day. This means that all the building occupants consume the available hot water in the storage vessels at the same time. Although it might seem like a safe sizing estimate, it will have an impact on the required storage vessel volume which will influence the capital expenditure of the installation. The sizing factor for this design was chosen to be 60% which represents the maximum percentage of stored capacity that can be utilized at any given time. The minimum required volume can therefore be calculated as:

$$V_{min} = \%_{factor} \times L_{max} \times N_{total} \quad (3.1)$$

with $\%_{factor}$ the equipment sizing factor, L_{max} the maximum hot water consumption per occupant per day (Litre) and N_{total} the total number of occupants in the building. The sizing of the hot water storage vessel for the installation at Building A required a total of 16000 litres. Two 8000 litre vessels were chosen for the design to include redundancy within the water heating system.

- Water heater sizing:

With the storage vessel capacity known the next step in the design process was to determine the water heater size. An energy efficient water heating solution was required by the client which had to include a backup electrical resistance heating solution. Air

source heat pump water heaters were chosen as primary heating method due to the moderate annual climate of Johannesburg and an in-line electrical resistance water heater was included as backup. The main input variables required for the sizing of the heaters were based on the average occupancy of the building, average consumption per occupant, the storage heat losses of the water heating system as well as the ring main return piping heat losses of the water heating system. The required water flow rate of the heating system was calculated with

$$m = \frac{N_{avg} \times L_{avg}}{t_{running}} \quad (3.2)$$

where,

m = water flow rate, kg/s

N_{avg} = average number of occupants

L_{avg} = the daily hot water consumption per person averaged per year, l/pd

$t_{running}$ = running time of heater unit, seconds/day

This was used as one of the input variables for the system heating capacity calculation. Concerning the storage and piping heat losses, a fixed estimated value of 17% was chosen for the vessel losses and 60% for the return piping losses, which were typical values provided by a commercial high rise building water heating system manufacturer and installer in South Africa. A final input variable required for the heating capacity design was the annual hot water supply and cold water inlet temperature differences. The following equation was then used to determine the system heating rate based on the required hot water consumption and overall losses:

$$Q_{system} = m \times c_p \times \Delta T_{annual} \times SV_{loss} \times RM_{loss} \quad (3.3)$$

where,

Q_{system} = system heating rate, kWt

c_p = specific heat of water, 4.184 kJ/kg.K

ΔT_{annual} = average winter and summer hot water supply temperature, °C

SV_{loss} = storage volume loss, %

RM_{loss} = ring main return loss, %

The heating capacity of the system design for Building A resulted in a heater size requirement of *103 kilowatt thermal (kWt)* which was calculated by using a measured ΔT_{annual} of 44.3°C . A *65kWt* together with a *50kWt* heat pump water heater were selected as the primary water heating units for the final hot water system design. A similar approach was used to determine the backup heater size using equations 3.2 and 3.3. L_{avg} in equation 3.2 was however replaced with L_{max} to determine the maximum required hot water for the specified building occupants without the assistance of the heat pump water heater units. This is only to ensure that the system remain operational should both of the heat pump water heaters be offline or in situations where the heat pump units could not sufficiently supply the required hot water to the system. The calculated backup heater size for the water heating system was *108kWt* with an external in-line heater sourced for the installation consisting of a two stage control panel to ensure the backup heater is not permanently activated. The installation of the water heating system is discussed in the following section and includes some details on the configuration and control.

Building A water heating system layout and control

The layout of the water heating system was based on the improved heat pump and in-line heater configuration as depicted by [29] which focuses on filling the hot water storage vessels using a stratification method. Both the primary and backup heater units were connected in parallel to the series connected storage vessels. All the cold water inlets of the heaters were connected to the main cold water supply at the bottom of vessel 2 ("Bottom Vessel") and the hot water outlets of the three heaters were connected to the top of vessel 1 ("Top Vessel") as shown in Figure 3.2. The ring main return piping of the building was connected to the middle of vessel 2, to avoid any lukewarm water mixture within vessel 1 and thereby negatively influence the stratification. During lower consumption intervals both vessels would be filled with hot water by the primary heaters until the set temperature of the thermostat in vessel 2 is reached. In higher consumption periods the available hot water storage volume in the vessels along with the primary heaters effectively supply the building with the required hot water. The backup heater only activates during heat pump failure conditions or when the thermostat in vessel 1 drops below the set temperature to assist the heat pumps during high demand intervals. Even though the control of the system had a static approach, the initial aim was only to ensure the sufficient supply of energy efficient hot water. Details concerning the system layout and control of Building B are discussed in the following section and the variances in the design configuration are compared with Building A.

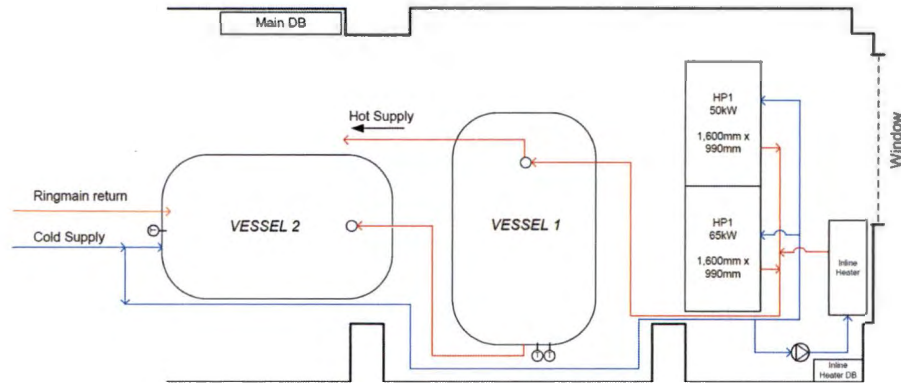


Fig. 3.2 Building A water heating system top layout

3.3.2 High rise apartment Building B

The installation and commissioning of the water heating system of Building B was completed in 2013. It is a seven (7) storey building similar to Building A with 150 apartment units and an estimated 373 occupants. All the apartment units in the building have generic layouts which include a kitchenette, bathroom and open plan room configuration. No laundromat facility, basement or rooftop apartment units exist in Building B and the installation of the water heating system was positioned in the basement area. The positioning of the water heating system in the basement area and the typical top view layout of each floor for Building B is showcased in Appendix A. These layouts include the highlighted cold and hot water piping reticulation of the building. As part of the design process the inputs are similar to that presented for Building A and will be discussed in the following sections.

Building B water heating system design

- Storage vessel volume:

The minimum storage vessel volume requirement for Building B was designed according to the specifications presented in the Building A water heating system design. A sizing factor of 50% of the maximum consumption was chosen instead of the 60% requirement used for Building A due to a lower predicted consumption levels. This resulted in a 14000 litre calculated volume using equation 3.1 for the system design whereby two 7300 litre vessels were selected for the design to include the redundancy factor for the Building B design.

- Water heater sizing:

Equations 3.2 and 3.3 were used to determine the heat pump sizes for Building B and resulted in a required thermal capacity of $108kWt$. Similar to the design of Building A, a $65kWt$ along with a $50kWt$ heat pump water heater unit was selected for the particular installation. The only major difference however, in comparison to the Building A design, was the backup heater selection. The installation of intank electrical resistance elements in both vessels were selected above the in-line heater option to reduce the installation cost. The disadvantage however of the intank elements is the gradual mixture of the cold and hot water in the vessels as explained by Rankin *et al.* [28], which requires a different control methodology compared to the in-line heater configuration. A total installed backup heating capacity of $120kWt$ was calculated which were distributed evenly between the two vessels as shown in Figure 3.3. Even though the backup heater control strategies of the two buildings differ the piping layouts are similar as explained in the following section.

Building B water heating system layout and control

Figures 3.2 and 3.3 illustrate similar water heating configurations of parallel connected heat pump water heaters coupled to the series connected hot water storage vessels. The only alteration between the two system layouts are the positions of the backup heaters. This affects the control of the system due to the effectiveness of the heating source. The intank elements of the Building A design need larger heating capacities to effectively heat the installed volume within a short time span which makes it more energy intensive. It is however a less expensive alternative than the in-line heater option which motivated the installation of intank elements for the Building B water heating system. The control philosophy included primary thermostats in the bottom vessel of Figure 3.3 which initiates the operation of the heat pump water heaters as well as the intank elements. The element bank of the top vessel will be operational when a heat pump fails or during peak demand intervals and the element bank of the bottom vessel will only operate during heat pump failure. A timer functionality was also incorporated into the water heating system configuration to switch on the intank elements as required. This was done in support of the primary heaters to build enough hot water storage during the peak electrical tariff intervals to limit the operation of any heater as part of a cost saving initiative.

A new system sizing and control approach is presented in Chapter 4 that includes improved energy saving capabilities and will be evaluated against the original water heating system designs of Building A and B. The rest of this chapter will be dedicated to the actual measured hot water consumption of the two high rise buildings.

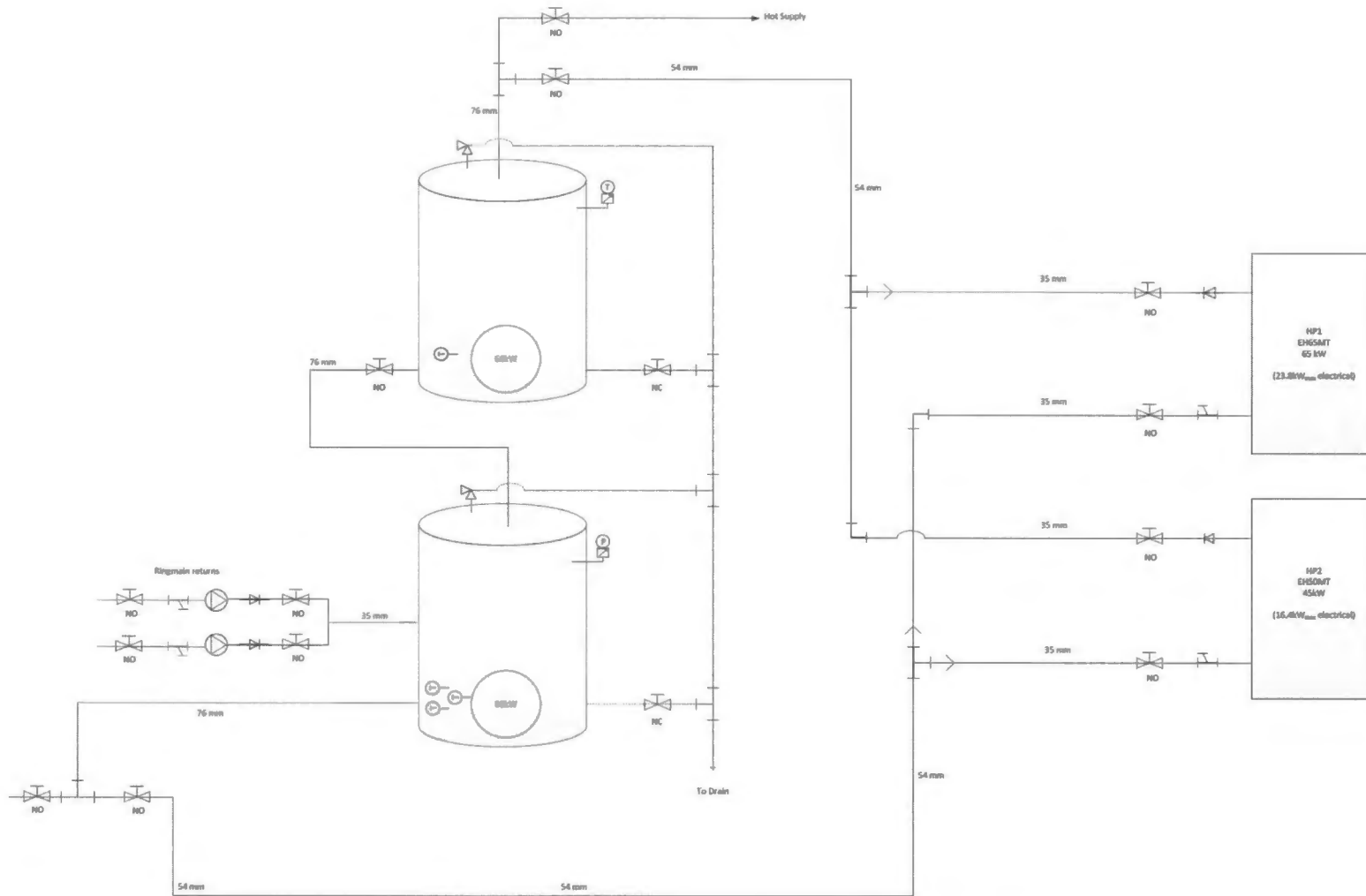


Fig. 3.3 Building B water heating system installation configuration

3.4 Newly measured hot water consumption profiles

After the final commissioning of the water heating systems at the two high rise buildings, the systems were monitored for a prolonged period to evaluate the performance. Building A was measured between January 2012 and December 2014 and Building B was being measured from January 2014 to December 2014. Hot and cold water consumption data was collected on a monthly basis per apartment unit via analogue flow meters for billing purposes. This data was structured as cumulative monthly consumption values measured in kilolitres (*kL*) and was monitored per floor of each building. Based on the data monitoring of Building A it became evident that the hot water consumption per person was substantially higher than originally anticipated. It did not correlate with the density group classifications as described in section 3.2. Fortunately the water heating system design was based on standard commercial building practices and not according to density group classifications. The system would have been undersized if the design was based on the lower consumption specifications of the high density apartment group in Table 3.2. Similarly, high consumption patterns were noted of the Building B measurements which resulted in the need to investigate the applicability of the existing consumption profiles used as input to water heating system designs. The respective consumption profiles of Building A and B are presented and described in the following sections.

3.4.1 Building A hot water consumption profiles

As mentioned before, the hot water consumption data of Building A spans over a three year period between 2011 and 2014 with significant variances in consumption between the various floors of the building exists. In the 2012 profile of Figure 3.4, the prominent peak consumption can be seen during the winter months of June, July and August with the exception of a slight peak in April. From the measurements per floor, a progressive increase in consumption were found from the ground floor up to the top (7th) floor even though the floors have an equal number of apartment units. The main cause of this occurrence might be due to the hot water which is pumped directly to the top floor and gravitationally fed to the rest of the floors in the building. Higher consumption measurements recorded at the lower floors are due to longer waiting periods for adequate water temperatures. This not only affected the monthly cost of the occupant residing at the lower levels but also increases the total water consumption of the building.

In 2013 the consumption profiles reached a noticeable peak during the month of April as shown in Figure 3.5 along with the predictable winter increase also seen during 2012. An interesting behaviour can be seen during May after the April peak consumption. May

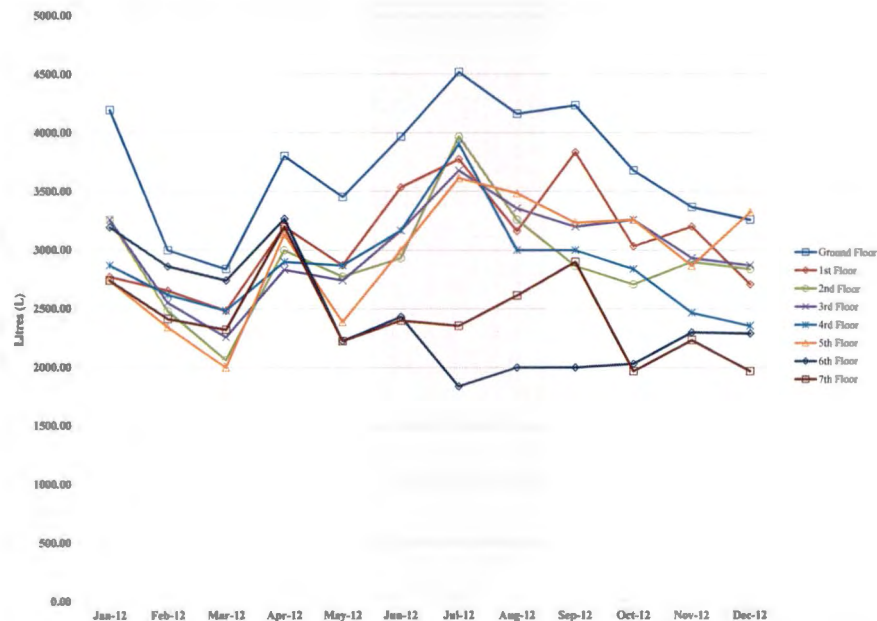


Fig. 3.4 Average hot water demand per floor per day - Buildings A (2012)

has the lowest average consumption due to the direct impact of the hot water costs to the consumer. The tenants are charged prorata by the building owner per kL consumed which is based on a fraction of the total electrical costs of the water heating system and the total hot water consumption of the building per month. Thus, in a high consumption month, the cost per kL will be directly proportional to the hot water consumption increase. The tenants are now attentive of the high incurring costs and naturally changes the consumption behaviour in the succeeding month. This behaviour can also be seen during February of all the consumption patterns. With a decrease in consumption during the December months, the January consumption naturally increases when the apartments are at full capacity.

When reflecting on the consumption patterns of each floor, none of the floors have a consistent annual average hot water consumption. The 3rd floor for example had an increase of 25% in hot water consumption from 2012 to 2014, as shown in Figure 3.4, 3.5 and 3.6, which added a further 900 L per day on average to the total building consumption. In contrast, the ground floor had a decrease of 210 L on average per day during the same period. This means that even though the consumers on the ground floor reduces their hot water consumption, the monthly cost is not reduced due to the higher consumption rate of the 3rd floor tenants. The average consumption of Building A have increased by 10% annually over the three year period and might be the cause of irregularities in occupancy levels. It

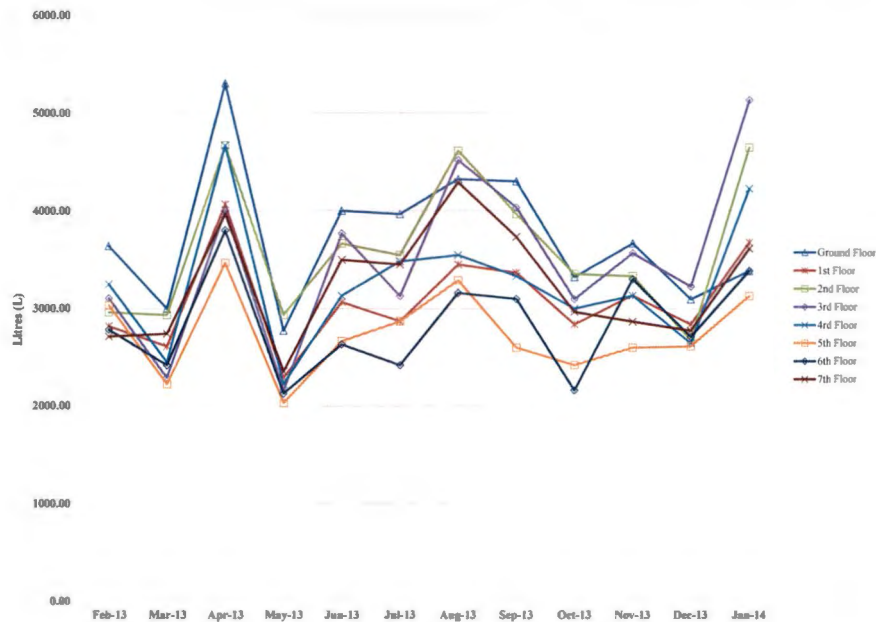


Fig. 3.5 Average hot water demand per floor per day - Buildings A (2013)

accentuates the need for up to date hot water consumption data of a specific building to improved water heating system design and control.

3.4.2 Building B hot water consumption profiles

Based on the preceding profiles for Building A, a similar trend can be seen in Figure 3.7 in relation to the profile behaviour of Figure 3.4. The consumption of the lower levels, especially the 1st floor, are noticeably higher than the top floors. Twenty three (23) apartment units on the 1st floor consume on average 50% more hot water than the same number of apartment units on the 6th floor. Compared to the ten (10) apartment units on the ground floor, the apartment units on the 6th floor consumes 6% more on average. A solution is therefore required to optimize the distribution of the hot water throughout the building to minimize the hot water delivery time to the respective occupants per floor which is beyond the scope of this study. The attention will now be shifted to the assessment part of different hot water consumption profiles where the respective hot water consumption of the buildings are compared to the existing apartment profiles of Meyer and Tshimankinda [36].

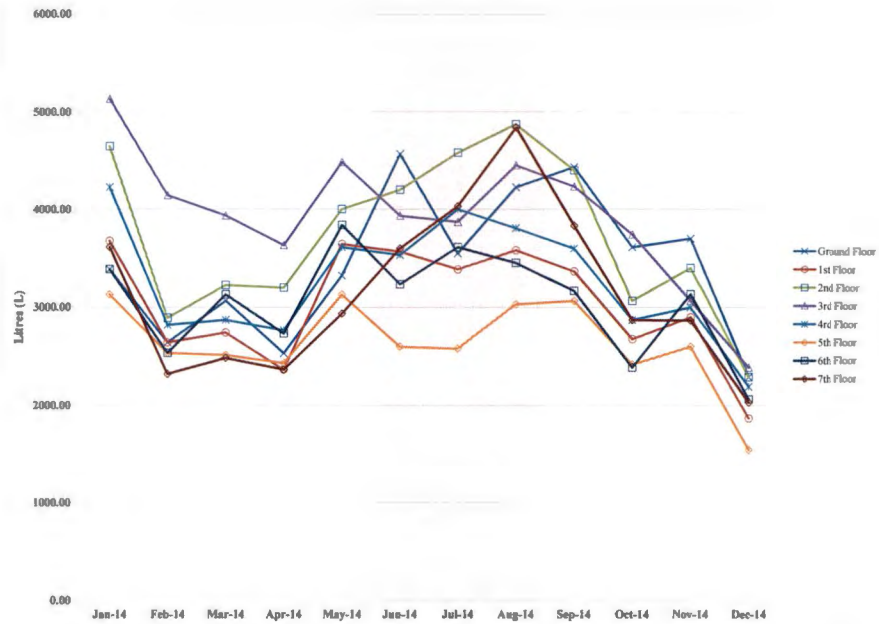


Fig. 3.6 Average hot water demand per floor per day - Buildings A (2014)

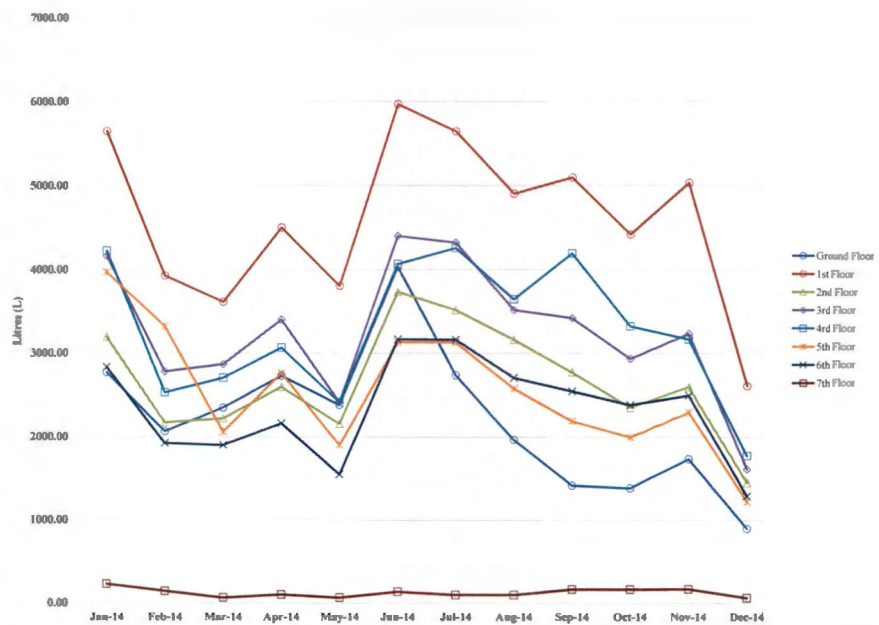


Fig. 3.7 Average hot water demand per floor per day - Buildings B (2014)

3.5 Assessment of hot water consumption profiles

The various consumption profiles measured by Meyer and Tshimankinda [35–37] have been utilized by South African engineers for more than a decade as part of the water heating system design process. To date no updated consumption profiles have been introduced with respect to high rise apartment buildings which limits the potential for an optimized system design. The measured profiles presented in section 3.4 are new additions and varies substantially from the existing profiles of Meyer and Tshimankinda [36]. The discrepancies between the consumption profiles are assessed in the form of annual consumption patterns as well as cumulative daily profiles which are addressed in the following sections.

3.5.1 Annual consumption profile comparisons

At the start of the assessment, the user classification discussed in section 3.2 had to be defined for the hot water consumption profiles of Building A and B. Both high rise buildings were assigned to the high density group classification of Table 3.2 due to the densely populated area of the respective buildings. This classification was categorized alongside the low user apartment profile of Meyer and Tshimankinda [36] in Figure 3.8 and 3.9. The low, medium and high density profiles plotted against the average annual consumption of Building A show substantial variances between the low user profile and the newly measured consumption profiles. Some of the monthly measurement even exceed the high user profiles, but none of the Building A profiles have any similarities with the summer and winter characteristics of the existing low, medium and high user consumptions. A relatively consistent consumption pattern is visible within the three measured years with the exception of a few peak intervals. The combined average representation of all the newly measured profiles of Building A is positioned between the medium and high user profiles in Figure 3.8 rather than the low user specifications as originally envisaged by the density group classifications.

A similar result can be seen for the measured consumption profile of Building B illustrated in Figure 3.9. The profile is much higher than the high density (low user) category but is aligned with the medium density profile. It is therefore imperative to use updated consumption data rather than outdated profile data to avoid the possibility of an undersized system design. Details on how the profiles can effectively be utilized in a water heating system designs are presented in the following section.

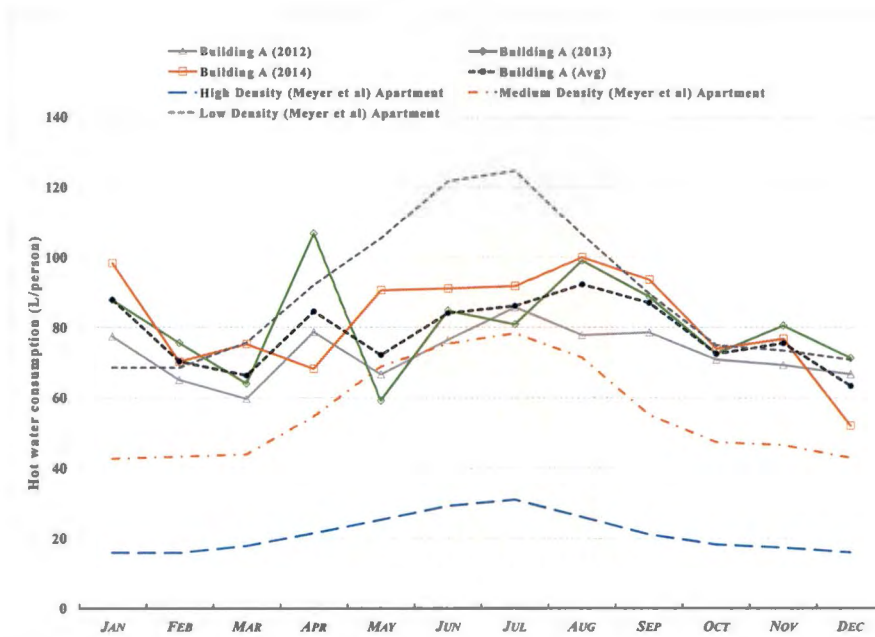


Fig. 3.8 Buildings A versus existing high density apartment consumption profiles

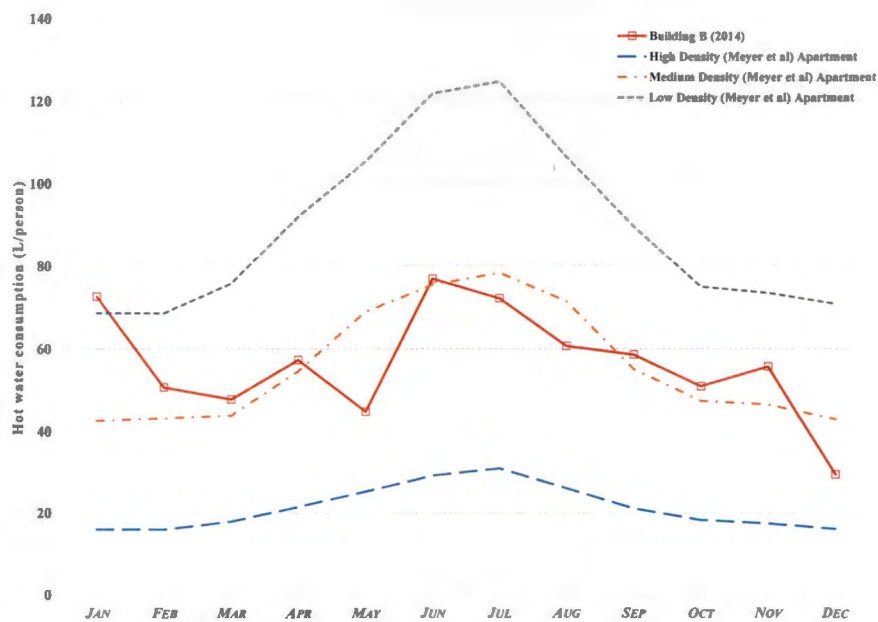


Fig. 3.9 Buildings B versus existing high density apartment consumption profiles

3.5.2 Cumulative consumption profile comparison

The hot water consumption of Building A and B was limited to the collective monthly measurements described in the previous section which made it difficult to determine the required hourly consumption of the buildings. In an attempt to process hourly profiles of Building A and B, the average daily hot water consumption per person per day was determined by dividing the total consumption per month by the number of occupants in the building. Because of the extensive research done on the 90 apartment units by Meyer [3] the assumption is made that a similar daily profile exist in the annual profiles of Building A and B. The profiles will then have the same distinct morning and evening peaks as indicated in Figure 3.10.

The process of acquiring the correct profile within available consumption data is usually built around the total consumption per person per day. A cumulative representation of the profiles shown in Figure 3.10 unveils the required values which are then used as input to the water heating system design. The categorized summer and winter consumption profiles in Figure 3.10 are illustrated in Figure 3.11 as a cumulative consumption graph to retrieve the required hourly hot water consumption per person. These profiles are compared to the newly processed cumulative data of Building A and B which are categorized according to the low, medium and high user profiles of Meyer and Tshimankinda [36].

As seen in Figure 3.11, the low user consumption of 24.74 litres per person per day is much lower than the daily cumulative consumption of the two measured buildings. On average a Building B occupant consumes nearly 56 litres per day which is closer to the medium user profile, and a Building A occupant consumes between 72 and 82 litres per day. This variance in consumption between the respective profiles makes it difficult to determine which profile to use for a water heating system design of a high rise apartment building. A dynamic and site specific consumption profile would be the ideal solution instead of selecting a profile similar to a particular design. The following section introduces a method on how to calculate accurate hot water consumption usage based on recorded profiles.

3.6 Hot water consumption profile forecasting

It is evident from the analysis of the various consumption profiles throughout this chapter that consumption data used by engineers require up to date profiles to frequently compare the validity of historic data. The dynamic behavioural patterns of hot water consumption influences the design and eventually the efficiency of a hot water heating system. A solution to the inconsistency of profile data is to predict the behaviour of a profile related to the design criteria of a system. The actual hot water consumption per person at a specific time of day

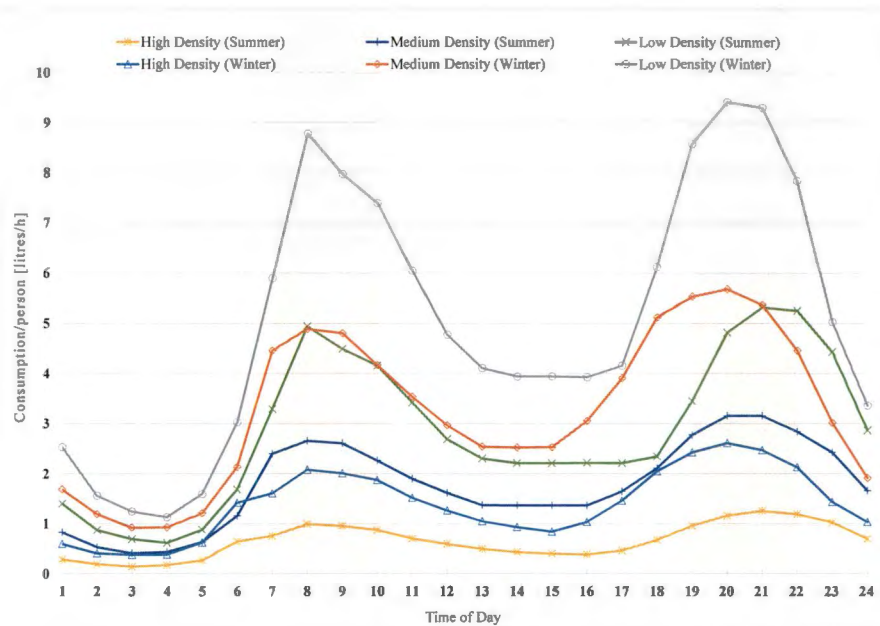


Fig. 3.10 Summer twin peaks hot water consumption profiles for apartments [36]

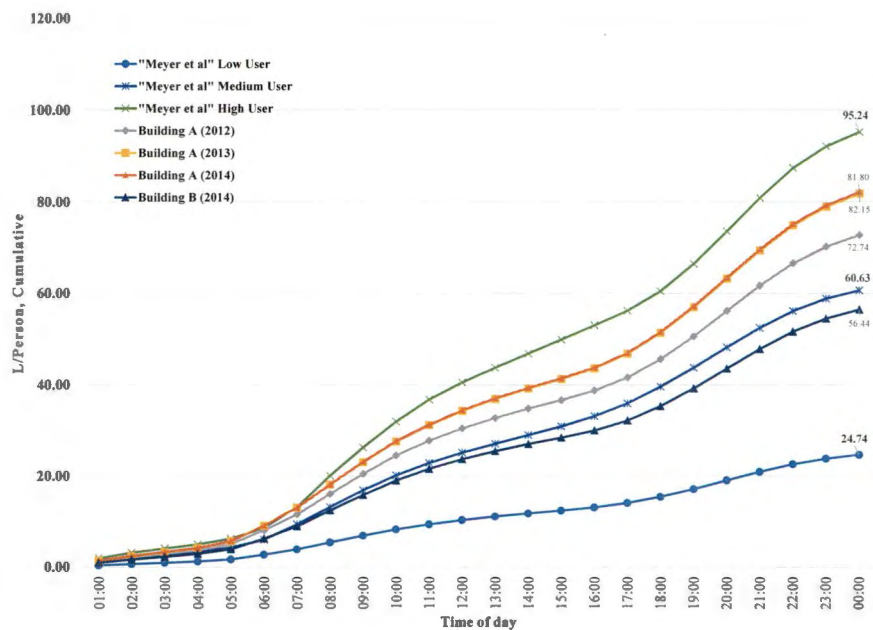


Fig. 3.11 Cumulative daily hot water consumption profile comparison

will then be determined using actual recorded cumulative consumption data. This section presents the process on how to calculate the required consumption profile which will be utilized as input to the hot water scheduler to be discussed in Chapter 4.

3.6.1 Cumulative profile prediction model

The initial step towards estimating the predicted consumption profile start of by selecting an existing cumulative consumption profile. This profile should relate to the household sector where the water heating system will be installed. Figure 3.12 shows a few variations of available cumulative profiles within the commercial and industrial sectors of South Africa. These profiles include the twin peaks consumption data illustrated in section 3.5 as well as the hotel and mining residence profiles measured by Rankin [41]. A distinct morning peak interval can be seen between 06:00 and 13:00 in the hotel profile with a more linear progression in daily consumption for the mining residence profile. Conversely, the twin peak profile has the unique morning and evening peak intervals. The correct selection from the available profiles is therefore crucial as input to the predictive model due to the large variances in the hourly hot water demand. For explanatory purposes the twin peak profiles will be selected to define the predictive profile modelling, based on the commercial high rise buildings described in this chapter. This profile is more in line with the typical consumption in an apartment building.

The high and low user cumulative twin peak profiles of Meyer and Tshimankinda [36] in Figure 3.13 illustrated the boundary conditions of the typical consumption per person in an apartment building. These boundaries are used as reference to eventually determine the water consumption per person at a specific time of day. To calculate the consumption per person one requires a curve fit mathematical approach to simplify the data capturing process. Looking at the cumulative graphs in Figure 3.13, the 6th order polynomials, shown in dotted lines, for the low and high user graphs are accurate representations of the actual cumulative consumption profiles. These curve fit equations will be utilized to determine a new cumulative consumption profile within the boundaries of the actual cumulative consumption profiles. The y variable in both equations represent the consumption per person and the x variable the time of day.

All the discrete hourly data points of the two polynomials are used to determine the minimum and maximum hot water consumption per person per day as well as the minimum and maximum values per person at a specified hour. The specific hour is chosen by the designer within the hot water scheduler to be presented in Chapter 4 to dynamically test the water heater system design for optimum sizing and control purposes. To determine the actual hot water consumption per person at the specified time requires a new data set within the

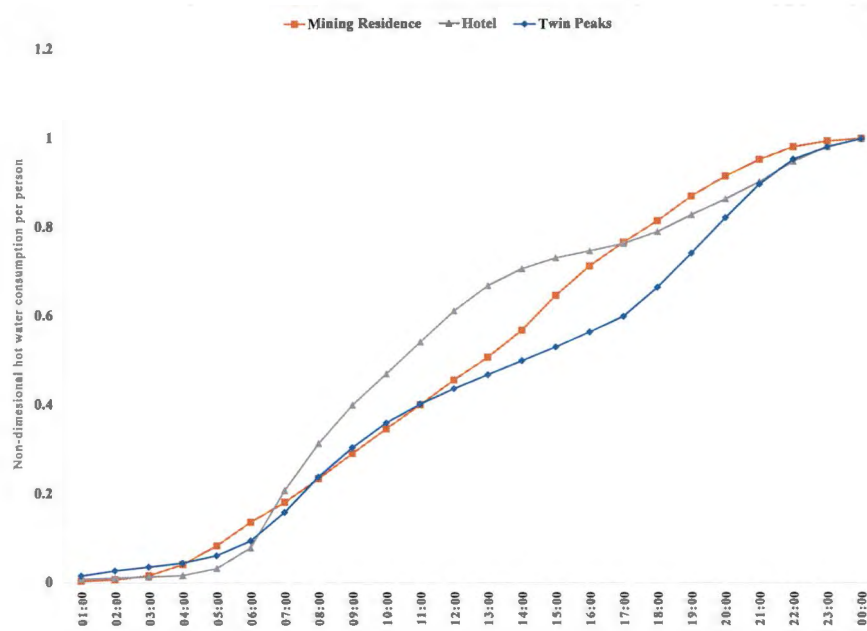


Fig. 3.12 Non-dimensional cumulative hot water consumption profiles

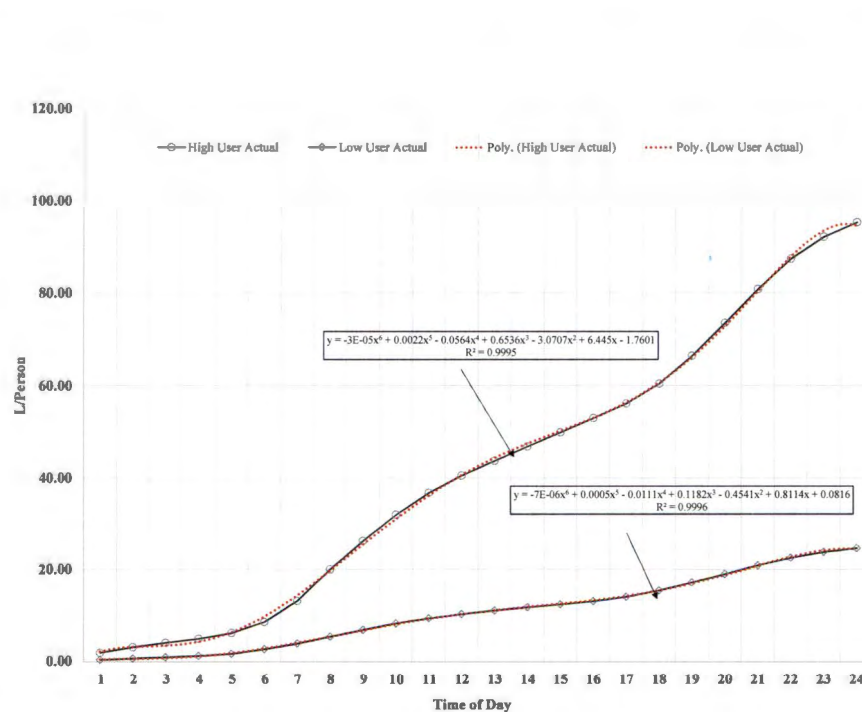


Fig. 3.13 Low and high user cumulative consumption profile polynomial graphs

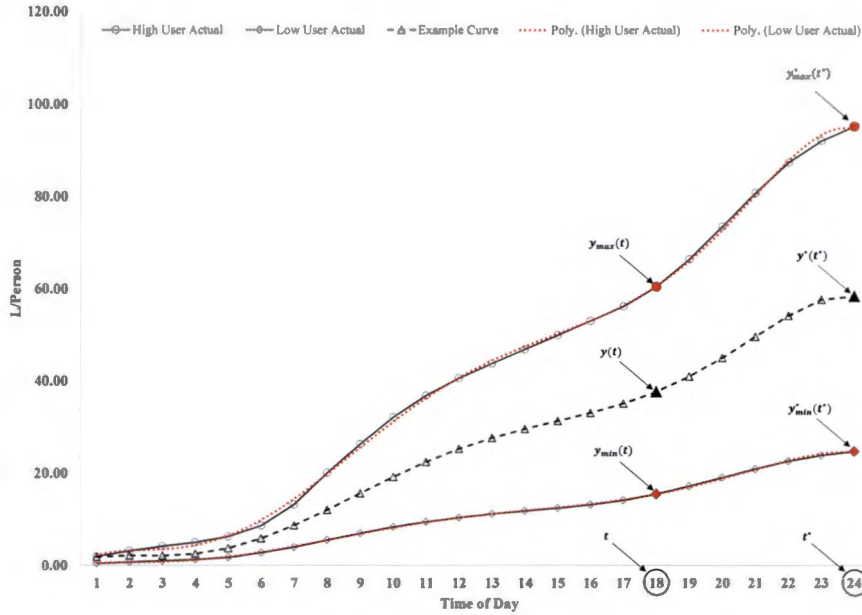


Fig. 3.14 Interpolation variables of low and high user forecasting graphs

polynomial boundaries of the low and high user polynomial graphs. The assumption is made that the hot water consumption per person will never exceed the high user profile values or be less than the low user profile values during any time of the day. Polynomial interpolation is used to determine the new 24 hour consumption data described in the following equation:

$$\frac{y(t) - y(t)_{min}}{y(t)_{max} - y(t)_{min}} = \frac{y^*(t^*) - y^*(t^*)_{min}}{y^*(t^*)_{max} - y^*(t^*)_{min}} \quad (t, t^* > 0) \quad (3.4)$$

where,

- $y(t)$: new estimated consumption per hour,
- $y(t)_{min}$: low user current hour consumption,
- $y(t)_{max}$: high user current hour consumption
- $y^*(t^*)$: projected total consumption per day,
- $y^*(t^*)_{min}$: low user total daily consumption,
- $y^*(t^*)_{max}$: high user total daily consumption,
- t : current specified time
- t^* : 24th hour,

As an example the unknown consumption value, $y(t)$, in Figure 3.14 is calculated at the 18th (t) hour. The dynamic variable in the calculation is the projected total consumption ($y^*(t^*)$) per person per day. A value is chosen for the total hot water consumption of the

building at the 18th hour which is divided by the number of occupants in the building. This will result in a consumption value per person per day and used with the discrete consumption values of the low and high user profiles to calculate the unknown consumption on the hour. Similarly the new consumption values for each hour of the day will be calculated which generates the new consumption graph as depicted in Figure 3.14. The predicted consumption values can now be utilized as input for the sizing of the water heating system. This is done by changing the projected hot water consumption with random values to test the resilience of a design with respect to different generated consumption profiles. Another advantage of the generated consumption values is the potential to predict the water heating control philosophy.

3.7 Summary

The aim of this Chapter was to introduce the newly measured hot water consumption profiles of two high rise buildings situated in the CDB of Johannesburg, South Africa. It was compared with similar profiles within the commercial sector of South Africa which showcased the diversity in hot water consumption between the available profiles. The data presented substantial evidence that regularly updated profiles are required in the market due to the dynamic movements within the demographics of South Africa.

The fundamental input to any water heating system design is the hot water consumption requirement by a specific user. With inaccurate consumption data the design might have certain flaws that could influence the cost and performance of the system.

Chapter 4

Hot Water System Scheduler Using Predicted Consumption Profiles

The need for control strategies to improve the energy efficiency of commercial apartment buildings are increasing due to the pressure of rising energy prices. Utilizing the predicted hot water consumption profiles discussed in Chapter 3 as input to a hot water equipment scheduler for high rise apartment buildings will be the discussion of this chapter. The scheduler's main objectives are to improve system efficiencies which includes the operating cost of the heating equipment as well as the energy efficiency of a water heating system. A detailed summary of the design and software architecture of the hot water scheduler will be explained along with the requirements needed to implement the scheduler.

4.1 Purpose of the hot water system scheduler

As seen in Chapter 3 the hot water consumption profile of an apartment building is crucial in the design and optimization process of a hot water heating system. A concern however exists with the actual operating cost and energy efficiency of water heating system installations. Engineers tend to include a substantial safety factor concerning the storage volume of the hot water vessels and thermal capacity of the hot water heating equipment which directly affects the efficiency of a system. The desired solution to this problem would be to have a dynamic design environment to effectively optimize the hot water system design before an installation. Another aim would be to utilize the design software as a real time control instrument to maintain the projected efficiencies.

The main objectives for the development of the hot water scheduler are thus defined by the following:

- To optimize a water heating design using existing measured hot water consumption profiles as input to minimize operational and energy costs.
- To control the designed water heating system with the hot water scheduler to obtain the required efficiency levels by adapting to consumption changes.

4.2 Hot water scheduler overview

The hot water scheduling software employs an optimization algorithm together with the hot water consumption profiles of the water heating system to predict the optimum switching schedule for the heating equipment over a 24-hour horizon. The optimum schedule is based on actual total hourly consumption data of the building as well as the applicable electricity tariffs. The optimizer is able to update the switching schedules on a hourly basis enabling it to compensate for unforeseen events such as a deviation from previous predicted consumption profiles and changes in water heater availability. The scheduler will also be able to adjust the heater schedule in the case where one of the heaters are unavailable or off-line. Another feature of the scheduler is the ability to choose the applicable heat pump water heater (HPWH) based on the actual performance of the HPWH at a given ambient temperature.

Due to the various electricity tariff structures provided by the utility for the respective sectors in South Africa, load control options exists for Time-Of-Use (TOU) consumers. Various larger commercial consumers, as in the case of the high rise buildings discussed in Chapter 3, have the TOU structure which penalizes the client should they operate equipment during peak demand intervals. The tariffs are divided into off-peak, standard and peak

intervals with respective low, medium and high costs per kilowatt hour. The tariffs also differ during winter and summer seasons with winter tariffs considerably higher. The scheduler uses the applicable winter or summer tariff structure, along with the peak demand notification to reduce the probability of inefficient heater operations during the peak intervals. The electrical load during the peak periods are shifted to off-peak and standard periods to minimize the electrical cost incurred by the client. In order to realise the envisaged demand control potential of the water heating system, optimization within the software was developed to predict the necessary schedules for a hot water heating system. This software can be integrated with any Programmable Logic Controller (PLC) of a Supervisory Control and Data Acquisition (SCADA) system and implemented at the Central Processing Facility (CPF), if available, or into any other operating facility. This study however excludes any details concerning the integration of the hot water scheduler to the external software acquisition of the water heating system.

The hot water scheduler is made available to the external data acquisition facility in the form of a dynamic link library (DLL) accompanied by the relevant header file and a series of other files including other DLLs, text files and library files. This chapter describes the design architecture, subroutines and the variables that form the interface between the hot water scheduler and the middleware used to enable the functionality of the hot water scheduler.

4.3 Hot water scheduler software design

The architecture of the scheduler is divided into three key functional groups that enable the optimization process. As illustrated in Figure 4.1 the process flow starts when the exposed *System Scheduler* function is called. Within the initiation process a preprocessor examines the required input variables for any discrepancies before an output file is generated for the optimization calculations. The actual optimization begins when the hot water scheduler function collects all the necessary information obtained in the output file together with the fixed variables to generate the required predicted daily consumption profile and heater operating schedule. These results are then processed and categorized to determine the optimal water heating system size along with an efficient operating strategy. Details concerning the internal process flow of each functional group will be discussed in the following subsections.

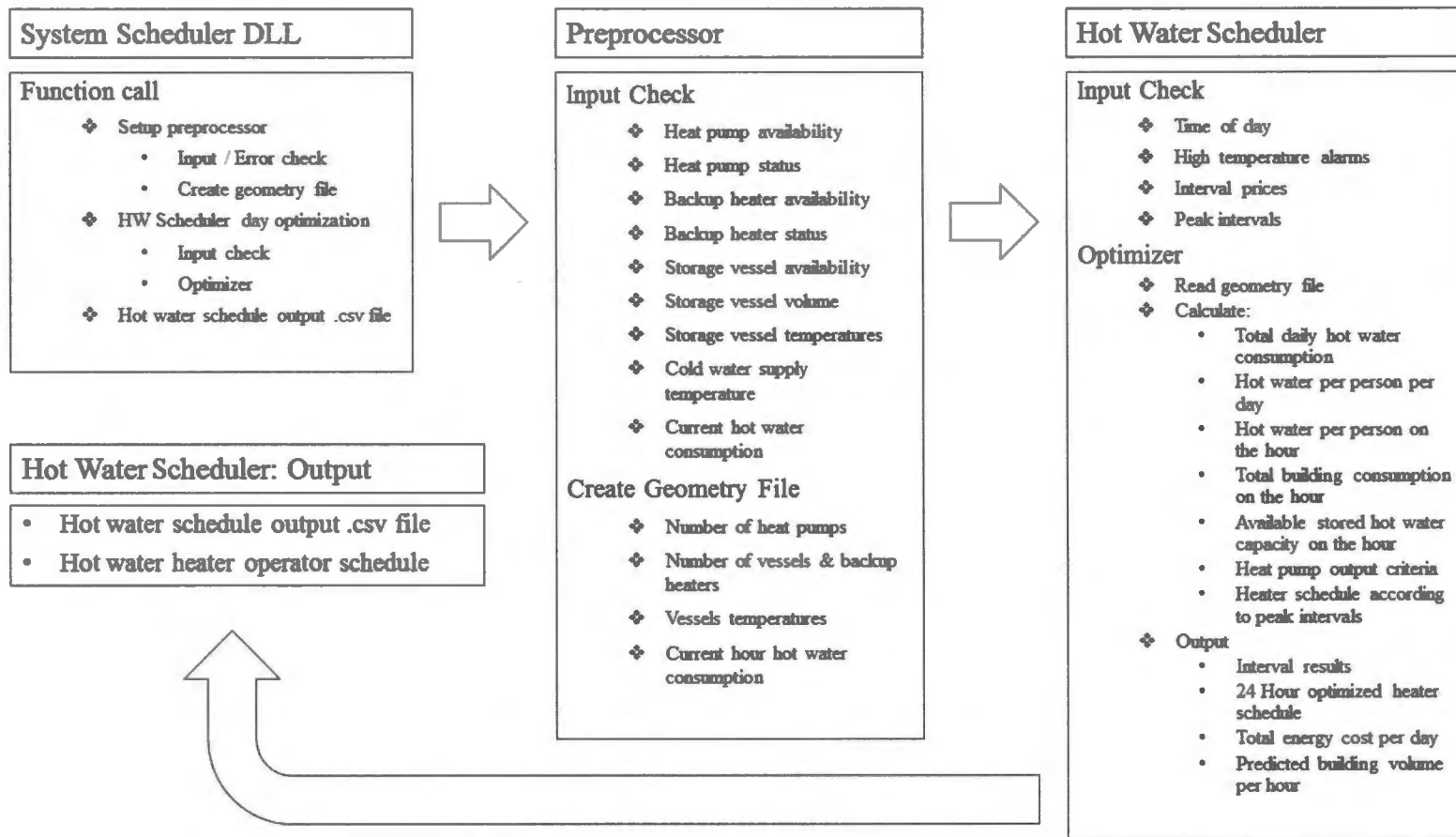


Fig. 4.1 Hot water sheduler operational process flow

4.3.1 Hot water system preprocessor

As mentioned in the previous section the core functionality of the *Preprocessor* is to ensure that the input variables collected from the relevant external data acquisition system is in the correct format before the optimization process commences. The input variables required by the preprocessor are listed in Table 4.1. Column 1 illustrates the dynamic variables that are imported from the external interface when the main function is called before every hour. The static variables in column 2 are fixed values that are explicitly populated before the initiation of the scheduler. In the event of incomplete or missing fixed values an error log file will be generated instructing the operator to include the necessary information. The more detailed description of the error log file is presented in Section 4.4. All the input

Table 4.1 Dynamic and fixed input variables for the hot water scheduler preprocessor function

<i>Dynamic Input Variables</i>	<i>Fixed Input Variables</i>
Heat pump availability	Specific heat capacity of water (cp)
Heat pump status	Number of building occupants
Backup heater availability	Number of installed heat pumps
Backup heater status	Number of backup heaters
Storage vessel availability	Number of storage vessels
Storage vessel temperatures	Number of temperature sensors per vessel
Cold water supply temperature	
Current hot water consumption	

variables are evaluated according to a set of boundary conditions within the scheduler which are hardcoded to ensure that the variables are in the correct format. The boundary conditions for the fixed variables are indicated in Table 4.2. For validation purposes the boundaries were set in relation to the water heating system specifications of the two high rise buildings discussed in Chapter 3. One of the required text files in the operating directory called `HWSCHEDULER_globalgeometry.txt` includes the static variables and can be configured according to the water heating system requirements. The preprocessor will continue to read the fixed values and ensure that the issued values are within the specified bandwidth. After evaluating the fixed values the preprocessor will continue to inspect the dynamic variables for any mismatches similar to the fixed variable evaluation. Even though the boundary conditions are fixed for the purpose of this study the scheduler can be modified to accommodate larger water heating systems.

The dynamic variables are crucial for the design and control of the hot water system. These values can be altered according to real world scenarios as part of the design process and assist with the optimum system control. The availability and status boundaries in Table 4.3

Table 4.2 Fixed input variables boundary conditions

<i>Fixed Input Variables</i>	<i>Boundary condition</i>
Specific heat capacity of water (cp)	= 4.184
Number of building occupants	> 0
Number of installed heat pumps	< 3
Number of backupheaters	< 3
Number of storage vessels	< 4
Number of temperature sensors per vessel	< 4

indicate the “ON“ and "OFF" conditions of the installed storage and heating equipment. Should a heat pump unit be off line due to scheduled maintenance of the unit, the 0-value of the heat pump availability boundary condition will be activated. This condition will inform the scheduler that only the remaining heaters are available for optimization. The “status” boundary conditions however refers to the current operating state of the heating equipment. A 0-value is indicative of a unit that might be available for operation but has not been utilized and the 1-value indicates a heater that is currently in operation.

Table 4.3 Dynamic input variables boundary conditions

<i>Dynamic Input Variables</i>	<i>Unit</i>	<i>Boundary condition</i>
Heat pump availability	On / Off	1 / 0
Heat pump status	On / Off	1 / 0
Backup heater availability	On / Off	1 / 0
Backup heater status	On / Off	1 / 0
Storage vessel availability	On / Off	1 / 0
Storage vessel temperatures	°C	0 → 90
Cold water supply temperature	°C	0 → 40
Current hot water consumption	Litre	0 → 3000
Top temperature sensor	°C	0 → 90
Middle temperature sensor	°C	0 → 90
Bottom temperature sensor	°C	0 → 90

Concerning the storage vessel temperature variable, the limit has been set to a maximum of 90°C. This is a precautionary measure to ensure that the vessel temperature remains within a safe operating spectrum at all times. In view of the cold water inlet temperature of the water heating system, a maximum value of 40°C is chosen. This value might never be achieved but in the case of an incorrect collected value or an actual high temperature value, the scheduler will not continue with the optimization process and will issue an error message in the error log file. All the status and availability tags of the dynamic variables are defined as integers with the exception of the temperature tags and the current hot water consumption.

These values must be defined as decimal values by the external data acquisition software to enable the preprocessor to continue with the processing of the required output file. Values in an incorrect format will terminate the scheduling process.

After the health status of the described variables have been confirmed by the general utilization source file the final step for the preprocessor would be to write the output file which is a requirement for the optimization process. This output file is in the form of a text file named, `HWSCHEDULER_geometry.txt`, and will be created in the main directory of the hot water scheduler. A typical example of the file can be viewed in Table 4.4. In this example the static variables are listed first which were configured in the *globalgeometry* file and include the physical installation specifications of the water heating system. The dynamic variables were configured using a DLL tester, discussed in Section 4.6, to mimic the input variables that will form part of the control sequence for the water heating system. The cold water supply temperature is written after the static variables followed by the storage vessel details. Each storage vessel is presented individually along with its volume and only the available vessels are displayed in the file. Temperature measurements per vessel follow the vessel capacity details and indicate the top, middle and bottom temperature sensor readings of each vessel. These readings will be utilized in the optimizer section to determine the available hot water per hour.

Concerning the water heaters of the system, two (2) HPWHs and one (1) backup heater were specified in this case with the heater numbers and thermal heating capacities presented after the vessel information. The final and most important variable illustrated in Table 4.4 is the total building hot water consumption on the hour. This value will enable the optimizer to determine the predicted consumption profiles which will be utilized to calculate the operating schedule of the heating equipment. After every hour the geometry file will be updated with the most recent input variables.

4.3.2 Hot water system scheduler

The hot water system scheduler function is the optimization part of the program which utilizes the predicted consumption profiles discussed in Chapter 3. This phase relies on the output data provided by the preprocessor to initiate the scheduler calculations. The scheduler starts off with a general utilization phase to evaluate the boundary conditions of additional static variables. These variables include a counter value which indicates the time of day, peak intervals that define the peak periods throughout the day, as well as the interval prices to determine the cost per hour. The counter value is supplied by the external data acquisition system and the peak intervals and interval prices are text files that need to be configured in the scheduler directory. With the availability of the required variables confirmed the

Table 4.4 Preprocessor output geometry file example

<i>Output Description</i>	<i>Value</i>
Building_Occupants:	373
Density:	1000
cp[kJ/kgK]:	4.184
Number_of_heatpump_units:	2
Number_of_vessels:	2
Number_of_backupheaters:	1
Cold_water_supply_temp(degC):	15
Vessel_number:	1
Volume[m ³]:	8000
Vessel_number:	2
Volume[m ³]:	8000
Vessel_number:	1
Top_Thermostat[degC]:	50
Mid_Thermostat[degC]:	50
Bottom_Thermostat[degC]:	50
Vessel_number:	2
Top_Thermostat[degC]:	50
Mid_Thermostat[degC]:	50
Bottom_Thermostat[degC]:	50
Heat_pump_number:	1
Heat_pump_power[kWt]:	50.0
Heat_pump_number:	2
Heat_pump_power[kWt]:	65.0
Backup_heater_number:	1
Backup_heater_power[kWt]:	50.0
midrule Total_heating_capacity[kWt]:	165
Total_Current_HW_Volume[Hour]:	1010.8

optimization will continue as described in the control algorithm section below. Detailed classifications of the daily forecasted hot water consumption, operating schedule per heater, cost per hour along with the current and next hour available hot water storage volume per vessel are calculated by the scheduler function.

4.3.3 Control algorithm

The algorithm of the hot water scheduler is made up of sequential steps to determine the specified outputs. All of the input variables have been described in the preceding sections and will now be incorporated within the simulation process. The initial process will start off by calculating the total hot water volume requirement of the apartment building, based on the readings of the main cold water inlet supply to the water heating system, as well as the total available hot water storage per vessels on the simulation hour. Heat pump performance curves are then used to determine the thermal and power capacities of the available installed heat pump units for the ambient temperature of a specific hour. Other specifications of the heat pump units, including the volume flow rates per hour are also generated to conclude the heat pump performance setup. With all the necessary heater information available the scheduling part commences by determining the operating schedule per heater unit by using the predicted volumes per hour. A descriptive summary of the six (6) main steps within the algorithm are presented below to clarify the scheduler process.

- Step 1: The total volume per hour (tvph) consumed by all the occupants in the apartment building can be calculated with equation 4.1. It requires the volume (V) per person per hour (ppph) as well as the number of building occupants as input. The predicted cumulative hot water consumption profile described in Chapter 3 provides the cumulative volume required per person per hour. A difference in the volume consumed during the previous hour and the current hour multiplied by the number of occupants in the building will result in the cumulative hot water volume of the building on the simulation hour. Twenty four (24) increments of this formula will be completed to obtain the predicted building volume per hour.

$$V_{tvph} = ((V - V_{(i-1)})_{ppph}) \times Occupants \quad (4.1)$$

- Step 2: An important output requirement every hour is the amount of available hot water in the storage vessels. This value will be determined by the installed temperature sensors which are categorized before the simulation is initiated. For explanatory purposes, an assumption is made that three (3) temperature sensors are installed per

vessel. A top, middle and bottom positioned sensor each supplies a temperature measurement to determine the total volume of available hot water. Although the positioning of the sensors will differ depending on the manufacturing specifications, another assumption is made that the positioning of the sensors are equal to a percentage of the total volume per vessel. Equations 4.2, 4.3 and 4.4 represent the top, middle and bottom temperature sensors respectively. In this study the bottom sensor represent 90% of the total volume and not 100% due to the fact that the installation of the bottom temperature sensor is usually installed above the cold water inlet of a vessel. The top sensor is assumed to measure 25% of the total vessel volume and the middle sensor 50%. The level percentages can however be modified by the designer should the exact positioning of the sensors be known.

To determine the available hot water per vessel, the temperature measurements per sensors will be collected during the simulation. If any one of the sensor values increases above the set temperature of 50°C the available volume will be calculated using the sensor percentage equations. The total combined volume of the installed vessels can be calculated by summing the available hot water per vessel as shown by equation 4.5. Only a maximum of three (3) vessels can be installed for this simulation.

$$V_{sensor1} = 0.25 \times V_{installed} \quad (4.2)$$

$$V_{sensor2} = 0.50 \times V_{installed} \quad (4.3)$$

$$V_{sensor3} = 0.90 \times V_{installed} \quad (4.4)$$

$$V_{total} = \sum_{i=1}^3 V(i)_{avail} \quad (4.5)$$

- Step 3: With the required volumes per hour known, the operating specifications of the installed water heating equipment will be defined. For descriptive purposes the information presented in the geometry file of the preprocessor which includes the two heat pump units will be used as reference in this section. To determine the actual performance criteria of the heat pump units, the ambient temperature and the heat pump performance curves are required per unit. Figure 4.2 illustrates the kilowatt-thermal (kWt) performance curves of four (4) air to water heat pump water heaters manufactured by Enerflow in South Africa with sizes ranging from 30kWt to 65kWt.

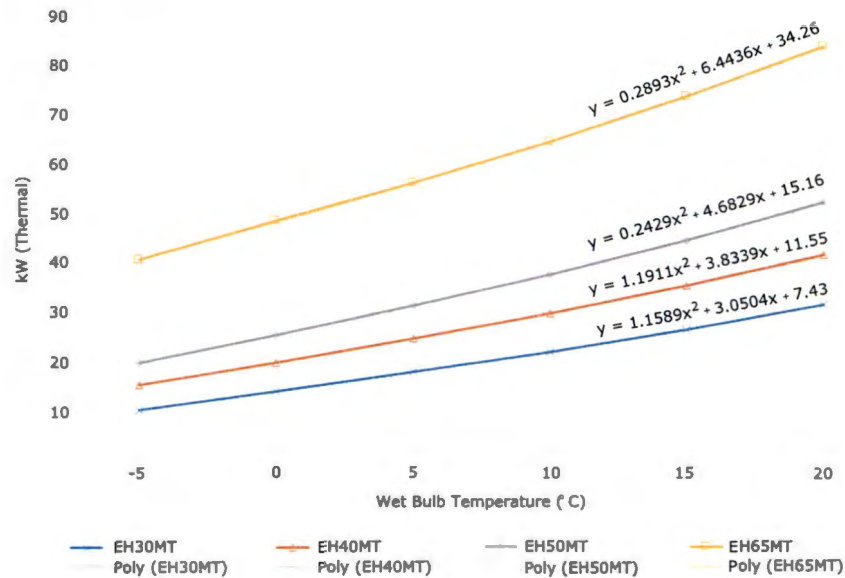


Fig. 4.2 Enerflow EH Series heat pump thermal performance curves

The performance of the units are directly influenced by the outside air wet bulb temperature values. Every hour a snap shot of the actual dry bulb temperature and humidity must be measured and supplied as input to the scheduler to calculate the required wet bulb temperature. This will enable the scheduler to accurately determine the performance of the specified heat pump unit for the next hour of the operating schedule.

Similar to the polynomial curves fitted for the hot water consumption profiles in Chapter 3, the 2nd order equations 4.6, 4.7, 4.8 and 4.9 have been fitted for each thermal performance curve as illustrated in Figure 4.2. The heating capacities are then calculated using these polynomial functions by inserting the wet bulb temperature collected on the simulation hour. An initial heat pump sizing is however required before the actual heating capacities can be calculated. This is part of the initiation and also the original design phase where the maximum thermal capacity per heat pump will be specified along with the other required static variables. The thermal capacities of the heat pump units can however be modified during the simulation process should the heating capacity be insufficient.

$$Q_{30} = 0.15893x^2 + 3.05036x + 7.43 \quad (4.6)$$

$$Q_{40} = 0.19107x^2 + 3.83393x + 11.55 \quad (4.7)$$

$$Q_{50} = 0.24286x^2 + 4.68286x + 15.16 \quad (4.8)$$

$$Q_{65} = 0.28929x^2 + 6.44357x + 34.26 \quad (4.9)$$

Another specification required of the heat pump units is the input power curves shown in Figure 4.3. These curves are utilized to determine the cost per kilowatt-hour (kWh) of each unit. The same principle for calculating the thermal capacities applies to the electrical power input capacities of the heat pumps. The 2nd order equations displayed in 4.10, 4.11, 4.12 and 4.13 are utilized to determine the input power capacities of the installed units based on wet bulb input temperature also used in the thermal performance calculations.

$$Q_{30} = -0.007x^2 + 0.927x + 4.28 \quad (4.10)$$

$$Q_{40} = -0.018x^2 + 1.125x + 6.00 \quad (4.11)$$

$$Q_{50} = -0.025x^2 + 1.481x + 7.88 \quad (4.12)$$

$$Q_{65} = -0.016x^2 + 0.504x + 20.73 \quad (4.13)$$

- Step 4: The heat pump flow rate per hour will now be determined in relation to the thermal heating capacity results obtained in step 3. Two water temperature measurements are required as illustrated in equation 4.14 with T_{hot} defined as the required outlet water temperature supplied to the storage vessels and T_{cold} defined as the inlet cold water temperature. The temperatures of T_{hot} and T_{cold} will be fixed at 60°C and 15°C respectively, for illustrative purposes as part of the simulation and economical feasibility results presented in Chapter 5 and 6.

$$\dot{m}_{hp} = \frac{\dot{Q}_{hp}}{c_p \times (T_{hot} - T_{cold})} \quad (4.14)$$

Concerning the backup heater, no performance curves have been included due to the fact that electrical resistance heaters are not influenced by any ambient temperature conditions. It is however dependant on the amount of electrical input power required

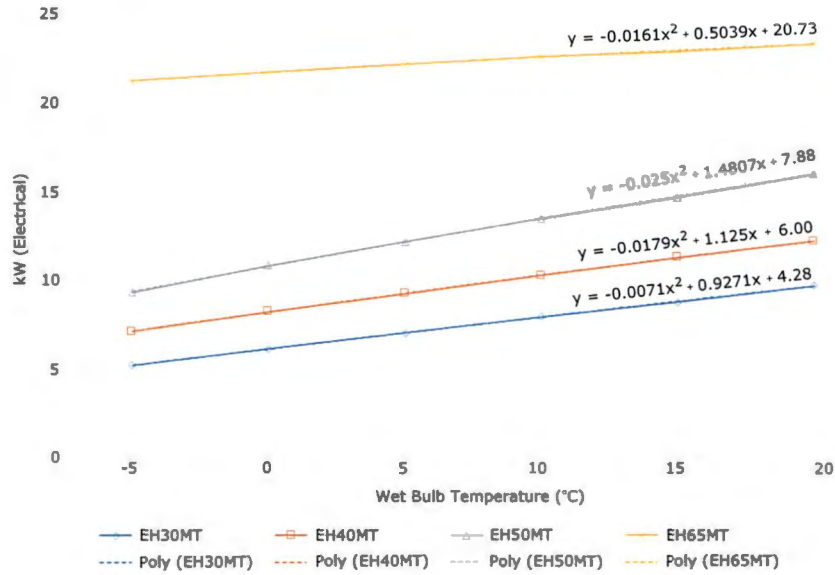


Fig. 4.3 Enerflow EH Series heat pump electrical performance curves

to produce a similar amount of thermal output energy. The coefficient of performance (COP) of the electrical resistance heaters describe the relationship between the electrical input and thermal output power performances. The heating capacity of the backup heater therefore equals the electrical input requirement of the heater. The flow rate of the installed heater will be calculated by using equation 4.15 and the cost incurred when the heater is operational will be determined by using the specified heating capacity of the backup heater.

$$\dot{m}_{backup} = \frac{\dot{Q}_{backup}}{c_p \times (T_{hot} - T_{cold})} \quad (4.15)$$

- Step 5: The volume per hour should then be calculated per heat pump as well as the backup heater, to determine the collective volume of the system. These values will only be determined if a specific heater is active within the simulation hour.
- Step 6: The final stage of the optimization process is to determine the operating schedule of the water heating equipment for the next 24 hours by utilizing the calculated values of the preceding steps. On the simulation hour the total building volume for the next hour will be calculated using equation 4.16 with $V_{current}$ the available volume within storage vessels and $V_{building}$ the amount of water consumed by the building on

the simulation hour. This calculated volume measurement will be used to determine the number of heater units required for the next 24 hours.

$$V_{next} = V_{current} - V_{building} \quad (4.16)$$

Table 4.5 illustrates the predefined water heater schedule operating conditions. Column 1 represents the predefined peak daily intervals which are defined as the peak tariff intervals provided by the energy utility. The second column illustrates the *targetlevel* comparisons which influences the decision making process of the hot water scheduler. Column 3 to 5 represent the output status of the hot water heater units with respect to the outcomes of the *targetlevel* results. For the purpose of the study no penalties are

Table 4.5 Water heater operating schedule conditions

Peak Intervals	Targetlevel	HP 1	HP 2	Backup Heater
0 or 1	$V_{next} < (\%_{target})(V_{total})$	Off	Off	Off
0 or 1	$V_{next} + V_{hp1} < (\%_{target})(V_{total})$	On	On	Off
0 or 1	$V_{next} + V_{hp1} + V_{hp2} < (\%_{low})(V_{total})$	On	On	On

included for any heater unit operating within the peak intervals. Both the peak and off-peak conditions are treated on equal terms due to the strict boundary terms implemented. The *targetlevel* boundary term limits the heating equipment from operating when the calculated volume required for consumption during the next hour is below a percentage of the total hot water volume available. This percentage is a crucial input by the user, for it enables the calibration of the hot water system to find the optimal and efficient operating point. Two percentages will be configured by the end user which includes a *targetlevel* and a low-level percentage. The *targetlevel* value forces the hot water system to maintain the hot water availability at the specified volume. It is managed by controlling the water heating units within the set boundary conditions. The low-level value is a safe operating boundary condition which forces the backup water heating unit to switch on. This will occur when the total volume flow of all the heat pumps along with the next hour available hot water storage volume drops below the low-level specified percentage. After the final schedule is established based on the volume availability the requirement to effectively operate the switching sequence of the heating equipment will be considered.

This is done by managing the operating hours of the hot water heating equipment and may lead to a more cost effective hot water system. The sequence control of the equipment eliminates the possibility of the under or over utilization of the water

heating equipment. Table 4.6 illustrates the switching philosophy within the hot water scheduler simulation that will be implemented within this study. An operating limit of two (2) consecutive hours are enforced to materialize the sequential switching between the equipment. This is another value that can be set based on the preferences of the end-user.

Table 4.6 Heat pump water heater switching sequence

<i>HP 1 Status</i>	<i>HP 2 Status</i>	<i>Running Hours</i>	<i>HP 1 Schedule</i>	<i>HP 2 Schedule</i>
On	Off	2	Off	On
Off	On	2	On	Off

4.4 Hot water scheduler integration

The hot water scheduler software consists of a series of dynamic-link libraries (DLL's) responsible for a series of different functions. The main DLL, which is of most importance to the software user, is named `HWSystemScheduler.dll`. The DLL exposes a function, named `HWSystemScheduler`, which can be called by the end user software to perform the necessary simulations and optimizations of the particular water heating system.

A series of actions are required before the exposed DLL function can be utilized. First of all, certain files are required and should be added to a directory within the external software to obtain access to the DLL. These files are predominantly fixed data that enables the scheduler to perform the necessary optimization steps (Refer to Appendix B for a list of all the related files). After the files have been added to the relevant directory, the external interface header file `ExternalInterface.h` and the hot water scheduler library file, `HWSystemScheduler.lib`, should be included to the additional dependencies of the software application. This will ensure that the external interface has access to the hot water scheduler DLL. The hot water scheduler has been compiled in the Microsoft Visual Studio 2010.NET framework but none of the .NET functionalities are used, making the DLL accessible without having to use the .NET framework.

The necessary variables required by the exposed function should also be declared and populated before the function is called. The header file `ExternalInterface.h` contains the declaration of the exposed function. All of the necessary variables are listed in the declaration as well as the type of variables required. The code extract below shows the format of the *ExternalInterface* header file. A detail description of the variables can be found in Appendix B.

```

#include "ExternalInterface.h"
#include "HWSystemSimulation.h"
#include "HWSystemprocessor.h"

void HWSystemScheduler (int counter ,
                        int season ,
                        int intervals ,
                        int total_sensors ,
                        int numberoflevels ,
                        int installedvessels ,
                        int buildingoccupancy ,
                        int totalnumberofheatpumps ,
                        int installedbackupheaters ,
                        int *peakintervals ,
                        int *heatpumpavail ,
                        int *heatpumpstatus ,
                        int *backupstatus ,
                        int *backupavail ,
                        int *storagevesselavail ,
                        int **schedule ,
                        double cp ,
                        double density ,
                        double coldwatersupplytemp ,
                        double currentHWconsump ,
                        double averagepowerfactor ,
                        double *costs ,
                        double *backuppowers ,
                        double *heatpumppowers ,
                        double *hightempalarms ,
                        double *backuppowers ,
                        double *storagevesselvolume ,
                        double *heatpumppowers ,
                        double *heatpumpcombinationflow ,
                        double **intervalprices ,
                        double **predictedlevels ,
                        double **storagevesseltemp )

```

With all the different input and output variables defined and populated, the exposed function *HWSystemScheduler* can be called. The function should be called by the external software approximately 5 minutes before every hour throughout the day. This will allow enough time for the scheduler to perform all of its calculations before the start of the actual scheduling interval which will commence at the beginning of the next hour. The optimized

schedule will therefore be calculated by using the data obtained at the end of the previous half-hour and the new pump schedule will be applicable at the start of the next half-hour.

The simulation software will generate an output file in the form of comma delimited (.csv) files as well as text (.log) files which will be accessible through Microsoft Excel or Notepad. All of the output files will be stored in a folder with a pathname */Optimizer_Results* on the local hard drive of the applicable server. Note that this directory should exist on the local hard drive of the server before the simulation software can be executed.

The filename format consists of the project name followed by “intervalresults” and the simulation time (yyyymmddhhmm) (e.g. *HWSCHEDULER_intervalresults_2015110515h00*). The generic hard coded project name, *HWSCHEDULER* can be changed in relation to a particular project in the simulation software with the time extracted from the relevant computer system information. This file contains the primary operating information including inter alia the heater schedule, the interval costs and predicted hot water consumption profile for the next 24-hour period.

A text file containing the errors and warning that occur during the execution of the hot water scheduler will be logged on a continuous basis. The filename format consists of the project name followed by *_errorlog* (e.g. *HWSCHEDULER_errorlog.log*). The file will contain the date and time at which a specific error/warning has occurred together with a short description of the type of error/warning. If an error occurs during the execution of the software, an error flag will also be passed to the external software, indicating that the hot water schedule could not be updated. If a warning occurs during an execution, a warning message will be logged by generating a warning flag but the the schedule will however still be updated.

4.4.1 DLL Tester

The DLL tester is an extract of the code used to execute the hot water scheduler by calling the exposed function. The exposed function *HWSystemScheduler.dll* is called from the main function of a C++ console application. Before the exposed function is called, all the necessary variables required by the function are instantiated and populated with realistic values. (Note that only few of the required variables are shown as an example in the code extract of section 4.6). The simulation results in Chapter 5 and Chapter 6 use input values of the two measured high rise buildings discussed in Chapter 3 for validation purposes. Various text files are utilized as part of the DLL Tester and can be modified to obtain the required water heating system size. Once the hot water system size is established the most cost effective operating schedule can be simulated. A summary of all the textfiles are included in Appendix B along with a description of the content within each file.

4.5 Prerequisites for the hot water scheduler integration

As described in the previous sections certain input data is required before the simulation or control phase of the hot water scheduler can continue. Appendix B summarizes the dynamic and static data definitions which enables the full functionality of the hot water scheduler. Each variable has an input boundary evaluated by the preprocessor for accuracy. Inaccurate or uncalibrated input data will affect the efficiency of the predicted output data produced by the scheduler. The initial characterization of the water heating system is therefore critical to produce the required operating outputs. All the active and passive software files of the hot water scheduler are also included in Appendix B.

4.6 Summary

The hot water scheduler software architecture and functionality are presented in this chapter which defines a water heating system sizing methodology. Various design and optimization methods exists in the market but the advantage of this hot water scheduler is the fact that it can be utilized as a hot water system sizing tool as well as a hot water system controller. No details concerning the internal performance characteristics of the water heating equipment in a hot water system are required as input to the scheduler which simplifies the simulation process. The core focus of the scheduler is therefore based on a method to effectively control a water heating system in alignment with the dynamic hot water requirements of the consumer. Chapter 5 will introduce random simulation results of the hot water scheduler with regards to input specification of the two measured high rise buildings described in Chapter 3. The results include system sizing samples which are coupled to the simulated water heater control sequences to optimize the savings.

Chapter 5

Hot Water System Scheduler Simulation Results

The main objective of this chapter is to evaluate the simulation models produced by the hot water scheduler discussed in Chapter 4. These models are generated by using the hot water consumption data of buildings A and B discussed in Chapter 3 to validate the design of the current installed water heating systems. Each model includes static and dynamic variables that enables the efficient sizing and control of the water heating equipment. The results include daily predicted hot water demand profiles at various operating conditions with a detailed discussion on how to acquire the optimum water heating system design using the simulated demand profiles.

5.1 Hot water scheduler results overview

The results produced by the hot water scheduler described in chapter 4 can be incorporated for newly built water heating systems as well as existing system upgrades. Whether the aim is to obtain some guidance for the sizing of water heating equipment or to optimize the control philosophy of existing systems, the hot water scheduler enables the designer to simulate various operating conditions to obtain the required design features. To effectively illustrate the simulation results, the chapter will be divided into two parts where the first part will focus on the sizing of the water heating equipment for design purposes and the second part on the control results obtained for each sizing simulation. All the simulated results will be evaluated against the actual average hot water consumption results of building A and B.

5.2 PART 1: System sizing

The initial step in obtaining the required water heating system size would be to define the static variables applicable to the high rise building layout and design. These variables include the estimated number of occupants of the building, the cold water supply temperature, time of day as well as the low or high demand season. Although these variables are classified as static they can be altered to simulate other operating conditions. After the initiation of the static variables the dynamic variables within the various text files, described in Appendix B, are modified until the required output data is acquired. In the following sections the altered dynamic input data will be categorized and simulated to produce hot water consumption profiles as part of a progressive comparison between various operating scenarios. These simulation scenarios form part of the equipment sizing process to test the agility of the specified design inputs.

5.2.1 Building A equipment sizing simulation results

To start the simulation process the water heating system design specifications of building A are used as input. These specifications include the 16000 litre installed vessel capacity, one 50kWt and one 65kWt heat pump water heater and a 108kWt in-line heater utilized as the backup heater unit. Another input specification required is the summer and winter wet bulb ambient temperatures as depicted in Figure 5.1. These temperatures are average values for the Johannesburg area and are only used as an estimate to determine the heating potential of the heat pump water heaters during certain ambient conditions. In practise, snapshots of the actual ambient temperatures can be collected and used as the input to determine the actual performance of the heating equipment.

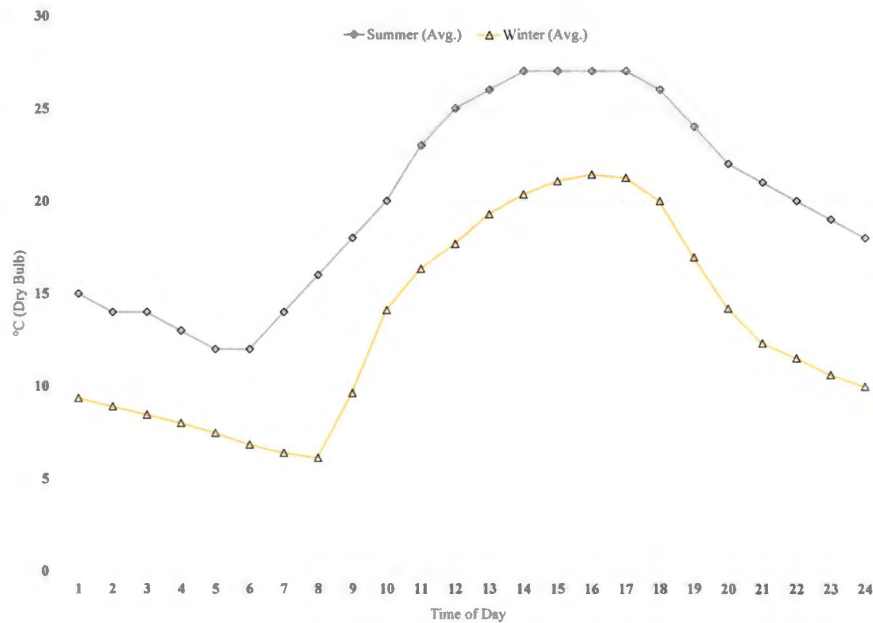


Fig. 5.1 Average dry bulb temperatures - Johannesburg

The key input variables for all the simulation scenarios are the target level percentages, storage vessel availability and sizes as well as the heating equipment availability and sizes. These variables are dynamically altered throughout the simulation process until the optimum heating equipment sizing is found. There are two target levels that are populated namely the low and average target percentages. The low target percentage represents the minimum allowable hot water capacity before the backup water heater may be operational to assist the heat pump water heaters during high consumption intervals, and the average target percentage represents the average hot water capacity that should be maintained throughout the day by the water heating system. The behaviour of the system can be investigated and are presented in the following sections as scheduled scenarios, where the schedule is defined by the static variables of the building and the scenario defined by the random input variables.

Simulation results: Schedule 1 Scenario A and B

As explained in Chapter 3 Section 3.3, the control philosophy of the existing water heating system at building A is based on the assumption that the storage vessels should always be loaded with the hot water during peak or off-peak intervals. To simulate this scenario the static values of the building are firstly populated which represents the specifications for schedule 1. The hot water consumption in Table 5.1 is the minimum average hot water consumption for building A of the actual captured data during the month of March in 2012.

Table 5.1 Static simulation input variables for hot water scheduler - Schedule 1 Building A

<i>Input Description</i>	<i>Value</i>	<i>Unit</i>
Building hot water consumption	815.86	kilolitre
Time of day	1	hour
Cold water supply input	15	°C
Demand season	2	High = 1; Low = 2

Table 5.2 Dynamic simulation input variables - Schedule 1, Scenario A and B

<i>Input Description</i>	<i>Scenario A Value</i>	<i>Scenario B Value</i>
Low target level	0.9	0.1
High target level	0.9	0.1
Vessel 1 availability	1	1
Vessel 2 availability	1	1
Vessel 1 set temperature (Top / Mid / Low)	50 / 50 / 50	50 / 50 / 50
Vessel 2 set temperature (Top / Mid / Low)	50 / 50 / 50	50 / 50 / 50

The time of day, cold water supply and the demand season are randomly chosen values that remain static during the different simulation scenarios. The low and average target levels are now set to 90% of the total installed storage capacity to ensure the maximum storage level of the system is maintained. Even though the system has a capacity of 16000 litres, a full capacity of hot water storage is unlikely due to the cold water mixture within the vessels.

In view of the dynamic variables for scenario A and B shown in Table 5.2, the availability of both vessels are set to 1 and indicate the availability of the total storage capacity of the water heating system. The top, middle and bottom temperatures for each vessel are then set to 50°C to indicate that the hot water storage vessels are fully loaded before the initiation of the simulation process. Simulation scenario A and B will produce 24 hour predicted stored hot water volume as illustrated in Figure 5.2. Both the profiles start off with a 14400 litre stored hot water capacity which is 90% of the total installed capacity. To illustrate the influence of the target level values on the simulated consumption profile the low and average target level values are changed to a minimum of 10% in scenario B. This profile starts on the same initial stored capacity as in scenario A but due to the lower set limits the system saturates at a much lower average consumption value as illustrated in Figure 5.2. These results clearly illustrates that the current installed capacity of building A is oversized in relation to the hot water demand of building A. To determine the actual required storage capacity for building A the target levels will be altered to produce new stored hot water volumes in the succeeding scenarios.

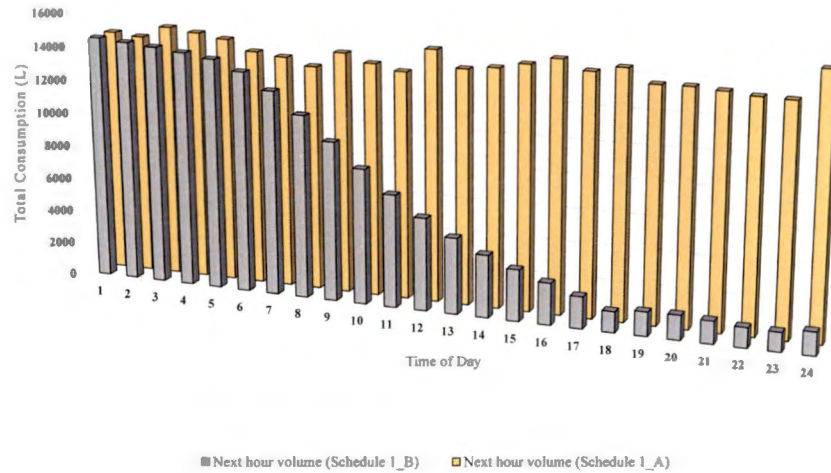


Fig. 5.2 Schedule 1 generated stored hot water volume prediction: Scenario A and B

Table 5.3 Dynamic simulation input variables - Schedule 1, Scenario C and D

<i>Input Description</i>	<i>Scenario C Value</i>	<i>Scenario D Value</i>
Low target level	0.1	0.1
High target level	0.1	0.2
Vessel 1 availability	1	1
Vessel 2 availability	0	0
Vessel 1 set temperature (Top / Mid / Low)	20 / 20 / 20	20 / 20 / 20

Simulation results: Schedule 1 Scenario C and D

With the knowledge that the storage capacity of building A is oversized the available storage capacity can now be reduced to one vessel by changing the set value of vessel two to 0 in the new simulations. To further test the ability of the heating equipment, the vessel 1 temperatures are set at 20°C which implies that the vessel must be charged with sufficient hot water whilst satisfying the hourly demand of the building. The target levels are kept at a minimum of 10% as in scenario B to initiate the testing phase. As depicted in Figure 5.3, the consumption profile of scenario C illustrate a shortage of hot water between 09:00 and 11:00 and at 22:00 due to the high demand from the occupants. The average target level value is thus too low and must be changed to lift the average maintained storage capacity. In scenario D, the average target value is changed to 20%, and even though the hot water shortage at 22:00 is recovered, the shortage in the morning remains a concern.

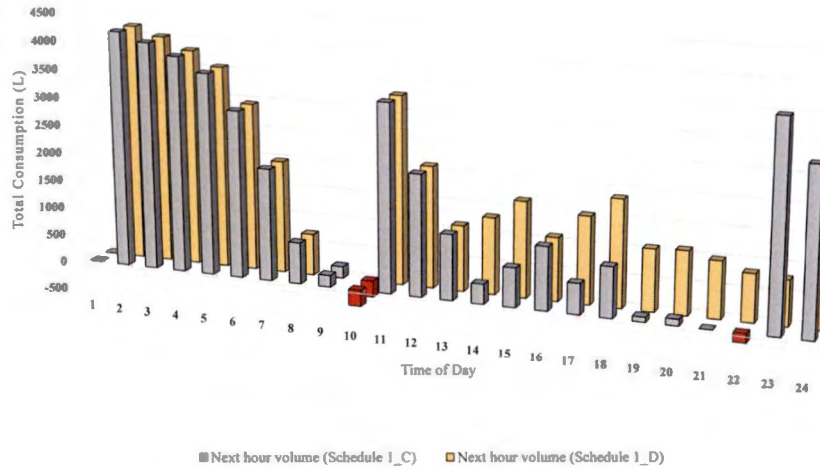


Fig. 5.3 Schedule 1 generated stored hot water volume prediction: Scenario C and D

Simulation results: Schedule 1 Scenario E and F

A continued effort to obtain the desired stored hot water volume of the system is depicted in the simulations of scenarios E and F shown in Figure 5.4. The 30% average target value of scenario E recovers the morning and evening hot water shortages of scenario C and D. The only issue might be the minimum available capacity at 10:00 in scenario E that could affect the system should one of the installed heating equipment be off-line. As precaution, the target level of scenario F is set to 40% illustrated in Table 5.4 to counter this effect and ensure that the remaining heating units can temporarily cope with the potential loss in heating supply. With the maximum hot water consumption of scenario F clearly below the 4500 litre mark, a final test must be completed before a decision can be made concerning the required storage vessel capacity of the water heating system. This test includes simulation profiles based on the high demand season as well as the maximum consumption of building A as input variables.

Simulation results: Schedule 2 Scenario A and B

Similar to the design approach of schedule 1, the static variables are changed to test the resilience of the heating equipment in other operating conditions. As illustrated in Table 5.5 the hot water consumption, cold water supply and demand season values are modified for the schedule 2 specifications. The hot water consumption value represents the actual maximum

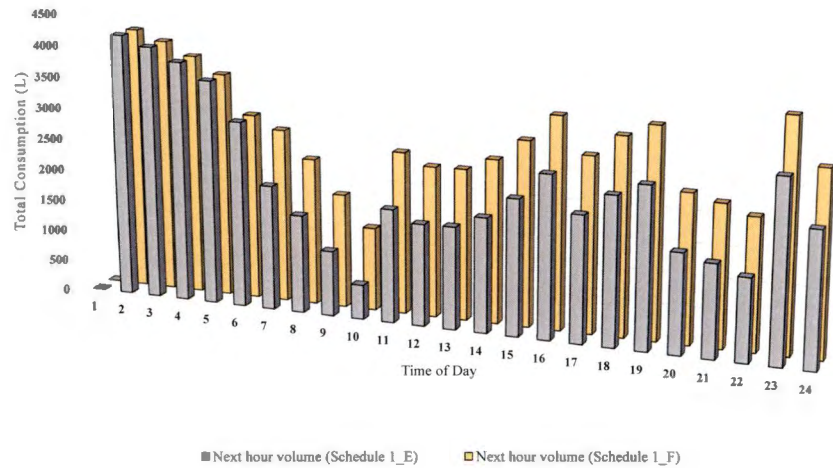


Fig. 5.4 Schedule 1 generated stored hot water volume prediction: Scenario E and F

Table 5.4 Dynamic simulation input variables - Schedule 1, Scenario E and F

<i>Input Description</i>	<i>Scenario E Value</i>	<i>Scenario F Value</i>
Low target level	0.1	0.1
High target level	0.3	0.4
Vessel 1 availability	1	1
Vessel 2 availability	0	0
Vessel 1 set temperature (Top / Mid / Low)	20 / 20 / 20	20 / 20 / 20

Table 5.5 Static simulation input variables for hot water scheduler - Schedule 2 Building A

<i>Input Description</i>	<i>Value</i>	<i>Unit</i>
Building hot water consumption	1365.59	kilolitre
Time of day	1	hour
Cold water supply input	10	°C
Demand season	1	High = 1; Low = 2

Table 5.6 Dynamic simulation input variables - Schedule 2, Scenario A and B

<i>Input Description</i>	<i>Scenario A Value</i>	<i>Scenario B Value</i>
Low target level	0.1	0.1
High target level	0.4	0.65
Vessel 1 availability	1	1
Vessel 2 availability	0	0
Vessel 1 set temperature (Top / Mid / Low)	20 / 20 / 20	20 / 20 / 20

consumption of building A captured in the winter month of August in 2014. This value is nearly 60% higher than the low demand summer value of schedule 1 and will affect the operating schedule of the heating equipment. The cold water supply value of the static variables is randomly selected lower than the summer temperature for schedule 2 simulation scenarios. By firstly simulating scenario A using the dynamic variables of schedule 1 scenario F, a shortfall in consumption can be noticed in Figure 5.5 during the morning peak intervals. Noticeably the thermal output of the water heating equipment is much lower than in schedule 1 due to the lower ambient temperatures used in Figure 5.1. To increase the average predicted consumption per day the average target value is now increased to 65% as seen in Table 5.6 but the minimum available consumption remains low during the 10:00 peak interval. Without repeatedly increasing the average target level, the low target level can be set to assist with the lower consumption margin. The 40% low target value increase of scenario C in Table 5.7 lifts the minimum morning peak consumption shown in Figure 5.6 and follows a similar average projection than in simulation scenario B.

Simulation results: Schedule 2 Scenario C and D

With every water heating system development the designer usually incorporates a safety factor when it comes to the size of the equipment. The low target levels can be modified as shown in Figure 5.7 to facilitate a more stringent operating schedule of the water heating equipment but it will not affect the size of the storage capacity. Based on the simulation results captured in the various scenarios, the maximum simulated storage capacity required for building A was 5324 litres. This value describes the minimum required storage capacity

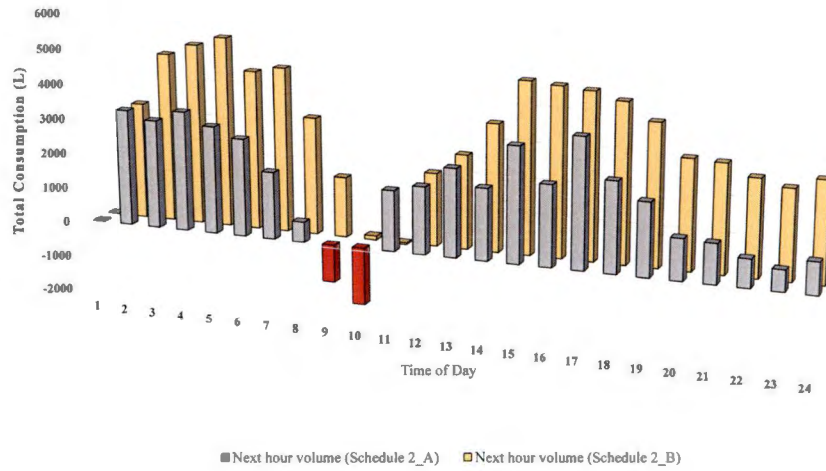


Fig. 5.5 Schedule 2 generated stored hot water volume prediction: Scenario A and B

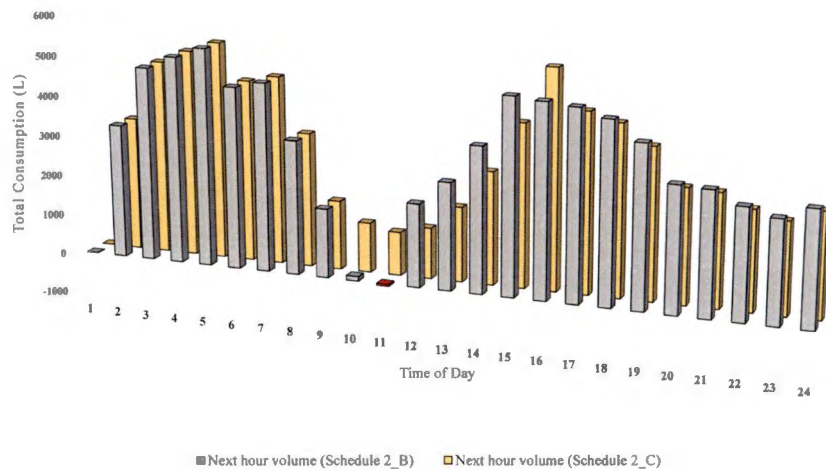


Fig. 5.6 Schedule 2 generated stored hot water volume prediction: Scenario B and C

Table 5.7 Dynamic simulation input variables - Schedule 2, Scenario C and D

<i>Input Description</i>	<i>Scenario C Value</i>	<i>Scenario D Value</i>
Low target level	0.4	0.6
High target level	0.65	0.65
Vessel 1 availability	1	1
Vessel 2 availability	0	0
Vessel 1 set temperature (Top / Mid / Low)	20 / 20 / 20	20 / 20 / 20

of the water heating system and a vessel size of between 5500 and 6000 litres will be sufficient for the system of building A. It must however be highlighted that the existing HPWH's and the backup in-line heater sizes of the current system were utilized within all the simulation scenarios. A change in water heater size will influence the storage capacity sizing of the system, due to the variance in heating potential of the equipment under the operating conditions. As an example, the one 50kWt unit is replaced with a 65kWt unit in scenario E and the simulation result is shown in Figure 5.8. The available hot water for consumption during the morning peak is substantially higher than the 50kWt and 65kWt combination due to the added heating potential of the 65kWt unit. During intervals where two units are operational, the combined heating capacity will increase the available hot water for consumption as illustrated in the profile of simulation scenario E. Fortunately the storage capacity remain within the 6000 litre boundary and no modification is required to the storage vessel size should a larger heating unit be chosen.

5.2.2 Building B equipment sizing simulation results

The simulation results for the equipment sizing of building B follows a similar path as presented in the building A simulation scenarios. Figure 5.9 illustrates the final seasonal simulated profiles related to the hot water system specifications of building B. Schedule A represents the low demand season with a much higher average stored hot water capacity than the high demand season profile of schedule B. This is mainly due to the higher hot water consumption during the winter months similar to the building A results. The low and average target levels were set to the specifications of scenario D in Table 5.7 to compare the impact of the similar set values on the building B scenarios. As seen in the results, the highest required stored capacity obtained was 5394 litres which is substantially lower than the current installed volume of 14600 litres. The actual choice in storage vessel size however remain with the water heating system designer but the hot water scheduler offers the designer the ability to verify the performance of the specified water heating equipment of a particular design.

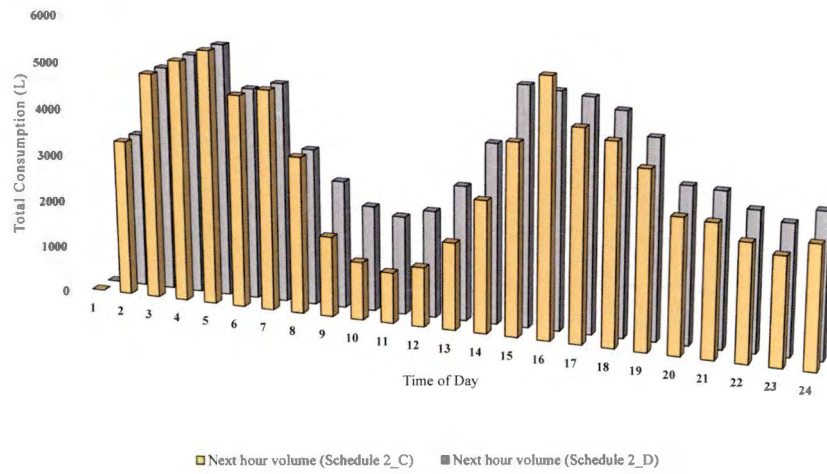


Fig. 5.7 Schedule 2 generated stored hot water volume prediction: Scenario C and D

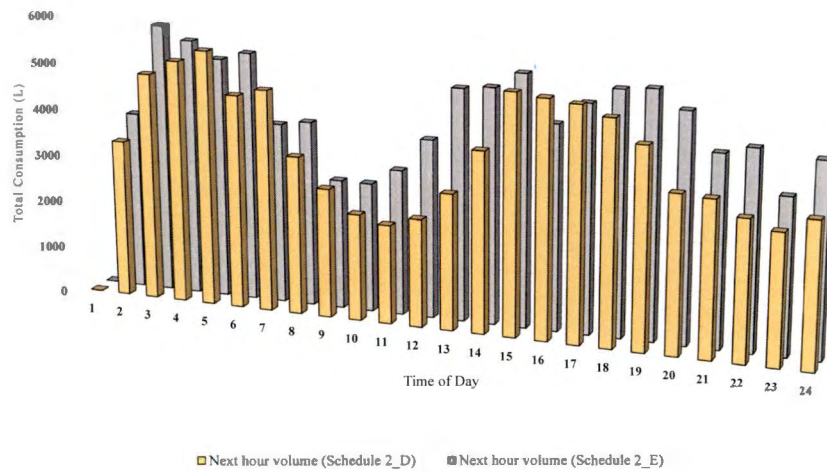


Fig. 5.8 Schedule 2 generated stored hot water volume prediction: Scenario D and E

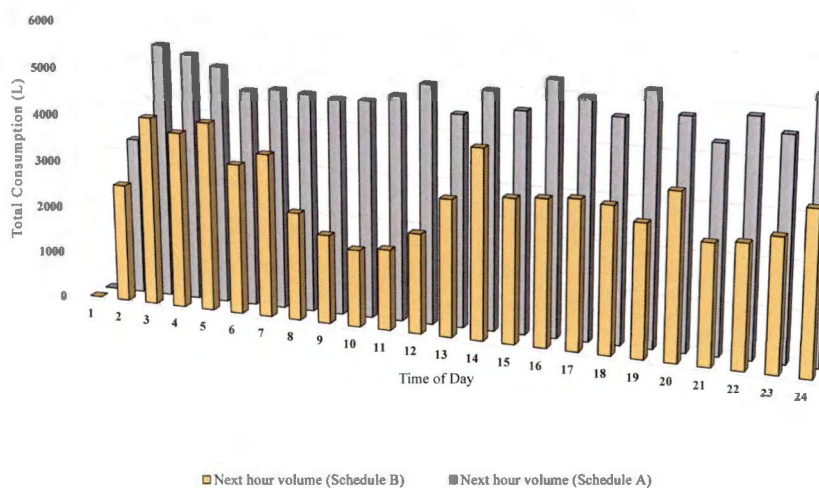


Fig. 5.9 Schedule A and B generated stored hot water volume prediction: Building B

After concluding the water heating equipment sizing simulations, the operating schedule produced by the hot water scheduler can be utilized to evaluate the potential switching sequence of the water heating equipment for an optimal cost analysis of the system. The specifications concerning the operating and energy costs of each simulation schedule will be further discussed in Chapter 6. Part 2 of this chapter will present an overview of the water heater operating schedule results of the preceding simulations illustrated in Part 1.

5.3 PART 2: System operating schedule

The sizing of the water heating equipment directly influences various factors of a system which includes the capital expenditure (Capex) in terms of the supply and installation of the equipment, as well as the operational expenditure (Opex). To be able to test and evaluate the performance of the water heating equipment before the approval of a design will vastly improve the overall efficiency of a system. The hot water scheduler tool presented in this thesis has the ability to fulfill this void and identify the water heating systems' performance before an installation commences. Not only does the scheduler produce the stored hot water volume as illustrated in Section 5.2, it also predicts the actual performance of the water heating equipment. This performance criteria includes the thermal and electrical kW capacities along with the operating schedule of each water heater unit. Attention will now

be drawn to the operating schedule of each water heater unit to highlight the impact of the different simulation scenarios on the operating intervals. Examples of the actual output files for each simulation scenario presented in this chapter can be viewed in Appendix C.

5.3.1 Building A water heating equipment control

The evaluation process of the operating schedules for the building A water heating equipment, will start off by comparing the final simulation scenarios D and E of schedule 2 which were utilized to determine the required storage volume of the water heating system. Figure 5.10 illustrates the resulting operating schedules for the two heat pump water heaters as well as the backup water heater for scenario D. As illustrated in the stored hot water capacity of scenario D in Figure 5.8, no hot water capacity is available during the initial hour of operation which requires the scheduling of all the heating equipment as depicted in Figure 5.10. After the initial hour, the system recovers due to the lower hot water consumption of the building between 02:00 and 06:00, and only requires the services of both the heat pump units to reach the average target level of 65%. At 05:00 the target level is achieved and all the heating equipment are switched off. During the hours of 06:00 to 14:00 in the high demand season, the average consumption of the building is 1761 litres per hour and requires the operation of both heat pump units to maintain the specified target level. The scheduler manages to maintain the target level from 15:00 to 19:00 by only utilizing one heat pump unit before the average required consumption of the building increases to 1949 litres per hour between 20:00 and 23:00.

In scenario E shown in Figure 5.11, where two 65kWt heat pump units are specified and simulated according to the operating conditions of scenario D, a clear distinction can be made when looking at the water heater operating schedule of the two scenarios. Heat pump 1 is operational for 21 hours within simulation scenario D compared to the 17 hours in scenario E, and heat pump 2 is operational for 17 hours in scenario D compared to the 13 hours of scenario E. This illustrates that by replacing the 50kWt unit with the 65kWt heat pump unit, the Opex of the system might be lower due to a decrease in the running hours for both the installed units, but the initial Capex of the installation might increase due to the differences in heat pump unit costs.

Steady state operating schedule comparison

As part of a validation process to determine the discrepancies between the simulated water heating system and the existing water heating system of building A, a comparison must be done concerning the operating schedules of both systems. Firstly, the operating conditions of

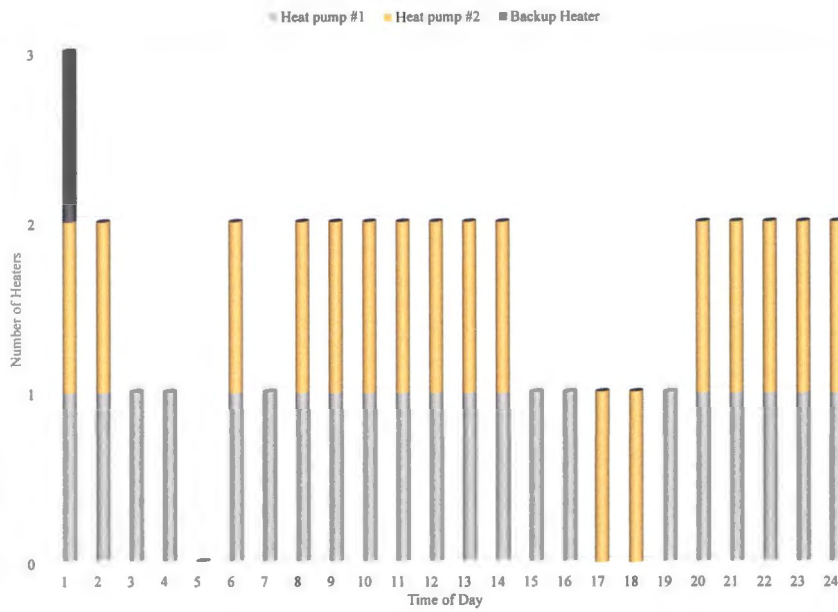


Fig. 5.10 Schedule 2 Scenario D water heater operating schedule: Building A

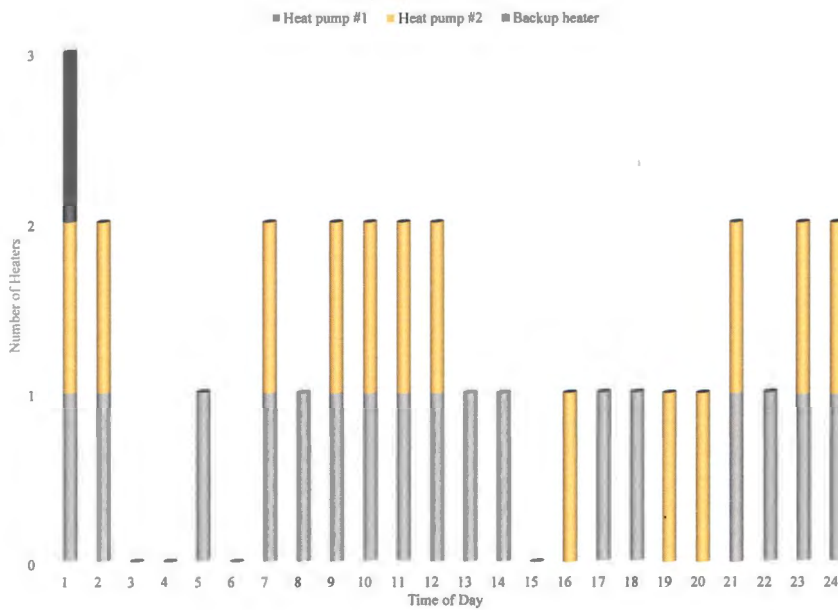


Fig. 5.11 Schedule 2 Scenario E water heater operating schedule: Building A

Table 5.8 Dynamic simulation input variables - Schedule 2, Scenario F and G

<i>Input Description</i>	<i>Scenario F Value</i>	<i>Scenario G Value</i>
Low target level	0.9	0.4
High target level	0.9	0.8
Vessel 1 availability (3000 L)	1	1
Vessel 2 availability (3000 L)	1	1
Vessel 1 set temperature (Top / Mid / Low)	50 / 50 / 50	50 / 50 / 50
Vessel 2 set temperature (Top / Mid / Low)	50 / 50 / 50	50 / 50 / 50

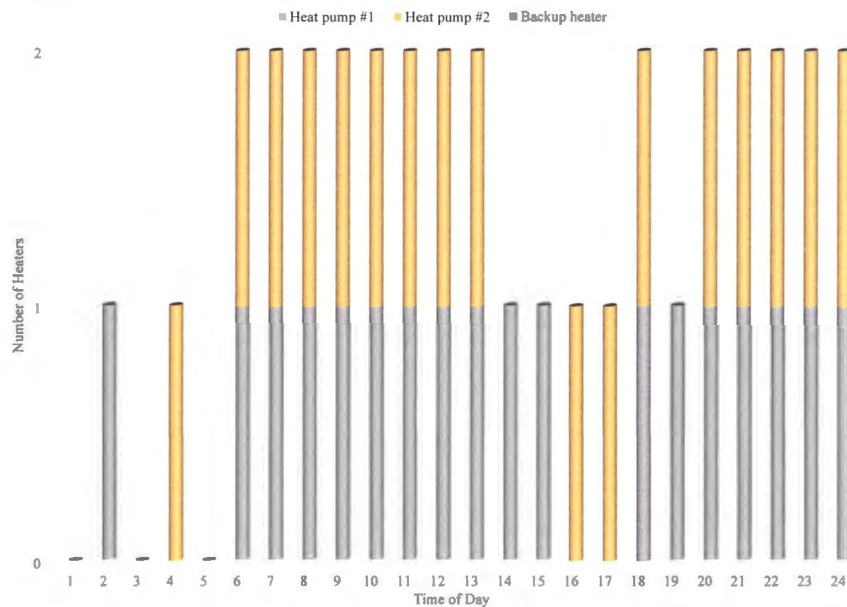


Fig. 5.12 Schedule 2 Scenario F water heater operating schedule: Building A

the water heating systems must have similar input variables which includes fully charged storage capacities as part of the steady state condition. Secondly, the target levels are set according to predefined specifications shown in Table 5.8 where the existing hot water system specifications duplicate schedule 1 scenario A with the exception of high demand season ambient temperature input variables. The existing system's operating schedule is based on the operating principles described in the simulation result section of schedule 1 scenario A and B where the total system capacity remain within 90% of the 16000 litre volume. Concerning the newly defined system specifications, which includes a total storage vessel volume of 6000 litre, the low and average target levels were set to 40% and 80% respectively.

Simulation scenario F shown in Figure 5.12, represents the operating schedule for the existing hot water system of building A and produces an 18 hour schedule for heat pump 1

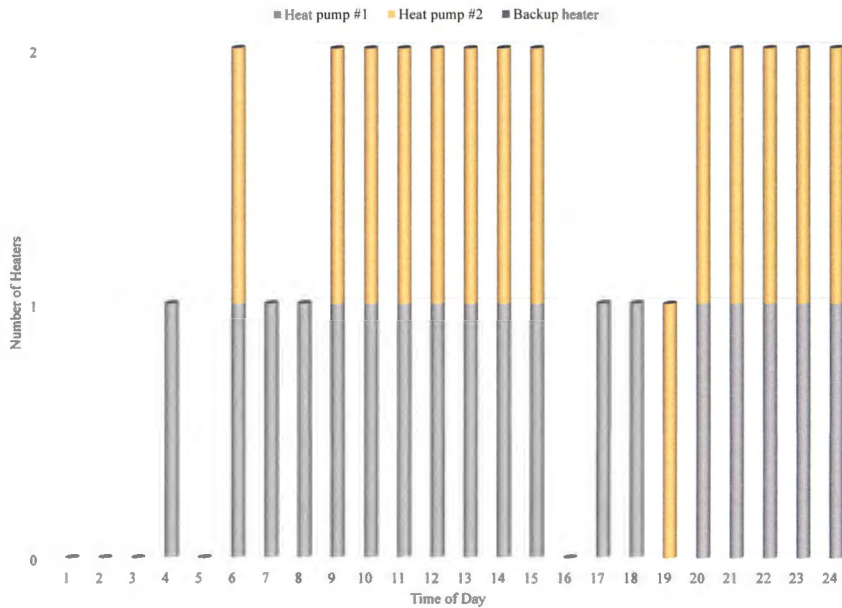


Fig. 5.13 Schedule 2 Scenario G water heater operating schedule: Building A

and a 17 hour utilization of heat pump 2. When a comparison is made with the operating schedule of the newly defined system design for building A, a difference in operating hours can be seen in the schedule of heat pump 2. Figure 5.13 illustrates an 18 hour schedule for heat pump 1, which equals the heat pump 1 schedule of scenario F, and a 14 hour simulated schedule for heat pump 2 which is less than the required 17 hours of scenario F. There might not be a substantial difference in the operating schedule of the two scenarios, but the Capex of the newly defined system design for building A will be less than the existing system due to the smaller vessel volume, and the reduction in the scheduled hours will contribute to the decrease in the Opex if the running hours during peak intervals can be limited for the water heating system.

5.3.2 Building B water heating equipment control

The comparison of the water heater operating schedule for building B has similar outcomes illustrated in the steady state results of building A. By simulating the existing water heating system of building B within a 90% margin of the 14600 litre installed volume, requires a 17 and a 14 hour schedule for heat pump 1 and 2 respectively as shown in Figure 5.14. On the other hand, the scheduling results for the newly proposed water heating system of building B requires a 17 hour daily operation for heat pump 1 but only requires a 12 hour schedule for heat pump 2. Again the smaller storage volume of the new system proposal as well as the

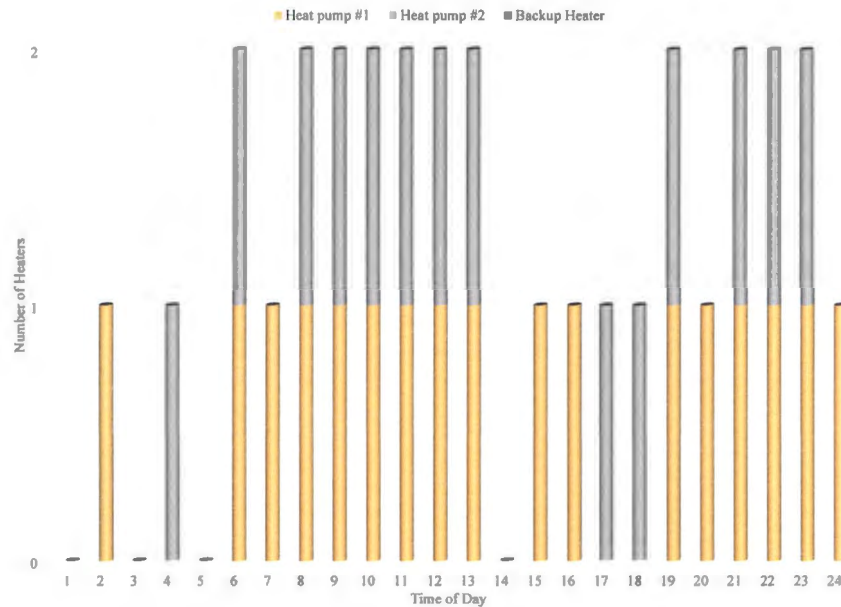


Fig. 5.14 Schedule A water heater operating schedule: Building B

slightly updated operating schedule will potentially improve the efficiency of the building B water heating system.

Another generic feature of the hot water scheduler is the predicted switching sequence of the water heaters which limits the consecutive operating hours per water heater. The maximum consecutive running hours allowed for a single water heating unit are two hours but can be set for longer intervals by the user. This is only applicable when one water heater is scheduled for operation and not where two or more units are required per hour. As illustrated in Figure 5.15, heat pump 1 is active for two hours between 16:00 and 18:00 and is replaced by heat pump 2 between 18:00 and 20:00. The main purpose of this feature is to distribute the daily working load between the various water heating equipment of a system.

5.4 Summary

The water heating system sizing and control results presented in this chapter demonstrates the benefit of utilizing the hot water scheduler, presented in Chapter 4, as design tool and as instrument to efficiently control the operating schedule of water heating equipment. A clear distinction can be made between the simulated results of the existing building A and B water heating systems and the newly proposed system results produced by the scheduler. These results determine the proposed storage capacity of each system and includes the equipment

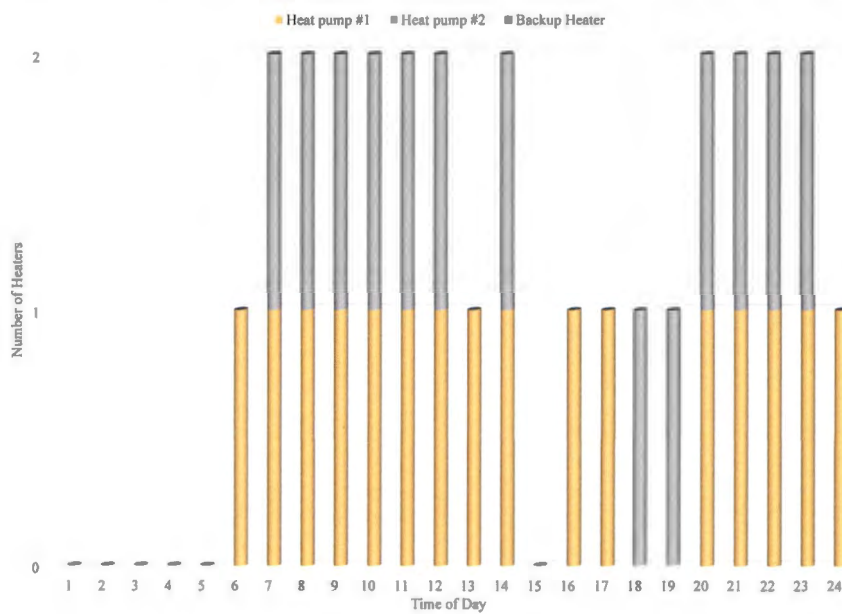


Fig. 5.15 Schedule B water heater operating schedule: Building B

operating schedule required to maintain the hot water demand based on target levels specified by the system designer. A techno-economical feasibility of the hot water scheduler will be presented in Chapter 6 where the installation and energy costs of the current water heating system designs for the two high rise buildings, are compared to the potential costs of the newly proposed system designs.

Chapter 6

Economic Feasibility of the Sanitary Hot Water System Scheduler

The main purpose for the development of the hot water scheduler is to assist a design engineer with the cost effective sizing and control of a water heating system. Chapter 5 illustrates the ability of the hot water scheduler to simulate water heater operating intervals based on the hot water consumption of commercial high rise buildings. Each simulation produces an output file with information concerning the performance of a predefined system, which includes the proposed scheduling of the heating equipment as well as the installation costs involved. The actual water heating equipment costs and the operating energy costs of the two high rise buildings will be compared in this chapter with the proposed water heating system scenarios presented in Chapter 5. Further discussions in this chapter includes the potential savings of introducing the hot water scheduler to the high rise buildings as well as the economical feasibility of the hot water scheduler in the commercial sector.

6.1 Cost analysis of high rise apartment buildings

The advantage of the hot water scheduler as tool to improve water heating system efficiencies has been illustrated within the simulation scenarios presented in Chapter 5. These scenarios have distinct output variables which are used to evaluate certain characteristics within the simulations. An important output variable that will be the focus within this chapter is the costs related to the operating schedule of the water heating equipment. With each simulation schedule the energy costs are calculated based on input criteria which is either inserted by the designer during the sizing of a system or collected from a database with actual field measurements. The input variable that influences the accuracy of the energy costs of the heating equipment is an up to date pricing schedule. This pricing schedule must represent the utility or local authority rates of the particular area where a new water heating system will be installed or an existing system is installed. Table 6.1 illustrates typical rates of the South African electrical utility, Eskom, that were used as input to the simulations in Chapter 5.

These rates are based on the non local authority pricing schedule and are only used to evaluate the potential costs within the simulations. The two case studies are billed on the same time of use (TOU) tariff structure but the actual pricing of each building were based on the tariffs of that measured year. For illustrative purposes, the recent 2015 tariffs were used within all the simulations and compared to the actual measurements of both the buildings. The idea was to establish whether energy savings were possible for various tariff structures. Standard, peak and off-peak intervals have different pricing structures for the low and high demand seasons as illustrated in Table 6.1, with the peak interval the most expensive per *kWh-e*. The aim of any commercial water heating operation would thus be to minimize the operating schedule of the heating equipment within these peak intervals. Two peak intervals exists per day and differs depending on the demand season. The low demand season timeslots are between 07:00 and 10:00 in the morning and 18:00 and 20:00 in the evening with the high demand season intervals between 06:00 and 09:00 in the morning and between 17:00 and 19:00 in the evening.

To compare the daily costs of the simulation results recorded in Chapter 5 with the actual high rise building monthly costs, the average hot water consumption per month per building had to serve as reference to the simulations. Based on these reference values, the daily costs were multiplied with the number of days per month to obtain the total simulated cost per month. The following sections illustrate the results of the simulated energy costs per water heating system against the actual energy costs. In addition to the energy cost analysis, details concerning the equipment costs of the existing and newly proposed water heating systems will also be presented.

Table 6.1 Energy pricing schedule (Eskom) - 2015

<i>Season</i>	<i>Transmission Zone</i>	<i>Voltage</i>	<i>Peak</i>	<i>Std</i>	<i>Off-Peak</i>
High demand	$\leq 300km$	< 500V	248.94c	75.74c	41.35c
Low demand	$\leq 300km$	< 500V	81.52c	56.25c	35.86c

6.1.1 Building A - Energy cost analysis

Building A energy costs: 2012

With building A having three consecutive years worth of measured data, a more extensive comparison was possible with regards to the annual energy savings potential of the building. Each year has a unique consumption pattern influencing the energy cost per month. Looking at the graph in Figure 6.1, the average hot water consumption and the actual energy cost per month, measured in 2012, have a distinct pattern with regards to the winter and summer months. The hot water consumption of the building can be seen as directly proportional to the energy cost which is linked to the varied summer and winter tariff structures. Based on the measured data the most energy intensive month, during 2012 for building A, was the month of July where the average hot water consumption of 28,1 kilolitres per day costing the building occupants nearly ZAR 25 000. This might have been the most energy intensive month but the summer month of September produced the second highest energy cost which defies the norm of lower energy costs during summer months. Even though the average hot water consumption of 25,8 kilolitres was similar to April that year, the costs were substantially higher. This can be justified by the fact that the heat pump units were offline and the more energy intensive backup heating had to supply the building with the required hot water demand.

The simulation results, based on the average hot water consumption of building A during 2012, are also presented in Figure 6.1 next to the actual costs per month. These simulation results represent a scenario where both heat pump units are fully operational and the backup heater unit is only utilized as required. A substantial difference in cost can be seen between the simulated summer and winter intervals but the variation in costs within each demand season is more consistent due to the predefined operating levels of the system. In relation to the actual energy costs of building A the simulated results are significantly lower except for the month of June where the actual costs are slightly less than the simulated results. This result can be improved by changing the target levels of the hot water scheduler, but it will not have an enormous effect on the total annual cost savings.

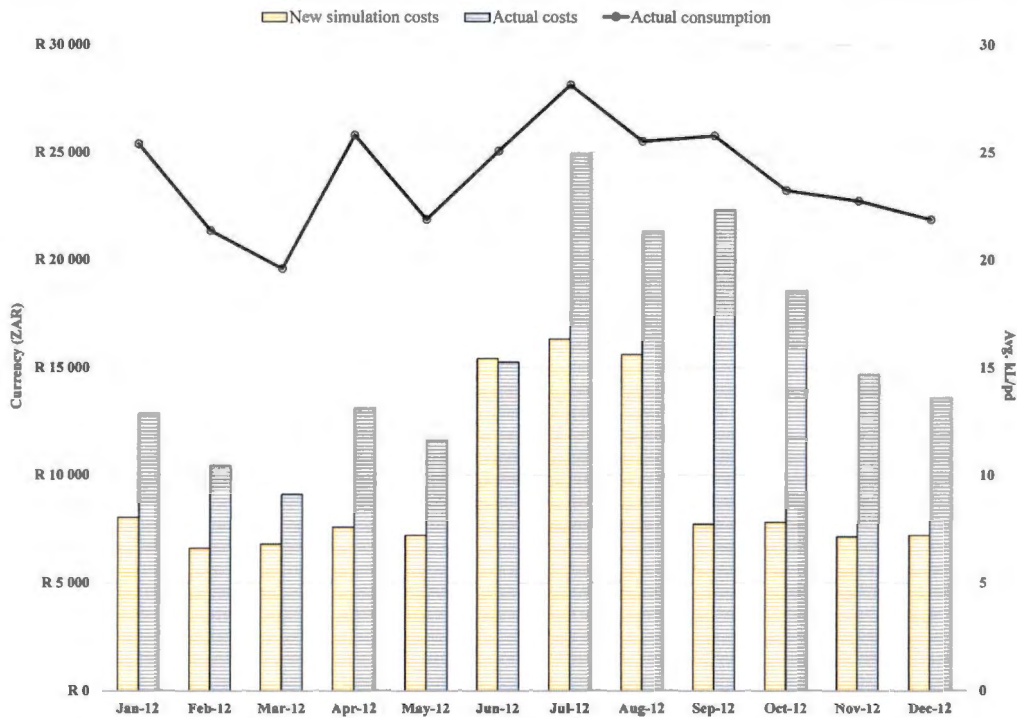


Fig. 6.1 Building A actual monthly energy costs versus simulated energy costs (2012)

Building A energy costs: 2013

During 2013, the annual hot water consumption of building A increased from approximately 24 kilolitres per day to 27 kilolitres per day. This was mainly due to the high consumption during the months of April and July as illustrated in Figure 6.2. The highest recorded energy cost was measured in August 2013 with a ZAR 25 730 energy bill even though the hot water consumption was slightly less than the highest recorded consumption in April. September had a much higher energy cost similar to the profile of 2012, reaching a total of ZAR 24 323 which might indicate potential inefficiencies of the water heating system during that interval.

The simulated energy costs illustrated in Figure 6.2 can be used to evaluate any abnormal energy consumption during a particular month. Looking at the simulated energy costs of September 2013, the obvious assumption can be made that heat pump units were offline judged by the unexpected high energy cost for a low demand season. The over utilization of the backup water heater could have caused the substantial variance in energy costs, compared to similar hot water consumption patterns of other low demand season intervals. Based on the simulation results produced by the hot water scheduler, the availability of the heat pump units create a scenario where optimal energy savings are possible even at higher hot water consumption levels. The simulated energy costs are maintained below the ZAR 10 000 level

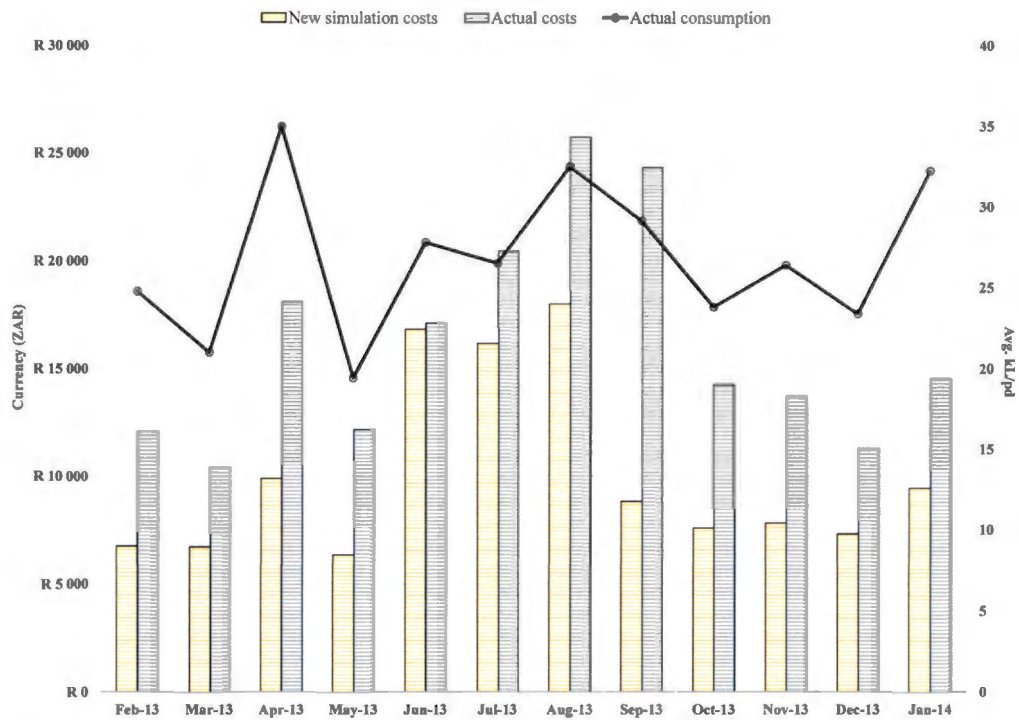


Fig. 6.2 Building A actual monthly energy costs versus simulated energy costs (2013)

during the summer months and ZAR 18 000 during the winter months and emphasizes the importance of an optimized control philosophy for water heating systems.

Building A energy costs: 2014

When comparing the hot water consumption measurements of Figure 6.2 to Figure 6.3, the average consumption per day over the twelve month period of each year was approximately 26,8 kilolitres. This data proves that a consistent occupancy level was maintained even though the monthly consumption varies between the two measured years. Occupancy levels are of interest to determine whether the rise in consumption are directly proportional to any variations in the number of consumers for a particular building. The focus can now be directed at the energy cost per month as part of an analysis to determine the performance of the water heating system.

Figure 6.3 displays a typical scenario of how an inefficiently operated water heating system can influence the energy cost. The hot water consumption of building A during March was similar to that of November month reaching a total consumption of approximately 25 kilolitres per day, but the energy cost of the latter was nearly 522% higher. This has an enormous effect on the hot water pricing for building A. As discussed in Section 3.4.1 of

Chapter 3, the cost per unit of hot water for the consumer is calculated by dividing the total energy cost per month with the total hot water consumption measured in kL . Effectively the consumer paid ZAR 8.99 per kL during March of 2014 and ZAR 47.64 per kL in November by consuming a similar amount of hot water. Even though the pricing structure of building A might differ in comparison to other high rise accommodation buildings, the consumer in this case is negatively affected by the inefficiently operated water heating system. It must be noted that the occupancy levels were not recorded and the simulation results are only based on a fixed maximum occupancy level of the building. The sudden decrease in consumption during December might be due to a decline in occupancy over the holiday season but the high energy costs in relation to the 32% lower average consumption per day does emphasize the inefficient operation of the water heating system during this period. Even with the fixed specified occupancy level of 373 users for building A, the scheduler still managed to generate a substantial energy saving potential.

When comparing the simulated results with the actual energy costs, it is evident that the system was not operating in an efficient state from July 2014 and onwards. The simulated results produced an annual average cost per kL of ZAR 12.17, which is 55% lower than the actual average costs of 2014. The only discrepancy in the simulation results are the higher energy costs during March and June. It can however be linked to the fixed occupancy levels specified during the hot water scheduler simulation setup, but a lower specified target level can improve the savings potential should the design engineer require a more optimum solution. Not only will the consumer benefit from the more efficient system but the optimized control of the water heating equipment will lower the operating cost for the building owner, and the lower electrical consumption will support the South African energy utility, Eskom, in the goal to reduce the national energy demand.

6.1.2 Building B - Energy cost analysis

Building B energy costs: 2014

As part of the verification process in this chapter, the measured data of building B is evaluated to determine any inconsistencies with reference to the results of building A. At first glance the hot water consumption of building B illustrated in Figure 6.4 have similar characteristics concerning the seasonal behaviour of the consumer. During the winter months between June and August the average hot water consumption is higher than in summer with the exception of January 2014 which had the second highest average consumption of the year. A gradual decrease in consumption can be seen from June to December which is similar to the downward consumption trend in Figure 6.3.

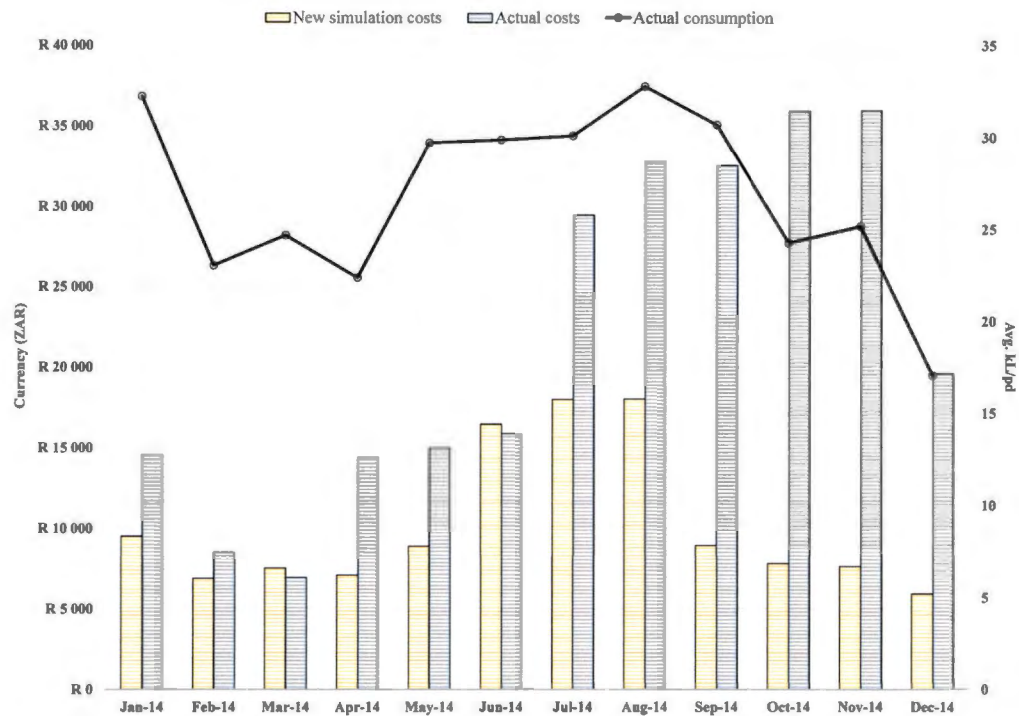


Fig. 6.3 Building A actual monthly energy costs versus simulated energy costs (2014)

When looking at the measured energy costs of building B illustrated in Figure 6.4, a similar consumer behaviour can be seen in comparison to the building A measurements. As the consumer experiences an increase in costs due to the excessive hot water consumption the natural response is to lower their consumption in the succeeding month. At the start of winter, the hot water consumption tends to increase due to the cooler ambient conditions but progressively decreases towards the summer months. The energy costs during the first quarter of the year are however considerably higher in comparison to the summer months in the last quarter. As demonstrated in the results of building A an inefficient water heating system might be to blame for the increase in energy costs. The intensive operating schedule of the heating equipment during the winter months and irregular maintenance schedules of the heat pump water heaters (HPWH) increases the risk of equipment failure. In the situation where the HPWH units are offline the electrical resistance heaters operate as primary heater and naturally increases the energy costs of the system. To counter the effect of equipment failure, an optimized operating schedule of the heating equipment is necessary as well as a proper notification method to report any malfunction of the water heating system.

The hot water scheduler simulation results presented in Figure 6.4 illustrates a potential improvement in energy costs based on actual average hot water consumption profiles for

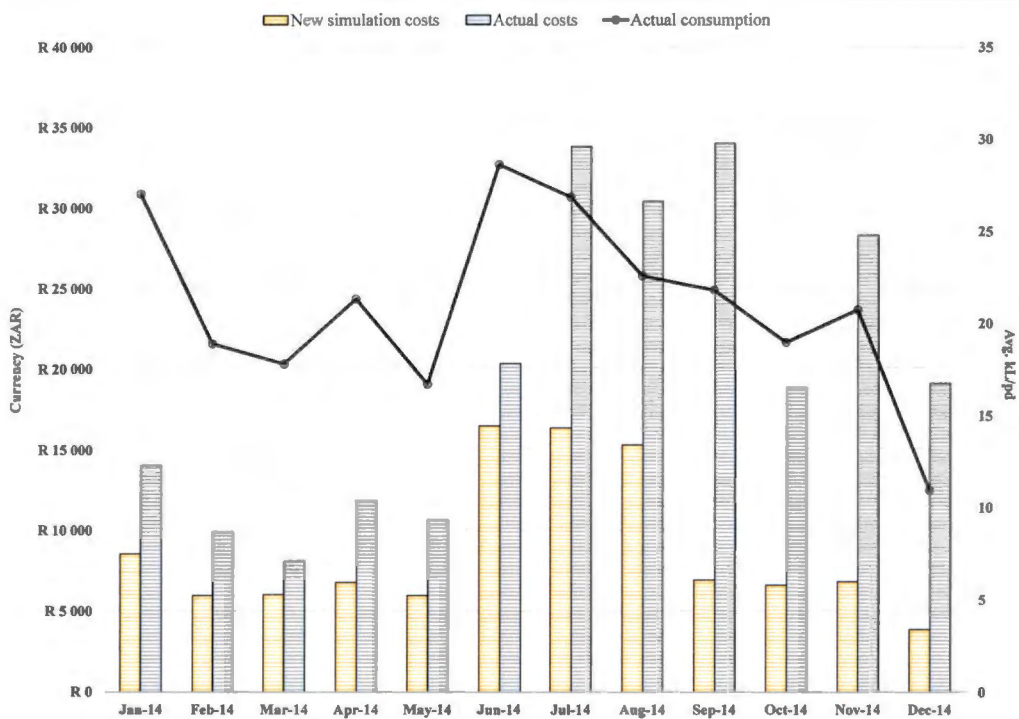


Fig. 6.4 Building B actual monthly energy costs versus simulated energy costs (2014)

building B. Heat pump water heaters (HPWH) were specified as the primary heaters as input to the simulation and the backup heater were only initiated when the heating capacity of both HPWH were insufficient at a certain time interval. A gradual increase in energy costs are visible during the winter months and the costs during the summer months produced similar results in the first and last quarter of the year. The simulated average annual costs per kL for building B was ZAR 13.15 compared to the actual average cost of ZAR 31.59. This is an improvement in energy cost of nearly 58% which emphasizes the importance of an optimized control strategy. To highlight the impact of the simulated results on the cost per kL for the consumer, a combined monthly average cost per kL was calculated over all three years for building A and the results are plotted against the actual combined monthly average costs in Figure 6.5. The lines plotted on the chart indicate the simulation as well as the actual costs per kL and the bar charts the percentage savings per month. Savings of between 20% and 40% are achieved in the simulations from January to April but reduced savings of 20% and below were possible at the start of winter. From July onwards the savings escalated from 26.4% in July to 59.19% in October of 2014. On average the consumer would have saved approximately 35% during 2014 on their hot water billing had the hot water system been more efficiently operated combined with the implementation of an optimized control.

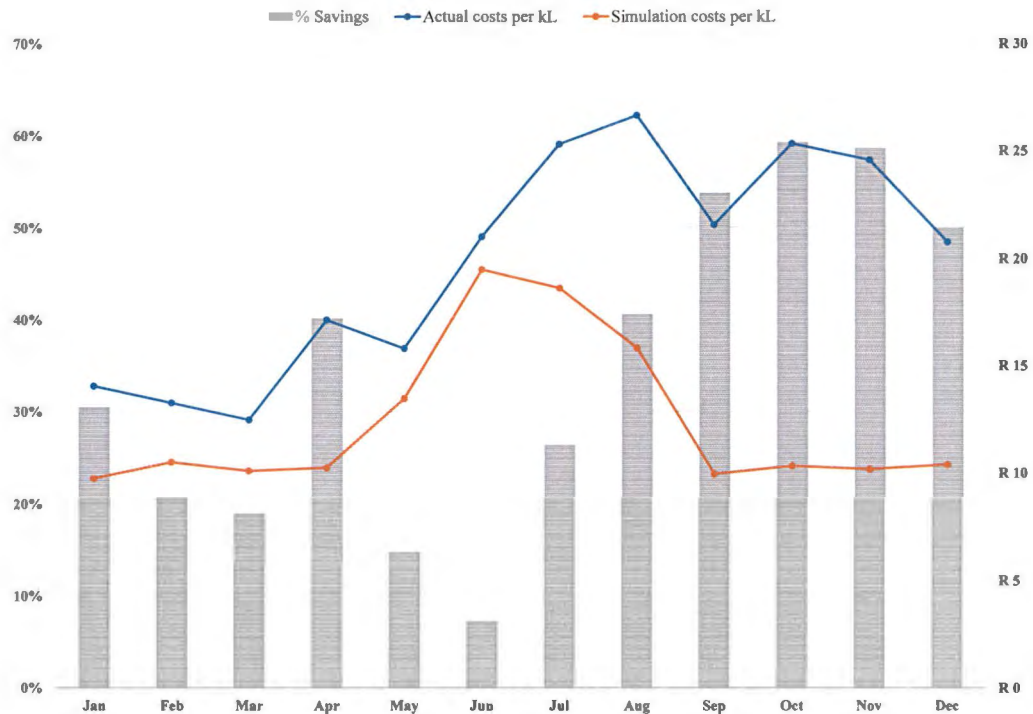


Fig. 6.5 Potential energy savings per *kL*: Building A

6.2 Energy cost analysis of simulated results

All the simulation results discussed in this chapter represents water heating systems with HPWH's as the primary heating source. This significantly lowers the average energy cost when compared to using conventional electrical resistance heaters. A reduction in energy savings would occur if the initial setup of the hot water scheduler simulations, for buildings A and B, utilized electrical resistance heaters as the primary heating source. Within each water heating system the combined operating schedule of HPWH's and electrical resistance heaters affects the overall efficiency of the system and requires the optimum scheduling of certain heating source operating combinations. The impact that hot water heating source combinations have on the energy costs of a water heating systems can be illustrated by simulating operating scenarios which includes predefined heating equipment. Heating equipment combinations are defined during the simulation setup of the hot water scheduler by enabling or disabling the availability of each heater unit. If a certain unit is unavailable, the scheduler will utilize the available heater units within the system for scheduling purposes.

The average energy cost per day for the heater combinations of building B produced by the hot water scheduler is used as an example to demonstrate the effectiveness of the

heating source combinations. Each combination is simulated using the average hot water consumption of building B over a twelve month period to determine the projected costs per day. The lowest simulated energy costs per day was achieved by the utilizing the two HPWH's as the primary heaters throughout the simulated year as shown in Figure 6.6. A second simulation scenario, which includes a single HPWH and the backup heater combination, resulted in an average cost of ZAR 546.21 per day which is 42.87% higher than the twin HPWH combination. When both HPWH's are unavailable, the backup water heating unit is utilized as the primary supply, which produces an average simulated cost of ZAR 922.52 per day and is 66.17% higher than the twin HPWH combination. When comparing the actual costs per hour of building B with the simulated results, a slightly higher cost per day can be seen during the first quarter of the year. It remains above the energy cost of the HPWH and backup heater combination until the beginning of winter and decreases within the vicinity of the double HPWH combination energy costs during June.

During the winter months of July and August the measured daily energy costs remain above the double HPWH simulated costs which implies that the single heat pump and backup heater combination might have been the primary hot water heater units during that time. The inefficient operation of the water heating system becomes visible during the latter part of the year when the average cost per hour increases above the backup heater simulation costs where no HPWHs are available. In view of the energy costs analysis of the measured data, the necessary deficiencies within the system can now be identified to potentially improve the operating schedule of the heating equipment. If no HPWHs are available, the design engineer will be able to optimize the operating schedule of the water heating system based on a worst case scenario to achieve the lowest possible energy cost.

Table 6.2 illustrates the potential savings in energy costs per annum when utilizing the simulated control strategy proposed by the hot water scheduler. The scheduler uses the time of use (TOU) tariff structure described in Section 6.1 where the tariffs are either provided as input to the scheduler by a central data processing facility at a building or inserted manually by the operator to determine the energy costs per day. In alignment with the simulated operating schedule for the hot water heating equipment, the energy costs are calculated based on the specified input criteria of the simulation. These results provide the design engineer or the building owner with an estimated cost analysis that can assist with the design process or the optimization of an existing operating schedule to potentially reduce energy costs per hour. When comparing the simulated energy costs of building A and B with the actual costs per annum in Table 6.2, the simulated costs are substantially lower for each respective year. Even though the 2015 TOU tariffs were used as input to all the simulation scenarios, a potential 39%, 37% and 53% reduction in energy costs were achieved by the scheduler for the 2012,

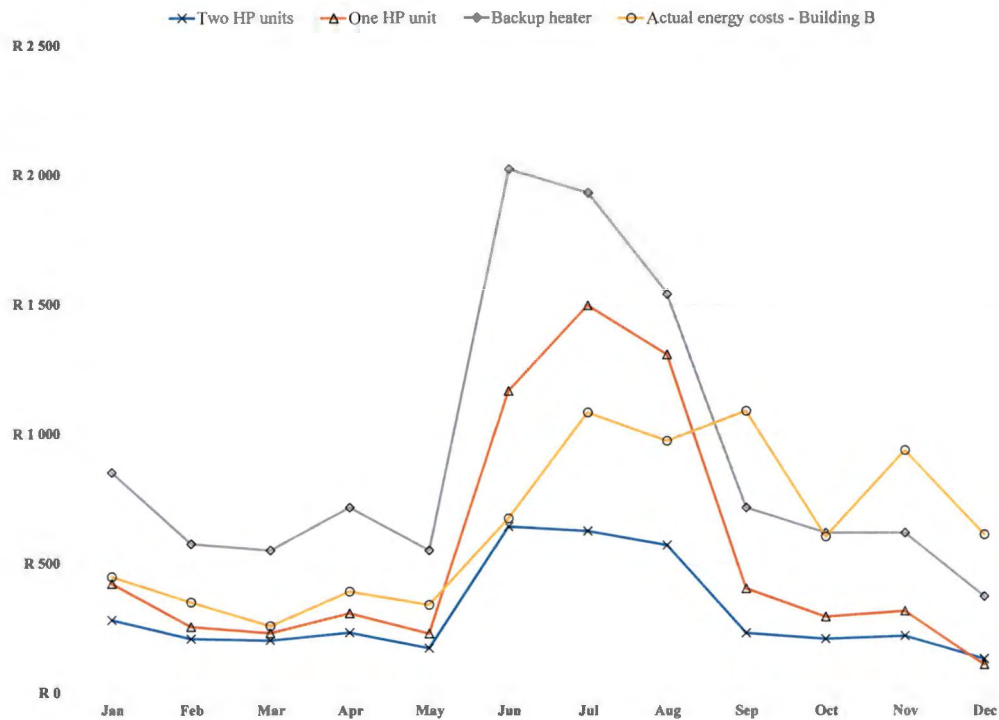


Fig. 6.6 Heating equipment energy cost comparison: Building B (2014)

Table 6.2 Hot water scheduler cost analysis summary

<i>Description</i>	<i>Actual</i>	<i>Hot water scheduler</i>
Building A annual energy cost (2012)	ZAR 187 711	ZAR 113 457
Building A annual energy cost (2013)	ZAR 194 136	ZAR 121 366
Building A annual energy cost (2014)	ZAR 261 277	ZAR 121 888
Building B annual energy cost (2014)	ZAR 238 070	ZAR 104 835

2013 and 2014 financial years. The savings potential for building B is even higher with a 55% potential reduction in energy costs per annum. To achieve the optimum savings per system, the input specifications needs to be defined or provided to the scheduler. When the desired energy saving levels are achieved the design engineer can use the operating schedule to evaluate the equipment costs of the predefined heating and storage capacities related to the optimum simulation results. The following section compares the water heating equipment costs of the two buildings with the proposed equipment sizes provided by the results of the simulation scenarios.

6.3 Equipment cost analysis of the simulated results

When designing a water heating system, the necessary sizing of the hot water storage vessels and the water heating equipment are adjusted until the most efficient operating point of the water heating system is achieved. This optimal point was achieved, in the preceding sections, by improving the operating schedule of available hot water heating equipment without affecting the comfort levels of the consumer. The simulation results of building A and B presented in Chapter 5 did not include any alterations with regards to the HPWH and backup water heater sizes of the respective buildings. The simulation scenarios solely focused on the performance evaluation of the actual installed systems. Throughout the simulations it did however come to light that the actual storage vessel capacities of the buildings were substantially larger than required by the consumer. The larger storage capacity influences the original capital expenditure of a water heating system installation but with a proper analysis, using the hot water scheduler, the initial equipment costs of a system can be drastically reduced.

To illustrate what the effect of water heating system prices have on the initial capital expenditure of a high rise building, a comparison is made between the actual and proposed system costs. The equipment costs were requested during 2015 from the manufacturers in South Africa who supplied the HPWHs, backup water heaters and the storage vessels to the water heating systems of building A and B. It should however be noted that only the prices of the primary components of the water heating system were collected and evaluated and no auxiliary equipment costs, which includes the piping, electrical and external reticulation pumps, were compared. Table 6.3 illustrates the prices collected for the respective primary heating equipment of building A and B as well as the proposed storage vessel price of the hot water scheduler. Both the current individual storage vessel capacities of building A and B are nearly double the manufacturing cost of the single storage vessel capacity that is proposed by the scheduler. This price difference not only influences the initial capital expenditure of the water heating system, it also influences the operational costs due to higher thermal losses of the larger storage capacities.

With no changes to the HPWH and backup water heater sizes within the simulations scenarios, the prices for the HPWHs of building A and B are illustrated in Table 6.3 to demonstrate the substantial price variance between the two units. By selecting a $65kW_t$ HPWH instead of a $50kW_t$ unit to compensate for any system design losses can result in a 30% higher cost in capital expenditure for the heat pump units. It is thus imperative to optimize the scheduler by synchronizing the required heating capacity with the storage capacity of the system to obtain the most cost effective system whilst maintaining a sufficient supply of hot water to the consumer.

Table 6.3 Hot water system equipment pricing - 2015

<i>Description</i>	<i>Size</i>	<i>Cost(ZAR)</i>
Building A storage vessel - actual	8000 litres	ZAR 111 451.40
Building B storage vessel - actual	7300 litres	ZAR 106 093.31
Proposed storage vessel - Building A and B	3000 litres	ZAR 53 949.90
Heat pump A	50 kW	ZAR 107 267.00
Heat pump B	65 kW	ZAR 159 244.00

6.4 Summary

In view of the energy and equipment costs of the water heating equipment presented in this chapter, a clear distinction can be made between the actual measured results of the two high rise buildings and the simulated results of the hot water scheduler. The energy costs are predominantly influenced by the occupancy levels of the building and the efficiency of the water heating equipment. The hot water scheduler managed to simulate several heating equipment operating scenarios, based on the hot water consumption data of both the buildings, which can potentially reduce the annual energy costs of the water heating systems by between 30% and 50%. This was achieved by only focusing on the hot water consumption profiles of the respective buildings. The simulation results of the hot water scheduler further enables the design engineer to determine the most cost effective equipment sizes and minimizes the potential of increasing the initial CAPEX of a water heating system design. An optimum water heating system design combined with a effective operating schedule for the water heating equipment increases the energy savings potential of the water heating system which in turn can benefit the consumer, building owner and Eskom.

Chapter 7

Closure and future recommendations

The introduction of a solution to optimally design and control a sanitary water heating systems for high rise accommodation buildings was the main objective throughout this study. Hot water consumption profiles were utilized within a developed hot water scheduler to improve water heating system efficiencies by controlling the operating intervals of hot water heating equipment. This chapter summarizes and concludes the initial specified purpose of this study with reference to the results depicted within all the preceding chapters.

7.1 Conclusions

The importance of hot water consumption profiles as input to the design of a sanitary water heating system have been reiterated throughout this study. With the limited available hot water consumption profiles for high rise buildings in the commercial sector of South Africa, a solution was presented to effectively predict consumption profiles by utilizing newly measured consumption data and improve the accuracy of the water heating system design. The consumption data of two high rise apartment buildings in the CBD of Johannesburg, South Africa, were collected over a period of four years with the aim to evaluate the consumption data based on density group classifications. The envisaged consumption of the buildings were originally compared to the low user categories presented by previous research completed within the residential and commercial sectors of South Africa. What became evident over the course of the study, was the higher than expected hot water consumption within the defined high density group classification of the buildings. Both the buildings had similar results which positioned the consumption data between the medium and high user categories rather than the low category as originally expected.

These consumption results highlighted the significance of accurate up to date consumption data for water heating system control and design purposes. A newly developed method to predict the hot water consumption of a high rise building was presented in chapter 4. The method generates new consumption profiles based on certain input criteria and is utilized as input to a developed hot water scheduler. The scheduler produces simulation results to evaluate the performance of water heating equipment under certain operating conditions. Several simulation scenarios were illustrated in Chapter 5 to test the effects of an efficient operating schedule on the energy and operating costs of a water heating system. The results illustrated that an updated control philosophy of the existing water heating heating equipment at the two measured high rise buildings reduced the energy costs of the two systems. An improvement of up to 55% was obtained for the buildings without substantially modifying the sizes of the heating equipment within the simulations.

Further assessment of the simulation results, that were based on the specifications of each building, revealed variances within the sizes of the proposed and existing water heating equipment in the respective buildings. Both the buildings required smaller hot water storage vessel capacities, in comparison to the actual heating equipment sizes described in chapter 3, without limiting the availability of hot water supply to the consumers. This functionality within the scheduler enables a design engineer to dynamically alter water heating system specifications, whether it being the heating capacity of a water heater or the storage capacity of a hot water vessel, until the desired operating conditions are achieved. The techno-economic summary presented in chapter 6 illustrated the significance of the synergy between

the improved water heating equipment design and control. It ultimately reduces the energy costs per day and lowers the risk of over capitalization of any new system design or the OPEX of an existing water heating system.

The results generated by the hot water scheduler, developed in this study, illustrates the relevance of predicted hot water consumption data for water heating system design and control. Not only is it relevant to high rise apartment buildings, but any commercial building supplying sanitary hot water to the consumer. The adaptability of the scheduler to update the predicted consumption data based on the dynamic requirements of the consumer offers the design engineer with a solution for improved system design and control. This solution will benefit both the energy utility and the consumer due to a reduction in energy costs versus hot water demand and it will improve the system efficiencies which will benefit the building owner due to a potential reduction in costs related to the CAPEX and OPEX of a system.

7.2 Recommendation for future research

Based on the results presented in this study, the following have been identified as recommended areas for future research.

1. The hot water scheduler software requires the necessary integration with a water heating system to test the capability of the scheduler related to the energy costs and hot water demand profiles of a high rise apartment buildings. Either a distributed or non-distributed control system can be implemented linked to a database which can supply the necessary input variables to the scheduler function.
2. Due to the limited availability of hot water consumption data in the commercial sector, additional studies should be initiated to collect energy and water consumption data of other commercial buildings due to the dynamic nature of consumption patterns. New data will further improve the ability to design and control water heating systems.
3. The algorithm within the hot water scheduler does not include the total volume within the piping distribution of the high rise building. If the volume can be included along with the time of delivery to the consumer a more accurate control model can be developed.
4. A dynamic hot water billing system for high rise apartment buildings have not been introduced in the South African market. The hot water scheduler can be integrated with a pre-paid billing system to automatically regulate the costs per kilolitre based on the energy savings obtained by the scheduler. This will benefit the consumer when the

energy costs are reduced but it would potentially reduce the water consumption if the consumers have the ability to manage their hot water consumption.

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Appendix A

High rise building layout and configurations

A.1 Building A

A.1.1 Apartment unit generic kitchen and bathroom layout

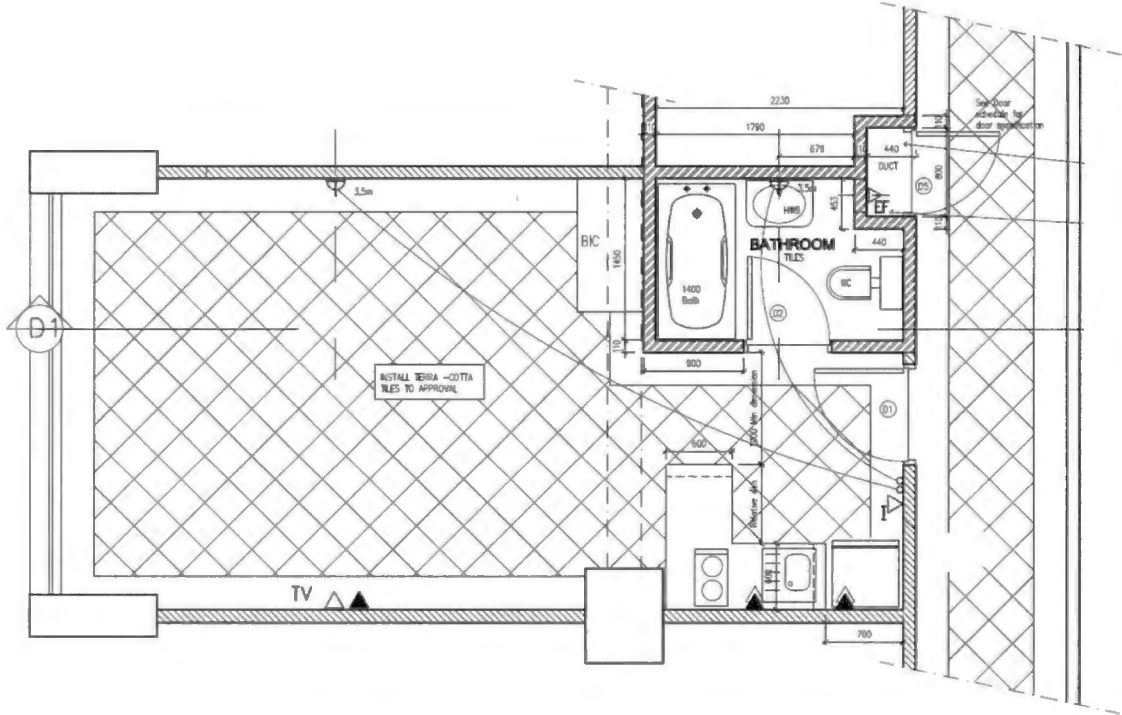


Fig. A.1 Detail layout of typical Building A apartment units

A.1.2 Apartment unit side elevation bathroom layout

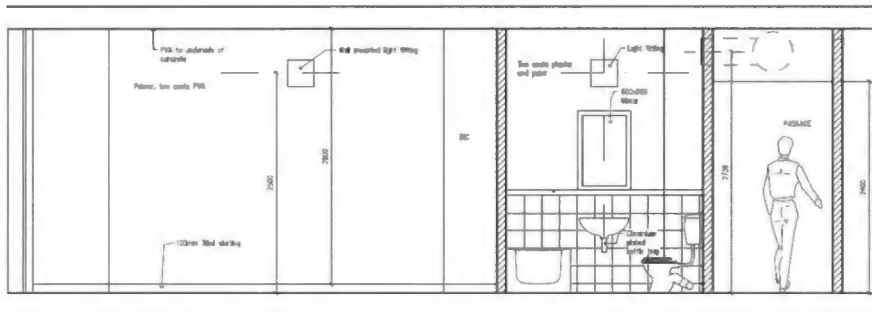


Fig. A.2 Detail side view layout of bathroom for Building A apartment units

A.1.3 Apartment unit side elevation kitchen layout

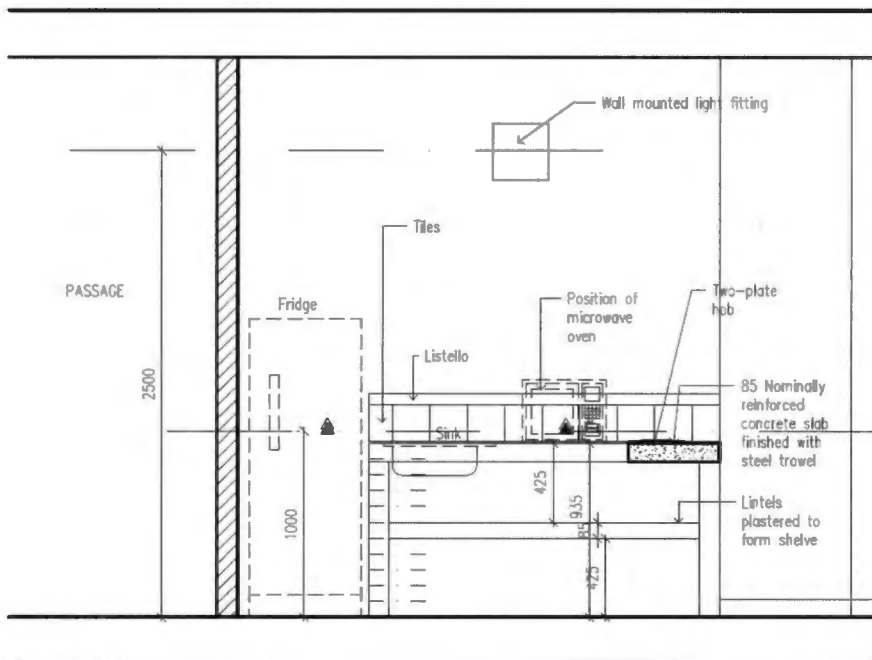


Fig. A.3 Detail side view layout of kitchen for Building A apartment units

A.1.4 Building layout

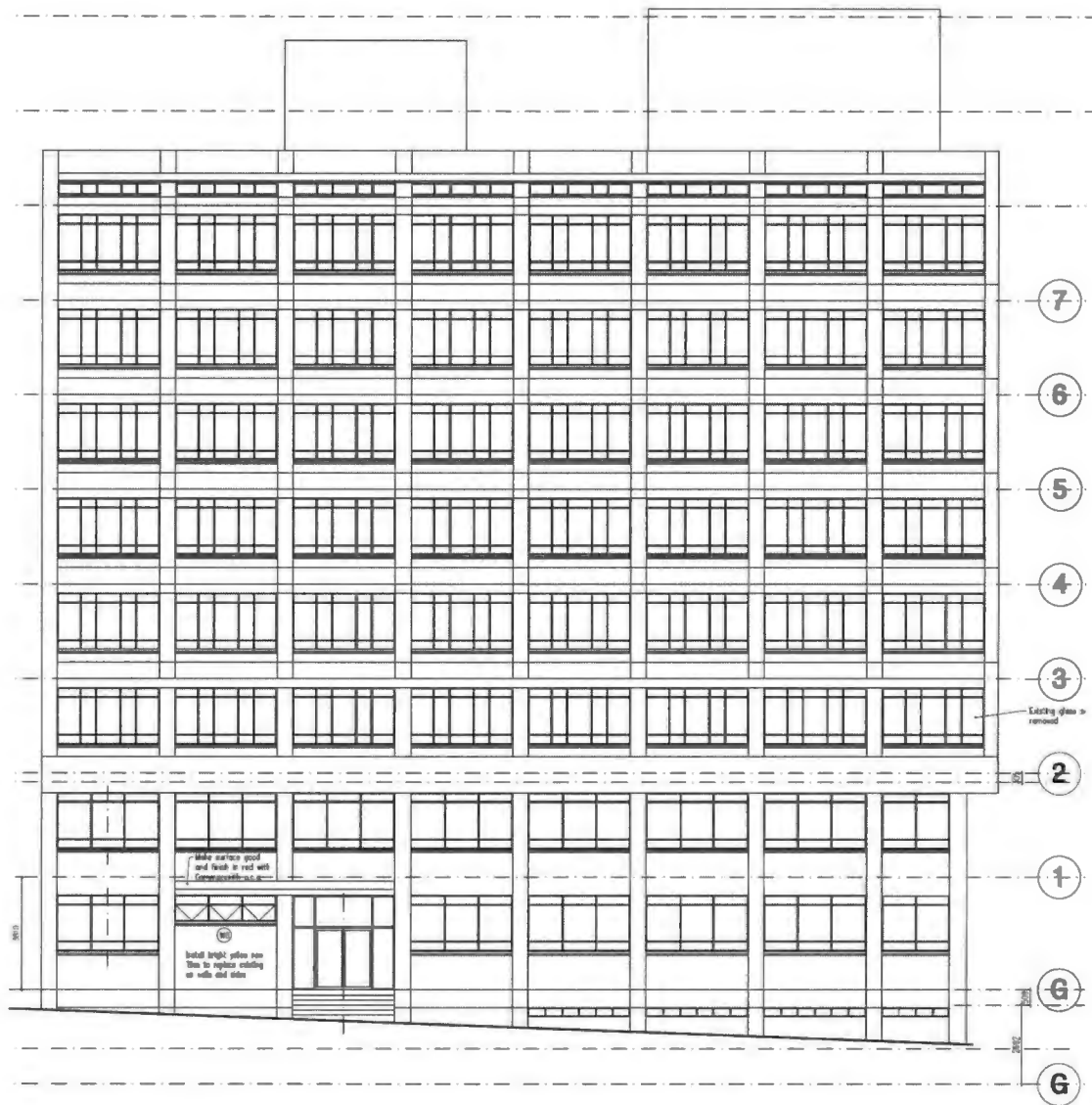


Fig. A.4 North elevation layout of building A

Appendix B

Description of Hot Water Scheduler Variables

The following section describes all the input and output variables required/generated by the exposed function (HWSystemScheduler). Some of the variable types can be found in the code extract shown in the Chapter 4 section 4.4.

B.1 Single Array Pointers

- `heatpumpavail[]`:

A single array consisting of user defined (maximum number of heat pump units + 1) single array. The first value will be ignored. The single array consists of n user defined values representing the availability of the specified heat pump units in the water heating system. If the specific heat pump is available, the value should be set to 1, otherwise the value should be set to 0. This will be an input from the designer as part of the design process or through the SCADA system during the hot water system control process.

- `heatpumpstatus[]`:

A single array consisting of user defined (maximum number of heat pump units + 1) single array. The first value will be ignored. The single array consists of n user defined values representing the status of the specified heat pump units in the water heating system. If the specific heat pump is operational, the value should be set to 1, otherwise the value should be set to 0. This will be an input from the designer as part of the design process or through the SCADA system during the hot water system control process.

- backupavail[]:

A single array consisting of user defined (maximum number of backup water heaters + 1) single array. The first value will be ignored. The single array consists of n user defined values representing the availability of the specified electrical resistance water heating units in the water heating system. If the specific heater is available, the value should be set to 1, otherwise the value should be set to 0. This will be an input from the designer as part of the design process or through the SCADA system during the hot water system control process.

- backupstatus[]:

A single array consisting of user defined (maximum number of backup water heaters + 1) single array. The first value will be ignored. The single array consists of n user defined values representing the status of the specified electrical resistance water heating units in the water heating system. If the specific heater is operational, the value should be set to 1, otherwise the value should be set to 0. This will be an input from the designer as part of the design process or through the SCADA system during the hot water system control process.

- storagevesselavail[]:

A single array consisting of user defined (maximum number of hot water storage vessels + 1) single array. The first value will be ignored. The single array consists of n user defined values representing the availability of the specified storage vessels in the water heating system. If the specific storage vessel is available, the value should be set to 1, otherwise the value should be set to 0. This will be an input from the designer as part of the design process or through the SCADA system during the hot water system control process.

- heatpumppower[]:

A single array consisting of user defined (maximum number of heat pump units + 1) single array. The first value will be ignored. The single array consists of a user defined value representing the thermal power rating of each specified heat pump unit in the water heating system. This will be a user defined input.

- heatpumppowerfactor[]:

A single array consisting of user defined (maximum number of heat pump units + 1) single array. The first value will be ignored. The single array consists of a user defined

value representing the electrical powerfactor rating of each specified heat pump unit in the water heating system. This will be a user defined input.

- `backuppowers[]`:

A single array consisting of user defined (maximum number of backup heaters + 1) single array. The first value will be ignored. The single array consists of a user defined value representing the thermal power rating of each specified electrical resistance backup heater in the water heating system. This will be a user defined input.

- `backuppowerfactor[]`:

A single array consisting of user defined (maximum number of backup heaters + 1) single array. The first value will be ignored. The single array consists of a user defined value representing the electrical powerfactor rating of each specified electrical resistance backup heater in the water heating system. This will be a user defined input.

- `storagevesselvolume[]`:

A single array consisting of user defined (maximum number of hot water storage vessels + 1) single array. The first value will be ignored. The single array consists of a user defined value representing the volume of each specified storage vessel in the water heating system. This will be a user defined input.

- `hightempalarms[]`:

A single array consisting of user defined (maximum number of temperature sensors + 1) single array. The first value will be ignored. The single array consists of a user defined value representing the volume of each specified storage vessel in the water heating system. This will be a user defined input.

- `peakintervals[]`:

An array of 25 values. The first value will be zero and will be ignored. It is followed by 24 hourly values of either 0 (during off-peak and standard periods) 1 (during the peak period) indicating the energy utility morning and evening peak periods on an hourly basis for the next 24-hours. This is a user defined input.

- `costs[]`:

An array of 25 values expressed in Rand. The first value will be a zero and will be ignored. It is followed by 24 values representing the estimated cost based on the active energy charge and the electricity consumed with regards to the predicted schedules over the next 24 hour period. This is an output variable.

B.2 Double Array Pointers

- `storagevesseltemp[][]`:

A double array consisting of a user defined number of storage vessel temperature sensors + 1 single arrays and total number of hot water storage vessels + 1 values each. The whole of the first array as well as the first value of the other single arrays will be ignored. Each of the 2 arrays will consists of values will either be defined by the end user or measured by the data aquisition system to obtain the available temperature per vessel. This is an input variable from the user or the SCADA system.

- `intervalprices[][]`:

A double array consisting of 3 (demandseason +1) single arrays with 25 (counter +1) values each. The whole of the first single array as well as the first value of the other single arrays will be ignored. Each of the 2 arrays will consists of values defined by the user representing the utility tariff prices per hour for the low and high demand seasons. An array of 24 values are expressed in R/kWh. This is an output variable.

- `schedule[][]`:

A double array consisting of 25 (counter +1) single arrays with user specified (heaters +1) values each. The whole of the first single array as well as the first value of the other single arrays will be ignored. Each of the 24 arrays will consists of n values defined by the user representing the number of heat pumps and backup heaters that should be switched on or off based on the volume requirement per hour. This is an output variable.

B.3 Other variables

- `counter`:

A single value between 1 and 24 indicating the number of the hours in which the scheduler will start to schedule the heating equipment (e.g. when the hot water scheduler is called at 00:55 it will provide an operating schedule from 01:00 onwards, the counter should therefore be set to 1 in this case). This is an input from the user or SCADA system.

- `errorflag`:

A single variable indicating that an error occurred during the execution of the hot water scheduler. If the errorflag is 1 it indicates that an error has occurred and the schedule

Table B.1 List of active software files

<i>File name</i>	<i>Type</i>
HWSystemScheduler.dll	Application extension
HWSystemScheduler.lib	Library file
ExternalInterface.h	Header file

should not be updated with the new, proposed operating schedule. The value of the errorflag will be 0 if no error has occurred. This is an output variable. Note that this variable should be initialized to 0 before it is passed to the exposed hot water scheduler function.

- demandseason:

A single variable indicating the demand season based on the tariff structure of the electrical utility. A value of 1 represents the high demand season and value of 2 represents the low demand season. This is a static input from the user for system design and control purposes.

B.4 List of required files

Active software files

The active software files refer to the files that will be actively used by the external data acquisition software to access the hot water scheduler software. These files should be stored in the same directory as the external application and should be included in the external software configuration as described in Chapter 4 Section 4.4. Table B.1 provides a list of the active software files that will be generated by the hot water scheduler.

Passive software files

The passive software files refer to the files that will not be actively used by external data acquisition software. However, these files should also be stored in the external data acquisition software directory to ensure that they are available for the end user whenever required. Note that these files should not be included in the external data acquisition software configuration. Table B.2 provides a list of the passive software files that will be generated by the hot water scheduler.

Table B.2 List of passive software files

<i>File name</i>	<i>Type</i>
HWPprocessor.dll	Application extension
HWScheduler.dll	Application extension
HWSCHEDULER_ambtempswb	Text file
HWSCHEDULER_backupavailability	Text file
HWSCHEDULER_backuppower	Text file
HWSCHEDULER_backuppowerfactor	Text file
HWSCHEDULER_backupstatus	Text file
HWSCHEDULER_cumulativeconsumption	Text file
HWSCHEDULER_globalgeometry	Text file
HWSCHEDULER_highprofilecoeff	Text file
HWSCHEDULER_hpavailability	Text file
HWSCHEDULER_hpheatingcoeff	Text file
HWSCHEDULER_hpinputpowercoeff	Text file
HWSCHEDULER_hppower	Text file
HWSCHEDULER_hppowerfactor	Text file
HWSCHEDULER_hpstatus	Text file
HWSCHEDULER_intervalprices	Text file
HWSCHEDULER_lowprofilecoeff	Text file
HWSCHEDULER_peakintervals	Text file
HWSCHEDULER_powerfactor	Text file
HWSCHEDULER_targetlevel	Text file
HWSCHEDULER_vesselavailability	Text file
HWSCHEDULER_vesseltemperatures	Text file
HWSCHEDULER_vesselvolume	Text file

Appendix C

Hot Water Scheduler Simulation Results

The following sections illustrate all the output variables produced by the hot water scheduler for the various simulation scenarios presented in Chapter 5.

C.1 Simulation schedule 1 - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Rand)
1	154.641	2.348	14400	14245.359	15	0	0	0	0
2	153.528	2.816	14245.359	14918.471	14	1	0	0	5.168
3	203.783	2.938	14918.471	14714.688	14	0	0	0	0
4	254.038	3.713	14714.688	14460.65	13	0	0	0	0
5	610.858	5.575	14460.65	13849.792	12	0	0	0	0
6	973.157	8.542	13849.792	13650.37	12	1	0	0	4.989
7	1251.574	12.358	13650.37	13225.435	14	1	0	0	8.100
8	1403.392	16.637	13225.435	14148.367	16	1	1	0	30.831
9	1424.543	20.98	14148.367	13660.729	18	0	1	0	18.789
10	1337.391	25.957	13660.729	13317.604	20	1	0	0	12.933
11	1178.158	28.649	13317.604	14727.133	23	1	1	0	21.96
12	986.981	31.658	14727.133	13740.152	25	0	0	0	0
13	801.773	34.103	13740.152	13932.645	26	1	0	0	8.924
14	655.164	36.1	13932.645	14271.747	27	1	0	0	8.924
15	572.679	37.846	14271.747	14693.334	27	0	1	0	13.036
16	570.209	39.584	14693.334	14123.125	27	0	0	0	0
17	649.853	41.566	14123.125	14467.538	27	1	0	0	8.924
18	794.943	43.989	14467.538	13672.596	26	0	0	0	0
19	966.99	46.937	13672.596	13699.872	24	0	1	0	18.892
20	1108.236	50.316	13699.872	13585.903	23	1	0	0	12.933
21	1152.3	53.829	13585.903	13427.869	21	1	0	0	8.924
22	1040.273	57.001	13427.869	13381.862	20	0	1	0	13.036
23	728.395	59.222	13381.862	15174.392	19	1	1	0	13.892
24	155.733	59.697	15174.392	15018.639	18	0	0	0	0

Table C.1 Output variables for schedule 1, scenario A - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCon(Rand)
1	154.641	2.348	14400	14245.359	15	0	0	0	0
2	153.528	2.816	14245.359	14091.832	14	0	0	0	0
3	203.783	2.938	14091.832	13888.049	14	0	0	0	0
4	254.038	3.713	13888.049	13634.011	13	0	0	0	0
5	610.858	5.575	13634.011	13023.153	12	0	0	0	0
6	973.157	8.542	13023.153	12049.998	12	0	0	0	0
7	1251.574	12.358	12049.996	10798.421	14	0	0	0	0
8	1403.392	16.637	10798.421	9395.029	16	0	0	0	0
9	1424.543	20.98	9395.029	7970.487	18	0	0	0	0
10	1337.391	25.057	7970.487	6633.096	20	0	0	0	0
11	1178.158	28.649	6633.096	5454.938	23	0	0	0	0
12	986.981	31.658	5454.938	4467.957	25	0	0	0	0
13	801.773	34.103	4467.957	3666.184	26	0	0	0	0
14	655.164	36.1	3666.184	3011.02	27	0	0	0	0
15	572.679	37.846	3011.02	2438.341	27	0	0	0	0
16	570.209	39.584	2438.341	1868.132	27	0	0	0	0
17	649.853	41.566	1868.132	1218.279	27	0	0	0	0
18	794.943	43.989	1218.279	1417.603	26	1	0	0	8.924
19	966.99	46.937	1417.603	1464.879	24	1	0	0	12.933
20	1108.236	50.316	1464.879	1330.91	22	0	1	0	18.892
21	1152.3	53.829	1330.91	1172.876	21	0	1	0	13.036
22	1040.273	57.001	1172.876	1126.869	20	1	0	0	8.924
23	728.995	59.232	1126.869	1363.674	19	1	0	0	5.604
24	155.753	59.697	1363.674	2144.825	18	0	1	0	8.265

Table C.2 Output variables for schedule 1, scenario B - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCon(Rand)
1	154.641	2.348	0	4173.388	15	1	1	1	52.179
2	153.528	2.816	4173.388	4019.86	14	0	0	0	0
3	203.783	2.938	4019.86	3816.077	14	0	0	0	0
4	254.038	3.713	3816.077	3562.039	13	0	0	0	0
5	610.858	5.575	3562.039	2951.182	12	0	0	0	0
6	973.157	8.542	2951.182	1978.024	12	0	0	0	0
7	1251.574	12.358	1978.024	726.45	14	0	0	0	0
8	1403.392	16.637	726.45	204.087	16	1	0	0	12.149
9	1424.543	20.98	204.087	-283.551	18	1	0	0	12.544
10	1337.391	25.057	-283.551	3315.305	20	1	1	1	119.866
11	1178.158	28.649	3315.305	2137.147	23	0	0	0	0
12	986.981	31.658	2137.147	1150.166	25	0	0	0	0
13	801.773	34.103	1150.166	348.393	26	0	0	0	0
14	655.164	36.1	348.393	687.495	27	1	0	0	8.924
15	572.679	37.846	687.495	1109.082	27	1	0	0	8.924
16	570.209	39.584	1109.082	538.873	27	0	0	0	0
17	649.853	41.566	538.873	883.287	27	0	1	0	13.036
18	794.943	43.989	883.287	88.344	26	0	0	0	0
19	966.99	46.937	88.344	115.621	24	1	0	0	12.933
20	1108.236	50.316	115.621	1.631	22	1	0	0	12.933
21	1152.3	53.829	1.631	-156.382	21	0	1	0	13.036
22	1040.273	57.001	-156.382	3612.422	20	1	1	1	82.71
23	728.995	59.232	3612.422	2883.828	19	0	0	0	0
24	155.753	59.697	2883.828	2728.074	18	0	0	0	0

Table C.3 Output variables for schedule 1, scenario C - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Rand)
1	154.641	2.348	0	4173.388	15	1	1	1	32.179
2	153.328	2.816	4173.388	4019.86	14	0	0	0	0
3	203.783	2.938	4019.86	3816.077	14	0	0	0	0
4	254.038	3.713	3816.077	3562.039	13	0	0	0	0
5	610.858	5.575	3562.039	2951.182	12	0	0	0	0
6	973.157	8.542	2951.182	1978.024	12	0	0	0	0
7	1251.574	12.358	1978.024	726.45	14	0	0	0	0
8	1403.392	16.637	726.45	204.087	16	1	0	0	12.149
9	1424.543	20.98	204.087	-283.551	18	1	0	0	12.544
10	1337.391	25.057	-283.551	3315.305	20	1	1	1	119.866
11	1178.158	28.649	3315.305	2137.147	23	0	0	0	0
12	986.981	31.658	2137.147	1150.166	25	0	0	0	0
13	801.773	34.103	1150.166	1342.66	26	1	0	0	8.924
14	655.164	36.1	1342.66	1681.761	27	1	0	0	8.924
15	572.679	37.846	1681.761	1109.082	27	0	0	0	0
16	570.209	39.584	1109.082	1533.139	27	0	1	0	13.036
17	649.853	41.566	1533.139	1877.553	27	1	0	0	8.924
18	794.943	43.989	1877.553	1082.61	26	0	0	0	0
19	966.99	46.937	1082.61	1109.887	24	0	1	0	18.892
20	1108.236	50.316	1109.887	955.917	22	1	0	0	12.933
21	1152.3	53.829	955.917	837.884	21	1	0	0	8.924
22	1040.273	57.001	837.884	791.877	20	0	1	0	13.036
23	728.595	59.222	791.877	1028.681	19	0	1	0	8.288
24	155.753	59.697	1028.681	1809.833	18	1	0	0	5.518

Table C.4 Output variables for schedule 1, scenario D - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Rand)
1	154.641	2.348	0	4173.388	15	1	1	1	32.179
2	153.328	2.816	4173.388	4019.86	14	0	0	0	0
3	203.783	2.938	4019.86	3816.077	14	0	0	0	0
4	254.038	3.713	3816.077	3562.039	13	0	0	0	0
5	610.858	5.575	3562.039	2951.182	12	0	0	0	0
6	973.157	8.542	2951.182	1978.024	12	0	0	0	0
7	1251.574	12.358	1978.024	1553.089	14	1	0	0	8.106
8	1403.392	16.637	1553.089	1030.726	16	1	0	0	12.149
9	1424.543	20.98	1030.726	543.088	18	0	1	0	18.789
10	1337.391	25.057	543.088	1793.383	20	1	1	0	31.825
11	1178.158	28.649	1793.383	1609.491	23	1	0	0	8.924
12	986.981	31.658	1609.491	1616.777	25	1	0	0	8.924
13	801.773	34.103	1616.777	1809.27	26	0	1	0	13.036
14	655.164	36.1	1809.27	2148.372	27	0	1	0	13.036
15	572.679	37.846	2148.372	2569.959	27	1	0	0	8.924
16	570.209	39.584	2569.959	1999.75	27	0	0	0	0
17	649.853	41.566	1999.75	2344.163	27	0	1	0	13.036
18	794.943	43.989	2344.163	2543.487	26	1	0	0	8.924
19	966.99	46.937	2543.487	1576.497	24	0	0	0	0
20	1108.236	50.316	1576.497	1862.528	22	0	1	0	18.892
21	1152.3	53.829	1862.528	1304.494	21	1	0	0	8.924
22	1040.273	57.001	1304.494	2851.907	20	1	1	0	21.96
23	728.595	59.222	2851.907	2123.312	19	0	0	0	0
24	155.753	59.697	2123.312	2904.463	18	1	0	0	5.518

Table C.5 Output variables for schedule 1, scenario E - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Readd)
1	154.641	2.348	0	4173.388	15	1	1	1	52.179
2	153.328	2.816	4173.388	4019.96	14	0	0	0	0
3	203.783	2.938	4019.96	3816.077	14	0	0	0	0
4	284.038	3.713	3816.077	3562.039	13	0	0	0	0
5	610.858	5.975	3562.039	2951.182	12	0	0	0	0
6	973.137	8.542	2951.182	2751.759	12	1	0	0	4.989
7	1251.574	12.358	2751.759	2326.824	14	1	0	0	8.106
8	1403.392	16.637	2326.824	1804.461	16	0	1	0	18.681
9	1424.543	20.98	1804.461	1316.823	18	0	1	0	18.789
10	1337.391	25.057	1316.823	2567.118	20	1	1	0	31.825
11	1178.158	28.649	2567.118	2383.227	23	1	0	0	8.924
12	996.981	31.658	2383.227	2390.512	23	1	0	0	8.924
13	801.775	34.103	2390.512	2583.005	26	0	1	0	13.036
14	655.164	36.1	2583.005	2922.107	27	0	1	0	13.036
15	572.679	37.846	2922.107	3343.694	27	1	0	0	8.924
16	570.209	39.584	3343.694	2773.485	27	0	0	0	0
17	649.853	41.566	2773.485	3117.898	27	0	1	0	13.036
18	794.943	43.989	3117.898	3317.222	26	1	0	0	8.924
19	966.99	46.937	3317.222	2330.232	24	0	0	0	0
20	1108.236	50.516	2330.232	2236.263	22	0	1	0	18.892
21	1123.3	53.829	2236.263	2078.229	21	1	0	0	8.924
22	1040.273	57.001	2078.229	3625.642	20	1	1	0	21.96
23	728.595	59.222	3625.642	2897.047	19	0	0	0	0
24	155.753	59.697	2897.047	3678.199	18	1	0	0	5.518

Table C.6 Output variables for schedule 1, scenario F - Building A

C.2 Simulation schedule 2 - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Readd)
1	279.422	3.601	0	3289.339	9	1	1	1	59.361
2	226.489	4.292	3289.339	3062.85	9	0	0	0	0
3	283.48	4.392	3062.85	3382.517	8	1	0	0	5.329
4	344.47	5.442	3382.517	3038.047	8	0	0	0	0
5	884.144	6.138	3038.047	2759.05	8	0	1	0	9.236
6	1446.458	12.548	2759.05	1895.771	7	1	0	0	9.362
7	1896.299	18.329	1895.771	561.018	6	1	0	0	30.775
8	2164.303	24.927	561.018	-1041.739	6	0	1	0	55.21
9	2233.804	31.746	-1041.739	-1585.719	10	1	1	0	89.348
10	2133.581	38.255	-1585.719	1703.402	14	1	1	1	109.967
11	1912.221	44.085	1703.402	1884.864	16	1	1	0	28.645
12	1623.183	49.04	1884.864	2469.518	18	1	1	0	29.111
13	1335.525	53.111	2469.518	2002.853	19	1	0	0	11.836
14	1099.875	56.465	2002.853	3231.896	20	1	1	0	29.368
15	963.538	59.408	3231.896	2266.358	21	0	0	0	0
16	964.924	62.35	2266.358	3630.352	21	1	1	0	29.368
17	1108.337	65.729	3630.352	2322.015	21	0	0	0	0
18	1375.968	69.924	2322.015	2040.886	20	1	0	0	39.492
19	1711.786	75.143	2040.886	1147.003	17	1	0	0	37.707
20	2023.048	81.311	1147.003	1104.431	14	1	1	0	28.168
21	2187.9	87.981	1104.431	786.719	12	1	1	0	27.681
22	2068.428	94.288	786.719	588.48	12	1	1	0	27.681
23	1515.686	98.908	588.48	889.138	11	1	1	0	16.977
24	332.356	99.921	889.138	2319.614	10	1	1	0	14.841

Table C.7 Output variables for schedule 2, scenario A - Building A

Time of day	Building per hour	CumulativePerPerson	CurrrHourVolume	NextHourVolume	AmbTemp	DynHPI Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Rand)
1	279.422	3.601	0	3289.339	9	1	1	1	59.361
2	226.489	4.292	3289.339	4773.102	9	1	1	0	14.703
3	285.48	4.392	4773.102	5092.77	8	1	0	0	5.329
4	344.47	5.442	5092.77	5353.446	8	1	0	0	5.329
5	884.144	8.138	5353.446	4469.302	8	0	0	0	0
6	1446.458	12.548	4469.302	4630.137	7	1	1	0	26.42
7	1896.299	18.329	4630.137	3295.383	6	1	0	0	30.775
8	2164.303	24.927	3295.383	1692.626	6	1	0	0	30.775
9	2235.804	31.744	1692.626	106.907	10	0	1	0	55.983
10	2135.581	38.255	106.907	-48.199	14	1	1	0	28.168
11	1912.231	44.085	-48.199	2059.97	16	1	1	1	110.444
12	1625.185	49.04	2059.97	2624.624	18	1	1	0	29.111
13	1335.523	53.111	2624.624	3558.112	19	1	1	0	29.341
14	1099.875	56.465	3558.112	4787.155	20	1	1	0	29.568
15	965.538	59.408	4787.155	4716.456	21	1	0	0	12.016
16	964.924	62.35	4716.456	4646.372	21	1	0	0	12.016
17	1108.337	65.729	4646.372	4432.875	21	0	1	0	17.553
18	1375.968	69.924	4432.875	3951.746	20	0	1	0	57.692
19	1711.786	75.143	3951.746	3057.863	17	1	0	0	37.707
20	2023.048	81.311	3057.863	3015.291	14	1	1	0	28.168
21	2187.9	87.981	3015.291	2697.579	12	1	1	0	27.681
22	2068.428	94.288	2697.579	2499.34	12	1	1	0	27.681
23	1515.486	98.908	2499.34	2799.998	11	1	1	0	14.977
24	332.356	99.921	2799.998	4230.474	10	1	1	0	14.841

Table C.8 Output variables for schedule 2, scenario B - Building A

Time of day	Building per hour	CumulativePerPerson	CurrrHourVolume	NextHourVolume	AmbTemp	DynHPI Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Rand)
1	279.422	3.601	0	3289.339	9	1	1	1	59.361
2	226.489	4.292	3289.339	4773.102	9	1	1	0	14.703
3	285.48	4.392	4773.102	5092.77	8	1	0	0	5.329
4	344.47	5.442	5092.77	5353.446	8	1	0	0	5.329
5	884.144	8.138	5353.446	4469.302	8	0	0	0	0
6	1446.458	12.548	4469.302	4630.137	7	1	1	0	26.42
7	1896.299	18.329	4630.137	3295.383	6	1	0	0	30.775
8	2164.303	24.927	3295.383	1692.626	6	1	0	0	30.775
9	2235.804	31.744	1692.626	1219.654	10	1	1	0	89.348
10	2135.581	38.255	1219.654	1064.547	14	1	1	0	28.168
11	1912.231	44.085	1064.547	1246.008	16	1	1	0	28.645
12	1625.185	49.04	1246.008	1830.663	18	1	1	0	29.111
13	1335.523	53.111	1830.663	2764.151	19	1	1	0	29.341
14	1099.875	56.465	2764.151	3993.194	20	1	1	0	29.568
15	965.538	59.408	3993.194	5356.573	21	1	1	0	29.568
16	964.924	62.35	5356.573	4391.649	21	0	0	0	0
17	1108.337	65.729	4391.649	4178.152	21	1	0	0	12.016
18	1375.968	69.924	4178.152	3697.023	20	1	0	0	39.492
19	1711.786	75.143	3697.023	2803.14	17	0	1	0	57.213
20	2023.048	81.311	2803.14	2760.568	14	1	1	0	28.168
21	2187.9	87.981	2760.568	2442.856	12	1	1	0	27.681
22	2068.428	94.288	2442.856	2244.617	12	1	1	0	27.681
23	1515.486	98.908	2244.617	2545.275	11	1	1	0	14.977
24	332.356	99.921	2545.275	3975.751	10	1	1	0	14.841

Table C.9 Output variables for schedule 2, scenario C - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHotter1 Schedule	TotalCost(Rand)
1	279.422	3.601	0	3289.339	9	1	1	1	59.361
2	226.489	4.292	3289.339	4773.102	9	1	1	0	14.703
3	283.48	4.392	4773.102	5092.77	8	1	0	0	5.329
4	344.47	5.442	5092.77	5353.446	8	1	0	0	5.329
5	884.144	8.138	5353.446	4469.302	8	0	0	0	0
6	1446.458	12.548	4469.302	4630.137	7	1	1	0	26.42
7	1896.299	18.329	4630.137	3295.383	6	1	0	0	30.775
8	2164.303	24.927	3295.385	2687.991	6	1	1	0	85.985
9	2235.804	31.744	2687.991	2215.018	10	1	1	0	89.348
10	2135.581	38.255	2215.018	2099.912	14	1	1	0	28.168
11	1912.231	44.085	2099.912	2241.373	16	1	1	0	28.645
12	1625.185	49.04	2241.373	2826.028	18	1	1	0	29.111
13	1335.525	53.111	2826.028	3799.515	19	1	1	0	29.341
14	1099.875	56.465	3799.515	4988.558	20	1	1	0	29.568
15	965.538	59.408	4988.558	4917.86	21	1	0	0	12.016
16	964.924	62.35	4917.86	4847.776	21	1	0	0	12.016
17	1108.337	65.729	4847.776	4634.278	21	0	1	0	17.553
18	1375.968	69.924	4634.278	4153.15	20	0	1	0	57.692
19	1711.786	75.143	4153.15	3299.267	17	1	0	0	37.707
20	2023.044	81.311	3299.267	3216.694	14	1	1	0	28.168
21	2187.9	87.981	3216.694	2898.983	12	1	1	0	27.681
22	2066.428	94.288	2898.983	2700.743	12	1	1	0	27.681
23	1515.486	98.908	2700.743	3001.401	11	1	1	0	14.977
24	332.356	99.921	3001.401	4431.878	10	1	1	0	14.841

Table C.10 Output variables for schedule 2, scenario D - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHotter1 Schedule	TotalCost(Rand)
1	279.422	3.601	0	3744.693	9	1	1	1	63.193
2	226.489	4.292	3744.693	5683.811	9	1	1	0	18.535
3	283.48	4.392	5683.811	5398.331	8	0	0	0	0
4	344.47	5.442	5398.331	5053.861	8	0	0	0	0
5	884.144	8.138	5053.861	5222.976	8	1	0	0	9.236
6	1446.458	12.548	5222.976	3776.519	7	0	0	0	0
7	1896.299	18.329	3776.519	3870.949	6	1	1	0	110.42
8	2164.303	24.927	3870.949	2782.011	6	1	0	0	55.21
9	2235.804	31.744	2782.011	2691.699	10	1	1	0	111.966
10	2135.581	38.255	2691.699	3029.117	14	1	1	0	34.505
11	1912.231	44.085	3029.117	3718.419	16	1	1	0	34.713
12	1625.185	49.04	3718.419	4826.485	18	1	1	0	34.913
13	1335.525	53.111	4826.485	4891.113	19	1	0	0	17.505
14	1099.875	56.465	4891.113	5225.316	20	1	0	0	17.553
15	965.538	59.408	5225.316	4259.778	21	0	0	0	0
16	964.924	62.35	4259.778	4728.933	21	0	1	0	17.553
17	1108.337	65.729	4728.933	5054.673	21	1	0	0	17.553
18	1375.968	69.924	5054.673	5112.783	20	1	0	0	57.692
19	1711.786	75.143	5112.783	4734.494	17	0	1	0	57.213
20	2023.044	81.311	4734.494	3967.946	14	0	1	0	17.253
21	2187.9	87.981	3967.946	4107.7	12	1	1	0	34.289
22	2066.428	94.288	4107.7	3213.099	12	1	0	0	17.145
23	1515.486	98.908	3213.099	3983.787	11	1	1	0	18.66
24	332.356	99.921	3983.787	3876.924	10	1	1	0	18.598

Table C.11 Output variables for schedule 2, scenario E - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHumid1 Schedule	TotalCost(Rand)
1	279.422	3.601	14600	14120.578	9	0	0	0	0
2	226.489	4.292	14120.578	14521.538	9	1	0	0	5.436
3	285.48	4.392	14521.538	14236.058	8	0	0	0	0
4	344.47	5.442	14236.058	14496.735	8	0	1	0	9.236
5	884.144	8.138	14496.735	13612.591	8	0	0	0	0
6	1446.458	12.548	13612.591	13773.425	7	1	1	0	26.42
7	1896.299	18.329	13773.425	13434.036	6	1	1	0	85.985
8	2164.303	24.927	13434.036	12826.644	6	1	1	0	85.985
9	2235.804	31.744	12826.644	12353.871	10	1	1	0	89.348
10	2135.581	38.255	12353.871	12198.565	14	1	1	0	28.168
11	1912.231	44.085	12198.565	12380.026	16	1	1	0	28.645
12	1625.185	49.04	12380.026	12964.681	18	1	1	0	29.111
13	1335.525	53.111	12964.681	13898.169	19	1	1	0	29.341
14	1099.875	56.465	13898.169	13693.134	20	1	0	0	12.016
15	965.538	59.408	13693.134	13622.435	21	1	0	0	12.016
16	964.924	62.35	13622.435	13552.351	21	0	1	0	17.353
17	1108.337	65.729	13552.351	13338.833	21	0	1	0	17.353
18	1375.968	69.924	13338.833	14291.803	20	1	1	0	97.184
19	1711.786	75.143	14291.803	13397.92	17	1	0	0	57.707
20	2023.048	81.311	13397.92	13359.347	14	1	1	0	28.168
21	2187.9	87.981	13355.347	13037.636	12	1	1	0	27.681
22	2068.428	94.288	13037.636	12839.396	12	1	1	0	27.681
23	1515.486	98.908	12839.396	12140.855	11	1	1	0	14.977
24	332.356	99.921	12140.855	14570.531	10	1	1	0	14.841

Table C.12 Output variables for schedule 2, scenario F - Building A

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHumid1 Schedule	TotalCost(Rand)
1	279.422	3.601	5400	5120.578	9	0	0	0	0
2	226.489	4.292	5120.578	4894.088	9	0	0	0	0
3	285.48	4.392	4894.088	4608.609	8	0	0	0	0
4	344.47	5.442	4608.609	4869.286	8	1	0	0	5.329
5	884.144	8.138	4869.286	3985.142	8	0	0	0	0
6	1446.458	12.548	3985.142	4145.976	7	1	1	0	26.42
7	1896.299	18.329	4145.976	2811.222	6	1	0	0	30.775
8	2164.303	24.927	2811.222	1208.445	6	1	0	0	30.775
9	2235.804	31.744	1208.445	735.493	10	1	1	0	89.348
10	2135.581	38.255	735.493	580.386	14	1	1	0	28.168
11	1912.231	44.085	580.386	761.848	16	1	1	0	28.645
12	1625.185	49.04	761.848	1366.302	18	1	1	0	29.111
13	1335.525	53.111	1346.502	2279.99	19	1	1	0	29.341
14	1099.875	56.465	2279.99	3509.033	20	1	1	0	29.568
15	965.538	59.408	3509.033	4872.412	21	1	1	0	29.568
16	964.924	62.35	4872.412	3907.489	21	0	0	0	0
17	1108.337	65.729	3907.489	3693.991	21	1	0	0	12.016
18	1375.968	69.924	3693.991	3212.862	20	1	0	0	39.492
19	1711.786	75.143	3212.862	2318.979	17	0	1	0	57.213
20	2023.048	81.311	2318.979	2276.407	14	1	1	0	28.168
21	2187.9	87.981	2276.407	1958.695	12	1	1	0	27.681
22	2068.428	94.288	1958.695	1760.456	12	1	1	0	27.681
23	1515.486	98.908	1760.456	2061.114	11	1	1	0	14.977
24	332.356	99.921	2061.114	3491.591	10	1	1	0	14.841

Table C.13 Output variables for schedule 2, scenario G - Building A

C.3 Simulation schedule - Building B

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHPI Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Rand)
1	68.686	1.401	0	3341.561	15	1	1	1	34.966
2	111.927	1.701	3341.561	3430.161	14	1	1	0	13.336
3	161.575	1.841	5430.161	5268.586	14	0	0	0	0
4	211.222	2.407	5268.586	5057.364	13	0	0	0	0
5	459.949	3.64	5057.364	4997.414	12	0	0	0	0
6	700.17	5.517	4997.414	4670.979	12	1	0	0	4.989
7	869.555	7.848	4670.979	4628.064	14	1	0	0	8.106
8	942.414	10.375	4628.064	4566.679	16	0	1	0	18.681
9	923.221	12.85	4566.679	4580.362	18	0	1	0	18.789
10	835.339	15.09	4580.362	4739.289	20	1	0	0	12.933
11	709.328	16.991	4739.289	5024.227	23	1	0	0	8.924
12	574.26	18.531	5024.227	4449.967	25	0	0	0	0
13	453.354	19.746	4449.967	4990.879	26	0	1	0	13.036
14	363.105	20.72	4990.879	4627.774	27	0	0	0	0
15	313.836	21.561	4627.774	5308.204	27	1	0	0	8.924
16	309.434	22.391	5308.204	4998.77	27	0	0	0	0
17	345.235	23.316	4998.77	4653.535	27	0	0	0	0
18	404.984	24.402	4653.535	5242.817	26	1	0	0	8.924
19	459.979	25.635	5242.817	4782.839	24	0	0	0	0
20	474.583	26.908	4782.839	4308.235	22	0	0	0	0
21	420.953	28.036	4308.235	4881.569	21	1	0	0	8.924
22	299.952	28.84	4881.569	4581.617	20	0	0	0	0
23	152.724	29.25	4581.617	5394.293	19	0	1	0	8.288
24	25.445	29.318	5394.293	5368.848	18	0	0	0	0

Table C.14 Output variables for schedule A Building B

Time of day	Building per hour	CumulativePerPerson	CurrentHourVolume	NextHourVolume	AmbTemp	DynHPI Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Rand)
1	236.069	2.88	13140	12903.931	9	0	0	0	0
2	209.798	3.442	12903.931	13321.582	9	1	0	0	5.436
3	271.163	3.555	13321.582	13050.419	8	0	0	0	0
4	332.528	4.447	13050.419	13323.038	8	0	1	0	9.236
5	826.537	6.665	13323.038	12496.501	8	0	0	0	0
6	1335.057	10.242	12496.501	12768.736	7	1	1	0	26.42
7	1734.291	14.892	12768.736	11595.89	6	1	0	0	30.775
8	1963.102	20.155	11595.89	11189.698	6	1	1	0	85.985
9	2011.451	25.547	11189.698	10941.079	10	1	1	0	89.348
10	1906.035	30.657	10941.079	11015.519	14	1	1	0	28.168
11	1694.016	35.199	11015.519	11415.195	16	1	1	0	28.645
12	1430.35	39.034	11415.195	12194.684	18	1	1	0	29.111
13	1169.33	42.169	12194.684	13294.366	19	1	1	0	29.341
14	959.641	44.741	13294.366	12334.725	20	0	0	0	0
15	840.819	46.995	12334.725	12388.746	21	1	0	0	12.816
16	838.906	49.245	12388.746	12444.68	21	1	0	0	12.816
17	960.247	51.819	12444.68	12379.272	21	0	1	0	17.553
18	1184.374	54.994	12379.272	12089.737	20	0	1	0	57.692
19	1459.052	58.906	12089.737	12782.085	17	1	1	0	94.919
20	1701.716	63.668	12782.085	11824.345	14	1	0	0	10.915
21	1810.11	68.321	11824.345	11884.422	12	1	1	0	27.681
22	1679.122	72.823	11884.422	12075.489	12	1	1	0	27.681
23	1208.262	76.062	12075.489	12683.37	11	1	1	0	16.977
24	262.34	76.765	12683.37	13071.116	10	1	0	0	5.542

Table C.15 Output variables for schedule B Building B

Time of day	Building per hour	Compressive/Parasit	CurrentFlow Volume	HeatFlow Volume	AmbTemp	DynHP1 Schedule	DynHP2 Schedule	DynHeater1 Schedule	TotalCost(Rand)
1	236 040	2 88	5408	5163 931	9	0	0	0	0
2	209 798	3 442	5163 931	4954 133	9	0	0	0	0
3	271 163	3 355	4954 133	4682 97	8	0	0	0	0
4	332 528	4 447	4682 97	4350 442	8	0	0	0	0
5	826 537	6 663	4350 442	3523 905	8	0	0	0	0
6	1335 057	10 242	3523 905	2772 027	7	1	0	0	9 562
7	1734 391	14 892	2772 027	1599 182	6	1	0	0	30 773
8	1963 102	20 135	1599 182	1192 99	6	1	1	0	85 985
9	2011 451	25 347	1192 99	944 37	10	1	1	0	89 348
10	1906 035	30 637	944 37	1018 81	14	1	1	0	28 168
11	1694 016	35 199	1018 81	1418 486	16	1	1	0	28 645
12	1430 33	39 034	1418 486	2197 975	18	1	1	0	29 111
13	1168 33	42 369	2197 975	3297 637	19	1	1	0	29 341
14	999 641	44 741	3297 637	3232 856	20	1	0	0	12 016
15	840 819	46 995	3232 856	3286 876	21	1	0	0	12 016
16	838 906	49 245	3286 876	3342 81	21	0	1	0	17 553
17	940 347	51 819	3342 81	3277 403	21	0	1	0	17 553
18	1184 374	54 994	3277 403	2987 868	20	1	0	0	39 492
19	1439 032	58 906	2987 868	2346 719	17	1	0	0	37 707
20	1701 716	63 468	2346 719	2625 479	14	1	1	0	28 168
21	1810 11	68 321	2625 479	2685 556	12	1	1	0	27 681
22	1679 122	72 823	2685 556	2876 623	12	1	1	0	27 681
23	1208 262	76 062	2876 623	3484 904	11	1	1	0	14 977
24	262 34	76 765	3484 904	3872 23	10	1	0	0	5 542

Table C.16 Output variables for schedule C Building B