Rethinking electrical water heaters

by

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Abstract

South Africa is, at the time of writing, in the midst of an energy crisis as the national utility is unable to meet the nation's energy demands. Electrical water heaters (EWHs) remain one of the main contributors to residential energy consumption in South Africa and other countries where they are used. Although educational material has been published to create awareness of energy saving actions for EWHs, it is unclear if users understand the content and efficiently control their EWHs. Additionally, insufficient feedback of usage data makes it difficult for consumers to understand their consumption patterns and make informed decisions regarding their future water and electricity use. This work presents a mobile based eco-feedback system for the energy and water consumption data of residential EWHs. The system consists of several components: an EWH model; an event detection algorithm; and an Android mobile application.

The physics based EWH model was developed in order to accurately simulate the energy input and output of an EWH for various control settings, usage profiles and orientations (i.e. vertical and horizontal). The accuracy of the model is validated against six datasets, four comprising 900 hours with multiple usage events and two with only standing losses. The results show that measured energy usage is modelled with an estimation error of less than 2% and 7% for schedule control and thermostat control respectively. As well as being accurate, the presented model has a low computational complexity, taking only 100 milliseconds to complete a 10 day simulation on a standard desktop machine, making it ideal for use in mobile devices.

A novel and non-invasive hardware solution and matching algorithm were developed to support the identification and classification of warm water usage events without the use of invasive and expensive water metering technologies. The algorithm was tested using 49 days of data which included 127 usage events and was found to accurately detect usage events with an accuracy of 91%. Additionally, the algorithm was able to detect very small usage events (0.5 litres was detected successfully). However, the estimated duration of events is within 2 minutes accurate 79% of the time. Additionally, the outlet temperature and water meter data were used as inputs to the EWH model for estimating the energy consumption under various control settings. The outlet temperature data was used to estimate both the total volume of warm water consumed and the energy input for the EWH with an error of less than 10% for 3 of the 4 datasets considered.

An Android mobile application was then created to allow consumers to remotely monitor and control their EWH from their mobile device. The EWH model was implemented as part of the functionality of the mobile application to provide a user with instantaneous feedback on the impact of changes in control settings and usage profiles. For example, this functionality in the mobile application allows users to determine how switching their EWH off intermittently will affect their energy consumption. Additionally, the event detection algorithm was utilised by the mobile application to establish usage profiles and provide recommended schedules for users, based on their consumption data. Finally, a usability study was conducted in order to evaluate the ease with which users are able to utilise the mobile application and to improve on any areas of difficulty that may exist. Several areas of difficulty were determined and these results were used to implement various changes to improve the application by making it more user friendly. The results of the study indicate that the system is user friendly and that participants had a positive overall experience with the mobile application.

Uittreksel

Suid-Afrika is, tydens finalisering van hierdie manuskrip, in die middel van 'n energiekrisis, aangesien die nasionale voorsiening nie in staat is om aan die energie behoeftes van die land te voldoen nie. Elektriese warmwatersilinders (EWs) bly een van die grootste bydraers tot residensiële energieverbruik in Suid-Afrika asook ander lande waar dit gebruik word. Alhoewel opvoedkundige materiaal al gepubliseer is om bewustheid van energiebesparende maatreels vir EWs te skep, is dit onduidelik of gebruikers die inhoud verstaan en hul EWs effektief beheer. Onvoldoende terugvoer van die gebruiksinligting maak dit ook moeilik vir verbruikers om hul verbruikspatrone te verstaan en ingeligte besluite te neem oor hul toekoemstige water en elektrisiteit verbruik. Hierdie werkstuk bied 'n selfoon-gebaseerde eko-terugvoerstelsel aan vir die energie en water verbruik data van residensiële EWs. Die stelsel bestaan uit verskeie komponente: 'n termiese EW model; 'n gebeurteniswaarnemingsalgoritme; en 'n Android mobiele toepassing.

Die fisika gebaseerde EW model is ontwikkel om die energie toevoer en afvoer van 'n EW vir verskeie beheerverstellings, gebruiksprofiele en EW oriëntasies akkuraat te simuleer. Die akkuraatheid van die model is bevestig met ses datastelle, vier wat 900 ure van verskeie gebeurtenise behels, en twee met slegs staande verliese. Die resultate toon aan dat gemete energieverbruik lewer met 'n beraamde fout van minder as 2% en 7% vir skedule beheer en termostaat beheer onderskeidelik. Sowel as 'n hoë akkuraatheid, het die model 'n lae berekenings-kompleksiteit en neem slegs 100 millisekondes om 'n 10 dag simulasie te voltooi op 'n standaard rekenaar, wat dit ideaal maak vir gebruik met mobiele toestelle.

'n Unieke en nie-indringende hardeware oplossing en 'n bypassende algoritme is ontwikkel wat die identifisering en klassifisering van warm water verbruiksgebeurtenise ondersteun sonder die gebruik van versteurende installasies en duur watermeting tegnologie. Die algoritme is getoets met 49 dae se data wat 127 gebruiksgebeurtenisse behels, en dit was bevind dat die algoritme gebeurtenise akkuraat kan waarneem met 'n akkuraatheid van 91%. Verder het die algoritme klein gebruiksgebeurtenise waargeneem (0.5 liter is suksesvol waargeneem). Tog is die duurteskattings van gebeurtenise binne 2 minute akkuraat 79% van die tyd. Daarna is die uitlaattemperatuur en water meter data gebruik as insette tot die EW model vir die beraming van die energieverbruik onder verskillende beheerverstellings. Die uitlaattemperatuur was gebruik om die totale volume warm water verbruik en energie-inset te skat met 'n fout van minder as 10% vir 3 van die 4 datastelle wat beskou was.

'n Android mobiele toepassing is geskep om verbruikers afstand monitering en beheer van hul EW te gee deur 'n mobiele toestel. Die EW model is as deel van die funksionaliteit van die mobiele toepassing geïmplementeer om 'n verbruiker van oombliklike terugvoer aangaande die impak van veranderinge in beheer verstellings en gebruiks profiele te voorsien. Byvoorbeeld, verbruikers kan bepaal hoe die tussenpose afskakel van hul EWs hul energieverbruik beïnvloed. Die gebeurteniswaarnemingsalgoritme is daarbenewens deur die mobiele toepassing gebruik om gebruiksprofiele te bepaal en skedules vir gebruikers aan te bevel op grond van hul verbruiks data. Ten slotte, is ’n bruikbaarheids studie uitegevoer om te bepaal hoe maklik gebruikers die gebruik van die mobiele toepassing vind om te gebruik om sodoende enige probleme wat mag bestaan te verbeter. Verskeie probleme is geidentifiseer en die resultate is aangewend om verskeie veranderinge aan te bring om die toepassing meer gebruikersvriendelikheid te maak. Die resultate van die studie dui daarop dat die stelsel wel gebruikersvriendelik is en dat in die geheel deelnemers se ervaring met die mobiele toepassing ’n positiewe een was.

Patents and Publications

The work in this manuscript has been published as follows:

- P.J.C. Nel, M.J. Booysen, B. van der Merwe, "ICT-enabled solutions for smart management of water supply in Africa", UMICTA, December 2014, Stellenbosch, South Africa.
- P.J.C. Nel, M.J. Booysen, B. van der Merwe, "Using thermal transients at the outlet of electrical water heaters to recognise consumption patterns for heating schedule optimisation", IFIP/IEEE NTMS , July 2015, Paris, France.
- Accepted for publication: P.J.C. Nel, M.J. Booysen, B. van der Merwe, "Electric water heater energy consumption determination using outlet temperature and volumetric estimation", IEEE CIASG, December 2015, Cape Town, South Africa.

Additionally, the work in this manuscript has been submitted for publication as follows:

- P.J.C. Nel, M.J. Booysen, B. van der Merwe, "A computationally inexpensive energy model for horizontal electrical water heaters with scheduling" submitted to IEEE Transactions on Smart Grid, revise and resubmit.
- P.J.C. Nel, M.J. Booysen, B. van der Merwe, "Smart metering and ICT support for water supply and infrastructure management in Sub-Saharan Africa" submitted to Water SA.

Finally, the work in this manuscript has been patented as follows:

- P.J.C. Nel, M.J. Booysen, B. van der Merwe, "Geyser Event Detection", Provisional Patent Application No. 2015/03775, 27 May 2015.
- P.J.C. Nel, M.J. Booysen, B. van der Merwe, "A Water Heater Controller", Provisional Patent Application No. 2015/04029, 3 June 2015.

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Contents

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Nomenclature

Acronyms and Abbreviations

°C	Degrees Celsius
ADT	Android Development Tools
API	Application programming interface
AUS	Australian
CO_2	Carbon Dioxide
CoT	Completed on time
DoE	Department of Energy
DR	Demand response
DSM	Demand side management
ETC	Estimated time to complete
ETSI	European Telecommunications Standards Institute
EWH	Electrical water heater
FIFO	First in first out
GHz	Gigahertz
GNI	Gross national income
GSM	Global System for Mobile Communications
HH	Household
HTTP	Hypertext Transfer Protocol
HVAC	Heating, ventilation and air conditioning
ICT	Information and communication technologies
IDE	Integrated development environment
ID	Identifier
IHD	In-home display
IMEI	International Mobile Station Equipment Identify
JSON	Javascript Object Notation
kB	kilobytes
kWh	kiloWatt-hour
kW	kiloWatt
K	Kelvin
M2M	Machine-to-machine
NERSA	National Energy Regulator of South Africa
OS	Operating system

PDE	Partial differential equation
QLD	Queensland
RAM	Random access memory
REST	Representational State Transfer
RTP	Real time pricing
SANEDI	South African Energy Development Institute
SANS	South African National Standard
SASGI	South African Smart Grid Initiative
SMS	Short messaging service
SSA	Sub-Saharan Africa
SUS	System usability scale
SWH	Solar water heater
ToT	Time on task
TOU	Time-of-use
ttl	time-to-live
UI	User interface
URL	Uniform resource locator
USA	United States of America
Wi-Fi	Wireless Fidelity
XML	Extensible markup language

Constants

$c_{p(copper)} = 385 \ \frac{J}{kg \cdot K}$
$c_{p(water)} = 4180 \ \frac{J}{kg \cdot K}$
$\rho_{Cu} = 8740 \ \frac{kg}{m^3}$
$\rho_{H_2O} = 1000 \ \frac{kg}{m^3}$

List of symbols used

A	Surface area for convection	m^2
A_{cond}	Contact surface area between nodes	m^2
$A_{cylinder}$	Surface area of EWH tank	m^2
$A_{exposed}$	Exposed surface area for given node	m^2
$A_{isosceles}$	Surface area of isosceles triangle	m^2
$A_{rectangle}$	Surface area of rectangle	m^2
A_{sector}	Surface area of circular sector	m^2
$A_{segment}$	Surface area of circular segment	m^2
c	Chord length	m
c	Specific heat capacity of material under consideration	$\frac{J}{kg \cdot K}$
d	Thermocline thickness	m
d_i	Inner diameter of outlet pipe	m
d_o	Outer diameter of outlet pipe	m
E_{cond}	Internodal energy transfer	kWh
E_{heat}	Energy required to heat entire contents of EWH tank	kWh
E_{hot}	Energy in the remaining hot water inside the EWH tank after usage event	kWh
E_{inside}	Energy inside EWH tank	kWh
E_{input}	Energy input by EWH element	kWh
E_{loss}	Maximum allowable standing losses over a 24 hour period, as stipulated by SANS 151,	kWh
$E_{loss(node)}$	Standing losses for node under consideration	kWh
E_{total}	Total energy contained in usage event	kWh
E_{usage}	Energy consumed by usage event	kWh
E_{warm}	Energy contained in warm water of usage event	kWh
e_η	Efficiency of EWH element	%
Δe	Observed change in error	%
G	Thermal conductance	$\frac{J}{m^2 \cdot °C}$
G_{node}	Thermal conductance of node under consideration	$\frac{W}{m^2 \cdot °C}$
h	Heat transfer coefficient	$\frac{W}{m^2 \cdot °C}$
k	Thermal conductivity of water	$\frac{W}{m \cdot K}$
L	Length of body under consideration	m
m_{tank}	Mass of water in EWH tank	kg
m_{total}	Total mass of water consumed by usage event	kg
m_{usage}	Mass of warm water consumed by usage event	kg
m_{warm}	Mass of warm water consumed by typical usage events	kg
P_{rated}	Power rating of EWH element	W
R	Thermal resistance	$\frac{°C \cdot day}{kWh}$

R_{node}	Thermal resistance of node under consideration	$\frac{°C\cdot day}{kWh}$
$R_{outside}$	Thermal resistance between outer pipe wall and surrounding environment	$\frac{°C\cdot day}{kWh}$
$R_{thermocline}$	Thermal resistance of thermocline	$\frac{K}{W}$
R_{wall}	Thermal resistance between inner and outer surfaces of the pipe	$\frac{°C\cdot day}{kWh}$
R_{water}	Thermal resistance between water inside the pipe and the inner pipe wall	$\frac{°C\cdot day}{kWh}$
r	Typical radius of EWH tank	m
s	Arc length of the circular sector	m
ΔT	Temperature difference	°C
$T_{adjusted}$	Adjusted temperature of specific end use of water	°C
T_{after}	Average temperature of water in EWH tank after occurrence of usage event	°C
$T_{ambient}$	Temperature of outside environment of EWH	°C
T_{before}	Average temperature of water in EWH tank before occurrence of usage event	°C
$T_{deadband}$	Thermostat deadband	°C
T_{inlet}	Temperature of the water entering the EWH tank from inlet pipe	°C
T_{inside}	Average temperature of water in EWH tank	°C
T_{lower}	Average temperature of water in lower node	°C
T_{node}	Average temperature of water in node under consideration	°C
T_{pipe}	Average temperature of outlet pipe system	°C
T_{set}	Set temperature of EWH	°C
T_{upper}	Average temperature of water in upper node	°C
$T_{typical}$	Typical temperature of specific end use of water	°C
T_{∞}	Ambient temperature of EWH surroundings	°C
$V_{adjusted}$	Adjusted volume of specific end use of water	litres
V_{hot}	Volume of the unused hot water remaining inside EWH tank after usage event	litres
V_{lower}	Volume of water in lower node	litres
V_{node}	Volume of water in node under consideration	litres
V_{tank}	Volume of water in EWH tank	litres
$V_{threshold}$	Threshold volume for two-node state transition	litres
$V_{typical}$	Typical volume of specific end use of water	litres
V_{upper}	Volume of water in upper node	litres
V_{usage}	Volume of water consumed by usage event	litres
$\dot{V}_{adjusted}$	Adjusted flow rate of specific end use of water	$\frac{litres}{min}$
$\dot{V}_{typical}$	Typical flow rate of specific end use of water	$\frac{litres}{min}$
Δx	Increment in variable under consideration	%
θ	Central angle of circular sector	radians
θ_n	n_{th} estimation of central angle	radians

Chapter 1

Introduction

1.1 Energy and water utility industries

Both global energy and water resources are under pressure due to growing demand as a result of increasing population size and rapid urbanisation, especially in developing regions [1]. For example, South Africa is, at the time of writing, in the midst of an energy crisis as the national utility is unable to meet the nation's energy demands. Additionally, many regions of Australia, especially South-East Queensland, are experiencing prolonged drought that threatens the sustainability of their potable water supply [2]. Furthermore, global water demand is projected to increase by 55% by 2050, with domestic consumption expected to increase by 130% [1]. Additionally, global electricity demand is expected to grow by 70% by 2035 [1]. In the industrial and agricultural sector, more efficient technology can lead to a decrease in the per unit consumption of production. However, this decrease typically leads to increased production, and there is, consequently, no net decrease in demand [1]. Therefore, in an effort to meet the present utility demand, many utilities are targeting residential consumers of water and electricity in an attempt to reduce their usage.

The management of the infrastructure assets to ensure adequate supply for service provision is a complex challenge faced by water and electricity service providers (i.e. utilities). Although the structure of their infrastructure may differ, these industries share challenges that can be addressed in similar means. The management of water and energy resources and supply is multifaceted as it is affected by numerous factors, including economical, health and environmental issues [1; 3], which can often be in conflict with one another. For example, providing reliable and safe water to the unserved population in developing countries provides economical and health benefits but it must be balanced with preserving biodiversity in these environments [1; 4]. Therefore a collaborative approach is required for the effective management of water and energy resources that incorporates all the stakeholders of the utility industry, including consumers, as all of them are affected by the benefits provided through electricity and water [1].

1.2 Eco-feedback technology

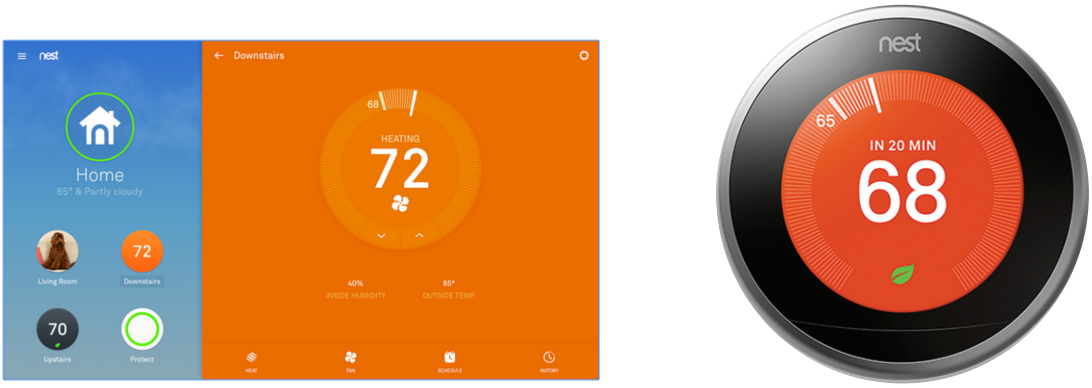
Insufficient feedback of usage data makes it difficult for consumers to understand their consumption patterns and make informed decisions regarding their future water and electricity use. Since monthly bills only detail cumulative monthly consumption, consumers have no way of linking particular activities to high resource usage. Moreover, the delivery of bills is not usually immediate, further delaying the feedback. Consumers are therefore not able to intelligently reduce their consumption using existing metering and billing.

Eco-feedback technology aims to improve consumers' awareness of the environmental impact of their daily actions and behaviours [5]. This is based on the assumption that consumers generally have a lack of knowledge or understanding of the environmental impacts of the various actions they perform on a daily basis (e.g. taking a shower) [5]. Eco-feedback technologies are used to monitor consumers' behaviour and provide them with useful information that can aid in understanding the impact of specific actions. This feedback can be implemented in a variety of methods. Ambient information display can be provided through dedicated in-home display (IHD) modules or other visual display devices placed in centralised and visible locations [6]. An example of an ambient feedback system for energy consumption is the Power-Aware Cord, which is a power cord that contains electroluminescent wires that illuminate when alternating current is passed through them [7]. The brightness of the wires varies according to the amount of current that flows through them, allowing users to become more aware of how and when they are using electricity. Alternatively, web-based applications can be used to relay information to consumers. For example, E2Home [8] provides an online interactive visualisation of electricity consumption and resident's location, therefore indicating usage patterns for consumers even when they are not actively using power at their home. Additionally, smartphone applications can provide users with convenient and mobile access to consumption data. For example, Sawacae [9] allows users to view their short or long term utility usage statistics on an Android device. However, the feedback and functionality provided by eco-feedback technology requires data with a high temporal resolution. Smart metering technology can be used to obtain the fine-grained data required to implement these applications.

1.3 Smart grids and enabling technologies

Smart meter devices allow utility service suppliers to obtain more detailed usage data from consumers at a more regular interval than possible with conventional metering solutions. This implies that service suppliers are able to make more informed decisions regarding demand management and are able to better monitor usage patterns. Other advantages of smart metering for suppliers include: remote monitoring of infrastructure assets [10]; and remote reading of meters [11], therefore eliminating the need for manual meter reading. Smart metering can also offer several benefits to consumers by leveraging eco-feedback technologies to provide additional insight into usage and to increase awareness of the impacts of specific activities.

The mobile industry will play a crucial role in enabling the functionality required by smart metering applications, such as advanced control and feedback of high resolution usage data. The global unique subscriber penetration rate was 50% at the end of 2014, which implies that approximately half of the global population has at least one mobile subscription. Additionally, Global System for Mobile Communications (GSM) coverage is estimated to reach 84% of the population in developing countries [12] and has outgrown access to reliable and affordable electricity and water services in sub-Saharan Africa (SSA) over the past 10 years [13]. The rapid growth of mobile network coverage is providing millions of people with first time access to modern infrastructure services. For example, 130 million people in SSA are covered by mobile networks but do not have access to an improved water source [13]. Furthermore, smartphones are becoming increasingly ubiquitous, comprising 37% of global mobile connections at the end of 2014 and expected



(a) Nest mobile application screenshot.

(b) Intelligent thermostat device.

Figure 1.1: (a) Nest Android application screenshot [15] and (b) intelligent thermostat device [16] by Nest Labs.

to increase to 65% by 2020 [14]. Although the penetration of smartphones in developing regions is lower, the price of handsets is rapidly decreasing and their adoption rate is expected to reach 63% in these regions by 2020 [14]. The ubiquity of smartphones makes them ideal for providing consumers with an interface for monitoring and controlling their household appliances.

A good example of the solutions that can be created by combining eco-feedback, mobile, smart metering technology is the Nest Learning Thermostat [16], created by Nest Labs and acquired by Google in 2014. This device leverages all of these technologies to create a unique solution that can aid consumers in reducing the energy cost of space heating and cooling by up to 12 and 15%, respectively [17]. Nest connects the households' thermostat to a home Wi-Fi network that allows the temperature to be controlled from a mobile phone (shown in Figure 1.1a), tablet or laptop. This thermostat also implements intelligence that is able to learn consumers' usage patterns and auto-schedules the temperature that is implemented after a week of monitoring. Nest can detect when users are away from home and will automatically turn the temperature control off to save energy. Additionally, a green leaf is displayed to users, shown in Figure 1.1, when they select a temperature that reduces their energy consumption, helping consumers to save energy. Additionally, other products, such as smoke detectors and lighting, can be interfaced to the Nest system for various home automation applications.

1.4 Demand side management and demand response

Electricity and water grids in many developing countries are struggling to meet the ever increasing demands [1]. Typically, utilities have focused on supply side management in the past, which involves the construction of additional infrastructure assets to increase generation capacity. However, with the advent of smart grid technologies, utilities are shifting their focus to demand side management (DSM). DSM aims to change the shape of the load curve (e.g. valley filling and peak shaving) through activities that intentionally modify consumer usage patterns [18], allowing for the deferral of costly infrastructure development [19]. The concept of DSM is by no means new. Ripple controllers allow direct control of consumer appliances that consume large amounts of energy [18]. This type of control can be considered as DSM and the first installations of these devices date as far back as 1928, when they were used to control public lighting in Paris, France [20].

However, smart metering is allowing for enhanced communication between appliances, consumers and utilities to allow for more advanced load management schemes. For example, smart metering devices allow for the implementation of time-of-use (TOU) tariffs in the electricity industry [18]. These TOU tariffs generally consists of peak and off-peak prices for resource consumption with the aim of influencing consumers usage through the financial incentive of discounted rates.

DSM load control techniques can be classified into two broad categories based on the the entity that is responsible for the control decisions. Direct (or centralised) load control refers to the remote control of customer appliances (e.g. water heaters) by a utility for the purposes of peak demand reduction or emergency situation handling [18]. Indirect (or decentralised) load control includes the involvement of consumers and provides them with the choice to participate in load reduction efforts. Customers are incentivised (e.g. TOU tariffs) to reduce their usage, especially during peak periods, or shift their demand to off-peak periods, often referred to as demand response (DR) [21; 22].

Residential electrical water heaters (EWHs) are commonly used to heat water for household consumption in developing countries where gas is not readily available. EWHs are opportune appliances for DR due to their ability to store thermal energy for prolonged periods of time without significant heat loss [23]. Appliances capable of storing energy, such as electric water heaters (EWHs), are ideal candidates for intelligent control as they provide the most flexibility in terms of their scheduling capabilities. Part of the energy consumed by EWHs is to replenish heat dissipated to the environment. This type of energy is referred to as standing losses, and could be as much as 20% of the EWH's consumption. These standing losses can be virtually eliminated with the use of a timer control unit and, if controlled correctly, these appliances are still able to provide warm water to meet household demand [24].

If customers are expected to participate actively in load management efforts, DR programs should increase consumers' understanding of the benefits of participation and improve their capability to participate [22]. However, in order to provide this type of feedback to consumers, an accurate water usage profile is essential to coordinate the switching times of their EWHs [25]. This is because consumer usage patterns vary between users, seasonally, and between regions. For example, in South Africa, it was found that warm water consumption increased by up to 70% from summer to winter [26] and that low-income households consumed up to four times more warm water than high-income households [26]. If generic assumptions are made about these patterns of use, they may be inaccurate and result in consumption being adversely affected. For example, ineffective switching of consumers' EWHs can result in a lack of warm water availability which inconveniences users. An obvious way to detect warm water consumption patterns is to use water flow meters. However, they are expensive (around $50 per standards-approved device) and their installation is invasive and labour-intensive.

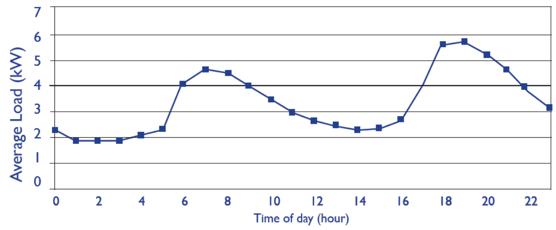
1.5 Synposis of electricity saving initiatives in South Africa

South Africa has a population of 54 million people and an electrification rate in the vicinity of 83 to 90% [27] (varies between national surveys and census). The national power utility, Eskom, is responsible for 95% of electricity supply in South Africa, of which 90% is generated in coal-fired power stations [28]. South Africa is, at the time of writing, battling with an energy crisis as the national utility is unable to meet national energy demands. However, this is not the first time the country has faced an electricity shortage. The start of 2008 saw the implementation of rolling blackouts (i.e. load shedding) across the country, which have subsequently returned. These blackouts typically last 2 to 4 hours and are implemented at different times according to the pressure on the grid and the area in which they occur. Additionally, these blackouts can be implemented during business hours, which has a devastating effect on the country's economy, with a predicted cost of R89 billion (US$ 7.2 billion) per month to the private sector due to lost production, revenue and wastage [29].

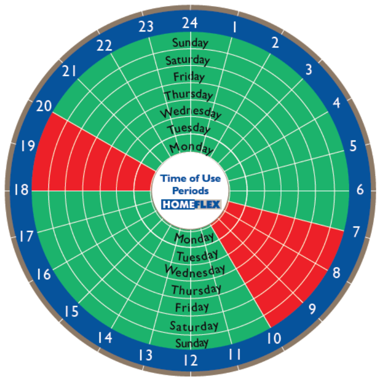
Since the beginning of the energy crisis in 2008, the government and Eskom have implemented various programmes to reduce the pressure on the national grid by promoting energy efficiency. The first of these initiatives is the Power Alert system which displays public messages on national television that are used to inform homeowners of the status of the national electrical grid due to the present demand [30]. Additionally, users may also view forecasts of the national electrical demand for the current day in half hour intervals. These messages are divided into four colour-coded alert states (green, orange, red and black) which indicate the increasing severity of the load on the national grid. Each message also presents suggestions on which appliances to switch off during the present state. For example in the red state (second most severe) users are instructed to switch off lights in all unoccupied rooms as well as their electric water heaters (EWH), pool pumps, air conditioners, dishwashers, tumble dryers and stoves.

Eskom has also released educational material, including several brochures, savings tips and videos, relating to energy conservation practices for commercial and residential customers [31]. Since EWHs are one of most energy-intensive appliances in households, this material includes several means of reducing the energy consumption of EWHs. For example, the EWH fact sheet published by Eskom suggests lowering the set temperature of the EWH, resulting in a reduction in the standing losses. Eskom also produced educational videos that encourage users to switch their EWH off during peak hours (5 pm to 9 pm). Although this may have no net effect on the overall usage of the EWH, it reduces the peak demand on the national grid. Other proposed methods of reducing warm water energy consumption include: insulating the EWH tank and pipes to increase its thermal resistance; and the use of a solar water heater (SWH), which may not reduce users' energy consumption, but can reduce the pressure on the electrical grid as energy is obtained from an alternative source.

The SWH rebate programme is a joint effort from the South African Department of Energy (DoE), Eskom and the National Energy Regulator of South Africa (NERSA) and is aimed at promoting the use of alternative energy. Initially, Eskom subsidised the purchase of SWHs to incentivise households to heat water using solar power. The programme aimed to install one million SWHs by 2013 but only between 400 000 and 420 000 installations have been subsidised to date [32; 33]. Although the program fell short of its ambitious target, it has still been successful in reducing national demand and providing warm water to communities who are not on the grid. However, Eskom has since withdrawn from the programme and it is presently being managed by the DoE, which suspended the programme due to numerous inefficiencies (e.g. poor quality of installations, lack of verification of number of installations). Additionally, the overall penetration of the SWH technology is still severely limited. A recent national household survey consisting of 2,518 participants conducted by the DoE indicated that only 1% of surveyed households had a SWH installed [27], indicating that the number of installations may be significantly lower than the reported estimates.



(a) Average residential load curve for South Africa.



(b) Homeflex tariff structure.

Figure 1.2: (a) Average residential load curve for South Africa and (b) proposed Homeflex TOU tariff structure designed by Eskom [35].

Interest in smart grids has been demonstrated by the establishment of the South African Smart Grid Initiative (SASGI) under the South African Energy Development Institute (SANEDI). SASGI was created with the purpose of assisting in the development of the South African smart grid and providing inputs and direction for related policies. South African municipalities are already in the process of conducting smart grid related pilot projects [34]. The City of Johannesburg and its power utility, City Power, are presently implementing a smart metering pilot project in certain suburbs which is aimed at reducing the effect of load shedding on its customers (residential, businesses and industry). Requests are sent to consumers, prompting them to reduce their usage to a specified limit, using messages sent via short messaging service (SMS) as well as the smart meter's in house display (IHD) unit. Since the IHD displays their present consumption, customers are able to disconnect appliances (e.g. stove, EWH) until their consumption is below the specified limit. If consumers fail to comply they will experience a 30 second power cut, followed by 30 seconds of power provision in which to reduce their usage. This process is repeated five times or until the user complies with the request. If consumption is still above the given limit after the fifth iteration, a 30 minute power outage is implemented. After this 30 minute period has expired the process is repeated until the user complies or load shedding is suspended. A total of 65 000 households were equipped with the smart meters necessary to implement this scheme in April of 2015 and this number is expected to reach 150 000 by October 2015 [34].

Finally, Eskom has designed a TOU tariff, called Homeflex [35], that consists of peak and off-peak electricity rates for various times of the day. The average residential electrical load curve for South Africa is shown in Figure 1.2a. From this load curve, there are two clear peaks in the residential demand at 07:00 and 18:00. In order to reduce the amount of electricity consumers use during these times, Eskom has proposed the tariff structure shown in Figure 1.2b. The timeslots highlighted in red indicate peak periods, when electricity will be more expensive and coincide with the peaks seen in the load curve. The energy charges suggested by Eskom indicate that consumers can expect to pay 50 and 300 % more in peak periods than in off-peak periods in summer and winter, respectively. The higher tariff increase in winter is as a result of the high demand during this season. Additionally, consumers can nominate high consumption appliances (i.e. EWH, swimming pool pump, underfloor heating and air conditioners) to be switched off during peak periods. Nominated appliances are automatically disconnected using an Appliance Control Device, which is essentially a switch that responds to control signals that it receives from a master station (managed by Eskom). Devices not eligible for nomination must be controlled manually by consumers. Initially, this tariff will be implemented on a voluntary basis for 10 000 residential customers in households that are equipped with smart meters.

It is estimated that there are over 5.4 million EWHs in South Africa and it is the main source of warm water for bathing purposes in 44% of formal urban households [27]. The heating of sanitary water, which consumes both energy and water, in South African commercial and residential buildings remains one of the largest contributors to the national electricity grid demand peaks [36]. It is responsible for 7% of the country's total demand, and 20% of the residential demand [37]. However, during peak hours, it constitutes between 30% and 50% [38]. These characteristics are not unique to South Africa, as warm water consumption is the second largest overall energy use activity in the residential sector in the USA (second to space heating) [36]. Also, residential usage of water constitutes two thirds of the total water consumption in Gold Coast, Australia [39].

1.6 Dissertation statements and hypotheses

Dissertation statement 1:
The energy consumption of a residential EWH can be determined using a thermodynamic model and a warm water usage profile.

A thermodynamic model of a residential EWH is developed that is able to determine the energy consumption of the appliance to within considerable accuracy. Additionally, the model is able to accommodate the EWH in a horizontal orientation.

Hypothesis 1.1:
The energy input by the EWH element can be determined by estimating the temperature of the water in the EWH tank.

Hypothesis 1.2:
The energy lost due to usage events and standing losses can be estimated by simplifying the temperature distribution of the water in the EWH tank into one or two components (i.e. nodes).

Hypothesis 1.3:
The energy input and output of an EWH can be accurately modelled for various control settings, usage profiles and orientations.

Hypothesis 1.4:
The impact of various energy saving actions (e.g. installing a thermal blanket on EWH) and control settings for several typical usage profiles can be estimated using the EWH model to simulate these conditions.

Dissertation statement 2:
A warm water usage profile for a residential EWH can be established using a temperature sensor on the outlet pipe of the EWH, as a cheaper alternative to a water meter.

An algorithm is developed for detecting when consumers are using warm water by monitoring the thermal transients that occur at the outlet pipe of the EWH with a temperature sensor. The approach uses temperature fluctuations apparent on the outlet pipe of an EWH to identify the start and end times of usage events. The approach is intended to be used as the sensing mechanism of an schedule control scheme for EWHs, in which heating schedules are created to meet usage patterns while saving energy and costs.

Hypothesis 2.1:
The time at which usage events occur can be determined with considerable accuracy using the outlet pipe temperature.

Hypothesis 2.2:
The start and end times of usage events can be estimated with reasonable accuracy in order to provide an estimate of the duration of events.

Hypothesis 2.3:
The volume of warm water consumed by usage events can be estimated using typical flow rates of specific end uses of warm water.

Dissertation statement 3:
A smartphone application can be used to allow users to remotely monitor and control their EWH in an intuitive and seamless manner.

An Android smartphone application is developed to allow users to monitor and control their EWH. This application implements the EWH model and event detection algorithm to provide functionality that will increase users' understanding of their EWH and allow them to control it more efficiently.

Hypothesis 3.1:
The smartphone application provides a convenient and user friendly interface for users to monitor and control their otherwise obscured EWH.

Hypothesis 3.2:
The application can utilise a model of a residential EWH to provide instantaneous feedback on the impact of control decisions.

Hypothesis 3.3:
The application can utilise a warm water usage profile to help consumers control their EWH more efficiently.

1.7 Research objectives

The following research objectives were defined in order to investigate the aforementioned hypotheses:
Research objective 1:
To develop an efficient and accurate thermodynamic model that can be used to simulate the energy usage of a residential EWH in a desktop or mobile environment.

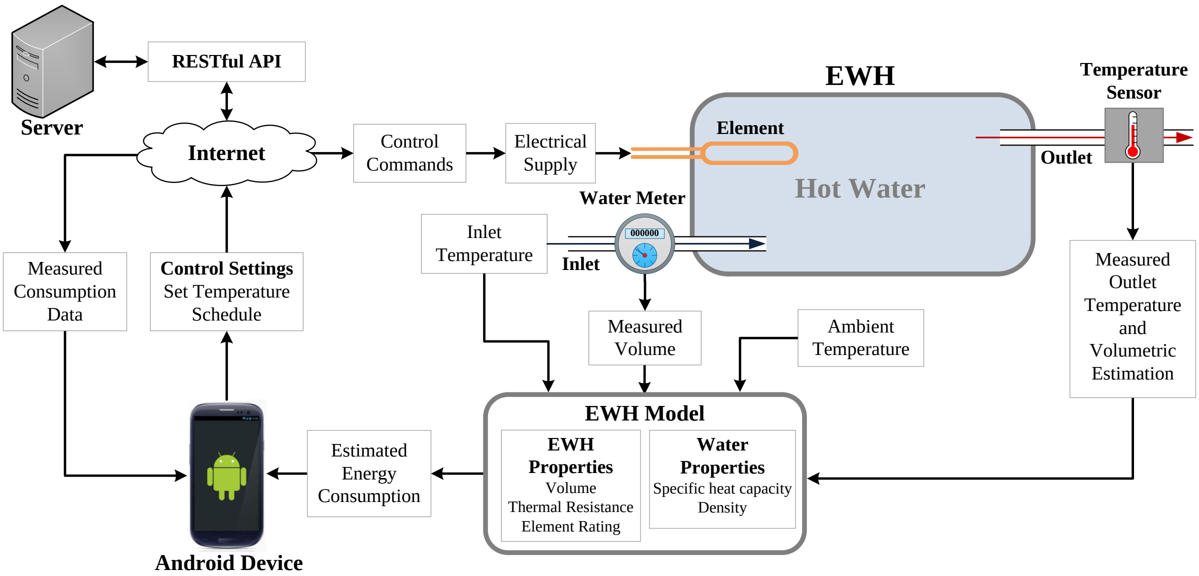


Figure 1.3: Diagram of system inputs and feedback.

Research objective 2:
To simulate and investigate the impact of various energy saving actions, control settings and seasonal variations on the energy consumption of a residential EWH.

Research objective 3:
To develop an algorithm that uses only the outlet temperature of a residential EWH to detect when warm water is consumed as well as estimate the volume and duration of detected usage events.

Research objective 4:
To develop and evaluate a user friendly Android smartphone application that allows users to easily control and monitor the energy and water consumption of their EWH from a mobile device.

1.8 Scope of work

This dissertation presents a mobile based eco-feedback solution for the energy and water consumption data of residential EWHs. Several tools were created to aid consumers in understanding their energy and warm water consumption as well as efficiently control their EWHs. A diagram of the system inputs and feedback are shown in Figure 1.3.

Firstly, a model of an EWH is developed in order to accurately simulate the behaviour of the EWH for various control settings. Secondly, an event detection algorithm is created that is able to detect when users consume warm water using only the outlet temperature of the EWH. This algorithm can be used to establish an accurate usage profile for users that can be used to co-ordinate the on/off control schedule in order to reduce the energy consumption of the EWH. The accuracies of the model and event detection algorithm are validated using actual household usage from a residential EWH. An Android mobile application is then created to allow consumers to remotely monitor and control their EWH from their mobile device. The model is implemented as part of the functionality of the mobile application to provide a user with instantaneous feedback on the impact of changes in control settings. For example, users can determine how switching their EWH off intermittently will affect their energy consumption. Additionally, the event detection algorithm is utilised by the mobile application to establish usage profiles and provide recommended schedules for users, based on their consumption data. Finally, a usability study is conducted in order to examine the ease with which users are able to utilise the mobile application and to improve on any areas of difficulty that may exist.

1.9 Contributions

EWHs remain one of the main contributors to residential energy consumption in South Africa and other countries where they are used. Although educational material has been published to create awareness of energy saving actions for EWHs, it is unclear if users understand the content and efficiently control their EWHs. A mobile based eco-feedback system is developed for the energy and water consumption data of residential EWHs. The system consists of several components: an EWH model; an event detection algorithm; and an Android mobile application.

The EWH model developed is able to simulate the energy input and output of a residential EWH for various settings, usage profiles and orientations. Additionally, it was validated using over 900 hours of actual household data and found to be accurately able to simulate the energy consumption of the appliance. Also, it had a low computational complexity, making it ideal for use in a mobile devices which typically have limited computational and battery power.

The event detection algorithm developed presents a non-invasive approach for establishing a warm water usage profile by monitoring thermal transients on the outlet. The algorithm is effective at estimating the time at which events occur and has limited accuracy in determining the duration. Also, volumetric estimation was used to estimate the amount of water that was consumed for usage events and yielding promising results that can be further investigated.

The Android mobile application developed implements both the model and algorithm presented in this research. This allows the mobile application to provide instantaneous feedback of the impact of control decisions on users' energy usage and help them to control their EWHs more efficiently by implementing recommended schedules that are generated based on their usage. A usability study was conducted to determine the ease with which users are able to utilise the mobile application. Several areas of difficulty were determined and these results were used to implement various changes to improve the application by making it more user friendly. Additionally, the results of the study indicate that the system is user friendly and that participants had a positive overall experience with the mobile application.

1.10 Dissertation structure

Chapter 2 describes the available EWH models in literature and the development of the the model used to simulate the energy consumption of a residential EWH. The accuracy of this model is validated using 6 datasets that contain actual household data and the results reported.

Chapter 3 presents the the event detection algorithm used to create a warm water usage profile using only the outlet temperature. The efficiency of the usage detection algorithm in detecting events, their duration and volume are reported.

Chapter 4 describes the Android mobile application that was developed as an implementation of the model and usage detection algorithm that provide users with a convenient interface for monitoring and controlling their EWHs. A usability study is then conducted to determine the ease with which users can accomplish various tasks and the results reported.

Chapter 5 concludes the work by validating the hypotheses from Chapter 1 using the results presented in Chapters 2 to 4. The main findings and contributions of the work in this dissertation are provided.

Chapter 2

EWH model

EWHs remain one of the main contributors to residential energy consumption in countries where they are used. EWH models serve as a step towards achieving optimised control, and can also be used to inform users of expected savings due to changes in control settings, if the model is energy-based. A suitable EWH model and warm water usage profile can be used to determine an accurate estimate of the overall energy usage of the EWH during the course of a day. These estimates could then be used by an eco-feedback application (e.g. IHD or smartphone) to provide users with instantaneous feedback on the effect of various control settings (e.g. decreasing set temperature) on the energy consumption of their EWH. However, for this to be accomplished, an accurate and simple EWH model is required. This section presents a theoretical simulation model of a residential EWH for: analysis of the thermal profile of the water inside the EWH tank; calculating the standing losses of the EWH, independent of its orientation; and simulating the effect of implementing a schedule that controls the on and off times of the EWH. The accuracy of the model is validated against six datasets (four comprising 900 hours with multiple usage events and two with only standing losses) and the results reported. The model is then used to simulate the impact of various energy savings actions (e.g. installation of a thermal blanket) in order to determine their impact on the energy consumption of the EWH.

2.1 Modelling of EWHs

An EWH consumes electricity to produce warm water and can therefore be classified as a heating system. Heating, ventilation, and air conditioning (HVAC) system models can generally be classified under three different types: data driven (black box or inverse); physics based (white box or forward); and grey box models, which are composed of a combination of physics based and data driven methods [40]. Data driven models (also referred to as black box or inverse) collect system performance data under typical use or for specific test cases [40]. The relationship between the input and output variables of the system is determined using various mathematical techniques including: frequency domain models with dead time; and data mining algorithms. Physics based models are based on the detailed knowledge of the process and its underlying physical principles [40]. These models are typically created using a thermal equivalent circuit or network where thermal resistivity and thermal capacitance are represented by resistors and capacitors, respectively, while heat and temperature are represented using current and voltage, respectively. The thermal equivalent circuit can then be used to derive time-domain differential equations to describe the behaviour of the system. Grey box models use physics based models to create their basic structure and then apply parameter estimation algorithms to measured system data to determine the parameters values [40]. Both data driven and grey-box models require measured data for parameter identification. However, it is not possible to obtain measurement data for the temperature distribution of an EWH tank that is both accurate and non-invasive, especially if it is horizontally orientated. A physics based model, on the other hand, requires only a detailed knowledge of the underlying process and was therefore used in the development of the model presented in this chapter.

2.1.1 Physics based models of EWHs

Dolan et al [41] presents an EWH model for use in the modelling of aggregate residential EWH loads. Their one-node model simulates the average thermal response of the water in the EWH tank using a single first-order differential equation. Assuming a uniform temperature distribution for the water in the tank accurately models the behaviour of the EWH in the absence of usage events [42]. However, when usage events occur, the cold water entering the tank causes thermal stratification of the water to occur, separating the higher density warm water from the lower density cold water [43]. Therefore the one-node model no longer accurately models the temperature distribution in the EWH tank after a usage event has occurred, which will result in an underestimation of the outlet temperature, and consequently of energy lost during usage events.

The mixing layer in between the warm and cold nodes is called the thermocline and it moves along the height of the EWH tank during water usage and heating events [43]. To more accurately model the stratification that occurs as a result of water withdrawal, two nodes are is used to model the warm and cold water layers separately. Kondoh et al [44] describes a two node model for a vertical EWH with two elements that operate independently. The thickness of the thrermocline is assumed to be zero to simplify the modelling process. Their model assumes fixed volumes for the lower, cold node and the upper, warm node and the temperature within each node is assumed to be uniform, with the upper node temperature always being higher than that of the lower node. The heat dissipation of each node to the surrounding environment is considered, but the value of thermal resistance of the EWH tank is estimated and not validated using measured data. Additionally, the water consumption profiles used for individual EWHs during simulations were estimated using measured average residential load profiles. Although Kondoh et al. improved upon the one-node model of Dolan et al., their assumption of fixed node volumes does not model the movement of the thermocline, and the model would therefore give erroneous energy flows for large usage events, and also would not accurately estimate the standing losses of the two nodes. Moreover, no validation process is reported to determine the accuracy of the model.

Diao et al [45] presents a model for a vertically orientated EWH that switches between the one and two-node state, depending on the operation of the EWH. When the EWH contains only warm water or has been fully depleted, they use the one-node state to model the behaviour of the EWH. In this state, their model is identical to that of [41] and it will remain in this state until a usage event occurs. Diao et al define a two-node state that their model enters into when water is withdrawn from the EWH and, similar to [44], the temperature of each node is assumed to be uniform. In the two-node state, their model defines an equation that describes the height (h) of the thermocline. This height moves along the length of the vertical tank during usage and heating events, simulating the movement of the thermocline. If the value of h reaches the full height of the EWH tank (i.e. all the water in the tank is warm), then the model returns to the one-node state until another water withdrawal occurs. When their model is in the two-node state, the temperature of the upper node is held constant at the value of the average temperature of the water at the time that the usage event occurred, which does not accurately model the standing losses for the warm node. Additionally, this model is suitable for a vertically orientated EWH only, because the cross-sectional area of the tank is assumed to be constant. Additionally, the simulated results of the model are not validated against measured data to confirm the validity and accuracy of the model.

Xu et al [42] developed a partial differential equation (PDE) based model for simulating the temperature profiles at various locations in a vertically orientated EWH. The entire tank was discretised into bins of size 0.01 meters and standard finite difference was applied to solve the PDE used by the model to describe the temperature at varying positions in the tank at different times. The EWH had two elements that operated independently and their states (and therefore the energy consumption of the EWH) were determined by computing the instantaneous temperatures at their respective positions. Four temperature sensors were installed along the tank from top to bottom to determine if the model was accurately simulating the thermal dynamics of the EWH. Their thermal model was validated against the measurement data collected over 250 hours, during which only four significant usage events occurred. The validation process indicated that the simulated temperature values at the locations of the sensors was in good agreement with the temperature measurements. However, the computational complexity of the PDE model is significantly higher than that of the one and two-node models of [41], [44] and [45]. According to [42], the PDE model took 22 minutes to perform the 240 hour simulation with 1 minute simulation time steps, in comparison to the one and two-node models that took only 15 seconds. This is problematic if the PDE model is to be used for demand response programs for which it will need to simulate the behaviour of thousands of EWHs, or if the simulation is to be performed on mobile devices.

The grey-box model presented by Farooq et al [46] uses 8 one-node models to create a stratified model of the EWH tank. Similar to Xu et al, 8 temperature sensors were installed along the height of the tank to validate the simulated response of the model. The values of the input variables were obtained using parameter estimation techniques and high resolution measurement data (10 second sample rate). Although the simulated response of the eight nodes accurately matched the measurement data, the validation of the model was limited (less than 4 days of measurement data). Only two scenarios were used to validate the model: scenario 1, consisting of 70 hours of measurement data, during which no usage events occurred, to determine the model's accuracy in the simulation of standing losses; and scenario 2, where the water in the EWH was heated to 60 °C and water was consumed at a constant rate of 90 grams per second over 2 hours. The response of the model when exposed to usage events of varying consumption amounts and draw rates at different intervals is not reported. Additionally, this model is unproven for EWHs that are horizontally orientated.

Despite EWHs commonly being installed in a horizontal orientation, existing models do not cater for this orientation. Although one-node EWH models inherently accommodate horizontal alignment, they cannot accurately model EWH energy usage, because they do not take stratification into account [42]. Horizontally installed EWHs have a non-uniform cross sectional area between the two nodes (called the thermocline), and the surface area subject to standing losses for each node can not be determined analytically. Existing models that incorporate two or more nodes are therefore not suited to this orientation and only support vertical EWHs [42; 44; 45; 46]. Additionally, the available

Table 2.1: Presented model compared to state of the art.

Property	[41]	[44]	[45]	[42; 46]	This model
Multinodal	×	✓	✓	✓	✓
Horizontal orientation	✓	×	×	×	✓
Schedule control	×	×	×	×	✓
Multinodal standing losses	N/A	✓	×	✓	✓
Validated model	×	×	×	✓	✓
Computationally inexpensive	✓	✓	✓	×	✓

two-node models do not accurately accommodate standing losses while in the two-node state [44; 45]. Many of the models presented in literature are not validated against measured data and their accuracy is unknown [41; 44; 45]. Moreover, none of existing works in literature validates modelled energy consumption against measured electrical energy. Only two of the existing sources report validation against measured data, and only validate the temperature values [42; 46].

Although some of the existing work (e.g. Dolan et.al [41]), investigate the impact on the grid of aggregate DSM-based schedule control, none of the existing EWH models take into account the impact of schedule control on temperature variation, and energy consumption of a single EWH, and assumes an always-on temperature-based (e.g. thermostat-) control. Additionally, the models available in literature are either too inaccurate, too complex or limited to their application to vertically orientated EWHs only. The contributions of the model presented in this chapter are summarised in Table 2.1. This chapter presents a theoretical simulation model for an EWH for: two node analysis of a horizontally orientated EWH with a varying thermocline position to accommodate horizontally oriented EWHs; calculating the standing losses for each node in the two-node state for both vertically and horizontally (varying exposed surface area) orientated EWHs; simulating the effect of implementing a schedule that controls the on and off times of the EWH. Additionally, the model is computationally inexpensive, and therefore suited to be used on a mobile device with limited processing power and battery capacity.

2.1.2 Energy impact analysis

The energy consumed to heat water for domestic purposes can be reduced through several methods. These include curtailment actions, such as shortening shower times (i.e. reducing water consumption) or lowering the set temperature of the appliance. Furthermore, users can implement efficiency actions. These types of actions include the installation of a thermal blanket or pipe insulation. Other factors that influence the energy consumption of the EWH are: tank size, as a larger tank surface area causes larger standing losses; the use of timer control to intermittently switch the EWH on and off, which can reduce the standing losses; the ambient temperature, which impacts the standing losses of appliance; and inlet temperature, which impacts the usage losses because the water consumed is replaced by colder water and more warm water is required to create the desired temperature at warm water outlets if the intlet temperature is lower.

Dutkiewicz [47] investigated the potential savings that can be achieved by various energy saving actions for EWHs based on the warm water requirements of typical middle income families in South Africa. This includes the impact of adding pipe and tank insulation in order to increase the thermal resistance of the system. The replacement of an EWH with an instant heater is also considered but is not considered optimum. This is because of the increased requirements of cabling and the installation cost of a 3-phase supply required to accomodate the increased wattage (21 kW) of the instant heater. Finally, Dutkiewicz highlights the importance of educating consumers on how to save energy for their EWHs (e.g. not running warm water unnecessarily or overfilling baths).

Bosman et al [48] investigated the impact of installing thermal blankets on the standing losses of standard EWHs in South Africa. The increased thermal resistance of the EWH reduces the standing losses of the device as heat is dissipated to the environment at a slower rate. The study included eighteen identical EWHs in a residential complex in Potchefstroom. Six of the EWHs were fitted with thermal blanked and periods where no warm water consumption occurred were used to determine the standing losses of the EWH. This data is then used to determine a linear approximation of the standing losses as a function of ambient and set temperature. It was determined that the standing losses of these devices could be decreased by 18% on average. It was also found that reducing the set temperature of an EWH from 75°C to 55°C would result in twice the reduction on standing losses than installing a thermal blanket.

Catherine et al [49] presents a usage profiling system to improve the efficiency of household EWHs. This system was installed in ten households and made use of a flow meter to determine the frequency and duration of warm water usage events during a day. A day was comprised of twelve 2 hour intervals, each of which would implement one of three different service levels (i.e. temperature set points) based on the amount of warm water used. The three service levels were defined as: high, which implements a temperature setting of 65°C; medium, which keeps the water temperature at 55°C; and low, where the set temperature was reduced to 45°C. This system was found to reduce the average temperature of a EWH by approximately 10°C, resulting in a reduction in the standing losses of the EWH while still satisfying users' warm water demands.

Booysen et al [24] examined the effect of implementing timer control which only heats water prior to usage for a typical 150 litre EWH. The usage profile is assumed to consist of one 75 litre warm water usage event every 12 hours. This would be the equivalent of almost 3 consecutive typical showers in South Africa [50]. The results of this analysis indicate that, even for the high usage profile assumed, the total energy consumption of the EWH can be reduced by approximately 15% if an efficient schedule is implemented. It should be noted that, although water heating should only occur before major usage events, enough water could be heated during these times to allow the EWH to still supply warm water for smaller usage events (e.g. washing dishes) that may occur in the interval between the major usage events.

Gardner and Stern [51] found that efficiency-improving actions tend to save more energy than curtailing the usage of inefficient appliances for households in the USA, but it should be noted that there may be unforeseen consequences as a result of these efficiency improvements. A rebound effect occurs when consumers use efficient appliances more regularly as a result of their efficiency, which can result in a net increase of energy consumption [52].

2.2 Development

This section describes the development of a model that accurately simulates the temperature and energy flows inside an EWH. The model is based on energy flow inside the tank that can be used to estimate the temperature distribution of the water inside the tank. With knowledge of these temperatures, the behaviour of the EWH heating element, and therefore the energy input into the EWH, can be estimated. Energy losses occur due to standing losses and warm water withdrawal from the EWH tank (i.e. usage). Firstly, a one-node model is described, similar to the solution in [41]. This model is then extended to a two-node model, taking into account the orientation and the standing losses of both nodes in the two-node state.

2.2.1 One-node state

For the one-node model, all the water in EWH tank is treated as a single body with uniform temperature. Therefore, when a usage event occurs, the water leaving the tank through the outlet pipe is assumed to be at the average temperature of the water inside the tank (T_{inside}). Additionally, the cold water entering the tank from the inlet pipe, to replace the water used, is assumed to instantaneously mix with the water inside the tank, to create a new average temperature. Under the assumption that water at the inlet temperature is the baseline for zero energy, all the energy inside the EWH is then held by the remaining hot water inside the tank and the resultant temperature of the water in the EWH at time t is given by the energy balance equation [24]:

$$E_{inside}(t) = E_{hot}(t) \tag{2.1}$$

Where: E_{inside} is the energy inside the EWH tank; and E_{hot} is the energy in the remaining hot water inside the EWH tank after a usage event. This results in the following equation:

$$c\rho V_{tank}[T_{inside}(t) - T_{inlet}] = c\rho V_{hot}(t)[T_{hot}(t) - T_{inlet}] \tag{2.2}$$

Where: c is the specific heat capacity of water; ρ is the density of water; T_{inlet} is the temperature of the water entering the tank from the inlet; $T_{inside}(t)$ is the average temperature of the water inside the EWH at time t; V_{tank} is the total volume of water in the EWH; and V_{hot} and T_{hot} are the volume and temperature of the unused hot water remaining inside the EWH respectively. Cancelling out the constants and solving for $T_{inside}(t)$ gives:

$$T_{inside}(t) = \frac{V_{hot}(t)}{V_{tank}}\Big[T_{hot}(t) - T_{inlet}\Big] + T_{inlet} \tag{2.3}$$

The energy (heat) lost during a usage event (E_{usage}) can then be obtained as follows:

$$E_{usage} = cm_{usage}\Delta T \tag{2.4}$$

$$E_{usage} = c\rho V_{usage}(t)[T_{before} - T_{after}] \tag{2.5}$$

Where: m_{usage} and V_{usage} are the mass and volume of water used (equal to the mass or volume to be heated), respectively; and ΔT is the temperature change that is required to reheat the water in the EWH from the average temperature after the usage event (T_{after}) to the temperature it was before the usage event (T_{before}).

In addition to energy being lost through usage events, Figure 2.1 shows the other energy input and output that occur within the EWH when it is in the one-node state: standing losses (E_{loss}); and the energy input by the element (E_{input}).

Energy input by the element (E_{input}), is assumed to be distributed uniformly and instantaneously to all the water in the EWH tank in the one-node state. The temperature increase (ΔT) in the water in the tank as a result of energy input by the element (E_{input}) can be calculated using:

$$E_{input} = cm_{tank}\Delta T \tag{2.6}$$

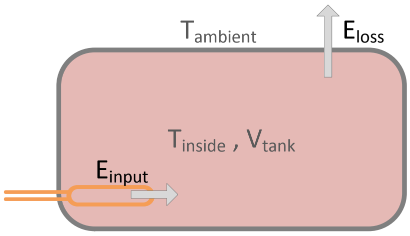


Figure 2.1: One-node state energy flow.

$$\Delta T = \frac{E_{input}}{c\rho V_{tank}} \tag{2.7}$$

Standing losses refer to the energy lost due to heat dissipation from the water inside the EWH to the outside environment as a result of the temperature difference between them. These standing losses can be modelled using a temperature decay of the water inside the EWH tank toward the ambient temperature as described by [41]:

$$cm_{tank}\dot{T}_{inside}(t) = \frac{-1}{R}\left[T_{inside}(t) - T_{ambient}\right] \tag{2.8}$$

Where: R is the thermal resistance of the EWH tank; and $T_{ambient}$ is the temperature of the outside environment of the EWH. Solving 2.8 for T_{inside}:

$$T_{inside}(t) = T_{ambient} + \left[T_{inside}(t_0) - T_{ambient}\right]e^{\frac{-(t-t_0)}{cm_{tank}R}} \tag{2.9}$$

Where: $T_{inside}(t_0)$ is the initial temperature of the water in the EWH tank. Equation 2.9 describes the exponential decay of the internal temperature of the EWH from its initial value at $t = t_0$ towards the ambient temperature over time t. The energy lost to the environment (E_{loss}) over a time interval t can then be calculated using:

$$E_{loss} = cm_{tank}\Delta T \tag{2.10}$$

$$E_{loss} = c\rho V_{tank}\left[T_{inside}(t_0) - T_{inside}(t)\right] \tag{2.11}$$

Where: m_{tank} is the total mass of water in the EWH tank. Therefore, the standing losses are given by the amount of energy needed to reheat all the water in the EWH tank to its initial temperature at $t = t_0$. The maximum allowable standing losses (E_{loss}) over a 24 hour period, as stipulated by South African National Standard (SANS) 151, for a closed type 150 litre EWH is 2.59 kWh at a set temperature of 65°C [53]. The worst case value of the thermal resistance of the EWH tank can then be calculated as follows [24]:

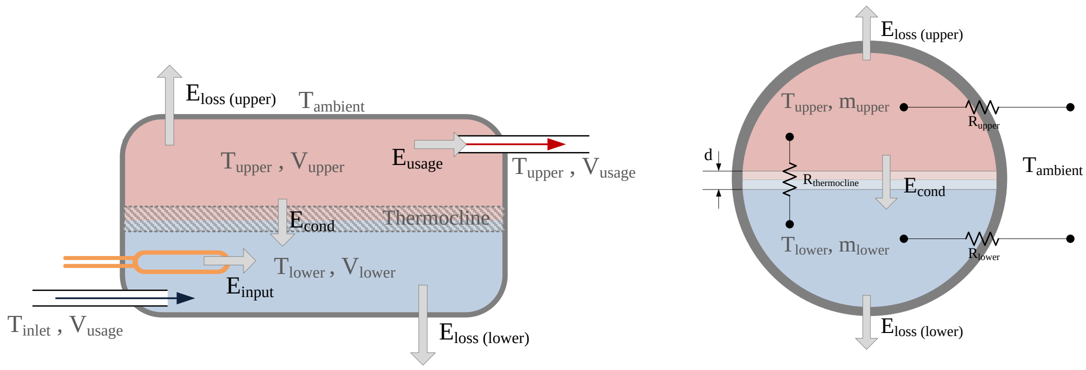
$$E_{loss} = \frac{1}{R}\left[T_{inside} - T_{ambient}\right] \tag{2.12}$$

Solving for R and substituting the maximum allowable standing loss:

$$R = \frac{1}{E_{loss}}\left[T_{inside} - T_{ambient}\right] = \frac{1}{2.59}\left[65 - 20\right] \tag{2.13}$$

$$R = \frac{1}{2.59}\left[65 - 20\right] = 17.4\ \frac{^{\circ}C \cdot day}{kWh} \tag{2.14}$$

To convert this value to $\frac{W}{m^2 \cdot {}^{\circ}C}$, the surface area of the EWH ($A_{cylinder}$) is required. The EWH used for validating the model has a 150 litre tank, which is the most common



(a) Energy flow, upper and lower nodes. (b) Thermal equivalent circuit.

Figure 2.2: Diagram of (a) energy flow, upper and lower nodes and (b) thermal equivalent circuit of two-node state.

EWH for domestic residences in South Africa. The typical length (L) and radius (r) of a 150 litre EWH are 1.0 and 0.219 meters respectively, resulting in a total surface area of 1.677 m^2 for the EWH tank. This results in an EWH thermal conductance (G) of:

$$G = \frac{1}{R} \times \frac{1000}{24 \cdot A_{cylinder}} \tag{2.15}$$

$$G = \frac{1}{17.4} \times \frac{1000}{24 \cdot 1.677} = 1.4279 \frac{W}{m^2 \cdot {}^{\circ}C} \tag{2.16}$$

This value is similar to that of Xu et al [42]. The one-node model accurately models the EWH in the absence of large usage events. If large volumes of water are drawn from the EWH over a short duration, the water in the tank becomes stratified and the one-node state no longer accurately models the temperature (and therefore energy) of the water leaving the tank during latter events [42].

2.2.2 Two-node state

The model remains in the one-node state until a significant volume of water, called the threshold volume ($V_{threshold}$), is consumed over a short duration. After this usage threshold volume has been exceeded, the model transitions to the two-node state where the water in the tank is divided into two separate nodes, mimicking the natural stratification that occurs in the EWH, as shown in Figure 2.2. The upper node consists of the remaining warm water in the tank after the usage event has occurred and the lower node consists of cold water from the inlet that has replaced the water drawn from the tank.

The following differential equations are used to determine the upper (T_{upper}) and lower (T_{lower}) node temperatures:

$$cm_{upper}\dot{T}_{upper} = -\frac{1}{R_{upper}}\left[T_{upper} - T_{ambient}\right] - \frac{1}{R_{thermocline}}\left[T_{upper} - T_{lower}\right] \tag{2.17}$$

$$cm_{lower}\dot{T}_{lower} = -\frac{1}{R_{lower}}\left[T_{lower} - T_{ambient}\right] - \frac{1}{R_{thermocline}}\left[T_{lower} - T_{upper}\right] + E_{input} \tag{2.18}$$

Where:m_{upper} and m_{lower} are the mass of the upper and lower nodes respectively; R_{upper} and R_{lower} are the thermal resistance of the upper and lower nodes respectively (as shown in Figure 2.2b); and $R_{thermocline}$ is the thermal resistance of the thermocline.

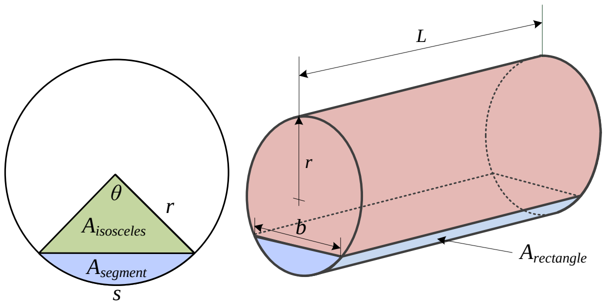


Figure 2.3: Surface areas of EWH in horizontal orientation.

In the two-state, when a usage event occurs, the volume of water leaving the upper node is replaced by water entering the lower node through the inlet pipe. It is assumed that the water entering the tank through the inlet pipe mixes instantaneously with the lower node. The temperature of the lower node (T_{lower}), after mixing with the water entering the tank at the inlet temperature, can be obtained by using the one-node model for the lower node, i.e. modifying Equation 2.3 to obtain:

$$T_{lower}(t) = \frac{V_{lower}(t) - V_{usage}(t)}{V_{lower}(t)} \Big[T_{lower}(t_0) - T_{inlet} \Big] + T_{inlet} \tag{2.19}$$

Where: V_{lower} is the total volume of the lower node; and $T_{lower}(t_0)$ is the temperature of the lower node before the usage event. Figure 2.2 shows all the energy transfers that are included in the two-node state, including: the standing losses for the upper node ($E_{loss(upper)}$) and lower node ($E_{loss(lower)}$); the internodal energy transfer (E_{cond}); and the energy put in by the EWH element. While in the two-node state, all energy put in by the EWH element is assumed to be transferred to the lower node alone. The temperature increase of the water in the lower node as a result of the energy input from the element can be calculated as follows:

$$E_{input} = c\rho V_{lower} \Delta T \tag{2.20}$$

$$\Delta T = \frac{E_{input}}{c\rho V_{lower}} \tag{2.21}$$

Where E_{input} is derived from the power rating of the element and the time it is estimated to be on. This temperature is added to the initial temperature of the bottom node. When the temperature of the lower node equals that of the upper node, the two layers merge and the model returns to the one-node state.

Figure 2.3 shows: the surface area of upper and lower nodes exposed to environment in the two-node state; the radius of the EWH tank (r); and the length of the EWH tank (L). The standing losses and subsequent thermal decay of the two nodes are considered separately in this state. The thermal resistance used to calculate the standing losses and thermal decay of a node is dependent on the surface area of the node exposed to the environment. This surface area for a horizontal EWH consists of: the area of the circular segments on either side of the cylinder, which are identical; and the area of the rectangle that makes up the portion of tank wall for a particular node. To calculate the surface area of this rectangle ($A_{rectangle}$), the arc length of the circular segment of each node must be known.

Figure 2.3 shows: the arc length of the circular sector (s); the central angle (θ); the area of the circular segment ($A_{segment}$); and the area of the isosceles triangle ($A_{isosceles}$) created by the chord that defines the circular segment. The circular segment and the isosceles triangle combined constitute the circular sector under consideration. Therefore, the area of the circular segment is given by the difference between the area of the sector (A_{sector}) and the isosceles triangle:

$$A_{segment} = A_{sector} - A_{isosceles} \tag{2.22}$$

$$A_{segment} = \frac{1}{2}r^2(\theta - \sin\theta) = \frac{1}{2}r^2\left[\frac{s}{r} - \sin\left(\frac{s}{r}\right)\right] \tag{2.23}$$

Equation 2.23 does not have an analytical solution, but a numerical solution for θ (and therefore s) can be obtained using the Newton-Raphson method [54]. Since the volume entering the EWH is measured, the volume of consumed water is known. This volume can then be used to calculate the surface area of the circular segment of the lower node using:

$$A_{segment} = \frac{V_{lower}}{L} \tag{2.24}$$

Where: L is the length of the EWH tank. Setting Equation 2.23 equal to Equation 2.24 results in:

$$\frac{V_{lower}}{L} = \frac{1}{2}r^2[\theta - \sin\theta] \tag{2.25}$$

$$\frac{2V_{lower}}{r^2L} = C \tag{2.26}$$

$$\theta - \sin\theta = C \tag{2.27}$$

For the Newton-Raphson method, the following function definition is used:

$$f(\theta) = C - \theta + \sin\theta \tag{2.28}$$

Equation 2.28 is a monotonically decreasing function over the range of $\theta = 0 \ to \ 2\pi$. An estimate of the arc length can then be obtained using the following equation, with an initial estimate of $\theta_0 = \pi$:

$$\theta_{n+1} = \theta_n - \frac{f(\theta_n)}{f'(\theta_n)} \tag{2.29}$$

Once the solution for Equation 2.29 has been determined, the area of the surrounding rectangle can be calculated using the arc length:

$$A_{rectangle} = s \times L = r\theta \times L \tag{2.30}$$

The total exposed surface area of each node of the EWH is then given by:

$$A_{exposed} = 2A_{segment} + A_{rectangle} \tag{2.31}$$

The exposed surface area can then be used to determine the thermal conductance value of each node (G_{node}) as follows:

$$G_{node} = \frac{1}{R} \times \frac{1000}{24 \cdot A_{exposed}} \tag{2.32}$$

Where: R is the value of the total thermal resistance of the EWH tank (from Equation 2.14) in $\frac{°C \cdot day}{kWh}$. The thermal resistance of each node can then be obtained by using the inverse of the value obtained from Equation 2.32.

When in the two-node state the stratification within the tank will decay (referred to as destratification [55]) as heat is transferred from the upper to the lower node due to the temperature difference between them. The thermocline between the two nodes is assumed to have a thickness of 10mm but has no mass. In other words, it acts only as an interface for energy transfer from the top to the bottom node. The thermal resistance of the thermocline can be determined using the following equation:

$$R_{thermocline} = \frac{d}{k\ A_{cond}} \tag{2.33}$$

Where: d is the thickness of the thermocline; k is the thermal conductivity of water; and A_{cond} is the surface area between the two nodes. The value of A_{cond} is given by the product of the chord length (b) and the length of the EWH tank:

$$A_{cond} = b \times L = 2r \sin\frac{\theta}{2} \times L \tag{2.34}$$

The value of k varies with the temperature of the water, as shown by Ramires et al [56]. The values obtained by Ramires et al were used to determine a linear approximation of the thermal conductivity as a function of temperature. The temperature of the thermocline is assumed to be the average of the upper and lower node temperatures. The thermal resistance values obtained for each node and the thermocline can then be used in equations 2.17 and 2.18 to determine the temperature of the two nodes. These differential equations can be solved through numerical integration. The minimum value of the time constants used for these equations was investigated for a thermocline thickness of 1 millimeter (i.e. worst case scenario). The minimum value of the time constants was found to be approximately 512 seconds over all 4 datasets used, shown in Table A.1 in Appendix A. Therefore, the temperature of the nodes can be calculated by simulating over one minute (60 second) time intervals as the minimum time constant is approximately nine times longer.

This model can also be applied to a vertical EWH. For a vertical EWH tank the cross-sectional area remains constant, eliminating the need for the estimation of arc length. This reduces the complexity of the calculations as the surface areas of the two nodes and the thermocline between them can be calculated analytically to determine the standing losses for each node separately and the internodal transfer.

2.2.3 EWH Simulator

The one-node model was implemented as an EWH simulator that can be used to simulate the effects of: warm water usage, such as the number of showers for a given usage profile; control settings (e.g. set temperature); efficiency actions, such as pipe insulation; EWH properties, including the size and element power rating; and seasonal temperature variations (i.e. ambient and inlet temperatures differences). The total volumes of water consumed for typical usage events in South Africa are summarised in Table 2.2.

The amount of water used by typical end use events (m_{warm}) can be calculated using the typical combined usage (m_{total}) shown in Table 2.2 in combination with the energy balance equation as follows:

$$E_{warm} = E_{total} \tag{2.35}$$

$$c\ m_{warm}(T_{warm} - T_{inlet}) = c\ m_{total}(T_{water} - T_{inlet}) \tag{2.36}$$

Table 2.2: Typical volume of water used per event for specific end uses [50].

End use	V_{total} (litres)	V_{warm} for $T_{warm} = 65°C$ (litres)	E_{event} (kWh)
Bath	80.0	35.91	1.876
Shower	59.1	26.53	1.386
Bathroom basin	3.8	1.71	0.089
Kitchen sink	6.7	3.01	0.157
Washing machine	113.6	50.99	2.664
Dishwasher	25.1	11.27	0.589

$$m_{warm} = m_{total} \frac{(T_{water} - T_{inlet})}{(T_{warm} - T_{inlet})} \tag{2.37}$$

From Table 2.2, a typical shower in South Africa consumes 59.1 litres of water in total [50] and the desired temperature (i.e. mixed temperature) of the water at the shower outlet is typically 40.2°C [50]. This implies that a typical shower event requires 26.53 litres for a warm water temperature of 65°C and inlet temperature of 20 °C. From Equation 2.37, as the set temperature decreases, additional warm water is required to create the desired temperature at an outlet. Based on the assumption that the amount of energy used by an event will remain constant for different warm water temperatures [57] and that water at the inlet temperature is at baseline energy [24]:

$$E_{event} = c\ m_{event} \Delta T \tag{2.38}$$

Where: E_{event} is the total energy used by the event; m_{event} is the mass of warm water consumed by the event; and ΔT is the difference in temperature between the inlet and set temperatures. Solving Equation 2.38:

$$E_{event} = (1.1611 \times 10^{-3})(26.53)(65 - 20) = 1.386\ kWh \tag{2.39}$$

Table 2.3 shows the energy consumed by an EWH for a typical set temperature of 65°C and an inlet temperature of 20°C. Furthermore, the energy consumption for various usage profiles that include typical events as, defined in Table 2.3, are also indicated. For profiles with 2 usage events, the events are assumed to occur within 12 hours of one another. For example, the profile with 1 shower and 1 bath event in Table 2.2 consists of one shower and one bath occurring once at 06:00 and 18:00, respectively. For profiles with 3 usage events, the 2 usage events are assumed to within 12 hours of one another, while the third usage event is assumed to occur with the first usage event at 06:00. For example, the profile with one bath and one shower occurring once at 06:00 and one shower occurring at 18:00. The profile consisting of 4 usage events assumes one shower and one bath occur together at both 06:00 and 18:00.

Finally, the typical energy consumption for developed households in Cape Town are shown in Table 2.4 [58]. It was assumed that each occupant of a household had one usage event per day and the household type (i.e. flat, duplex, house) was chosen based on the number of occupants.

2.2.4 Experimental setup

This section describes the setup of the experiment, including choosing the configuration constants and parameters, the chosen datasets captured from over 900 hours of actual household consumption, and the detail on the simulator that implements the EWH model developed.

Table 2.3: Baseline energy consumption for typical usage profiles.

Usage events		Energy consumption		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)
0	1	2.577	1.876	4.453
0	2	2.572	3.752	6.324
1	1	2.575	3.262	5.837
1	2	2.555	5.138	7.693
1	0	2.581	1.386	3.967
2	0	2.579	2.772	5.351
2	1	2.558	4.648	7.206
2	2	2.538	6.524	9.062

Table 2.4: Baseline energy consumption for typical household types and sizes.

# Events /Occupants	Household Type	Energy consumption (kWh/person/month)	Household energy consumption (kWh/month)
1	Flat	212	212
2	Duplex	216	432
3	House	193	579
4	House	167	668

Table 2.5: Values used to model the EWH.

Symbol	Description	Value	Unit	Ref
ρ	Water density	1000	$\frac{kg}{m^3}$	[42]
c	Specific heat capacity of water	4180	$\frac{J}{kg \cdot K}$	[24]
G	EWH thermal conductance	1.386	$\frac{W}{m^2 \cdot °C}$	[53]
$T_{deadband}$	Thermostat deadband	2	$°C$	[42]
T_{inlet}	Inlet temperature	17, 19, 20, 22	$°C$	[59]
T_{set}	EWH set temperature	65	$°C$	
d	Thermocline thickness	10	mm	
$V_{threshold}$	Threshold volume for two-node state transition	30	l	
V_{tank}	EWH tank volume	150	l	
r	EWH radius	0.219	m	
L	EWH length	1.0	m	
e_{η}	Element efficiency	100	%	
P_{rated}	Element power rating	3000	W	

2.2.4.1 Model constants and parameters

Table 2.5 lists the EWH parameter values used for the simulations. Minutely weather data from a local weather station was used to determine the ambient temperature for all the datasets that include usage events. For the datasets without usage events, only weather data reported every five minutes was available. Since the EWH is located indoors, it would be exposed to a higher temperature than the outdoor temperature and it was therefore decided to increase the ambient temperature value by 10%. Since the datasets span several months, the inlet temperature was varied from 17 to 22°C to account for the change in soil temperature fluctuations from season to season [59].

2.2.4.2 Dataset description

Table 2.6 details all the datasets used in the validation of the model. Datasets 5 and 6 consist of 7 consecutive days each without energy usage and were used to validate the thermal resistance value, since for these datasets, only standing losses impacted the energy input by the element. Dataset 5 applied schedule control from 04:15 to 06:00 while dataset 6 utilised always on thermostat control.

```
for each interval do
Energy out due to usage
    if usage event in present interval then
        if in one node state then
            if node V_threshold is exceeded then
                Update T_lower and T_upper
                Enter two node state
        else
            Update T_inside
    else in two node state
        Update V_lower, V_upper, T_lower, T_upper
        if (T_lower >= T_upper OR V_upper = 0) then
            T_inside = T_lower
            Enter one node state
    Calculate E_usage
Energy out due to standing losses
    if in one node state then
        Calculate E_loss and T_inside
    else in two node state
        Calculate arc and chord length using Newton-Raphson
        Update R_upper, R_lower, R_thermocline
        Update E_loss(upper), T_upper, E_loss(lower), T_lower, E_cond
        if (T_lower – T_upper <= ΔT_minimum) then
            T_inside = Average temperature of two nodes
            Enter one node state
Energy put in by the element
    if present interval is in an active time slot of schedule then
        Calculate E_input from element rating and time it is on
        if in one node state then
            Calculate ΔT_inside for full interval from E_input
            if T_inside + ΔT_inside < T_set + T_deadband / 2 then
                T_inside+ = ΔT_inside
            else element on for part of interval
                Calculate thermostat duty cycle and resulting E_input
                T_inside = T_set + T_deadband / 2
        else in two node state
            Calculate ΔT_lower for full interval from E_input
            T_lower + = ΔT_lower
            if T_lower + ΔT_lower >= T_upper then
                Calculate T_inside from T_upper and T_lower
                Enter one node state
```

Figure 2.4: Pseudocode implementation of model.

The datasets that include usage events are: dataset 1, which consists of 9 consecutive days in December 2014 (Summer) with a schedule implemented from 04:15 to 06:00; dataset 2, which is comprised of 10 consecutive days in March 2015 (Autumn) with a schedule implemented from 04:15 to 06:00; dataset 3 which is made up of 10 consecutive days in February 2015 (Summer) for always on thermostat control; and dataset 4, which consists of 10 consecutive days in June 2015 (Winter) for always on thermostat control.

2.2.5 Model development

The EWH model was developed in the Eclipse integrated development environment (IDE) using the Java programming language. Implementing the model in Java allows the model to run on a desktop PC as well as an Android smartphone, as Android is written in Java. This also allows the average run time of the algorithm on both systems to be determined. Figure 2.4 shows the pseudocode implementation of the model.

2.2.6 Simulator development

The model was used to simulate the behaviour of various EWHs under various control settings and usage profiles. Figure B.1 in Appendix B shows a screenshot of the software used to perform these simulations. The simulator allows the user to modify the settings and characteristics (e.g. size and insulation) of the EWH, the simulation environment (e.g. ambient and inlet temperature) as well as the usage profile used by the simulation (i.e. time and volume of usage events).

2.3 Results

This section describes the results of the model implemented using multiple datasets over several months. Additionally, the results of the energy impact analysis, performed using the simulator, are also presented. Finally, it details the sensitivity analysis performed on the model to illustrate the importance of accurate input variable values for models as a guide for future research.

2.3.1 Standing losses

Before validating the results of the model for the datasets including usage events, it was necessary to verify the thermal resistance value obtained from Equation 2.14 and used for the calculating the standing losses of the EWH. For event-free datasets 5 and 6, shown in Table 2.6, the energy input from the EWH element was calculated using the model and compared to the measured energy input. The value of G was varied from 1.190 to 1.785 $\frac{W}{m^2 \cdot {}^\circ C}$ and the overall error (defined as the difference between the calculated and measured energy values) was calculated for the two datasets. A value for G of 1.386 $\frac{W}{m^2 \cdot {}^\circ C}$ produced the best results for both datasets, with an error of 2.78% and 1.07% across 7 days of simulation for the schedule and thermostat datasets respectively.

2.3.2 Energy estimation

After verifying the value of the thermal resistance, the four datasets with usage events, shown in Table 2.6, were used to validate the accuracy of the developed EWH model. These datasets were simulated for a model that remains permanently in the one-node state, and separately for one that incorporates the two-node state. The results of these simulations are summarised in Table 2.6.

From Table 2.6, it is evident that the one-node model more accurately determines the energy consumption of the EWH when schedule control is implemented. For datasets 1 and 2, the one-node model has an estimation error of 0.25% and 0.92% respectively, while the two-node model's error is more than 5 percentage points higher for both datasets. However, when thermostat control is applied, the two-node model outperforms the one-node model. For datasets 3 and 4 the two-node model has an estimation error of 1.64% and 6.72% respectively. Figure 2.5 shows a graph of the simulation results of the two-node model for dataset 3. The graphed temperature is the average calculated temperature of water inside the EWH tank. From the graph, it is clear that the modelled energy input closely follows the measured data value. The graphs generated by the two-node model for all four datasets can be found in Appendix A.

An attempt was made to model the temperature variation of the water entering the EWH tank at the inlet pipe. If water is stagnant in the inlet pipe for an extended period of time its temperature tends towards the ambient temperature (i.e. energy is transferred due to the temperature difference between them). This was modelled by modifying the temperature of the initial volume of water entering the EWH tank. Instead of assuming

Table 2.6: Results for one- and two-node models.

Dataset	Days	Control Mode	# Small Events	# Medium Events	# Large Events	Total Events	Energy Input (Measured)	One-node model Energy Input (Calculated)	One-node model Error (%)	Two-node model Energy Input (Calculated)	Two-node model Error (%)
1	9	Schedule	14	12	7	33	38.90	38.81	**0.25**	41.20	5.91
2	10	Schedule	8	9	7	24	41.86	42.23	**0.88**	44.84	7.11
3	10	Thermostat	2	6	6	14	52.35	48.65	7.07	51.50	**1.64**
4	10	Thermostat	13	1	18	32	115.20	92.89	19.37	107.46	**6.72**
5	7	Schedule	0	0	0	0	16.34	16.79	2.78	16.79	2.78
6	7	Thermostat	0	0	0	0	19.05	18.85	1.07	18.85	1.07

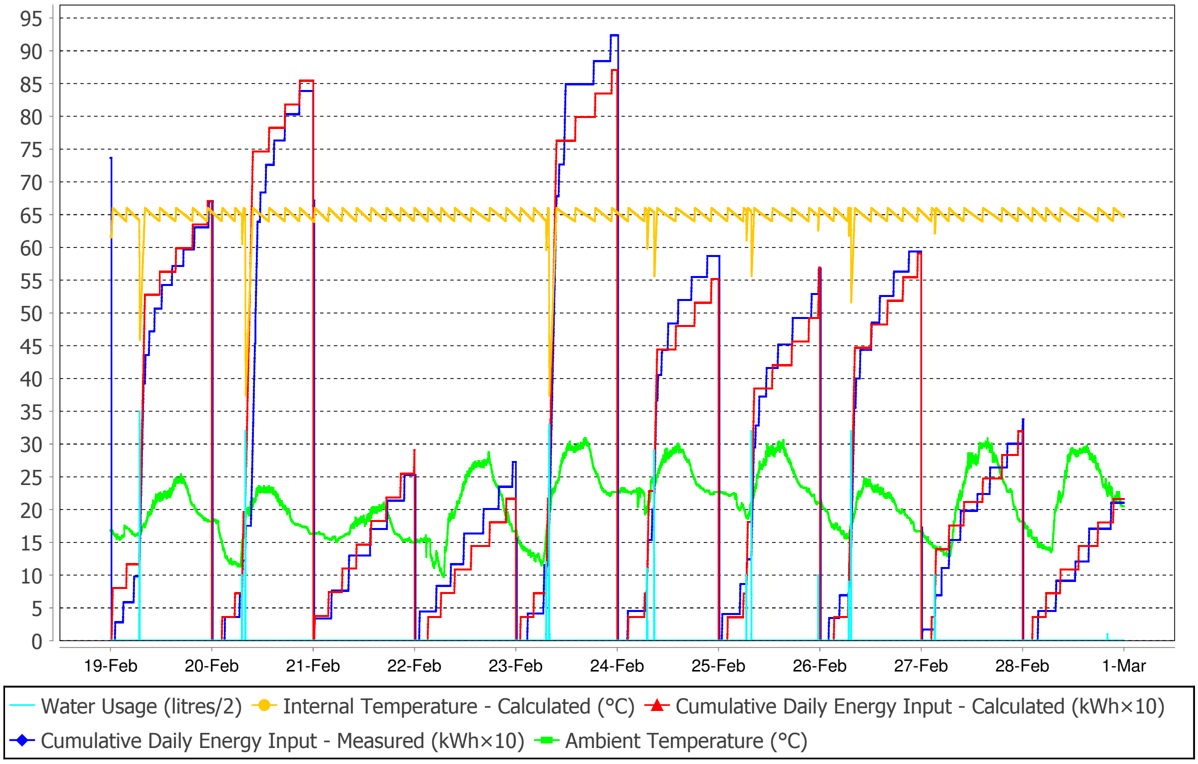


Figure 2.5: Graphed output of the two-node model for dataset 3.

that all the water entering the tank was at the inlet temperature, the first several litres were assumed to be at the ambient temperature. The volume of water entering the tank at ambient temperature was varied from 1 to 25 litres in increments of 1 litre but yielded no improvement in the estimation accuracy and was therefore excluded from the final model.

2.3.3 Internodal energy transfer

The only means of transitioning from the two-node state to the one-node state is if the temperatures of the upper and lower nodes (T_{upper} and T_{lower} respectively) are equivalent. This occurs when: T_{upper} decays to the T_{lower} as a result of energy lost to the atmosphere; or T_{lower} increases to T_{upper} through heating by the element and internodal energy transfer. However, the destratification in the tank is difficult to model, as it depends on: the mixing of the water from the inlet with the water already in the tank; heat conduction along the EWH tank; heat conduction between nodes at different temperatures; and heat dissipated to the environment through EWH tank [55].

2.3.4 Computational complexity

The time taken by the algorithm to complete a simulation of ten days on a desktop machine (Intel Core i7 2.30 GHz, 8 GB RAM) varied from 30 to 100 milliseconds. This time taken depends on both the number of usage events and the time spent in the two-node state, where the model is more computationally expensive, due to the iterative nature of the Newton-Raphson method. A simulation consisting of one day with schedule control (i.e. long periods in two-node state) was run on a Samsung Galaxy S4 (1.6 GHz and 1.2 GHz Quad Core, 2GB RAM) and took between 40 and 55 milliseconds to complete.

2.3.5 Energy impact analysis

The following values were used to establish the baseline energy consumption of an EWH for this analysis: 150 litre tank size; set temperature of 65°C; no pipe insulation or thermal blanket installed; regular thermostat control (i.e. heating allowed all day); and an inlet and ambient temperature of 20°C. The results of the simulations for various energy saving actions and seasonal variations in variables are summarised in Tables 2.7 and 2.8 for single- and three-person households respectively. For the pipe insulation and thermal blanket variables, the thermal resistance of the system was simply increased by 6% [47] and 18% [48] respectively. For schedule control, the EWH started heating water 2 hours before the occurrence of a usage event and stopped heating 15 minutes before the usage event occurrence. The baseline household (HH) energy consumption values used in this analysis are identical to those shown in Table 2.4. The results for all the simulations can be viewed in further detail by referring to the tables included in Appendix B.

From the results in Table 2.7, the set temperature value of the EWH has a significant impact on the energy consumption for a single-person household. By simply decreasing the set temperature of the EWH by 5°C (to 60°C), a single-person household can achieve a similar total EWH energy reduction as reducing their warm water consumption by 20%. Furthermore, this same reduction can be achieved by installing a thermal blanket and pipe insulation. This is because the standing losses constitute a larger portion of the EWH energy consumption for lower occupancy households. Therefore, reducing the standing losses has a larger impact on the total EWH energy consumption for these households

The results in Table 2.8 indicate that reducing the set temperature of the EWH by 5°C would result in the same reduction in EWH energy consumption as reducing the volume of water consumed by usage events by approximately 12% for a 3-person household. Additionally, this same reduction can also be realised by installing both a thermal blanket and pipe insulation on an EWH implementing thermostat control for a set temperature of 65°C. Furthermore, the results indicate that the inlet temperature has almost twice the effect on the energy consumption of the EWH for a three-person household than for a single-person household. This is as a results of the higher usage volumes from higher occupancy households, with a 5°C change in inlet temperature causing a change in approximately 15.7% of the total EWH energy consumption for 3-person households (compared to 8.6% for single-person households).

For both single- and three-person households, the results indicate that schedule control has the most significant impact on the standing losses of the EWH. When schedule control, pipe insulation and a thermal blanket are implemented in combination the EWH energy consumption can be significantly reduced, resulting in total EWH energy reductions of 25.1% and 14.7% for single- and three-person households respectively.

2.3.6 Sensitivity analysis

To determine the effect of each variable on the output of the one and two-node models, a one-factor-at-time sensitivity analysis was performed. Each variable was considered individually (x) and incremented (by Δx) over a range of values and the change in the error (Δe) observed. Table 2.9 summarises the average change in the overall error of the one- and two-node model, as a percentage, for each variable, under both schedule and thermostat control, including: the inlet temperature; the EWH set temperature; the ambient temperature modifier for the EWH model ($T_{amb(mod)}$); and the modifier of the thermal resistance of the EWH tank (R_{mod}). The results indicate that the one-node model is more sensitive (approximately 10% more) than the two-node model to changes in input variables. The set temperature value has the most significant effect on the accuracy of both models. This highlights how important it is to consider the effect of different EWH control settings. The set temperatures of EWHs may vary from 55°C to 70°C and estimation errors of 5°C can cause an energy estimation error of 10% or higher. Additionally, an error of 5% for the thermal resistance value or inlet temperature can cause an error of approximately 2% in the overall accuracy of the one and two-node models. This error may not be significant when providing estimates to a single individual, but when simulating the energy consumption of thousands of EWHs, as is typical for DR programs, it can create significant errors in the overall estimates. This highlights the importance of validating choices for input variable values, such as the value of thermal resistance which is often assumed for models in literature without any validation [44; 45]. Finally, it is important for DR programs to consider seasonal and regional variations in inlet and average ambient temperature when modelling energy consumption in order to obtain accurate estimates.

2.4 Conclusion

A two-node EWH model was developed that can be used to accurately simulate EWHs during periods of usage and non-usage, regardless of orientation. The developed model was validated using 6 datasets that span several seasons, implement both schedule and thermostat control and include over 900 hours of measurement data with usage events, as well as 14 days of measured standing losses data. The results show that measured energy usage is modelled with an estimation error of less than 2% and 7% for schedule control and thermostat control respectively. As well as being accurate, the presented model has a low computational complexity, taking only 100 milliseconds to complete a 10 day simulation on a standard desktop machine, making it ideal for use in mobile devices. The model was also used to simulate the energy consumption of an EWH under various control settings and to evaluate the impact of several seasonal temperature variations and efficiency actions. The impact of input parameter values on the accuracy of the one- and two-node models under schedule and thermostat control was also investigated. The results of this sensitivity analysis are used to make recommendations for future work on the modelling of EWHs.

Table 2.7: Energy impact analysis results for one-person household.

Variable	**Value**	**Standing losses (kWh/day)**	**Usage energy (kWh/day)**	**Total EWH energy (kWh/day)**	**Total EWH energy (kWh/month)**	**Total HH energy (kWh/month)**
Baseline	N/A	2.581	1.386	3.967	120.663	212.0
T_{set}	55°C	2.003	1.386	3.389	103.082	194.419
	60°C	2.294	1.386	3.680	111.933	203.270
	70°C	2.868	1.386	4.254	129.392	220.61
$T_{ambient}$	10°C	3.155	1.386	4.541	135.385	229.459
	15°C	2.868	1.386	4.254	129.392	220.730
T_{inlet}	10°C	2.575	2.072	4.647	141.346	232.683
	15°C	2.578	1.729	4.307	131.005	222.342
V_{usage}	-5%	2.582	1.317	3.899	118.595	209.932
	-10%	2.582	1.248	3.830	116.496	207.833
	-15%	2.582	1.178	3.760	114.367	205.704
	-20%	2.583	1.109	3.692	112.298	203.635
Thermal blanket	N/A	2.187	1.386	3.573	108.679	200.016
Pipe insulation	N/A	2.457	1.386	3.843	116.89	208.228
Thermal blanket + pipe insulation	N/A	2.096	1.386	3.482	105.911	197.248
Schedule control	N/A	1.895	1.386	3.281	99.797	191.134
Schedule control + thermal blanket + pipe insulation	N/A	1.586	1.386	2.972	90.398	181.735
200 litre tank	N/A	3.016	1.386	4.402	133.894	225.231

Variable	**Value**	**Δ Standing losses (kWh/day)**	**Δ Usage energy (kWh/day)**	**Δ Total EWH energy (kWh/day)**	**Δ Total EWH energy (kWh/month)**
T_{set}	55°C	-0.578	0.0	-0.578	-17.581
	60°C	-0.287	0.0	-0.287	-8.730
	70°C	+0.287	0.0	+0.287	+8.730
$T_{ambient}$	10°C	+0.574	0.0	+0.574	+17.459
	15°C	+0.287	0.0	+0.287	+8.730
T_{inlet}	10°C	-0.006	+0.686	+0.680	+20.683
	15°C	-0.003	+0.343	+0.34	+10.342
V_{usage}	-5%	+0.001	-0.069	-0.068	-2.068
	-10%	+0.001	-0.138	-0.137	-4.167
	-15%	+0.001	-0.208	-0.207	-6.296
	-20%	+0.002	-0.277	-0.275	-8.365
Thermal blanket	N/A	-0.394	0.0	-0.394	-11.984
Pipe insulation	N/A	-0.124	0.0	-0.124	-3.772
Thermal blanket + pipe insulation	N/A	-0.485	0.0	-0.485	-14.752
Schedule control	N/A	-0.686	0.0	-0.686	-20.866
Schedule control + thermal blanket + pipe insulation	N/A	-0.995	0.0	-0.955	-30.265
200 litre tank	N/A	+0.435	0.0	+0.435	+13.231

Table 2.8: Energy impact analysis results for three-person household.

Variable	Value	Standing losses (kWh/day)	Usage energy (kWh/day)	Total EWH energy (kWh/day)	Total EWH energy (kWh/month)	Total HH energy (kWh/month)
Baseline	N/A	2.558	4.648	7.206	219.182	579.0
T_{set}	55°C	1.980	4.648	6.628	201.602	561.419
	60°C	2.269	4.648	6.917	210.392	570.21
	70°C	2.884	4.648	7.492	227.882	587.699
$T_{ambient}$	10°C	3.126	4.648	7.774	236.459	596.277
	15°C	2.844	4.648	7.492	227.882	587.699
T_{inlet}	10°C	2.523	6.949	9.472	288.107	647.924
	15°C	2.543	5.799	8.342	253.736	613.553
V_{usage}	-5%	2.562	4.417	6.979	212.278	572.095
	-10%	2.564	4.185	6.749	205.282	565.100
	-15%	2.567	3.951	6.518	198.256	558.073
	-20%	2.569	3.719	6.288	191.260	551.078
Thermal blanket	N/A	2.167	4.648	6.815	207.290	567.107
Pipe insulation	N/A	2.437	4.648	7.085	215.502	575.320
Thermal blanket + pipe insulation	N/A	2.076	4.648	6.724	204.522	564.339
Schedule control	N/A	1.825	4.648	6.473	196.887	556.705
Schedule control + thermal blanket + pipe insulation	N/A	1.501	4.648	6.149	187.032	546.850
200 litre tank	N/A	3.000	4.648	7.648	232.627	592.444

Variable	Value	Δ Standing losses (kWh/day)	Δ Usage energy (kWh/day)	Δ Total EWH energy (kWh/day)	Δ Total EWH energy (kWh/month)
T_{set}	55°C	-0.578	0.0	-0.578	-17.581
	60°C	-0.289	0.0	-0.289	-8.790
	70°C	+0.286	0.0	+0.286	+8.699
$T_{ambient}$	10°C	+0.568	0.0	+0.568	+17.277
	15°C	+0.286	0.0	+0.286	+8.699
T_{inlet}	10°C	-0.035	+2.301	+2.266	+68.924
	15°C	-0.015	+1.151	+1.136	+34.553
V_{usage}	-5%	+0.004	-0.231	-0.227	-6.905
	-10%	+0.006	-0.463	-0.457	-13.900
	-15%	+0.009	-0.697	-0.688	-20.927
	-20%	+0.011	-0.929	-0.918	-27.923
Thermal blanket	N/A	-0.391	0.0	-0.391	-11.893
Pipe insulation	N/A	-0.121	0.0	-0.121	-3.680
Thermal blanket + pipe insulation	N/A	-0.482	0.0	-0.482	-14.661
Schedule control	N/A	-0.733	0.0	-0.733	-22.295
Schedule control + thermal blanket + pipe insulation	N/A	-1.057	0.0	-1.057	-32.150
200 litre tank	N/A	+0.442	0.0	+0.442	+13.444

Table 2.9: Sensitivity analysis results.

		One-Node Model		Two-Node Model	
		Schedule	Thermostat	Schedule	Thermostat
Variable (x)	$\|\|\mathbf{\Delta x}\|\|$	$\|\|\mathbf{\Delta e}\|\|$	$\|\|\mathbf{\Delta e}\|\|$	$\|\|\mathbf{\Delta e}\|\|$	$\|\|\mathbf{\Delta e}\|\|$
T_{inlet}	1 %	0.250	0.313	0.215	0.309
T_{set}	1 %	1.382	1.806	1.159	1.597
$T_{amb(mod)}$	1 %	0.188	0.162	0.154	0.134
R_{mod}	1 %	0.257	0.413	0.188	0.393

Chapter 3

Usage detection algorithm

As a result of seasonal and regional variation in consumer usage patterns, an accurate warm water usage profile is essential to efficiently coordinate the switching times of EWHs [25]. If generic assumptions are made about these patterns of use, they may be inaccurate and have a detrimental effect on consumer comfort (i.e. no warm water when needed). This section presents a non-invasive hardware solution and matching algorithm to support the identification and classification of warm water usage events without the use of invasive and expensive water metering technologies. The data generated by this method is then used to create a usage profile for a household that is subsequently utilised as an input to the EWH model presented in Chapter 2 to estimate the energy consumption of the EWH for various control settings and warm water usage patterns.

3.1 Usage event detection and profiling

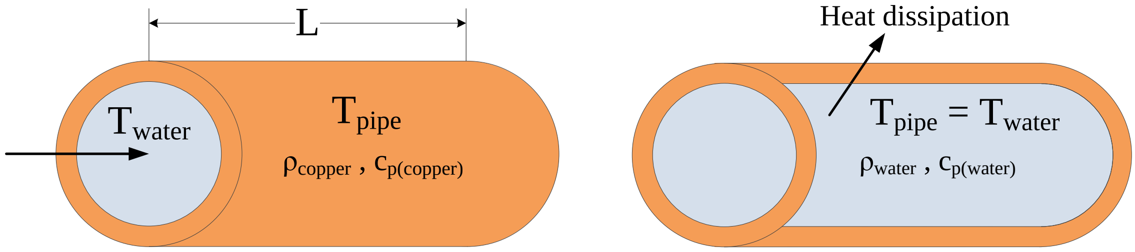
Paull et al [60] extracted electric water heater load from household load data recorded by smart meters with a 15 minute sampling interval. EWH have a large energy rating (typically 2 kW or higher) and therefore generate a rapid increase in the household load. These rapid increases and subsequent decreases were extracted from household data and used to estimate the warm water usage. These results were then used to develop a water usage profile which was, in turn, used in conjunction with a physical EWH model to estimate the temperature of the water in the EWH tank. Although this method is able to determine the household water usage profile for an EWH under normal thermostat control, it is not applicable if an EWH is controlled using a schedule as energy input may not coincide with usage events. Additionally, the method may be prone to errors when multiple high-power devices (e.g. kettle, stove) are operating simultaneously, which is likely to occur in a 15 minute interval, and create a similar load curve to the EWH.

Beal et al [61] used high resolution water meters (0.014 litres/pulse logged in five second intervals) for 252 residences in South-east Queensland, Australia over a two week continuous period. This data was then analysed using flow trace analysis software capable of disaggregating the data into end usage events, even when events occur simultaneously. This paper highlights the importance of feedback to users as actual and perceived consumption for these households were not well matched. Additionally, this misperception held across gender, education and socio-demographic groups. This method of determining end uses is very effective but requires the use of sophisticated software and high resolution hardware that is expensive and generates a significant volume of data that needs to be stored and analysed. Such high resolution data is not necessary for making useful estimates of EWH energy and water consumption.

Weihl and Kempton [62] describe the development of an instrumentation system based on a single flow meter at the EWH inlet and temperature probes on the EWH outlet pipe and at each end point (i.e. outlet) in the domestic warm water distribution system. The proposed system is used to disaggregate measured warm water usage into end uses. The temperature at each outlet is recorded in one minute intervals when the warm water flow reaches at least 0.1 litres per minute and continues for an additional five minutes after flow drops below this minimum threshold. A five-step algorithm is then used to infer which tap used the water for a specific usage event by determining the outlet with the highest rise in absolute temperature. This method requires at least one minute of zero flow to distinguish between subsequent water events, and multiple events occurring simultaneously will be treated as a single event (although an attempt is made at attributing a secondary usage event if two events occur together, but the success of this is limited). If the system is unable to determine which tap consumed the water, then the event is considered as undetermined but is still included in the total volumetric usage of the EWH. A sample of 5 houses in central Michigan (USA) with a total of 231 days of measurement data including 7075 total usage events were used to evaluate the efficiency of the system. The end usage point of 96% of all events was inferred, with most of the undetermined events being smaller usage events (typically less than 1 litre).

Fogarty et al [63] presents a low-cost microphone-based sensor system for elder activity sensing. Battery powered sensors are attached to pipes at critical locations in the household's water distribution system. These sensors collect audio samples every 2 seconds which can be used to identify end use activities. Although water pipes are good conductors of sound, this also implies that they will conduct the ambient noise well (e.g. sound of central air conditioning) which can lead to erroneous detection of events. Since the sensors are mounted to pipes, a plumber is not needed for installation. However, the suitable placement of the sensors is essential for the system to function correctly and professional installation of the system will be required. However, proper placement of the sensors leads to accurate detection of events including: 94% of shower usage; 95% of dishwasher usage; as well as 73 and 81% of bathroom and kitchen sink activity, respectively, lasting 10 seconds or longer.

Larson et al [64] uses a centralised low-cost pressure-based sensor for automatic disaggregation of water usage events in ten households. The opening and closing of water fixtures causes a pressure wave (i.e. surge/water hammer) which propagates through the water distribution system which is observed by the sensor. This pressure wave signature differs depending on the valve type, location and the way in which the valve is opened or closed. These pressure transients are then classified into specific end uses as well as individual fixtures. For example, if two identical toilets are located in two separate bathrooms of a single household, each pressure wave traverses a different path to the sensor, creating unique signatures which can be used to differentiate between the two fixtures. The system is able to classify the end uses of water, the specific valve used during usage events and classify events as hot or cold water events with accuracies greater than 90%. Additionally, the flow rates of individual fixtures were estimated in four households and with three of the four had error rates less than 8%. The fourth household had an error rate of 22%, which is believed to be as a result of incorrect placement of the sensor.



(a) Heating state of outlet pipe. (b) Cooling state of outlet pipe.

Figure 3.1: Temperature distribution for (a) heating and (b) cooling states of EWH outlet pipe.

3.2 Development

This section presents the detection of warm water usage events using the outlet pipe temperature of the EWH. An obvious way to detect warm water consumption patterns is to use water flow meters. However, they are expensive (around $50 per standards-approved device) and their installation is invasive and labour-intensive. This algorithm is developed with the aim of replacing the water flow meter with an inexpensive and non-invasive temperature sensor attached to the surface of the EWH outlet pipe.

3.2.1 EWH outlet pipe model

In order to detect water usage events, the outlet temperature is monitored with the use of a temperature sensor mounted on the pipe's surface. A usage event is defined by a sudden increases in outlet temperature as warm water flows through the pipe (i.e. start condition), followed by a gradual decrease in this temperature as the pipe cools (i.e. stop condition. The optimal values for these start and stop conditions can be determined using a combined analytical and empirical approach.

A lumped-heat-capacity analysis is used to model the temperature of the cross-section of a copper outlet pipe and the water inside it. This implies that the water and the pipe can be considered to have a uniform temperature which only varies with time. During the heating state, the warm water and pipe temperatures are not identical and only the pipe is being heated. In the cooling state, the pipe and the water are at the same temperature and are therefore cooling together. These two states are shown in Figure 3.1. For this analysis, we assume a starting condition in which the pipe has been exposed to some ambient temperature for a prolonged period of time and that the water in the EWH tank is warm (i.e. at set temperature).

A standard 22 mm residential copper piping 100 mm in length (L), with an outer diameter (d_o) of 22.22 mm and an inner diameter (d_i) of 18.92 mm [65], is considered during the analysis. Additionally, only heat transferred in the radial direction is considered. Although this analysis is performed on a copper tube of a specific size, the parameter values may be adjusted for pipes of other materials and dimensions, as long as the Biot number of the system remains at a suitable level to justify the use of a lumped analysis [66]. Weihl and Kempton [62] compared the response of copper and steel pipes and determined that, although steel has a more sluggish response, it still exhibited a clear rise in temperature.

During the heating state warm water flows through the outlet pipe as a result of being drawn from the EWH for a usage event. The temperature of the water is higher than that of the pipe, which causes heat transfer from the water to the pipe. This results in

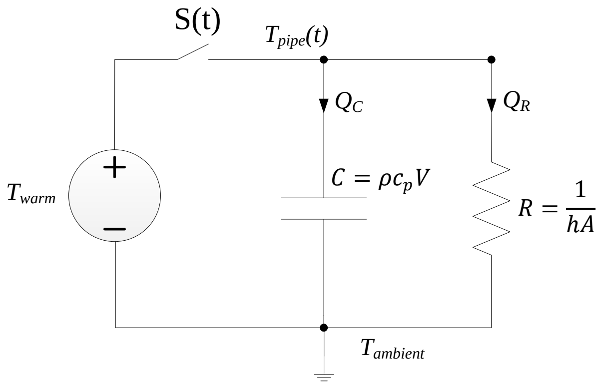


Figure 3.2: Thermal equivalent circuit for outlet pipe.

an increase in the temperature of the pipe to a maximum value of the temperature of the water. When the temperature of the pipe reaches this maximum value, it will be maintained at this value until the end of the usage event. During this state, we consider the temperature increase of the pipe in isolation and therefore make use of the specific heat capacity ($c_{p(Cu)}$) and density (ρ_{Cu}) of copper when calculating the temperature of the pipe.

In the cooling state no water is being drawn from the EWH and the water inside the pipe is stagnant. The temperature of the outlet pipe and the water are equivalent and can be assumed to remain in good agreement throughout the duration of this state as the thermal conductivity of copper is high and the pipe wall is thin, therefore the temperature drop across the pipe wall is negligible [66]. Since the temperature of the system is higher than the ambient temperature of its surroundings, heat is dissipated to the environment through the pipe surface during this state as a result of the temperature difference. The temperature of the system will continue to decrease until it reaches the ambient temperature of the air surrounding the pipe, or another usage event occurs.

Figure 3.2 shows the thermal equivalent circuit for the outlet pipe system as sensed by the temperature sensor. R and C are the total thermal resistance and capacitance, respectively, for the outlet pipe system during a specific state. The temperature of the pipe at a given time (t) can therefore be modelled using an RC transient circuit analysis and is determined using the following equation:

$$T_{pipe}(t) = T_{\infty} - \left[T_{\infty} - T_{pipe}(0)\right] e^{\frac{-t}{RC}} \tag{3.1}$$

Where: $T_{pipe}(t)$ is the temperature of the outlet pipe system at time t; T_{∞} is the temperature that the system is being exposed to (T_{warm} for heating and $T_{ambient}$ for cooling); and $T(0)$ is the initial/starting temperature of the system. The value of the time constant can be determined using:

$$R = \frac{1}{hA} \quad ; \quad C = \rho c_p V \tag{3.2}$$

Where C is given by the product of the density (ρ), specific heat capacity (c_p) and volume (V) of the material under consideration. The value of R is determined from the inverse of the product of the surface area for convection (A) and the overall heat transfer coefficient (h) of the system. The overall heat transfer coefficient can be broken down into three components [67]: convective heat transfer between the water inside the pipe and the inner pipe wall; conductive heat transfer from the inner and outer surfaces of the pipe; and convective heat transfer from the outer pipe wall to the surrounding environment. Figure 3.3 shows the total thermal resistance network for the outlet pipe system. The

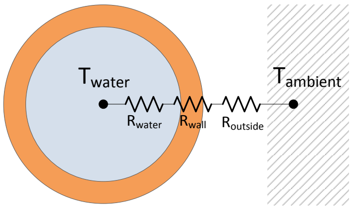


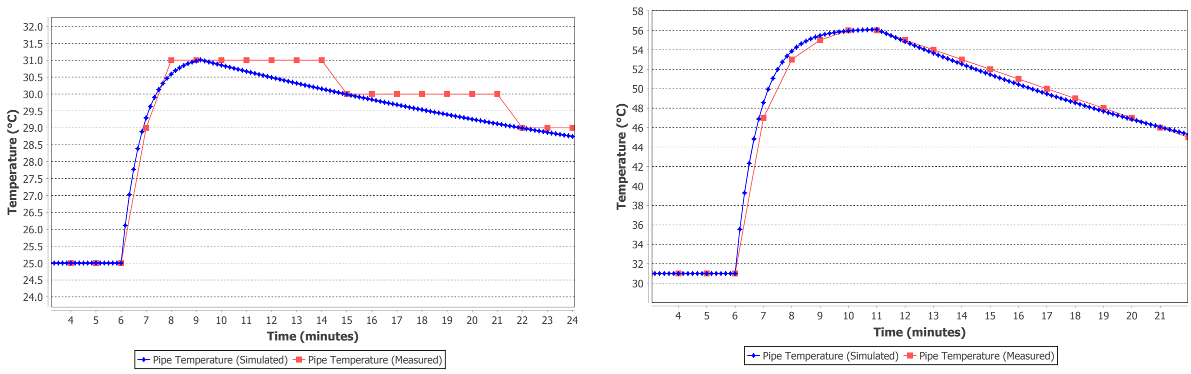
Figure 3.3: Total thermal resistance of system.

value of h is dependent on the flow rate of the water in the pipe but, if the algorithm is designed to capture the minimum increase in temperature as a result of smaller usage events with lower flow rates, then the larger events with higher flow rates will also be detected.

Table 3.1 shows the parameter values used for Equation 3.3 to determine the overall heat transfer coefficient for the heating and cooling states. The value of A for the heating state is given by the inner surface area of the pipe which is exposed to the warm water and for the cooling state it is given as the outer surface area of the pipe, which is exposed to the environment. The value of V for the heating state is given by the volume of the copper tube that makes up the outlet pipe and for the cooling state it is given by the volume of the water inside the pipe as all the thermal energy of the system is stored in the water as copper has a much lower heat capacity than water. The simulated and measured pipe temperatures are shown in Figure 3.4a for a small usage event (7 litres) for an EWH with a set temperature of 65°C. The EWH implemented schedule control and was only allowed to turn the element on from 04:15 to 06:00. The event shown occurred mid morning after two significant usage events (25 and 95 litres), resulting in a lower tank temperature. Additionally, it was a warm day with a maximum temperature of 28°C which lead to an increased pipe temperature. These conditions capture the "worst case" scenario as the increase in the outlet temperature will be lower due to the decreased warm water temperature and flow rate as well as the increased initial pipe temperature. Furthermore, the remaining water in the pipe (and therefore outlet temperature) will take longer to cool down as a result of the increased ambient temperature and lower warm water temperature. Figure 3.4b shows the measured and simulated outlet pipe temperatures for a large usage event (74.5 litres) for an EWH with a set temperature of 65°C. The EWH implemented regular thermostat control (i.e. on all day) and the event shown occurred 8 hours after the previous event. These conditions exhibit the "best case" scenario for the detection of usage events as the increase in outlet temperature will be large and rapid due to the high temperature and flow rate of the warm water. Also, the remaining water in the pipe (and therefore outlet temperature) will cool down faster than in the "worst case' scenario as a result of the increased warm water temperature. The overall heat transfer coefficient for each state was determined empirically using measurement data and by rearranging

Table 3.1: Thermal circuit parameter values for heating and cooling states [66; 68].

	$\rho(\frac{kg}{m^3})$	$c_p(\frac{J}{kg{\cdot}°C})$	$A(m^2)$	$V(m^3)$
Heating	ρ_{Cu}= 8740	$c_{p(Cu)}$= 385	$\pi d_i \times L$	$\frac{\pi}{4}(d_o^2 - d_i^2) \times L$
Cooling	ρ_{H_2O}= 1000	$c_{p(H_2O)}$= 4180	$\pi d_o \times L$	$\frac{\pi}{4}d_i^2 \times L$



(a) Small, low temperature usage event ("worst case" scenario).

(b) Large, high temperature usage event ("best case" scenario).

Figure 3.4: Measured and simulated outlet pipe temperatures for (a) a small, low temperature and (b) a large, high temperature usage event. The resolution of the sensor is 1°C.

Equation 3.1 to obtain:

$$h = \frac{\rho c_p V}{A \cdot t} \, ln \left[\frac{T(t) - T_\infty}{T(0) - T_\infty} \right] \tag{3.3}$$

The simulated temperature of the pipe was calculated in 10 second intervals to clearly illustrate the overall shape of the temperature curve. It should be noted that the initial start of the temperature may lag or lead the measured data as it is not possible to determine when exactly during the one minute sampling interval the usage event started. Additionally, since the temperature at the surface of the pipe was measured, the temperature sensor reading reaches a maximum value that is lower than the set temperature of the water in the tank. The exposed temperature value for the heating state in Equation 3.3 was adjusted accordingly in order to obtain more accurate simulation results. The simulation results have a similar shape to the EWH outlet temperatures measured in 10 second intervals by Weihl and Kempton [62] and are in good agreement with the measured outlet temperature values. From the "worst case" scenario shown in Figure 3.4a, it can be seen that the minimum rise in temperature that needs to be detected for a small usage event is 6 degrees over 2 samples and that the pipe takes approximately 13 samples to fall by 2°C. However, in order to obtain accurate duration estimates of the events, the decay must be adjusted for events that cause the outlet temperature to rise by a more significant amount (i.e. closer to the set temperature), as shown by the "best case" scenario illustrated in Figure 3.4b. Therefore an increase of 4°C over 2 samples was chosen as the characteristics of a start event. For a stop event, a decrease in 2°C was chosen and the number of samples was varied depending on the maximum outlet temperature reached after a start event. A value of seven samples was chosen for events that increase the outlet temperature above 35°C and a value of 14 samples for an outlet temperature below 35°C.

3.2.2 Typical temperature profile

The purpose of the event detection algorithm is to identify warm water usage events using only the outlet temperature reported in by a temperature sensor attached to the outlet pipe of the EWH, as shown for the EWH configuration in Figure 3.5. The identified consumption patterns can then be used to create a recommended control schedule for

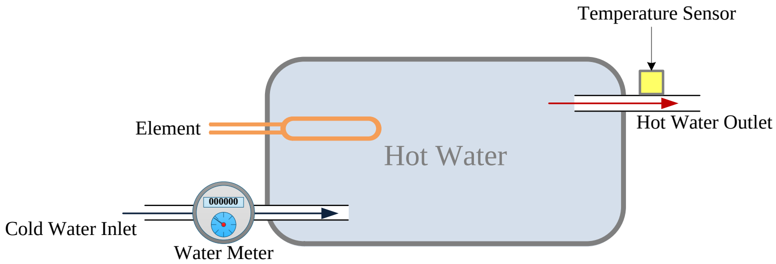
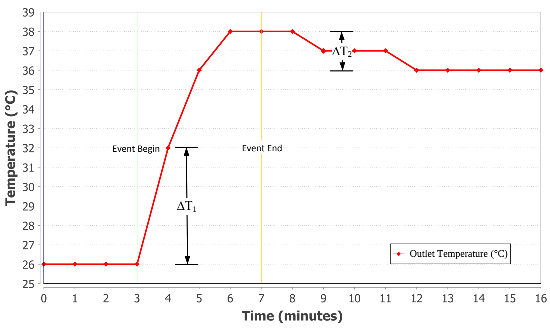
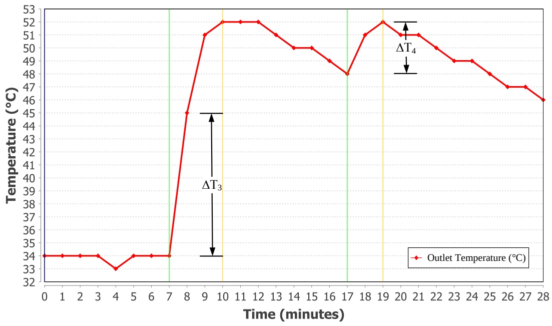


Figure 3.5: Hardware configuration of intelligent EWH.



(a) Isolated usage event



(b) Two consecutive usage events.

Figure 3.6: Measured outlet temperature for: (a) an isolated usage event; and (b) two consecutive usage events.

users. This is done by allowing the EWH element to turn on only for a period of time before expected usage events occur, which significantly reduces standing losses.

Figure 3.6a shows the typical temperature profile at the outlet for an isolated usage event. The event detection algorithm determines the start and stop times of events by analysing the slope of the outlet pipe temperature. The fluctuations in temperature that define start and stop events are dependent on the difference between the set temperature of the EWH and the ambient temperature of its environment, and will vary between setups. However, it is reasonable to assume that a residential EWH will have a set temperature higher than 50°C to prohibit the growth of the harmful bacteria, Legionella pneumophila [69]. It should be noted that this algorithm will not work for low water temperatures as well as instances where the ambient temperature exceeds the temperature of the warm water.

As shown in Figure 3.6a, there is an increase in temperature of 6°C (ΔT_1) between minutes 2 and 4, which meets the criteria for a start event. However, it is clear from the figure that the start of the usage event is at minute 3, and not minute 2, because this is where the outlet temperature begins to increase. The detection algorithm will compare the temperature values at minute 2 and 3 to determine if they are equal and, if so, shift the starting index one sample later. Between minute 6 and 13, there is a decrease in temperature of 2°C (ΔT_2), which constitutes a stop event. However, it can be seen from Figure 3.6, that the stop event is situated at minute 7. The algorithm was therefore adapted to take the subsequent sample as the end of the event. due to the fact that the decay of the temperature in the pipe is gradual and the duration of events was being overestimated by the algorithm.

Table 3.2: Total volume of water used per event for specific end uses [50; 70].

End Use	Low	Typical	High	$\dot{V}_{typical}(\frac{litres}{min})$
Bath	39.0	80.0	189.0	9.0
Shower	7.6	59.1	303.0	30.0
Bathroom basin	0.3	3.8	60.0	4.8
Kitchen sink	0.6	6.7	73.0	9.0
Washing machine	60.0	113.6	200.0	8.5
Dishwasher	15.1	25.0	43.0	3.8

When events occur within a few minutes of one another (i.e. events are not well isolated), the algorithm will not shift the start event sample forward as described in the previous paragraph. Figure 3.6b shows a scenario with two back-to-back events. The first event at minute 6 is detected using the temperature increase (ΔT_3) in a similar manner as an isolated event and the start event is shifted forward to minute 7. For the second event at minute 17, however, the temperature of the outlet pipe is still significantly higher than the ambient temperature. In this case, the start event is not shifted forward because the increase in temperature (ΔT_4), as a result of the usage event, is indeed occurring at minute 17.

The duration of the events is then determined by taking the difference, in minutes, between the start and stop times of the event. If this duration is greater than 20 minutes, the event is discarded as the length is too long for a typical usage event. This value was chosen based on the length of events seen for the 49 days of data that was analysed. The longest events that were registered for this data were 17 minutes in length and used up to 100 litres of warm water.

3.2.3 Event classification

Warm water in residential buildings is used for indoor-type events and can be broken down into 6 end uses [50]: bath; shower; bathroom basin; kitchen sink; washing machine; and miscellaneous indoor usage. Table 3.2 shows the typical volumetric usage amounts for specific indoor end uses (combined hot and cold water consumption) in South African suburbs [50]. Warm and cold water are mixed to create a blended (i.e. desired) water temperature for usage events at an end point. The desired temperature is typically 40.2°C and can be assumed to remain constant over different seasons for specific individuals [50]. The presented event detection algorithm is only able to approximate the volume of water consumed by usage events using warm water flow rates for specific end uses, such as those shown in Table 3.2. However, the volume of water used for events can differ significantly depending on the duration of the event and the type of fixture at the tap (e.g. low-flow shower heads). For example, the total volume of water consumed by a shower event can be as low as 7.6 litres and as high as 303 litres.

Usage events can be classified as being either fixed energy or fixed volume [57]. A shower or bath, for example, can be considered as fixed energy events as the hot and cold water are mixed to create a certain blended (i.e. desired) temperature at an outlet tap. If the temperature of the warm water is lower, a higher ratio of warm water will be required to deliver the same desired temperature (i.e. thermal energy) at the tap. Washing machine and dishwasher events, however, can be considered fixed volume events as they draw a specific volume of warm water regardless of the set temperature [57]. Fixed energy events need to have their flow rate scaled according to the set temperature of the EWH. The nominal warm water temperature setting for EWHs in South Africa is

65°C (i.e. typical water temperature, $T_{typical}$) and is used to determine the flow rates of events [26]. Typical flow rates ($\dot{V}_{typical}$) for water at 65°C can be used and scaled according to the set temperature of the EWH using the first law of thermodynamics [26], based on the assumption that the amount of energy used by each event will remain constant and that water at the inlet temperature is at baseline energy [24]:

$$E_{adjusted} = E_{typical} \tag{3.4}$$

$$\rho c_p \dot{V}_{adjusted}(T_{adjusted} - T_{inlet}) = \rho c_p \dot{V}_{typical}(T_{typical} - T_{inlet}) \tag{3.5}$$

$$\dot{V}_{adusted} = \dot{V}_{typical} \cdot \frac{(T_{typical} - T_{inlet})}{(T_{adjusted} - T_{inlet})} \tag{3.6}$$

Where: $E_{typical}$ is the energy of a usage event at the typical temperature 65°C; and $E_{adjusted}$ and $V_{adjusted}$ are the energy and scaled flow rate of the usage event. Warm water events can be classified into three separate categories: small, which consists of warm water usage events that consume 15 litres or less; medium, where more than 15 but less than or equal to 30 litres are used; and large, which are events for which more than 30 litres of warm water are consumed. The amount of water used by typical end use events (m_{warm}) can be calculated using the typical combined usage (m_{total}) shown in Table 3.2 in combination with the energy balance equation as follows:

$$E_{warm} = E_{total} \tag{3.7}$$

$$m_{warm} c_p (T_{warm} - T_{inlet}) = m_{total} c_p (T_{water} - T_{inlet}) \tag{3.8}$$

$$m_{warm} = m_{total} \frac{(T_{water} - T_{inlet})}{(T_{warm} - T_{inlet})} \tag{3.9}$$

The amount of warm water used by each typical end use was calculated using Equation 3.9 with: a set temperature of 65°C (T_{warm}); a blended temperature of 40.2°C (T_{water}); and an inlet temperature (T_{inlet}) of 20°C. This usage amount was then used to classify each event into one of the three categories mentioned above and the results summarised in Table 3.3. Bathroom basins, kitchen sinks and dishwashers are categorised as small events as their usage volumes are typically quite low. The flow rate for small usage events was therefore chosen as 3 litres per minute to allow all of these events to be captured by this category. Showers are the only event categorised as a medium event size. A typical shower is 3 to 4 minutes in duration and typically consumes 26 litres of warm water. A flow rate of 6 litres per minute was designated to medium events in order to capture both of these typical events. Since both washing machines and baths are considered large events, the flow rate for a large event was chosen as 9 litres per minute. The flow rates used are for typical events in South Africa but can be modified further for: different regions (e.g. USA); additional end uses (e.g. washing of face or hands); sub-categorisation of end uses (e.g. large or small shower); or even specific types of fixtures (e.g. low-flow shower head).

3.3 Experimental setup

The water usage events registered by the water meter were compared to the events detected by the thermal system, to determine the accuracy of the algorithm in terms of detecting events and estimating their duration. The event detection algorithm was tested on 49 days' outlet temperature and water meter data sampled at a frequency of once per

Table 3.3: Classifications of warm water end uses.

End Use	Small	Medium	Large
Bath			×
Shower		×	
Bathroom basin	×		
Kitchen sink	×		
Washing machine			×
Dishwasher	×		

Table 3.4: Results of Event Detection Algorithm

	# Detected	# Missed	# False Positives	% Accuracy
Small	48	6	Unknown	88
Medium	44	0	Unknown	100
Large	34	1	Unknown	97
Total	126	7	5	91

minute. This data was obtained from a 150 litre EWH with a 3 kW element installed in a residential household. Water usage events were classified into three categories according to the volume of warm water used: small events, which were less than 15 litres (10 percent of the EWH tank volume); medium events, which between 15 and 30 litres (between 10 and 20 percent of the EWH tank volume); and large events, which were greater than 30 litres (more than 20 percent of the EWH tank volume). The volumetric estimation accuracy of the algorithm was evaluated using the 4 datasets described in Section 2.2.4.2. However, for dataset 3, the outlet temperature sensor stopped reporting data for an hour on the second day. During this 2 hour interval, the water meter was still recording data but the event detection algorithm was unable to detect events that occurred due to the loss of data. The first 2 days of this dataset were therefore removed, reducing the total number of days included in dataset 3 to 8 for the purposes of the volumetric estimation analysis.

3.4 Results

3.4.1 Detection accuracy

A water meter was installed on the water inlet pipe of the EWH, as shown in Figure 3.5, to determine the actual volume of warm water consumed by usage events to test the thermal approach. The water meter outputs a pulse for every 0.5 litres of water used, but requires a flow of more than 2 litres per minute. The total number of pulses generated in a sampling interval (typically a minute) is reported to an online server. Figure 3.7 shows a screenshot of the software that was developed to determine the accuracy of the event detection algorithm. Using the water meter data, the start of a water usage event was classified as a non-zero value detected after at least two zero values. The end of a water usage event was classified as two consecutive zero values following the start of an event. Two consecutive zeroes were chosen for water usage events that occur sufficiently close to one another to be considered as a single usage event. The results of the algorithm are shown in Table 3.4.

The results show that the algorithm was able to detect 91% of usage events successfully. Of the 7 events that were not detected by the algorithm, 6 of these were small usage events where less than 2.5 litres of water was used. These events were too small to cause a large

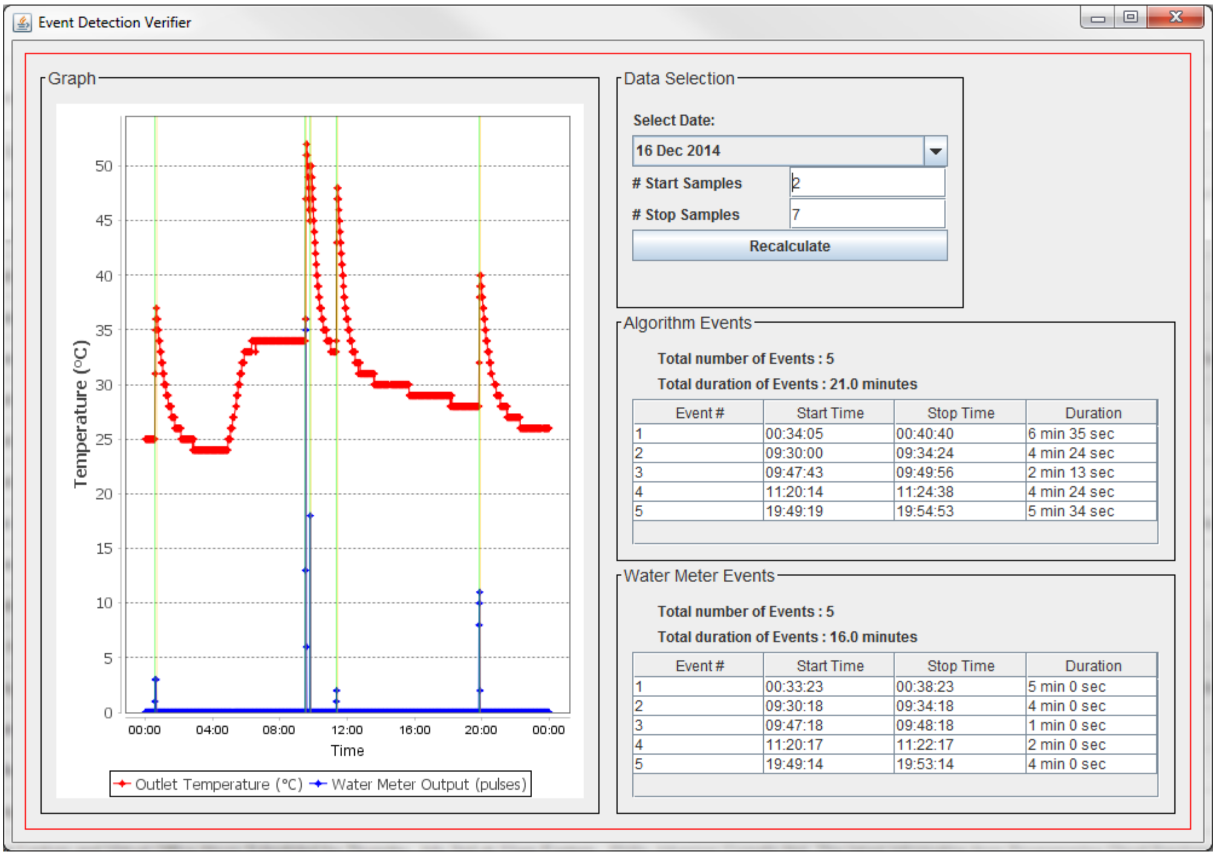


Figure 3.7: Screenshot of software developed to analyse usage patterns and to compare water meter data with the thermal event detection algorithm.

enough increase in the outlet temperature and, hence, were not detected by the algorithm. The large event that was missed by the event detector was an event that occurred 7 minutes after another large water usage event. The temperature of the outlet had not decayed sufficiently after the first event, which meant the increase in outlet temperature was below the detection threshold of 4°C. However, the algorithm was able to correctly detect two large usage events that occur within 10 minutes of one another.

False positives are events indicated by the algorithm where no warm water usage was registered by the water meter. Five such events were detected and are caused by one of two possible scenarios: a low flow rate warm water draw that causes hot water to flow through the outlet pipe but is below the minimum flow rate registered by the water meter (i.e. 2 litres per minute); low volume usage events that are less than the minimum volume of water that would cause the water meter to generate a pulse (i.e. 0.5 litres per pulse). The algorithm was also tested on 5 days' data (separate to the 49 days with usage events) where the tank was heated but no usage events occurred. The outlet temperature on these days fluctuated by over 4°C due to changes in ambient temperature and no events were detected by the algorithm as these fluctuations occurred over the course of the day and not over a small number of samples.

3.4.2 Duration estimation

The estimation of the duration is inaccurate for very short usage events (i.e. one minute events). This is because the temperature decay takes much longer than the rapid increase in temperature at the start of an event. Also, a minimum of 3 samples is required to create

Table 3.5: Duration Estimation Error Results

	0 minutes	1 minute	2 minutes	3 minutes	>3 minutes
Small	18%	29%	33%	16%	4%
Medium	26%	47%	19%	3%	5%
Large	15%	19%	23%	16%	27%
Total	20%	33%	26%	11%	10%

Table 3.6: Summary of usage events for datasets.

Dataset	# Small Events	# Medium Events	# Large Events	Total Events	Total Volume Measured [litres]	Total Volume Estimated [litres]	Error [%]
1	14	12	7	33	650	687	5.69
2	9	9	7	25	706	648	8.21
3	2	5	4	11	343	315	8.16
4	13	1	18	32	1489	576	61.3
Total	**38**	**27**	**36**	**101**	**3188**	**2226**	30.18

an event (i.e. a start event followed directly by a stop event) so the algorithm cannot accurately estimate the duration of the event if it is less than 2 minutes in duration. Additionally, the duration of longer events (i.e. greater than 10 minutes) is underestimated when smaller amounts of water are used towards the end of the event. For example, slight adjustments to the temperature of a bath after it has been filled.

For these longer events, smaller amounts of warm water (typically less than 1 litre) are drawn from the EWH several minutes after the initial usage event. These small draws maintain the temperature of the outlet at a high level, causing the algorithm to incorrectly estimate the duration of an event. Sixteen such usage events were omitted from the 126 total events detected to produce the results shown in Table 3.5. The results show that 79% of the 110 events considered have a duration estimation error of less than 2 minutes. Some longer events (between 7 – 10 minutes) had a higher estimation error of around 3 to 4 minutes. This is due to the more rapid decrease in the outlet temperature as a result of the warm water in the tank being replaced with cold water from the inlet pipe (which, in turn, travels through the outlet pipe) after a long period of usage.

3.4.3 Volumetric estimation

The mobile application can typically be used to obtain input from users in order to classify events. However, in the absence of user input, the events were classified using water meter data. Each detected event was classified as small, medium or large according to the amount of water recorded by the water meter. Once classified, the relevant flow rate was assigned to each usage event over the duration detected by the outlet temperature algorithm. In some instances, events with very low usage amounts (i.e. less than 0.5 litres) or flow rates (i.e. less than 2 litres per minute) are detected using the outlet temperature but are not registered by the water meter. These events consume little warm water and are therefore classified as small events.

After the event classification process, the one- and two-node models were used to simulate an EWH with a set temperature of 65°C for 4 datasets with varying schedule settings spanning several seasons. The one-node model was used for the datasets that implement schedule control (i.e. 1 and 2) and the two-node model was used for the datasets that implement thermostat control (i.e. 3 and 4). Additionally, Table 3.6 shows a summary of the number of each type of usage events included in the datasets, as well as the total volume of warm water consumption measured by the water meter (V_{total} $Measured$) and the estimated amount of warm water consumed using the outlet data (V_{total} $Estimated$).

Table 3.7: Energy estimates using water meter and outlet temperature data.

		Water Meter		Outlet Temperature	
Dataset	Energy Input (Measured) [kWh]	Energy Input (Calculated) [kWh]	Error [%]	Energy Input (Calculated) [kWh]	Error [%]
1	38.90	38.81	0.25	38.50	1.05
2	41.86	42.23	0.88	41.25	1.46
3	37.26	36.48	2.08	34.55	7.27
4	115.20	107.46	6.72	64.28	44.21

These results illustrate that the volumetric estimation was able to determine the amount of warm water consumed with an error of less than 10% for the first 3 datasets. Finally, Table 3.7 contains the results of the simulations for each dataset using the water meter and the outlet temperature (i.e. volumetric estimation) data.

The overall estimated energy input of the EWH (E_{input}) was in good agreement with the measured values for both the water meter and outlet temperature data. The calculated energy input error was less than 10% for the first 3 datasets, with dataset 4 yielding inaccurate results. As expected, the water meter data yielded more accurate results for the energy estimation than the outlet temperature data for all the datasets.

Dataset 4 includes several extremely large usage events that warrant further consideration. Six of the 18 large events in dataset 4 consumed more than 95 litres of water each. This results in a significant error in the estimation of the EWHs energy usage when using both the water meter and outlet temperature data. This is because the one node model is not able to accurately model such large events as it does not account for the stratification that occurs within the tank when large amounts of water are withdrawn [42]. Additionally, the duration estimates from the outlet temperature for such large events are inaccurate. This is because the events consume enough warm water to empty the EWH tank and reduce the water temperature flowing through the outlet pipe to the inlet temperature. This causes a sudden drop in the outlet pipe temperature which, in turn, leads the event detection algorithm to significantly underestimate the duration of these events and therefore the amount of water consumed. It may therefore be necessary to further classify larger end uses, such as showers and baths, as the volume of water consumed by these events can vary drastically, which concurs with the findings in Table 3.2.

3.5 Conclusion

This section presents a hardware and algorithmic solution that uses thermal transients at the outlet of an EWH to measure consumption patterns. The solution was tested using 49 days of data which included 127 usage events and was found to accurately detect usage events with an accuracy of 91%. Additionally, the algorithm was able to detect very small usage events (0.5 litres was detected successfully). However, the event duration is within 2 minutes accurate 79% of the time. Thereafter, the outlet temperature and water meter data were used as inputs to a physical model of a domestic EWH for estimating the energy consumption under various control settings. The outlet temperature data was used to estimate both the total volume of warm water consumed and the energy input for the EWH with an error of less than 10% for 3 of the 4 datasets considered. The limitations of the volumetric estimation as well as the one node EWH model when estimating energy usage for high volume usage events as a result in differences of user behaviour (e.g. shower/bath duration) are illustrated.

Chapter 4

Android mobile application

For indirect load management programs, where consumers are responsible for the control of their devices, customer participation is important. Users need to be able to control and understand their energy consumption in a simple and convenient manner. This is not currently the case with EWHs, which are often positioned in hard to reach locations (such as on roofs or in attics). Additionally, users don't always know the best means of controlling their EWHs. For example, they may not know when to switch it on and off to reduce energy consumption but still have warm water when needed. This section describes an Android application that utilises the EWH model and the usage detection algorithm, developed in Chapters 2 and 3 respectively, to allow users to: monitor the status and usage data of a residential EWH; control the on/off times and temperature of an EWH and provide instantaneous feedback on the impact of control changes; and generate recommended heating schedules based on their warm water usage. A usability study is then conducted to determine the ease with which users can accomplish various tasks.

4.1 Smartphone based eco-feedback

Smartphones and tablet devices (referred to as mobile devices in this paper) have become increasingly popular and worldwide shipments are expected to reach over two billion units by 2016 [71; 72]. Additionally, it is estimated that tablet shipments will exceed the total personal computer (PC) shipments (desktop and portable PCs combined) by 2017 [72]. The smartphone market has experienced exponential growth in recent years, and sales numbers have surpassed those of feature phones for the first time in history [73]. A total of 225 million smartphone units were sold worldwide, accounting for 51.8 percent of total mobile phone sales in the second fiscal quarter of 2013 [73]. The differences between smartphones and other mobile phones (such as feature phones) are not succinct. In this chapter, the concept of smartphones refers to those devices which enhance the traditional capabilities of feature phones with the use of superior hardware and an advanced operating system (e.g. Android or iOS). The ubiquity of mobile devices places them in a unique position to support smart metering efforts in a number of ways. Additionally, these devices can be interfaced to other technologies (such as smart meters) to realise unique solutions.

Paay et al [74] presents two mobile application systems (Water Advisor [75] and Power Advisor [76]) that are aimed at promoting pro-environmental behaviour and reducing domestic resource consumption. Each of these applications were tested over several weeks which included 3 weeks of continuous usage by participants. The Water Advisor application was developed to support gardeners in using water more efficiently by helping them decide whether or not to water their gardens using various sources of information, including: weather data; expert advice; and garden community information. The study included 10 participants (5 of which used mobile application and 5 the desktop equivalent application) and was conducted in Melbourne, Australia. During the 3 week deployment phase participants received 6 messages (both in application inbox and SMS) from the 3 sources of information. The first 3 messages were from a single source while the other 3 combined 2 sources of information. For example, for the mixed messages, users received advice from the expert on whether to water their garden of skip a watering day and were also shown what the gardening community plan to do.

The Power Advisor application was developed with the goal of determining whether a mobile application providing tailored information can raise users' awareness of electricity consumption in their household. The system was tested in 10 households in Aalborg, Denmark with automatic meter readers that record the energy consumption every hour by photographing the existing energy meter readout. Participants were able to view their personal consumption data in 4 different forms: total household energy usage of the present week in comparison to similar household in the northern region of Denmark; the cumulative household energy consumption during the previous 24 hours; and the daily energy consumption of the present week in comparison to the previous week's usage; and the last value measured by the smart meter. Similar to the Water Advisor application, users were also provided with information from: an expert, which takes into account users' consumption data to inform them whether they should reduce their usage as well as providing general advice on reducing consumption; and community behaviour, which notifies users whether other users have achieved their energy reduction goals for the current week. As with Water Advisor, participants received 9 messages during the 3 week deployment period: 3 of these were persuasive messages relating to individual power consumption; 3 of the messages were about the community; and 3 messages consisted of advice from the expert. The results from both these systems found that: self-comparison is an important factor for promoting conservation as users always compared the information they received to their own circumstances/usage; tailored information is more useful and influential than generic information; and the majority of users preferred the mobile application (to manually reading meter or desktop application).

4.1.1 Android operating system

Android is an open source, Linux based operating system (OS) designed for mobile devices and is currently being developed by Google. Although primarily designed for touchscreen devices such as smartphones and tablets, Android has also been modified for use on devices such as televisions, gaming consoles, cars and wearables (e.g. watches). The versatility of Android has allowed for the development of a wide variety of devices, with varying price ranges and screen sizes, making it a very competitive OS that dominates the smartphone market with an 82.8% share in the second quarter of 2015 [77]. Mobile applications are typically distributed via the Google Play Store, which hosts the largest collection of applications of any store, with an estimated 1.6 million applications available as of July 2015 [78].

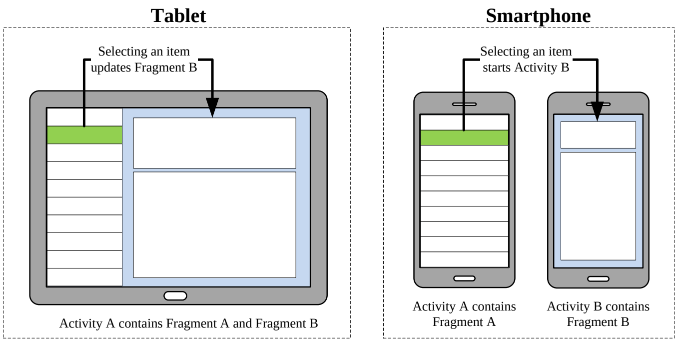


Figure 4.1: Example of fragment combination in UI layouts for different mobile devices. Adapted from [79].

4.1.1.1 User interface

The Activity class in Android is an application component that provides a screen with which users can interact in order to perform various actions. Each activity is given a window in which to draw its user interface (UI) which contains certain elements. The Fragment class represents a portion of the UI inside an Activity [79]. Fragments must always be embedded in an activity and are directly affected by any changes to the state of the hosting activity. For example, if the activity is closed or paused (i.e. minimised), so are all the fragments that it hosts. Fragments were added to Android to allow for more flexibility in an application's UI design by allowing the creation of multi-pane layouts which can be recomposed and recombined based on the available screen size. Figure 4.1 shows an example of how two fragments can be combined to create a multi-pane layout in a single activity for a tablet when displaying an item that has been selected from a list. However, the fragments are separated into two activities, one for selecting and one for displaying, on a smartphone due to its limited screen space.

4.1.1.2 Networking tasks

Networking tasks, such as interacting with a web server, may take a considerable amount of time depending on the connection speed and the amount of data that is being transferred and/or received. Android, therefore, does not allow networking tasks to be performed on the main thread, which is also referred to as the UI thread since it manages events typically related to the UI elements (e.g. button clicks). This implies that networking tasks must be performed on a background thread to improve the user experience by keeping the application responsive.

Android's IntentService class provides an elegant mechanism for processing asynchronous requests, such as networking tasks, on demand on background threads. Unlike the AsyncTask class (which is commonly used for background tasks), IntentService is not affected by most UI lifecycle events that would typically cause AsyncTask to fail (e.g. screen rotation). Additionally, an IntentService will only run when there are intents to process, unlike AsyncTask which, if not handled properly, can cause memory leaks. Although these shortcomings of AsyncTask can be handled through various means, IntentService intrinsically avoids them altogether. The shortcomings of IntentServices are that they cannot be cancelled or interrupted and that work requests run sequentially, that is, requests are executed in first in first out (FIFO) queue.

(a) Status tab. (b) Usage tab. (c) Graph tab.

Figure 4.2: Screenshots of tabs implemented in first version of Android mobile application.

4.2 Application development

This section describes the development of the Android mobile application aimed at increasing users' awareness of their energy and warm water consumption. Additionally, the application allows users to control their EWH in a more convenient, as well as efficient, manner. The application was developed using Android Development Tools (ADT), a plugin for the Eclipse IDE. At the time of development, ADT was the official IDE for Android, which has since changed to Android Studio. The various aspects relating to the user interface (UI) of the application are first presented, followed by a description of the back-end used to perform networking tasks. The application was designed for devices that run Android version 4.0.3 (API 15) and above, which constitutes approximately 95% of all active Android devices [80].

4.2.1 UI navigation

Fragments in Android, which were detailed in Section 4.1.1.1, allow for the design of more complex layouts, such as a tabbed interface. Figure 4.2 shows the tabbed interface that was initially used to implement the Android application before the control functionality was available and optimisation functionality was developed. The presently selected tab is indicated by underlining the relevant label from the tab navigation bar. A tabbed interface is well suited to a small number of equally important views. However, as further functionality was added to the application, this type of navigation became less advantageous as tab labels are hidden due to lack of screen space. Additionally, the tab navigation bar consumes a considerable amount of space, which can become problematic for smaller screen sizes.

The navigation drawer is a common pattern often implemented in Google applications (e.g. Google Play Store) [81]. It consists of a panel (i.e. drawer) that displays the applications main navigation options on the left edge of the screen when opened. The drawer is displayed over other content while it is open and darkens the content behind the drawer, as shown in Figure 4.3, until a selection is made. The drawer is hidden by default and can be revealed by touching the drawer icon on the action bar or by swiping a finger on the left edge of the screen. Additionally, the presently selected navigation

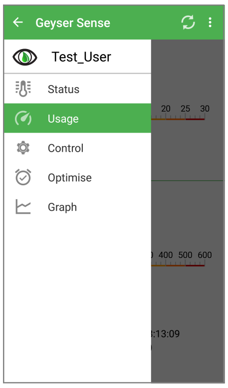


Figure 4.3: Navigation drawer opened and displayed over selected tab.

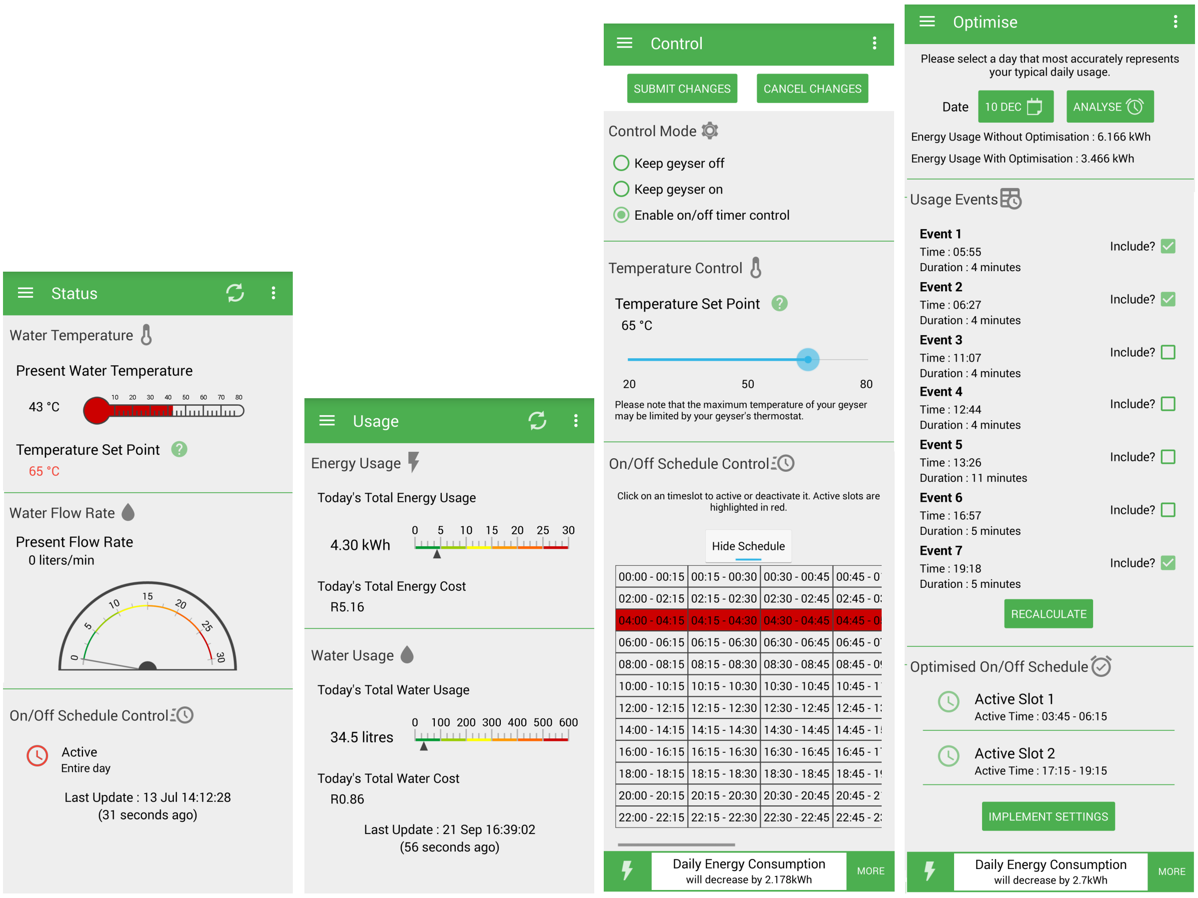
option is typically highlighted in order to indicate the tab that the user has open behind the navigation drawer. This receding menu is space efficient as it can be used to display more navigation options than a tabbed interface while only being displayed when a user is interested in navigating to a different part of the application [82]. Drawer navigation was therefore implemented in the second version of the mobile application to accommodate the additional navigation options that were added as the functionality of the application was expanded.

4.2.2 UI implementation

Figure 4.4 shows the screenshots of all the tabs (excluding the Graph Tab) that were implemented in the second version of the Android mobile application. The mobile application was also updated to implement the new Android Material design that was released with Android 5.0 (API 21). This design specification provides a guide for visual, motion and interaction design across platforms and devices. Additionally, many of the UI elements initially used for display purposes were replaced with custom views, described in more detail in section 4.2.2.1. Finally, after the creation of the EWH model in Chapter 2, a pop-up dialog window was created to display the changes in energy consumption as a result of modifications made to the control control settings of the EWH, detailed further in Section 4.2.2.1.

4.2.2.1 Custom views

The first version of the application displayed the temperature and cumulative consumption data on speedometers. These speedometers consume a considerable amount of space and may be confusing to users as they are not the conventional means of displaying this type of data. For example, users are much more accustomed to viewing temperature information on a thermometer. The Android framework provides a set of base classes and extensible markup language (XML) tags for extending the View class and defining various attributes for a custom view. Two custom views were implemented to display the usage and temperature in a more space efficient manner, namely: Thermometer (shown in Figure 4.4a), which is used to display the internal temperature of the EWH; and RangeBar (shown in Figure 4.4b), which is a rectangular bar used to display a range of values, with each interval being represented by a specific colour. These views present information to users in a more conventional means that users are more accustomed to.



(a) Status tab. (b) Usage tab. (c) Control tab. (d) Optimise tab.

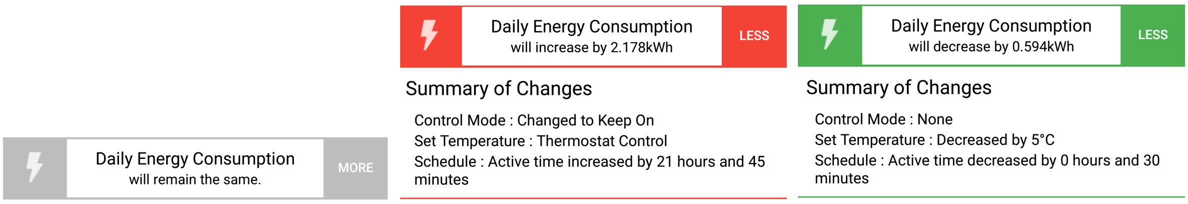
Figure 4.4: Screenshots of tabs implemented in second version of Android mobile application.

4.2.2.2 Status tab

Users are able to view the status and present settings for the control unit that manages the EWH asset on the Status tab shown in Figure 4.4a. This includes: the present water temperature value; the temperature set point, which is only enforced when the control unit is enabled; the present on or off state of the EWH element; the present energy usage of the asset; the status of the timer control unit (i.e. whether or not control unit is enabled); and the on/off schedule that is implemented by the control unit (which is an expandable table that can be minimised to save space). The dial used to display the present flow rate was created by editing a custom library, called SpeedometerView [83].

4.2.2.3 Usage tab

The Usage tab, shown in Figure 4.4b, can be used to view the most recent data reported by the EWH asset. It provides the user with an overview of the asset's daily resource consumption and the associated cost thereof (in Rands). The data is also timestamped so that users are able to determine when last these values were updated. The data summarised by this tab can help users to better understand their daily usage patterns without providing excessive amounts of data that would overwhelm and confuse users. Additionally, the tab provides both a usage value (either kWh or litres), for those users who are perhaps more technical or interested on the environmental impact of their usage,



(a) No change in energy usage. (b) Increased energy usage. (c) Decreased energy usage.

Figure 4.5: Screenshots of pop-up window indicating change in EWH energy consumption.

as well as a monetary value, for users who may be non-technical users or interested in financial incentives for reducing their energy and water consumption.

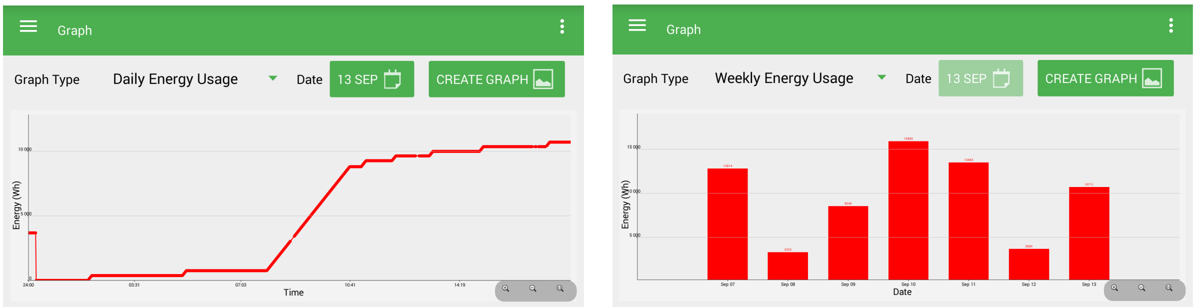
4.2.2.4 Savings/Summary window

A small pop-up window widget was created in order to display the energy estimates calculated by the EWH model presented in Section 2. The implementation of this widget can be seen in Figure 4.5 where the colour of the window is dependent on the change in energy consumption. These colours include: grey if no change in energy usage occurs; red if the energy consumption increases; and green if the energy usage is estimated to decrease. Additionally, the window can be expanded, by tapping on the "More" label shown in Figure 4.5a, to display a summary of how the control settings have been modified (shown in Figure 4.5b and 4.5c). This pop-up window is displayed each time a control setting is modified in the Control tab or a recommended schedule is generated in the Optimise tab, which are both presented in the following sections.

4.2.2.5 Control tab

Figure 4.4c shows the Control tab that allows users to control the various settings for their EWH from their mobile device. Users are able to modify: the control scheme/mode of the EWH (i.e. keep off, keep on or schedule control); the set temperature of the EWH; and the on/off schedule which controls when the EWH is allowed to turn on when implementing schedule control. The control scheme and set temperature can be adjusted using standard Android widgets. The control scheme can be modified using the RadioGroup class, which establishes a set of radio buttons, one for each mode of control. The set temperature is set using a SeekBar class, which defines a bar that allows the user to set a point on a progress bar that can be moved to a specific point on the bar by tapping on or sliding a finger to the desired point.

A custom class, called CustomButton, was created in order to allow control of the schedule of the EWH. This class extends the Button class in Android with the added feature of being able to store its present state (i.e. active or inactive). The schedule for a day consists of 96 timeslots (15 minutes each) which can either be active or inactive. The table shown at the bottom of Figure 4.4c contains 96 custom buttons that are used to indicate the schedule being implemented. The state of a timeslot is reflected in the UI by changing the colour of the button to red or white if the timeslot is active or inactive, respectively, and can be modified by tapping on the relevant button. Additionally, the table can be scrolled horizontally if the device does not have enough space to display all the buttons (e.g. 4.7-inch smartphone in vertical orientation) and is hideable, in order to save space when it is not needed. This tab also displays a savings window which indicates the estimated increase or decrease in the energy consumption of the EWH as a result



(a) Graph of daily total energy consumption. (b) Graph of energy usage for last 7 days.

Figure 4.6: Cumulative energy consumption of EWH for (a) selected day and (b) past week.

of any changes to the settings of the EWH (e.g. lowering the set temperature), using the EWH model developed in Chapter 2. The potential savings are calculated using the previous and new control settings when applied to a typical usage profile of one shower at 06:00 in the morning and another shower at 18:00 in the evening.

4.2.2.6 Optimise tab

Figure 4.4d shows the Optimise tab within the smartphone application, which is responsible for generating recommended heating schedules. In order to generate a recommended schedule, the user selects a day that represents their typical usage. The outlet temperature for this day is obtained from the server and used by the event detection algorithm, developed in Chapter 3, to determine when warm water is being consumed. Users can then select the events that are part of their daily routine, from the list of events that are detected, to ensure that the algorithm doesn't take into account atypical events. The recommended schedule, based on the usage of the selected day, is displayed to the user, as well as the potential energy savings as a result of implementing this schedule in comparison to the user's existing control settings. The estimates indicating the difference in energy consumption are calculated using the model for the EWH described in Chapter 2. Similar to the Control tab, the savings are calculated using the previous and recommended control settings when applied to the warm water usage profile (estimated or measured) of the day selected by the user.

4.2.2.7 Graph tab

The application also allows users to graph various types of daily usage data and weekly energy usage in order to better understand their usage. An example of a daily graph and the weekly energy graph, as generated by the Graph Tab, are shown in Figure 4.6. The weekly energy graph generates a bar graph using the total energy consumption data of the previous 7 days. This functionality was created with the use of AChartEngine, an open source graphing library for Android [84]. This library can be used to produce a variety of graphs on a set of axes that are capable of being panned or zooming in and out. The user can choose the type (e.g. energy consumption) and date of the data they wish to view. The data for an entire day is obtained from the server and displayed in time intervals of one minute. Users are also able touch anywhere on the graph to obtain the time and data values for a particular point (the annotation and vertical line in Figure 4.6).

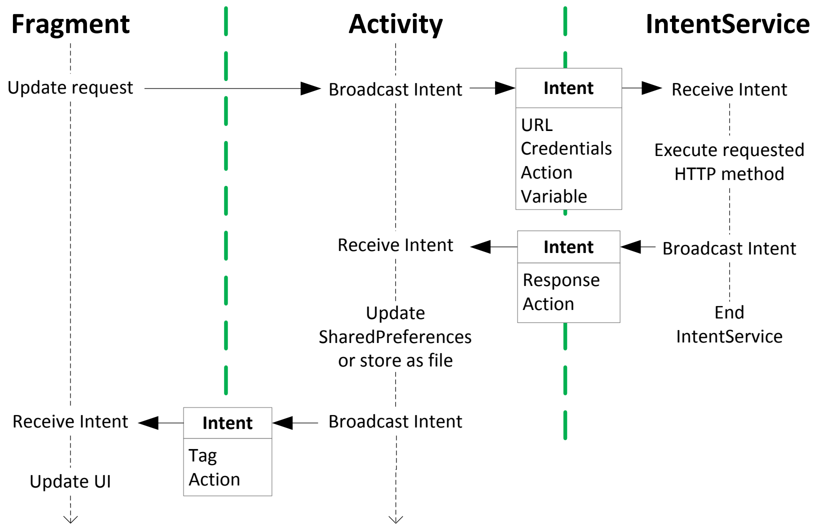


Figure 4.7: Interaction between UI and server.

4.2.3 Server communication

The Android application was originally designed to interface to the Trintel SMART platform [85]. This is a cloud based platform that can be utilised to manage, monitor and control devices for machine-to-machine (M2M) applications. M2M devices exchange data (e.g. measured outlet temperature) and commands (e.g. schedule to implement on EWH) with the SMART platform via a cellular modem. Additionally, the SMART platform allows for the creation of an online interface that provides various components for the visualisation of data (e.g. graphs) and control settings (e.g. buttons, adjustable knobs). Additionally, the SMART platform allows read and write access to data and variables through its representational state transfer (REST) application programming interface (API) using suitable Hypertext Transfer Protocol (HTTP) requests (i.e. GET and POST methods).

The IntentService class described in Section 4.1.1.2 was used to implement the background thread that executes networking tasks. IntentService uses a work queue to offload tasks from the application's UI thread and all requests are processed sequentially on a single worker thread. IntentService is well suited to the requirements of the mobile application presented in this section as it will not need to service many HTTP requests and the data downloaded is typically small in size. For example, an entire day's worth of data (i.e. 1440 data points) for a single variable is only 23 kilobytes (kB) in size. Additionally, updating the UI on the application or the control settings on the server takes a maximum of 2 and 3 HTTP requests, respectively. Requests are sent to the service by passing it an Intent, which is a data structure that holds an abstract description of an action that must be performed. Additional information can be attached to an Intent using a Bundle, which is a mapping from String values to various Parceable types (e.g. Integer, Character array).

Figure 4.7 illustrates the interaction between: the presently displayed Fragment and its hosting Activity in the UI thread; and the IntentService in the background thread that executes given requests. From Figure 4.7, the presently displayed Fragment creates an update request based on some input from the user (e.g. submit new control settings) or the mobile application (e.g. auto-refresh). The hosting Activity contains the methods that Fragments can use to communicate with the IntentService. The LocalBroadcast-

Manager class is used by the various components of the application to communicate with one another. This class ensures that: the data transferred is only accessible within the application (i.e. private data is secure); other applications are unable to broadcast messages to exploit any security vulnerabilities that the application may have; and it is more efficient that broadcasting a global broadcast message [86]. The Activity packages the request into an Intent, which is uses to start the IntentService and pass relevant information, including: the uniform resource locator (URL) for the request; the credentials of the user for authentication; the action to be performed (e.g. retrieve latest data); and the value and name of the variable to be modified or retrieved if the request is to update a control setting or generate a graph. It should be noted that there is a separate URL used to obtain a list of the latest data points. This is done to avoid sending multiple requests to obtain the latest data point of each value separately.

The Intent is then received by the IntentService, which executes the relevant HTTP method based on the contents of the Intent. Once completed, the response of the HTTP method is then broadcast back to the Activity that initiated the request using an Intent, which also contains the action that the Activity must perform. If an error occurs, the details of the error are transferred back to the UI. For example, if the HTTP method was unable to contact the server (e.g. due to lack of connectivity) then the Intent will notify the Activity that the server could not be contacted and that an error message should be displayed on the UI, notifying the user of the failure. If the method is executed successfully, the response is stored locally by the Activity by updating the SharedPreferences of the application. The SharedPreferences class allows the reading and writing of a collection of key-value pairs that can be shared by all clients that have access rights to the collection. However, when the Graph or Optimise tab request a day's worth of data, the application does not store this data in the SharedPreferences because it is too large and is not suitable to be stored as a key-value pair. Instead, the day's data is saved as a file in the application's private storage that is accessible only to the GeyserSense application. After saving the server's response, the Activity then broadcasts an Intent containing, the tag of the currently displayed Fragment and action that needs to be performed on this fragment (i.e. refresh data, display error). The Intent is then received by the intended Fragment which carries out then updates the UI based on the action provided. By keeping the interface between application components as generic as possible, the reusability of the code is greatly enhanced. This communication interface can be used by any Android application that wishes to obtain data for any type of asset on the Trintel SMART platform, as long as it has the required credentials. For example, an Android application could use the server communication interface to monitor a minibus taxi for a fleet monitoring application by only modifying the front-end code. In other words, the application need only modify the UI elements (for displaying data in useful format) and the processing of the response from the server on the UI thread (i.e. mapping of response to UI elements).

Initially the SMART platform only allowed read access to data through its REST API using suitable HTTP requests (i.e. GET methods). The server can convey raw data to users for graphing or display purposes. For example, the present power consumption of the EWH can be requested to determine if the element is actively heating the water in the EWH tank at a given time. Alternatively, the server can provide users with metric values, which have been processed by the server to create a useful summary of the raw data. The cumulative daily energy consumption for the present day is an example of such a value. Below is an example of the URL that can be used to request a list of all the metrics available for a given asset from the Trinity SMART platform:

`http://smart.trintel.co.za/api/core/metric_values/?object_id=11469&object_type=asset`

Where the "object_id" query parameter specifies the specific asset that the application is interested in. All HTTP requests sent to the server require basic authentication (i.e. username and password) in order to obtain access to data of any kind. Figure 4.8 shows an example of how a single metric is returned in the response from the server for a metric request. All data is returned from the server in JavaScript Object Notation (JSON) data-interchange format. This format allows the creation of objects containing sets of name-value mappings which can then be parsed using classes from the standard org.json package to extract the data that is used to populate the UI elements [87]. For example, the JSON formatted metric shown in Figure 4.8 is for the temperature set point of the EWH as indicated by the "name" property. Additionally, the temperature set point can be obtained by reading the value of the "value" property inside the "data" object of the metric. If the application is only interested in a single metric, it can either request a specific metric from the server (using an additional query parameter in the request URL) or it can filter the array of JSON objects returned by the server using the "id" property, which uniquely identifies each metric.

The RESTful API was further developed by Trintel in December 2014 to allow applications to send control requests (i.e. POST methods). This functionality allows users to modify various settings, including: the control mode of the EWH system (i.e. always on, timer control, keep off); the set temperature of the EWH; the on/off schedule of the asset. These requests consist of commands and data writes. If a specific command has not been defined to modify a certain value, the value of a variable can be modified using a data write action. When issuing a command or data write action, the HTTP request must contain a header indicating, among other things, the type of action that must be performed (i.e. command or data write) and the value that must be assigned


```
{
  "description" : "Maximum temperature the controller will allow the geyser to reach.",
  "name" : "Geyser Temperature Set Point",
  "created" : "2012-09-06T08:19:32",
  "class_name" : "Metric",
  "metric_model_id" : 252,
  "modified" : "2012-09-06T08:19:32",
  "units" : "°C",
  "position" : "755, 10",
  "data" : {
        "name": "Geyser Temperature Set Point",
        "timestamp": "2015-08-28T09:08:42",
        "value" : "65",
        "units" : "°C",
        "property" : {
              "path" : "/status",
              "type" : "int",
              "access_rights" : "RO",
              "name": "s52"
        },
        "id" : 0
  },
  "id" : 1413,
  "size" : "169, 327"
 }
```


Figure 4.8: Example of JSON formatted response returned by server for metric request.

```
{
    "unit": {
        "assetId" : "GT",
        "uniqueId" : "353270040671226",
        "name" : "Control mode change Android."
    },
    "ttl" : 3600000,
    "command" : {
        "name" : "c01",
        "args" : [2]
    }
}
```


(a) Command action header.


```
{
    "unit" : {
        "uniqueId" : "353270040671226",
        "assetId" : "GT"
    },
    "ttl" : 3600000,
    "name" : "Set temperature change Android.",
    "dataWrite" : {
        "path" : "param",
        "data" : {
            "p01" : 60,
        }
    }
}
```


(b) Data write action header.

Figure 4.9: HTTP request headers for (a) command and (b) data write actions.

to a particular variable (e.g. set temperature value). Figure 4.9 shows the headers for a command and data write action. Both headers must specify the unit details, which includes: the unique identification (ID) of the asset to be accessed ("assetId"); and the International Mobile Station Equipment Identity (IMEI) of the device that is being modified ("uniqueId"). There are also several optional parameters that may be specified. For example, the request can specify a time-to-live ("ttl") parameter, which specifies the amount of time that is allowed to elapse before the action is cancelled. Below is an example of the URL that can be used to perform command and data write actions:

```
http://api.trintel.co.za/api/v2/jobs?token=353270040671226%
3AMTQyOTk2MDkxNA%3A4cbaFAGuXR%2FLnGFT7LG10D72gew
```

Where the "token" query parameter is the security token required to modify data. These security tokens were added to the RESTful API to ensure data privacy and to prevent users from sending unauthorised commands. A user can only obtain a security token to access or modify data for a specific asset that is associated with their account. This is done by uniquely identifying each asset with the IMEI of the modem that is responsible for reporting data for the given asset. If a user account attempts to obtain a token for another asset with a different IMEI that is not associated with their account, they will receive an unauthorised response message.


```
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<om2m:contentInstance xmlns:om2m="http://uri.etsi.org/m2m" xmlns:xmime="http://
www.w3.org/2005/05/xmlmime" om2m:id="CI_33957544" href="nscl/applications/geyser_110/
containers/DATA/contentInstances/CI_33957544">
    <om2m:creationTime>2015-09-17T13:47:40.965+02:00</om2m:creationTime>
    <om2m:lastModifiedTime>2015-09-17T13:47:40.966+02:00</om2m:lastModifiedTime>
    <om2m:delayTolerance>2015-09-17T17:07:40.965+02:00</om2m:delayTolerance>
    <om2m:contentSize>216</om2m:contentSize>
    <om2m:content>eyJWZXIiOjIxLCJJRCI6MTEwLCJWc3RhdGUiOiJPUEVOIiwiUnN0YXRlIjoiT04iL
    CJHc3RhdGUiOiJPSyIsIlQxIjo1NSwiVDIiOjM5LCJUMyI6MjEsIlQ0IjoyMSwiS1ciOjAuMDA3MTE
    2LCJLV0giOjAuOTg0NzQwLCJITG1pbiI6MC4wMDAwMDAsIkNMbWluIjowLjAwMDAwMCwiS
    Ex0b3RhbCI6MS4zODEzMzMsIkNMdG90YWwiOjAuMDAwMDAwLCJUc3RhbXAiOjE0NDI0OT
    A0NjB9</om2m:content>
</om2m:contentInstance>
```


(a) Response to GET request from OM2M server.


```
{
  "Ver" : 21,
  "ID" : 110,
  "Vstate" : "OPEN",
  "Rstate" : "ON",
  "Gstate" : "OK",
  "T1" : 55,
  "T2" : 39,
  "T3" : 21,
  "T4" : 21,
  "KW" : 0.007116,
  "KWH" : 0.98474,
  "HLmin" : 0,
  "CLmin" : 0,
  "HLtotal" : 1.381333,
  "CLtotal" : 0,
  "Tstamp" : 1442490460
}
```


(b) Base64 decoded data in JSON format.

Figure 4.10: (a) Response and (b) decoded data from OM2M server

4.2.4 OM2M Implementation

The European Telecommunications Standards Institute (ETSI) released a set of specifications for a common M2M service platform. OM2M provides an open source service platform for M2M interoperability based on the ETSI-M2M standard [88]. This platform also provides a HTTP-based RESTful API for managing and creating M2M resources. The mobile application was modified to interface to a server running an OM2M implementation of an EWH management application. The interaction between the UI and the server shown in Figure 4.7 remained unchanged. To interface to this platform the URLs that are used to access data and send control commands were modified. Additionally, the responses from the OM2M server are returned in XML format, as shown in Figure 4.10a. XML is similar to JSON in that it is a data interchange format. Essentially, an XML document consists of a root element and, typically, several child elements to form a tree structure. In Figure 4.10a, the contentInstance is the root element and has 5 child elements. From this figure, the XML data can be parsed using the XML Parser, from the standard org.xmlpull.v1 package, to extract the desired content from the "<om2m:content>" tag. The data contained in this tag is Base64 encoded and must be Base64 decoded before it can be processed further by the application. Base64 encoding is a group of binary-to-text encoding schemes used to represent and transfer binary data over mediums that allow only printable characters [89]. Figure 4.10b shows the resulting JSON object that is obtained after Base64 decoding the received data. Once in this format, the data can be processed in a similar fashion to the data received from the Trinity SMART platform and used to populate the mobile application's UI. For example, the "KWH" and "HLtotal" properties inside the JSON object contain the cumulative energy and warm water consumption for the present day, respectively.

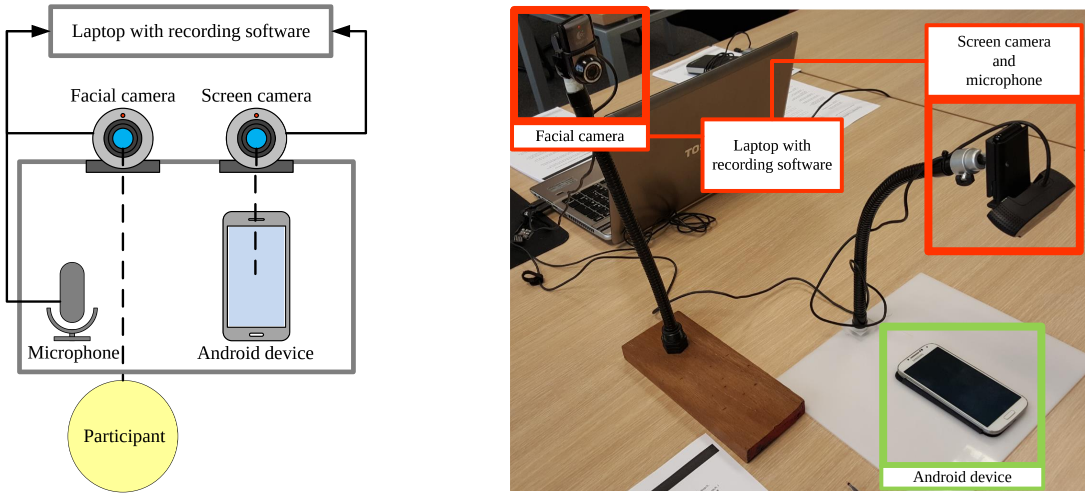
4.3 Usability study development

The purpose of this study is to evaluate the usability of the Geyser Sense Android mobile application from the perspective of a typical user. The specific goals include:

- Viewing the present status of their EWH, including: energy and warm water usage (both instantaneous and cumulative); and the temperature of the water inside the tank.
- Controlling the settings of their EWH manually, including: the control scheme; the set temperature of the asset; and the on/off schedule of the asset.
- Determining the effect of changes in control settings on their energy consumption.
- Understanding how to control their EWH more efficiently and reducing their energy usage with the application's analytical functionality.
- Viewing historical data using the application's graphing functionality.

4.3.1 Test procedure

Participants were tested one at a time in a designated venue. A set script was used to present each participant with a short introduction of the test procedure, test equipment as well as a brief description of the EWH assets that the Geyser Sense application monitors



(a) Diagram of usability study. (b) Photo of usability study.

Figure 4.11: (a) Diagram and (b) photo of usability study setup and equipment.

and controls in order to provide context for the mobile application. Participants were then presented with several task scenarios that allow them to interact with each aspect of the mobile application. After each scenario, the user was provided with a post-task questionnaire to evaluate the ease with which they were able to complete a specific task. Once all task scenarios were completed by a participant, he/she was then asked to complete a system usability scale document, which is used to gauge the general usability of the system. The documents used during this study can be found in Appendix C.

4.3.2 Test environment and equipment

While performing the designated task scenarios, users were monitored in several ways. The test setup and equipment is shown diagrammatically in Figure 4.11a. The screen camera shown was used to monitor the screen of the mobile device and the user's hands while performing the scenarios. The facial camera monitored the user's facial expression while performing the tasks. The microphone was used to capture all audio from the user while thinking aloud as well as any interaction that the user required from the moderator. A photo of the equipment and setup implemented for the study is shown in Figure 4.11b. All participants were provided with a Samsung Galaxy S4 device with the Geyser Sense application installed. The mobile application was reinstalled for each participant to ensure that all users had an identical experience (i.e. no residual data between sessions).

4.3.3 Usability scenarios

The following scenarios are designed to evaluate the Geyser Sense Android mobile application relative to the test objectives.The estimated time to complete (ETC) a given scenario is also indicated.

Scenario 1:

You are about to go home after work or shopping and would like to take a warm shower when you are home. Before you leave, you want to make sure that the water in the geyser is warm enough for you to shower when you arrive at home.

Process steps:

1. Select the status tab if not already selected.

2. View present temperature of the water in the geyser's tank.

ETC : 1 minute

Scenario 2:

Your friend tells you that his geyser consumes a considerable amount of energy and is costing him R15.00 a day in energy bills (That's about R450.00 a month!). This prompts you to see: how much energy your geyser is consuming in a day; how much this is costing you; and if this amount is high.

Process steps:

1. Select the usage tab if not already selected.

2. View present day's total energy usage and the cost thereof.

3. Determine if this usage is low/high using the RangeBar.

ETC : 1 minutes

Scenario 3:

Your neighbour tells you that his geyser burst and he had to pay a large bill to replace it. To make the matter worse, he says he had no idea it had been leaking for several days and has to pay a massive water bill as well. You know that no-one is currently using any hot water in your house and you want to know if your geyser might be leaking.

Process steps:

1. Select the water tab if not already selected.

2. Determine present flow rate of hot water for geyser.

ETC : 1 minute

Scenario 4:

You see on the news that Eskom is asking everyone to only turn their geyser on from 03:00 till 07:00 in the morning to reduce their energy consumption. You decide to do this in order to try and avoid further load shedding.

Process steps:

1. Select the control tab if not already selected.

2. Enable on/off timer control if not already enabled.

3. Open the schedule to allow modification to be made.

4. Disable the relevant timeslots.

ETC : 3 minutes

Scenario 5:

You keep burning yourself when you climb into the shower and decide that the water in *your geyser is too hot. In order to fix this problem, you decide to lower the temperature of the water in your geyser by 10°C.*

Process steps:

1. Select the control tab if not already selected.
2. Enable on/off timer control if not already enabled.
3. Decrease the set temperature of the geyser by 10°C.

ETC : 1 minutes

Scenario 6:

You are going away on holiday and decide to turn off your geyser while you are away to save energy and money. How much energy and money will you save by doing this?

Process steps:

1. Select the control tab if not already selected.
2. Enable "Always Off" control.
3. Determine energy savings from the dialog window.

ETC : 1 minute

Scenario 7:

Your neighbour has also invested in an intelligent geyser system and tells you he has decreased his energy usage significantly by using the settings recommended by the mobile app for his geyser. You decide you also want to save money and energy by attempting to do the same. How do the optimised settings differ from your current settings?

Process steps:

1. Select the analysis tab if not already selected.
2. Select a suitable/typical day and analyse it.
3. Determine effects of changes on energy usage and control settings.
4. Optional: Select the usage events that are relevant.
5. Optional: Recalculate analysis.

ETC : 3 minutes

Scenario 8:

Your colleague tells you that your geyser is constantly using power to keep the water in the tank warm, even when you're sleeping. This makes you want to see what your energy usage looks like over the space of a day so you can see when you are using energy.

Process steps:

1. Select graph tab if not already selected.

2. Select "Daily Energy Usage" as graph type if not already selected.

3. Create graph and view data.

ETC : 2 minute

Scenario 9:

Your friend tells you that he is using almost twice the amount of energy on weekends than weekdays and he thinks it's because his whole family showers after coming back from the beach. This interests you and you want to find out what days of the week you use the most energy.

Process steps:

1. Select graph tab if not already selected.

2. Select "Weekly Energy Usage" as graph type if not already selected.

3. Create graph and view data.

ETC : 1 minute

4.4 Usability study results

This section details the method used to evaluate usability of the Geyser Sense mobile application. Nielsen and Landauer [90] found that the detection of usability problems as a function of the number of users tested is well modelled using a Poisson model. Using this model and mean values for the parameters, it is estimated that by examining 5 participants in a usability study, approximately 80% of a system's usability flaws can be discovered. 10 participants were included in the usability study presented in this section, which is estimated to reveal approximately 95% of usability problems. Unfortunately, on the first day of the study, the recording software malfunctioned and the recordings of two participants were lost. However, the notes from their interviews and the results from their post-task questionnaires were used in this evaluation. For the completion rate and time on task metrics, only the data from 8 participants was included. The age group distribution of the participants is as follows: 5 participants are between the ages of 18 and 24; 4 users are between 25 and 34 years old; and 1 participant is between 35 and 44 years of age. Additionally, 7 of the 10 participants included in the study were engineering students and only one participant was female. Therefore the group consisted mainly of young, tech-savvy male users and women were under-represented in the sample. The results of the usability study are illustrated in Table 4.1 and are discussed further in the following sections.

4.4.1 Completion rate

Completion rate refers to the percentage of participants who are able to successfully complete a task without critical errors. A critical error is defined as an error which creates an incorrect or incomplete outcome. For example, if the mobile application crashes it is considered to be a critical error. Additionally, if a participant requires assistance in order to complete a task then the task will be scored as a critical error. The completion rate

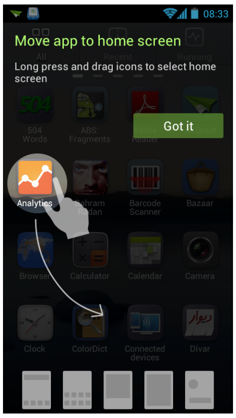


Figure 4.12: Example of tutorial to explain functionality in Android for first time user.

in Table 4.1 indicate that scenarios 2 and 7 have the highest failure rates. Scenario 2 presented users with the task of viewing their daily energy consumption for the present day. The low completion rate of scenario 2 can be attributed to the lack of an auto-refresh capability. 5 of the 8 participants did not notice the refresh icon displayed in the upper action bar of the application and had to be given assistance in order to complete the task. The auto-refresh functionality was initially not included in order to reduce the data usage of the application. However, this can easily be rectified by automatically generating a GET request when the user selects the Usage tab and allowing users to disable the auto refresh functionality in a separate "Options" menu. This lack of viewing was also observed for the savings window that displays the change in energy consumption as a result of a modifying the settings of the EWH. 4 of the 10 participants did not notice the savings window. This is because the size and location of the savings window is similar to the typical placement of advertisements within mobile applications. Participants therefore ignored the window when it was displayed as they assumed it was an advertisement. A possible solution for this lack of visibility would be to initially display the full summary of the changes in energy consumption (i.e. expanded version), instead of the minimised version of the window. The window's height increases threefold when it is fully displayed (in comparison to minimised size) and can be minimised by users through the "Less" button.

Scenario 7, which has the lowest score, asked users to use the optimisation functionality in order to determine the energy savings that can be achieved by implementing the settings recommended by the mobile application. For this task, it was difficult to create the context in which this functionality would typically be utilised. For example, this tab presents users with a list of events that form part of their typical daily usage. However,

Table 4.1: Results of usability study.

Scenario #	Completion rate [%]	ETC	Mean time on task	Completed on time [%]	Mean score
1	75.0	1 m 0 s	1 m 12 s	36.5	4.2
2	12.5	1 m 0 s	1 m 05 s	36.5	4.3
3	62.5	1 m 0 s	0 m 49 s	75.0	4.4
4	75.0	3 m 0 s	1 m 50 s	87.5	3.6
5	75.0	1 m 0 s	0 m 48 s	87.5	4.4
6	87.5	1 m 0 s	0 m 48 s	75.0	4.4
7	12.5	3 m 0 s	2 m 25 s	62.5	2.7
8	75.0	2 m 0 s	2 m 11 s	50.0	4.0
9	100	1 m 0 s	0 m 42 s	87.5	4.6
Average	**63.9**	**N/A**	**N/A**	**66.4**	**4.1**

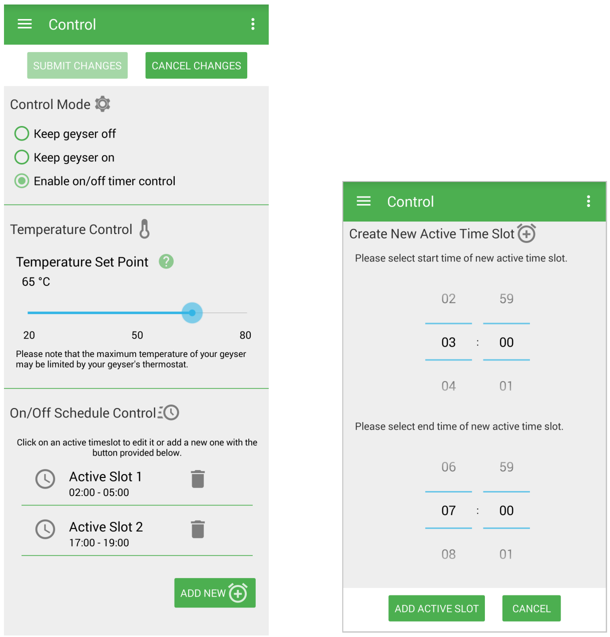
since their is no universal profile that all users conform to, it was difficult for participants to recognise events as being part of their daily usage profile during testing. For example, the application presented users with a profile that typically had 2 to 3 usage events that occur in the morning between 06:00 and 09:00. However, several of the participants only shower or bath in the evening and were therefore unable to recognise these events as being part of their "typical" usage profile. It may be necessary to implement a tutorial interface to guide users through the optimisation process the first time they try to access this functionality. An example of such a tutorial is shown in Figure 4.12, which is used to explain to new users how to move icons to the home screen on an Android phone the first time the phone is started.

Alternatively, instead of asking users to identify their usage events from a list of detected usage volumes, the application could ask users to specify the time intervals during which they require warm water. For example, users could specify they require warm water between 06:00 and 08:00 in the morning. Alternatively, the application could implement a rule set that automatically optimises the EWH control schedule. For example, it could determine which events to include in the analysis by exclude low volume warm water usage events below a certain threshold (e.g. less than 5 litres). However, if large typical events occur within the "typical" day specified by users, the application would have no means of excluding it from the analysis without input from the user.

During the study, the understanding of the tasks caused some confusion. Scenario 3, for example, has a completion rate that is slightly lower the average for this study. This is mainly as a result of confusion around the task itself. Participants were asked to determine if their EWH was leaking water. Although the task encouraged users to interact with the water flow rate UI element, the task was not suitable as most users expect the application to automatically warn them of a potential leakage or burst. Additionally, many users assumed that if they refresh the usage tab and there is not change in the volume of water consumed for the present day then there is no leakage present, given that they had to assume that no-one was presently using water. Although this is logically correct, it doesn't fulfil the goal of having users interact with the water flow rate UI element and is therefore considered as a failure.

4.4.2 Post-task questionnaire

As discussed in Section 4.3, after each scenario, participants were provided with a post-task questionnaire to evaluate the ease with which they were able to complete a specific task. The questionnaire consisted of a five-level Likert scale ranging from 1 (very difficult) to 5 (very easy) as well as a comment area in which participants could provide additional information on how the task could be made easier. The mean post-task questionnaire score for each scenario is summarised in Table 4.1. 7 out of the possible 9 scenarios had a mean score of 4.0 or higher. The two tasks that were below this mean value were scenarios 4 and 7. Scenario 4 presented participants with the task of modifying the schedule of their EWH to only be in the active state from 03:00 till 07:00 in the morning. The table used to present the schedule consists of 96 buttons, one for each 15-minute interval during a day. Users found the number of time slots overwhelming and found it tedious to activate or deactivate each time slot one at a time. Additionally, participants took a considerable amount of time to complete this task as they struggled to determine how the schedule functions. For example, certain users interpreted each column in the table as a day of the week. Figure 4.13a shows the alternative layout designed to allow users to modify the schedule of their EWH. This layout has a similar design to Google calendar [91], where



(a) Revised Control tab layout.

(b) Active slot creation screen.

Figure 4.13: Screenshots of (a) revised Control tab layout and (b) active slot creation screen.

active slots are created by selecting a start and an end time to create a heating interval. For example, users could then create the schedule for scenario 4 by clicking the "Add New" button and then selecting 03:00 as the starting time and 07:00 as the end time on the active slot creation screen shown in Figure 4.13b.

Although scenario 2 had a very low completion rate, it has a very high average score. The reason for this discrepancy is that 5 of the 8 participants did not see the refresh icon and had to be assisted. Once users were shown the refresh icon, however, they found it very simple to accomplish this task. This result highlights the importance of a usability study in finding flaws that can be remedied with relative ease and have a significant impact on the usability of the system. Additionally, although scenarios 8 and 9 have high completion rates, there were many problems reported during testing for the graphing interface. This includes: the graph label text size being too small; ineffective zooming and panning; and preferring days of the week to dates to be displayed on the time axis for weekly graphs, instead of dates. Additional functionality for the graphing was also requested by participants. For example, users wanted to be able to overlay different days and/or weeks on the same set of axes to compare their usage across days and weeks. Another difficulty observed during testing was the users confusing display UI elements for control UI elements. For example, users attempted to tap on the thermometer, schedule and the status indicator shown in the status tab to change the modify the settings of the EWH. This can be remedied by placing small "Modify" buttons next to these elements that will navigate users to the Control tab to allow them to edit the desired settings.

4.4.3 Time on task and completed on time

The time on task (ToT) is defined as the time taken by participants to complete a given scenario and the completed on time (CoT) value refers to the percentage of users that were able to complete the task within the ETC. This time is measured from the time the participant starts the scenario until the time that he/she indicates the completion of the scenario. The ETC, mean ToT and CoT, for each scenario, are shown in Table 4.1. From these results, the mean ToT for scenarios 1 and 2 exceeded the ETC and these scenarios had the lowest CoT. The problems associated with scenario 2 were discussed in Section 4.4.1 as this task had a low completion rate as well. The refresh icon was only shown to users once they had thought they were done, which also increased the time taken to complete this task. As was the case with scenario 3, the goal of scenario 1 caused some confusion amongst users. Scenario 1 asked participants to determine if the water in the EWH was warm enough for a shower. The users that failed to complete the task successfully, or within the estimated time, assumed that the water in the EWH was too cold, without consulting the temperature UI element, and navigated to the Control tab to modify the EWH settings in order to start heating the water. Additionally, since this was the first task presented to users, they were curious to investigate the available functionality and spent a considerable amount of time exploring the navigation to become more familiar with the application before attempting to complete the task.

The mean ToT for Scenario 8 also exceeded the ETC and it has the second lowest CoT. Scenario 8 asked users to examine their energy usage over the space of a day and to determine which periods of the day they are using energy. Although participants were able to generate the graph rapidly, they took a considerable amount of time attempting to interpret the resulting curve. Firstly, certain users expected an instantaneous energy graph, instead of the cumulative graph that is generated. Since the EWH element only has two states, the “Instantaneous Power” graph type could be used to determine when the EWH is switched on. However, this value is presented in kiloWatt and not kiloWatt-hours and may confuse users and it may be necessary to add an additional graph type for “Instantaneous Energy Usage” instead. Secondly, the inefficiencies with text size and graph controls (i.e. zooming and panning) also caused participants to take longer than expected to complete this scenario. Finally, as with scenario 7, it is difficult to create a context in which users can determine the times that their EWH uses energy as the graphs generated are not based on their individual consumption. The energy consumption of the EWH will depend on both the water usage profile of the user as well as the control settings that he or she implements.

4.4.4 System usability scale

The system usability scale (SUS) is a simple, five-level Likert scale that is commonly used to provide a general view of usability by covering a variety of aspects related to system usability. The SUS (shown in Appendix C) consists of 10 items used to evaluate various aspects, such as complexity, inconsistency and the need for training. Each item will contribute a score which ranges between 0 to 4 and is added together to create the total score. For odd numbered items, the score contribution is the scale position minus 1 and for even numbered items the score contribution is 5 minus the scale position. This total is converted to a value between 0 and 100 by multiplying the final score by 2.5. This score is not meant to be used as a diagnostic tool and cannot highlight areas of difficulty. However, in combination with the post-task questionnaire results and participant comments collected during the usability testing, a thorough insight into the usability of the mobile application can be obtained. In a sample of 500 usability studies, the mean SUS score obtained was 68, which can be considered as an average score [92]. The mean SUS score of the Geyser Sense mobile application was 84.5. This score is significantly above the average, indicating that the system is user friendly, in general, and that users had a positive overall experience with the mobile application.

4.5 Conclusion

This chapter presented an Android mobile application that aids users in understanding the resource consumption of their EWH and to more efficiently and conveniently control their household EWH. Additionally, the application was interfaced to residential EWH applications on two different M2M platforms, (i.e. Trintel's SMART platform and OM2M). Feedback consisted of both the status and resource consumption (present and historic usage data) of the appliance, as well as the impact of control decisions on future energy consumption. The ease of use of the mobile application was evaluated using a usability study. Several areas of difficulty were determined and these results were used to implement various changes to improve the application by making it more user friendly. In general, the results of the study indicate that the system is user friendly and that participants had a positive overall experience with the mobile application.

Chapter 5

Conclusion

For indirect load management programs, where consumers are responsible for the control of their devices, customer participation is important. Users need to be able to control and understand their energy consumption in a simple and convenient manner. This is not currently the case with EWHs, which are often positioned in hard to reach locations (such as on roofs or in attics). Additionally, the temperature of the water in the EWH tank is a complex function which depends on several factors (e.g. ambient temperature, volume of warm water extraction, etc.) that can make it difficult for consumers to understand.

A mobile based eco-feedback solution for the energy and water consumption data of residential EWHs was then developed. The mobile application created allows consumers to remotely monitor and control their EWH from their mobile device. Additionally, a physics based EWH model and an event detection algorithm were developed and implemented as part of the mobile application. This functionality is used to assist users in making more informed decisions on the control settings of their EWH by providing instantaneous feedback of the impact changes as well as generating recommended heating schedules based on consumers' usage profiles. The mobile application was evaluated using a usability study and the results thereof used to improve the aspects of the application that users found challenging while interacting with the available functionality.

5.1 Evaluation of work

This section provides a summary of the work and results presented in Chapters 2 to 4, with reference to the dissertation hypotheses stated in Chapter 1.

5.1.1 Physics based model of residential EWH

A physics based model of an EWH is developed in Chapter 2 and the results reported in Section 2.3. The energy lost due to usage events and standing losses was estimated by simplifying the temperature distribution of the water in the EWH tank into one or two nodes, depending on the amount of usage that occurred. The model was validated using 6 datasets that span several seasons, implement both schedule and thermostat control and include over 900 hours of measurement data with usage events, as well as 14 days of measured standing losses data. The results show that measured energy usage is modelled with an estimation error of less than 2% and 7% for schedule control and thermostat control respectively. These results confirm Hypothesis 1.1, 1.2 and 1.3:

Hypothesis 1.1:

The energy input by the EWH element can be determined by estimating the temperature of the water in the EWH tank.

Hypothesis 1.2:

The energy lost due to usage events and standing losses can be estimated by simplifying the temperature distribution of the water in the EWH tank into one or two components (i.e. nodes).

Hypothesis 1.3:

The energy input and output of an EWH can be accurately modelled for various control settings, usage profiles and orientations.

The model was used to simulate the behaviour of various EWHs under various control settings and usage profiles. Furthermore, the impact of seasonal temperature variations and several efficiency actions were also considered. The results of this analysis confirm Hypothesis 1.4:

Hypothesis 1.4:

The impact of various energy saving actions (e.g. installing a thermal blanket on EWH) and control settings for several typical usage profiles can be estimated using the EWH model to simulate these conditions.

5.1.2 Usage profile determination

A hardware and algorithmic solution that uses thermal transients at the outlet of an EWH to measure consumption patterns is developed in Chapter 3 and the results reported in Section 3.4. The solution was tested using 49 days of data which included 127 usage events and was found to accurately detect usage events with an accuracy of 91%. Additionally, the event duration is within 2 minutes accurate 79% of the time and the algorithm was able to detect usage events as small as 0.5 litres. These results confirm Hypothesis 2.1 and 2.2:

Hypothesis 2.1:

The time at which usage events occur can be determined with considerable accuracy using the outlet pipe temperature.

Hypothesis 2.2:

The start and end times of usage events can be estimated with reasonable accuracy in order to provide an estimate of the duration of events.

The volume of water consumed by a water event was then estimated by assigning a flow rate (scaled according to size of event) to each usage event over the duration detected by the outlet temperature algorithm. This estimated water usage profile was then compared to the measured water consumption data from the water meter. The volumetric estimation was able to determine the total volume of water consumed with an error of less than 10% for 3 of the 4 datasets considered. Additionally, the outlet temperature (with volumetric estimation) and water meter data were used as inputs to a physical model of a domestic EWH for estimating the energy consumption under various control settings. The outlet temperature data was used to estimate the total energy input with an error of less than 10% for 3 of the 4 datasets considered. This confirms Hypothesis 3.3:

Hypothesis 2.3:
The volume of warm water consumed by usage events can be estimated using typical flow rates of specific end uses of warm water.

5.1.3 Smartphone application

An Android mobile application was developed in Chapter 4 and the results of the usability study used to evaluate the application are reported in Section 4.4. The results of the usability study highlighted several areas of difficulty which were used to generate solutions that would enhance the usability of the mobile application. Additionally, the mobile application achieved a system usability score that is significantly above average, indicating that the system is easy to use and that participants had a positive overall experience. This confirms Hypothesis 3.1:

Hypothesis 3.1:
The smartphone application provides a convenient and user friendly interface for users to monitor and control their EWH.

The EWH model presented in Chapter 2 was implemented as a savings window in the mobile application to provide instantaneous feedback on the impact of control decisions on future energy consumption. The model was tested on a Samsung Galaxy S4 device and was able to simulate the behaviour of an EWH for one day within 55 milliseconds. Also, the usage detection algorithm, presented in Chapter 3, was implemented as part of the mobile application's "Optimise" functionality and used to generate recommended schedules based on the user's selected daily warm water consumption profile. This confirms Hypothesis 3.2 and 3.3:

Hypothesis 3.2:
The application can utilise a model of a residential EWH to provide instantaneous feedback on the impact of control decisions.

Hypothesis 3.3:
The application can utilise a warm water usage profile to help consumers control their EWH more efficiently.

5.2 Future work

Utilities need a means of estimating the effect of implementing DR programs as the optimal switching of thousands EWHs is not a trivial task (e.g. cold load pick-up). The EWH model developed in Chapter 2 can be used to evaluate the effect of various DR programs by simulating the impact of various control settings and usage profiles on the aggregate load profile of multiple EWHs. Although the model was validated using several datasets of actual household data that span several seasons, it is recommended that the model be tested on other similar EWHs to further verify and improve the initial model. For example, the model can be modified to simulate the energy input and output of a 200 litre EWH and as well as account for the increased thermal resistance provided by a thermal blanket. Additionally, the model should be tested using various settings to determine at which point the one-node state becomes more accurate than the two-node state at simulating the thermal distribution of the water in the EWH tank. Furthermore, additional temperature sensors for measuring the inlet and ambient temperature could be used to further increase the accuracy of the model by providing more accurate values for these variables.

The event detection algorithm could be further improved by applying machine learning (e.g. clustering) to better classify events and to obtain additional insight into consumers' usage patterns.

The functionality of the Android mobile application can be further extended and improved as follows:

- Further improvements can be made to the control functionality. For example, allowing users to: implement different control settings for each day of the week (similar to the Nest thermostat) or for different settings for weekends and weekdays; and implement a "Boost" or "Visitor" functionality that allows the user to turn on the EWH temporarily if they require warm water outside of their typical usage profile.

- Additional improvements can also be made to the optimisation functionality. With the advent of TOU tariffs (e.g. Homeflex), a cost function can be implemented to take into account the varying tariff rates to determine the optimal time for users to switch their EWH to reduce their energy consumption while also minimising their electricity cost.

- A summary tab could be added to the application that provides a detailed breakdown of the resource consumption for each usage event, including: the amount of water used; the amount of electricity consumed; and the financial cost of these resources. This could allow users, for example, to link the resource consumption and the associated cost thereof to specific usage events, such as a shower or bath.

- The graphing functionality has significant potential for improvement. Either an alternative graphing library can be used (e.g. AFreeChart [93]) or, preferably, a custom graphing library can be developed in order to provide the types of graphs requested by participants of the usability study. For example, overlaying of different days or weeks to compare temporal differences in usage.

- Users could be provided with normative feedback by including social media (e.g. Twitter, Facebook) into the mobile application. This would allow users to compare their own water and energy consumption with that of their community or other similar households.

- The mobile application should also be implemented on iOS, Apple's mobile operating system, as it has the second largest share of the smartphone market [77]. Objective-C is used to develop iOS applications which implies that the EWH model and event detection algorithm will also need to be reimplemented to provide the functionality available in the Android application.

Appendices

Appendix A

EWH model outputs

Table A.1: Minimum time constant values obtained for datasets.

Dataset #	**Minimum time constant value**
1	561.457
2	522.125
3	551.336
4	512.692

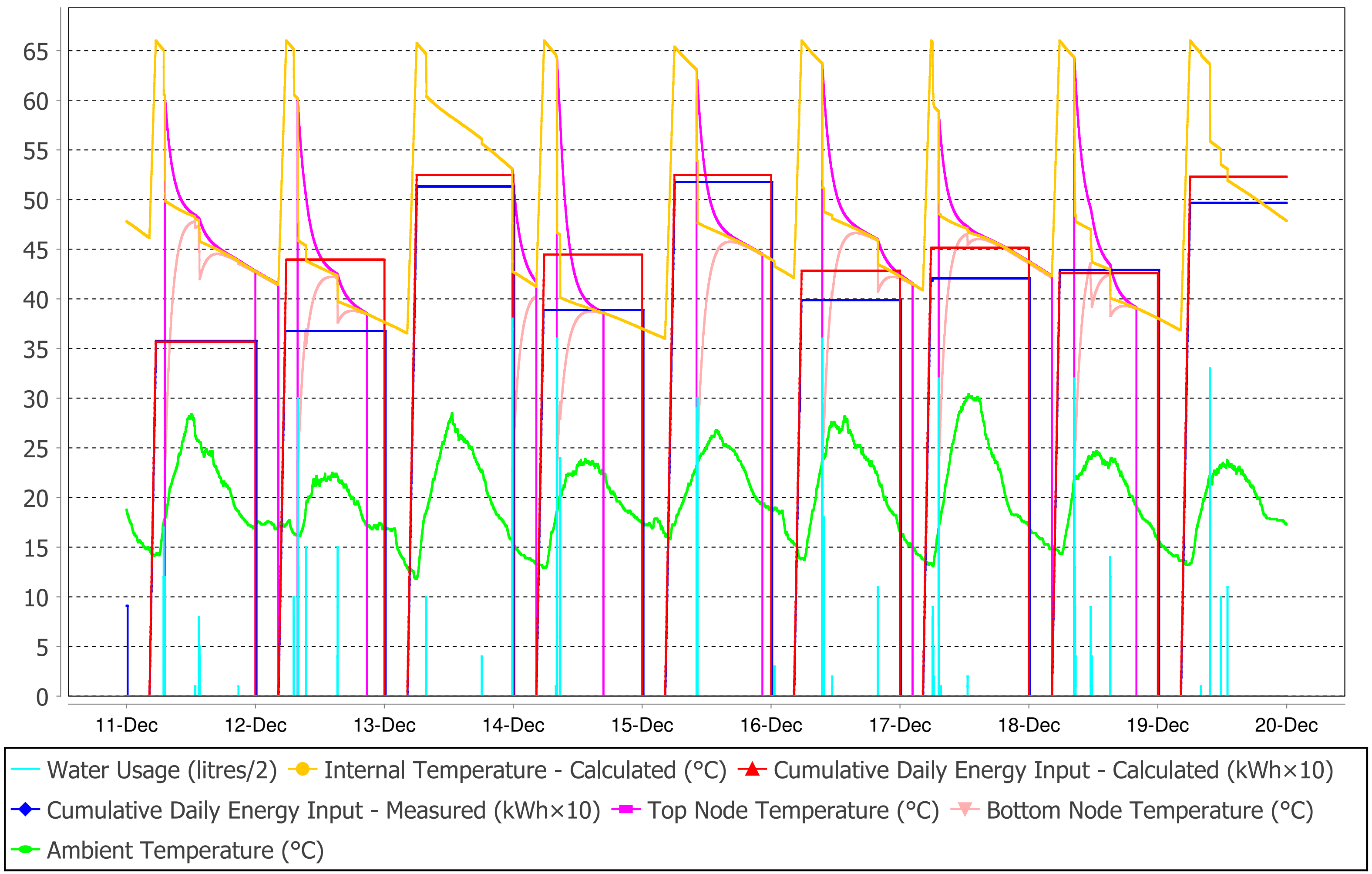


Figure A.1: Graphed output of one-node model for dataset 1, which consists of 9 consecutive days in December 2014 (Summer) with a schedule implemented from 04:15 to 06:00

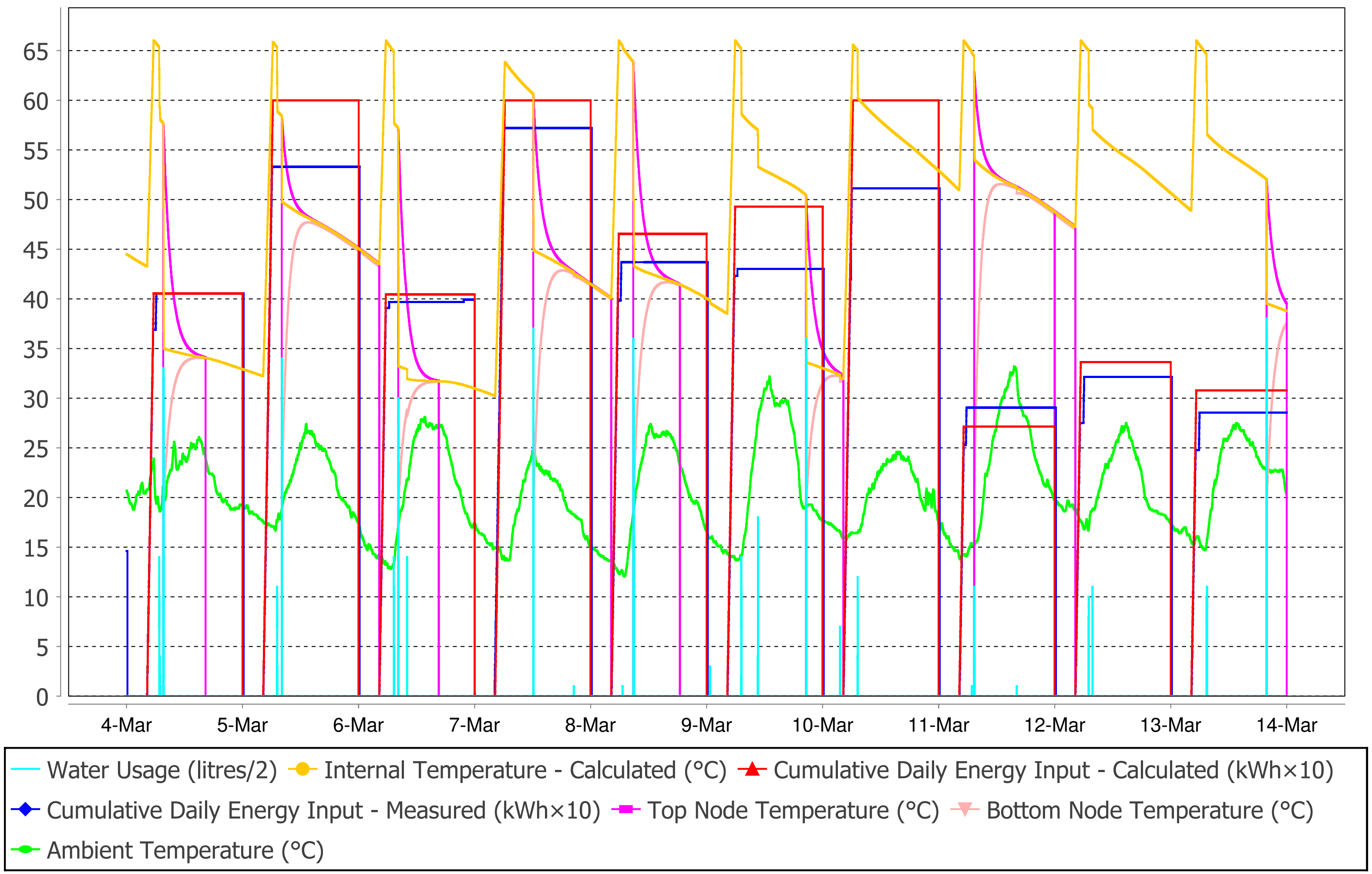


Figure A.2: Graphed output of one-node model for dataset 2, which is comprised of 10 consecutive days in March 2015 (Autumn) with a schedule implemented from 04:15 to 06:00.

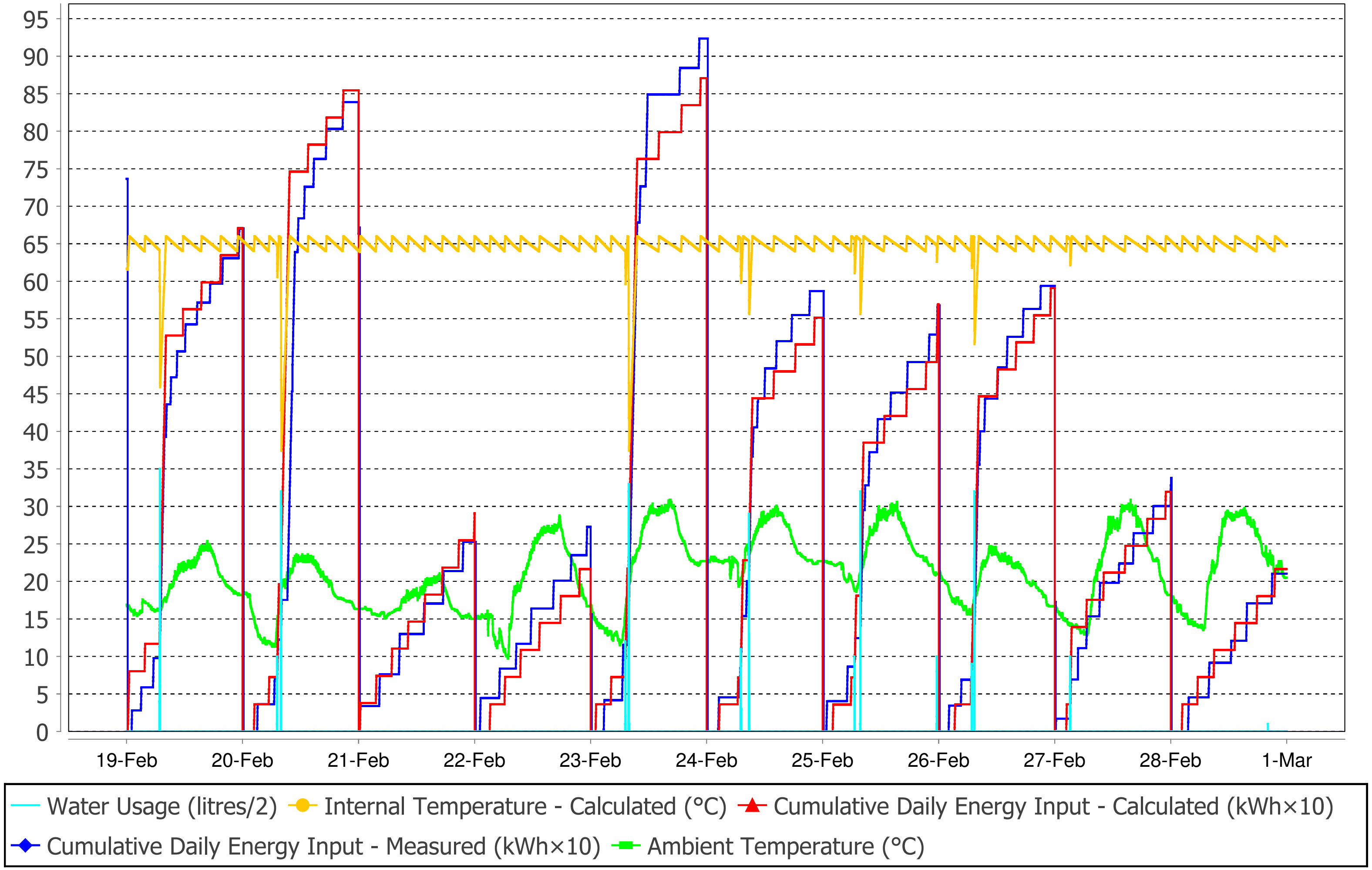


Figure A.3: Graphed output of two-node model for dataset 3, which is made up of 10 consecutive days in February 2015 (Summer) for always on thermostat control.

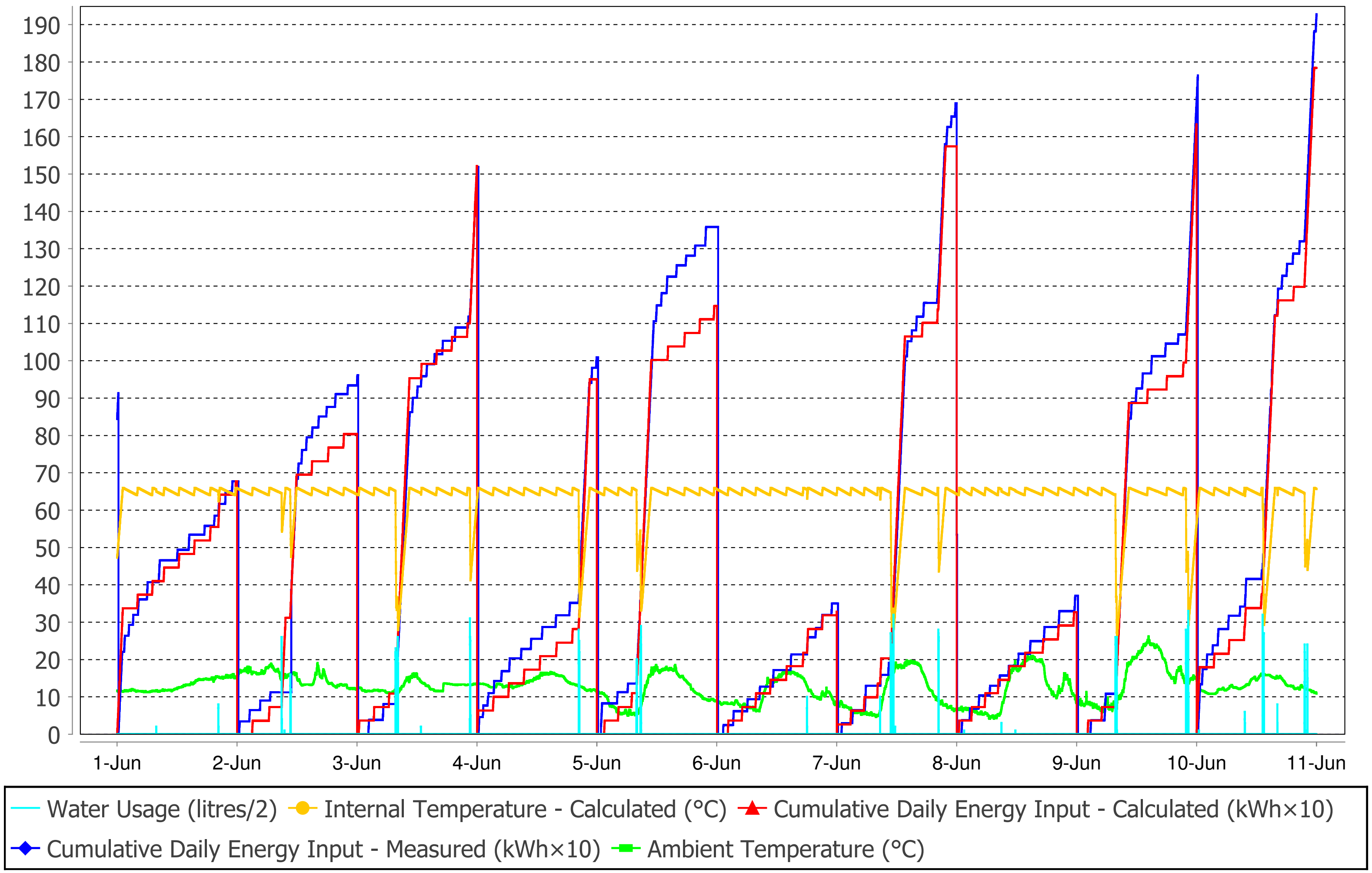


Figure A.4: Graphed output of two-node model for dataset 4, which consists of 10 consecutive days in June 2015 (Winter) for always on thermostat control.

Appendix B

EWH simulator results

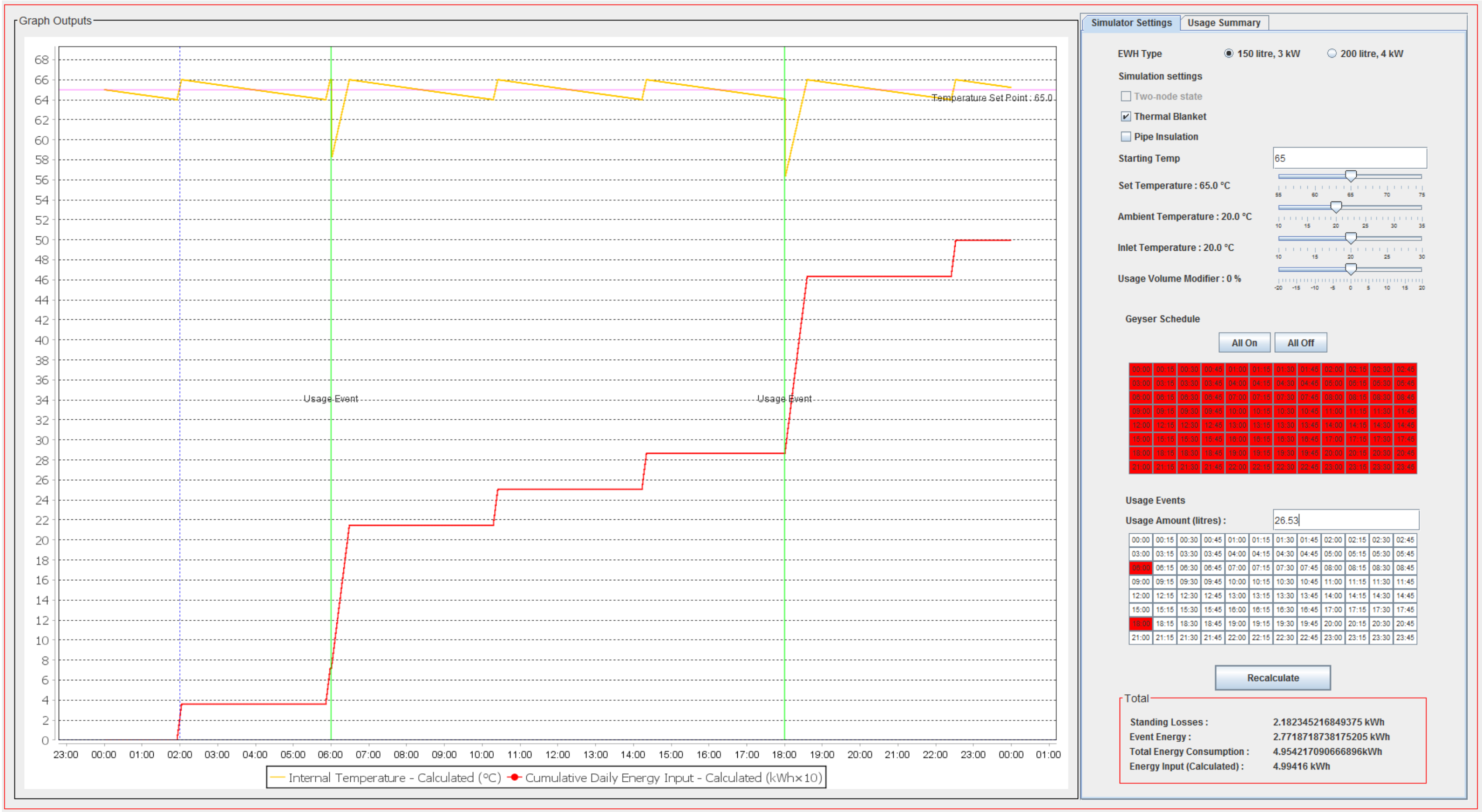


Figure B.1: Screenshot of software developed to analyse impact of various energy saving actions and seasonal variations on energy usage of EWH.

Ambient	**10°C**										
Usage events		**Energy consumption**			**Impact on Energy Consumption**				**Monthly Savings**		
# Showers	**# Baths**	**Standing losses (kWh)**	**Usage energy (kWh)**	**Total energy (kWh)**	**Standing losses (kWh)**	**Usage energy (kWh)**	**Standing losses (%)**	**Total energy (%)**	**Change in monthly EWH energy (kWh)**	**Monthly HH energy usage (kWh)**	**Change in household energy usage (%)**
0	1	3.150	1.876	5.026	0.573	0.000	22.24	12.868	17.190	212.0	8.108
0	2	3.143	3.752	6.895	0.571	0.000	22.20	9.029	17.130	432.0	3.965
1	1	3.146	3.262	6.408	0.571	0.000	22.17	9.782	17.130	432.0	3.965
1	2	3.123	5.138	8.261	0.568	0.000	22.23	7.383	17.040	579.0	2.943
1	0	3.155	1.386	4.541	0.574	0.000	22.24	14.469	17.220	212.0	8.123
2	0	3.150	2.772	5.922	0.571	0.000	22.14	10.671	17.130	432.0	3.965
2	1	3.126	4.648	7.774	0.568	0.000	22.20	7.882	17.040	579.0	2.943
2	2	3.105	6.524	9.629	0.567	0.000	22.34	6.257	17.010	668.0	2.546
	AVERAGE						**22.22**	**9.79**	**17.111**		**4.57**

Ambient	**15°C**										
Usage events		**Energy consumption**			**Impact on Energy Consumption**				**Monthly Savings**		
# Showers	**# Baths**	**Standing losses (kWh)**	**Usage energy (kWh)**	**Total energy (kWh)**	**Standing losses (kWh)**	**Usage energy (kWh)**	**Standing losses (%)**	**Total energy (%)**	**Change in monthly EWH energy (kWh)**	**Monthly HH energy usage (kWh)**	**Change in household energy usage (%)**
0	1	2.864	1.876	4.740	0.287	0.000	11.14	6.445	8.610	212.0	4.061
0	2	2.856	3.752	6.608	0.284	0.000	11.04	4.491	8.520	432.0	1.972
1	1	2.860	3.262	6.122	0.285	0.000	11.07	4.883	8.550	432.0	1.979
1	2	2.840	5.138	7.978	0.285	0.000	11.15	3.705	8.550	579.0	1.477
1	0	2.868	1.386	4.254	0.287	0.000	11.12	7.235	8.610	212.0	4.061
2	0	2.863	2.772	5.635	0.284	0.000	11.01	5.307	8.520	432.0	1.972
2	1	2.844	4.648	7.492	0.286	0.000	11.18	3.969	8.580	579.0	1.482
2	2	2.823	6.524	9.347	0.285	0.000	11.23	3.145	8.550	668.0	1.280
	AVERAGE						**11.12**	**4.90**	**8.561**		**2.29**

Figure B.2: Simulation results for varying ambient temperature.

Ambient	25°C									
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings	
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.290	1.876	4.166	-0.287	0.000	-11.14	-6.445	-8.610	212.0	-4.061
0	2	2.283	3.752	6.035	-0.289	0.000	-11.24	-4.570	-8.670	432.0	-2.007
1	1	2.287	3.262	5.549	-0.288	0.000	-11.18	-4.934	-8.640	432.0	-2.000
1	2	2.265	5.138	7.403	-0.290	0.000	-11.35	-3.770	-8.700	579.0	-1.503
1	0	2.294	1.386	3.680	-0.287	0.000	-11.12	-7.235	-8.610	212.0	-4.061
2	0	2.291	2.772	5.063	-0.288	0.000	-11.17	-5.382	-8.640	432.0	-2.000
2	1	2.270	4.648	6.918	-0.288	0.000	-11.26	-3.997	-8.640	579.0	-1.492
2	2	2.247	6.524	8.771	-0.291	0.000	-11.47	-3.211	-8.730	668.0	-1.307
	AVERAGE						**-11.24**	**-4.94**	**-8.655**		**-2.30**

Ambient	30°C										
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.000	1.876	3.876	-0.577	0.000	-22.39	-12.958	-17.310	212.0	-8.165
0	2	1.993	3.752	5.745	-0.579	0.000	-22.51	-9.156	-17.370	432.0	-4.021
1	1	1.998	3.262	5.260	-0.577	0.000	-22.41	-9.885	-17.310	432.0	-4.007
1	2	1.976	5.138	7.114	-0.579	0.000	-22.66	-7.526	-17.370	579.0	-3.000
1	0	2.003	1.386	3.389	-0.578	0.000	-22.39	-14.570	-17.340	212.0	-8.179
2	0	2.001	2.772	4.773	-0.578	0.000	-22.41	-10.802	-17.340	432.0	-4.014
2	1	1.980	4.648	6.628	-0.578	0.000	-22.60	-8.021	-17.340	579.0	-2.995
2	2	1.959	6.524	8.483	-0.579	0.000	-22.81	-6.389	-17.370	668.0	-2.600
	AVERAGE						**-22.52**	**-9.91**	**-17.344**		**-4.62**

Ambient	**35°C**										
Usage events		**Energy consumption**			**Impact on Energy Consumption**				**Monthly Savings**		
# Showers	**# Baths**	**Standing losses (kWh)**	**Usage energy (kWh)**	**Total energy (kWh)**	**Standing losses (kWh)**	**Usage energy (kWh)**	**Standing losses (%)**	**Total energy (%)**	**Change in monthly EWH energy (kWh)**	**Monthly HH energy usage (kWh)**	**Change in household energy usage (%)**
0	1	1.716	1.876	3.592	-0.861	0.000	-33.41	-19.335	-25.830	212.0	-12.184
0	2	1.708	3.752	5.460	-0.864	0.000	-33.59	-13.662	-25.920	432.0	-6.000
1	1	1.712	3.262	4.974	-0.863	0.000	-33.51	-14.785	-25.890	432.0	-5.993
1	2	1.691	5.138	6.829	-0.864	0.000	-33.82	-11.231	-25.920	579.0	-4.477
1	0	1.718	1.386	3.104	-0.863	0.000	-33.44	-21.754	-25.890	212.0	-12.212
2	0	1.716	2.772	4.488	-0.863	0.000	-33.46	-16.128	-25.890	432.0	-5.993
2	1	1.695	4.648	6.343	-0.863	0.000	-33.74	-11.976	-25.890	579.0	-4.472
2	2	1.674	6.524	8.198	-0.864	0.000	-34.04	-9.534	-25.920	668.0	-3.880
	AVERAGE						**-33.63**	**-14.80**	**-25.894**		**-6.90**

Inlet	10°C										
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.567	2.805	5.372	-0.010	0.929	-0.39	20.638	27.570	212.0	13.005
0	2	2.552	5.610	8.162	-0.020	1.858	-0.78	29.064	55.140	432.0	12.764
1	1	2.560	4.877	7.437	-0.015	1.615	-0.58	27.411	48.000	432.0	11.111
1	2	2.515	7.682	10.197	-0.040	2.544	-1.57	32.549	75.120	579.0	12.974
1	0	2.575	2.072	4.647	-0.006	0.686	-0.23	17.141	20.400	212.0	9.623
2	0	2.568	4.144	6.712	-0.011	1.372	-0.43	25.434	40.830	432.0	9.451
2	1	2.523	6.949	9.472	-0.035	2.301	-1.37	31.446	67.980	579.0	11.741
2	2	2.479	9.754	12.233	-0.059	3.230	-2.32	34.992	95.130	668.0	14.241
	AVERAGE						**-0.96**	**27.33**	**53.771**		**11.86**

Inlet	15°C										
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.572	2.341	4.913	-0.005	0.465	-0.19	10.330	13.800	212.0	6.509
0	2	2.563	4.682	7.245	-0.009	0.930	-0.35	14.564	27.630	432.0	6.396
1	1	2.568	4.070	6.638	-0.007	0.808	-0.27	13.723	24.030	432.0	5.563
1	2	2.537	6.411	8.948	-0.018	1.273	-0.70	16.314	37.650	579.0	6.503
1	0	2.578	1.729	4.307	-0.003	0.343	-0.12	8.571	10.200	212.0	4.811
2	0	2.574	3.458	6.032	-0.005	0.686	-0.19	12.727	20.430	432.0	4.729
2	1	2.543	5.799	8.342	-0.015	1.151	-0.59	15.765	34.080	579.0	5.886
2	2	2.512	8.140	10.652	-0.026	1.616	-1.02	17.546	47.700	668.0	7.141
	AVERAGE						**-0.43**	**13.69**	**26.940**		**5.94**

Figure B.3: Simulation results for varying inlet temperature.

Inlet	**25°C**										
Usage events		**Energy consumption**			**Impact on Energy Consumption**				**Monthly Savings**		
# Showers	**# Baths**	**Standing losses (kWh)**	**Usage energy (kWh)**	**Total energy (kWh)**	**Standing losses (kWh)**	**Usage energy (kWh)**	**Standing losses (%)**	**Total energy (%)**	**Change in monthly EWH energy (kWh)**	**Monthly HH energy usage (kWh)**	**Change in household energy usage (%)**
0	1	2.581	1.412	3.993	0.004	-0.464	0.16	-10.330	-13.800	212.0	-6.509
0	2	2.578	2.824	5.402	0.006	-0.928	0.23	-14.579	-27.660	432.0	-6.403
1	1	2.580	2.455	5.035	0.005	-0.807	0.19	-13.740	-24.060	432.0	-5.569
1	2	2.569	3.867	6.436	0.014	-1.271	0.55	-16.340	-37.710	579.0	-6.513
1	0	2.583	1.043	3.626	0.002	-0.343	0.08	-8.596	-10.230	212.0	-4.825
2	0	2.583	2.086	4.669	0.004	-0.686	0.16	-12.745	-20.460	432.0	-4.736
2	1	2.571	3.498	6.069	0.013	-1.150	0.51	-15.779	-34.110	579.0	-5.891
2	2	2.560	4.910	7.470	0.022	-1.614	0.87	-17.568	-47.760	668.0	-7.150
	AVERAGE						**0.34**	**-13.71**	**-26.974**		**-5.95**

Set Temp	55°C										
Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	1.998	1.876	3.874	-0.579	0.000	-22.47	-13.002	-17.370	212.0	-8.193
0	2	1.993	3.752	5.745	-0.579	0.000	-22.51	-9.156	-17.370	432.0	-4.021
1	1	1.997	3.262	5.259	-0.578	0.000	-22.45	-9.902	-17.340	432.0	-4.014
1	2	1.976	5.138	7.114	-0.579	0.000	-22.66	-7.526	-17.370	579.0	-3.000
1	0	2.003	1.386	3.389	-0.578	0.000	-22.39	-14.570	-17.340	212.0	-8.179
2	0	2.001	2.772	4.773	-0.578	0.000	-22.41	-10.802	-17.340	432.0	-4.014
2	1	1.980	4.648	6.628	-0.578	0.000	-22.60	-8.021	-17.340	579.0	-2.995
2	2	1.959	6.524	8.483	-0.579	0.000	-22.81	-6.389	-17.370	668.0	-2.600
	AVERAGE						**-22.54**	**-9.92**	**-17.355**		**-4.63**

Set Temp	60°C										
Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.290	1.876	4.166	-0.287	0.000	-11.14	-6.445	-8.610	212.0	-4.061
0	2	2.283	3.752	6.035	-0.289	0.000	-11.24	-4.570	-8.670	432.0	-2.007
1	1	2.287	3.262	5.549	-0.288	0.000	-11.18	-4.934	-8.640	432.0	-2.000
1	2	2.265	5.138	7.403	-0.290	0.000	-11.35	-3.770	-8.700	579.0	-1.503
1	0	2.294	1.386	3.680	-0.287	0.000	-11.12	-7.235	-8.610	212.0	-4.061
2	0	2.291	2.772	5.063	-0.288	0.000	-11.17	-5.382	-8.640	432.0	-2.000
2	1	2.269	4.648	6.917	-0.289	0.000	-11.30	-4.011	-8.670	579.0	-1.497
2	2	2.247	6.524	8.771	-0.291	0.000	-11.47	-3.211	-8.730	668.0	-1.307
	AVERAGE						**-11.25**	**-4.94**	**-8.659**		**-2.30**

Figure B.4: Simulation results for varying set temperature.

Set Temp	70°C										
Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.864	1.876	4.740	0.287	0.000	11.14	6.445	8.610	212.0	4.061
0	2	2.856	3.752	6.608	0.284	0.000	11.04	4.491	8.520	432.0	1.972
1	1	2.860	3.262	6.122	0.285	0.000	11.07	4.883	8.550	432.0	1.979
1	2	2.840	5.138	7.978	0.285	0.000	11.15	3.705	8.550	579.0	1.477
1	0	2.868	1.386	4.254	0.287	0.000	11.12	7.235	8.610	212.0	4.061
2	0	2.863	2.772	5.635	0.284	0.000	11.01	5.307	8.520	432.0	1.972
2	1	2.844	4.648	7.492	0.286	0.000	11.18	3.969	8.580	579.0	1.482
2	2	2.823	6.524	9.347	0.285	0.000	11.23	3.145	8.550	668.0	1.280
	AVERAGE						**11.12**	**4.90**	**8.561**		**2.29**

Set Temp	75°C										
Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	3.150	1.876	5.026	0.573	0.000	22.24	12.868	17.190	212.0	8.108
0	2	3.143	3.752	6.895	0.571	0.000	22.20	9.029	17.130	432.0	3.965
1	1	3.146	3.262	6.408	0.571	0.000	22.17	9.782	17.130	432.0	3.965
1	2	3.123	5.138	8.261	0.568	0.000	22.23	7.383	17.040	579.0	2.943
1	0	3.155	1.386	4.541	0.574	0.000	22.24	14.469	17.220	212.0	8.123
2	0	3.150	2.772	5.922	0.571	0.000	22.14	10.671	17.130	432.0	3.965
2	1	3.126	4.648	7.774	0.568	0.000	22.20	7.882	17.040	579.0	2.943
2	2	3.105	6.524	9.629	0.567	0.000	22.34	6.257	17.010	668.0	2.546
	AVERAGE						**22.22**	**9.79**	**17.111**		**4.57**

Usage Modifier		-20%									
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.580	1.501	4.081	0.003	-0.375	0.12	-8.354	-11.160	212.0	-5.264
0	2	2.577	3.002	5.579	0.005	-0.750	0.19	-11.781	-22.350	432.0	-5.174
1	1	2.580	2.610	5.190	0.005	-0.652	0.19	-11.084	-19.410	432.0	-4.493
1	2	2.567	4.111	6.678	0.012	-1.027	0.47	-13.194	-30.450	579.0	-5.259
1	0	2.583	1.109	3.692	0.002	-0.277	0.08	-6.932	-8.250	212.0	-3.892
2	0	2.582	2.218	4.800	0.003	-0.554	0.12	-10.297	-16.530	432.0	-3.826
2	1	2.569	3.719	6.288	0.011	-0.929	0.43	-12.739	-27.540	579.0	-4.756
2	2	2.556	5.220	7.776	0.018	-1.304	0.71	-14.191	-38.580	668.0	-5.775
	AVERAGE						**0.29**	**-11.07**	**-21.784**		**-4.80**

Usage Modifier		-15%									
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.579	1.595	4.174	0.002	-0.281	0.08	-6.265	-8.370	212.0	-3.948
0	2	2.576	3.190	5.766	0.004	-0.562	0.16	-8.824	-16.740	432.0	-3.875
1	1	2.579	2.773	5.352	0.004	-0.489	0.16	-8.309	-14.550	432.0	-3.368
1	2	2.564	4.368	6.932	0.009	-0.770	0.35	-9.892	-22.830	579.0	-3.943
1	0	2.582	1.178	3.760	0.001	-0.208	0.04	-5.218	-6.210	212.0	-2.929
2	0	2.581	2.356	4.937	0.002	-0.416	0.08	-7.737	-12.420	432.0	-2.875
2	1	2.567	3.951	6.518	0.009	-0.697	0.35	-9.548	-20.640	579.0	-3.565
2	2	2.552	5.546	8.098	0.014	-0.978	0.55	-10.638	-28.920	668.0	-4.329
	AVERAGE						**0.22**	**-8.30**	**-16.335**		**-3.60**

Figure B.5: Simulation results for varying usage event volumes.

Usage Modifier	-10%											
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings			
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)	
0	1	2.579	1.689	4.268	0.002	-0.187	0.08	-4.155	-5.550	212.0	-2.618	
0	2	2.575	3.378	5.953	0.003	-0.374	0.12	-5.867	-11.130	432.0	-2.576	
1	1	2.577	2.937	5.514	0.002	-0.325	0.08	-5.534	-9.690	432.0	-2.243	
1	2	2.561	4.626	7.187	0.006	-0.512	0.23	-6.577	-15.180	579.0	-2.622	
1	0	2.582	1.248	3.830	0.001	-0.138	0.04	-3.453	-4.110	212.0	-1.939	
2	0	2.580	2.496	5.076	0.001	-0.276	0.04	-5.139	-8.250	432.0	-1.910	
2	1	2.564	4.185	6.749	0.006	-0.463	0.23	-6.342	-13.710	579.0	-2.368	
2	2	2.548	5.874	8.422	0.010	-0.650	0.39	-7.062	-19.200	668.0	-2.874	
	AVERAGE						0.15	-5.52	-10.853		-2.39	

Usage Modifier	-5%											
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings			
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)	
0	1	2.578	1.783	4.361	0.001	-0.093	0.04	-2.066	-2.760	212.0	-1.302	
0	2	2.573	3.566	6.139	0.001	-0.186	0.04	-2.925	-5.550	432.0	-1.285	
1	1	2.576	3.100	5.676	0.001	-0.162	0.04	-2.758	-4.830	432.0	-1.118	
1	2	2.558	4.883	7.441	0.003	-0.255	0.12	-3.276	-7.560	579.0	-1.306	
1	0	2.582	1.317	3.899	0.001	-0.069	0.04	-1.714	-2.040	212.0	-0.962	
2	0	2.580	2.634	5.214	0.001	-0.138	0.04	-2.560	-4.110	432.0	-0.951	
2	1	2.562	4.417	6.979	0.004	-0.231	0.16	-3.150	-6.810	579.0	-1.176	
2	2	2.544	6.200	8.744	0.006	-0.324	0.24	-3.509	-9.540	668.0	-1.428	
	AVERAGE						0.09	-2.74	-5.400		-1.19	

Usage Modifier		5%									
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.576	1.970	4.546	-0.001	0.094	-0.04	2.088	2.790	212.0	1.316
0	2	2.570	3.940	6.510	-0.002	0.188	-0.08	2.941	5.580	432.0	1.292
1	1	2.574	3.426	6.000	-0.001	0.164	-0.04	2.793	4.890	432.0	1.132
1	2	2.550	5.396	7.946	-0.005	0.258	-0.20	3.289	7.590	579.0	1.311
1	0	2.580	1.456	4.036	-0.001	0.070	-0.04	1.739	2.070	212.0	0.976
2	0	2.578	2.912	5.490	-0.001	0.140	-0.04	2.598	4.170	432.0	0.965
2	1	2.554	4.882	7.436	-0.004	0.234	-0.16	3.192	6.900	579.0	1.192
2	2	2.533	6.852	9.385	-0.005	0.328	-0.20	3.564	9.690	668.0	1.451
	AVERAGE						**-0.10**	**2.78**	**5.460**		**1.20**

Usage Modifier		10%									
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.575	2.064	4.639	-0.002	0.188	-0.08	4.177	5.580	212.0	2.632
0	2	2.568	4.128	6.696	-0.004	0.376	-0.16	5.882	11.160	432.0	2.583
1	1	2.572	3.589	6.161	-0.003	0.327	-0.12	5.551	9.720	432.0	2.250
1	2	2.547	5.653	8.200	-0.008	0.515	-0.31	6.590	15.210	579.0	2.627
1	0	2.580	1.525	4.105	-0.001	0.139	-0.04	3.479	4.140	212.0	1.953
2	0	2.577	3.050	5.627	-0.002	0.278	-0.08	5.158	8.280	432.0	1.917
2	1	2.551	5.114	7.665	-0.007	0.466	-0.27	6.370	13.770	579.0	2.378
2	2	2.527	7.178	9.705	-0.011	0.654	-0.43	7.096	19.290	668.0	2.888
	AVERAGE						**-0.19**	**5.54**	**10.894**		**2.40**

Usage Modifier	15%										
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.574	2.158	4.732	-0.003	0.282	-0.12	6.265	8.370	212.0	3.948
0	2	2.566	4.316	6.882	-0.006	0.564	-0.23	8.824	16.740	432.0	3.875
1	1	2.571	3.752	6.323	-0.004	0.490	-0.16	8.326	14.580	432.0	3.375
1	2	2.545	5.910	8.455	-0.010	0.772	-0.39	9.905	22.860	579.0	3.948
1	0	2.579	1.594	4.173	-0.002	0.208	-0.08	5.193	6.180	212.0	2.915
2	0	2.576	3.188	5.764	-0.003	0.416	-0.12	7.718	12.390	432.0	2.868
2	1	2.549	5.346	7.895	-0.009	0.698	-0.35	9.561	20.670	579.0	3.570
2	2	2.523	7.504	10.027	-0.015	0.980	-0.59	10.649	28.950	668.0	4.334
	AVERAGE						**-0.26**	**8.31**	**16.343**		**3.60**

Usage Modifier	20%										
Usage events		Energy consumption			Impact on Energy Consumption				Monthly Savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.573	2.251	4.824	-0.004	0.375	-0.16	8.331	11.130	212.0	5.250
0	2	2.564	4.502	7.066	-0.008	0.750	-0.31	11.733	22.260	432.0	5.153
1	1	2.570	3.915	6.485	-0.005	0.653	-0.19	11.102	19.440	432.0	4.500
1	2	2.541	6.166	8.707	-0.014	1.028	-0.55	13.181	30.420	579.0	5.254
1	0	2.579	1.664	4.243	-0.002	0.278	-0.08	6.957	8.280	212.0	3.906
2	0	2.575	3.328	5.903	-0.004	0.556	-0.16	10.316	16.560	432.0	3.833
2	1	2.546	5.579	8.125	-0.012	0.931	-0.47	12.753	27.570	579.0	4.762
2	2	2.517	7.830	10.347	-0.021	1.306	-0.83	14.180	38.550	668.0	5.771
	AVERAGE						**-0.34**	**11.07**	**21.776**		**4.80**

200 litre tank											
Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	3.014	1.876	4.890	0.437	0.000	16.96	9.814	13.110	212.0	6.184
0	2	3.010	3.752	6.762	0.438	0.000	17.03	6.926	13.140	432.0	3.042
1	1	3.012	3.262	6.274	0.437	0.000	16.97	7.487	13.110	432.0	3.035
1	2	2.997	5.138	8.135	0.442	0.000	17.30	5.745	13.260	579.0	2.290
1	0	3.016	1.386	4.402	0.435	0.000	16.85	10.965	13.050	212.0	6.156
2	0	3.014	2.772	5.786	0.435	0.000	16.87	8.129	13.050	432.0	3.021
2	1	3.000	4.648	7.648	0.442	0.000	17.28	6.134	13.260	579.0	2.290
2	2	2.985	6.524	9.509	0.447	0.000	17.61	4.933	13.410	668.0	2.007
	AVERAGE						**17.11**	**7.52**	**13.17**		**3.50**

Pipe insulation											
Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.454	1.876	4.330	-0.123	0.000	-4.77	-2.762	-3.690	212.0	-1.741
0	2	2.449	3.752	6.201	-0.123	0.000	-4.78	-1.945	-3.690	432.0	-0.854
1	1	2.453	3.262	5.715	-0.122	0.000	-4.74	-2.090	-3.660	432.0	-0.847
1	2	2.433	5.138	7.571	-0.122	0.000	-4.77	-1.586	-3.660	579.0	-0.632
1	0	2.457	1.386	3.843	-0.124	0.000	-4.80	-3.126	-3.720	212.0	-1.755
2	0	2.456	2.772	5.228	-0.123	0.000	-4.77	-2.299	-3.690	432.0	-0.854
2	1	2.437	4.648	7.085	-0.121	0.000	-4.73	-1.679	-3.630	579.0	-0.627
2	2	2.418	6.524	8.942	-0.120	0.000	-4.73	-1.324	-3.600	668.0	-0.539
	AVERAGE						**-4.76**	**-2.10**	**-3.67**		**-0.98**

Figure B.6: Simulation results for miscellaneous energy saving actions and variables.

Thermal Blanket

Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.184	1.876	4.060	-0.393	0.000	-15.25	-8.826	-11.790	212.0	-5.561
0	2	2.176	3.752	5.928	-0.396	0.000	-15.40	-6.262	-11.880	432.0	-2.750
1	1	2.180	3.262	5.442	-0.395	0.000	-15.34	-6.767	-11.850	432.0	-2.743
1	2	2.164	5.138	7.302	-0.391	0.000	-15.30	-5.083	-11.730	579.0	-2.026
1	0	2.187	1.386	3.573	-0.394	0.000	-15.27	-9.932	-11.820	212.0	-5.575
2	0	2.182	2.772	4.954	-0.397	0.000	-15.39	-7.419	-11.910	432.0	-2.757
2	1	2.167	4.648	6.815	-0.391	0.000	-15.29	-5.426	-11.730	579.0	-2.026
2	2	2.149	6.524	8.673	-0.389	0.000	-15.33	-4.293	-11.670	668.0	-1.747
	AVERAGE						**-15.32**	**-6.75**	**-11.80**		**-3.15**

Schedule Control

Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	1.767	1.876	3.643	-0.810	0.000	-31.43	-18.190	-24.300	212.0	-11.462
0	2	1.934	3.752	5.686	-0.638	0.000	-24.81	-10.089	-19.140	432.0	-4.431
1	1	2.014	3.262	5.276	-0.561	0.000	-21.79	-9.611	-16.830	432.0	-3.896
1	2	1.755	5.138	6.893	-0.800	0.000	-31.31	-10.399	-24.000	579.0	-4.145
1	0	1.895	1.386	3.281	-0.686	0.000	-26.58	-17.293	-20.580	212.0	-9.708
2	0	2.082	2.772	4.854	-0.497	0.000	-19.27	-9.288	-14.910	432.0	-3.451
2	1	1.825	4.648	6.473	-0.733	0.000	-28.66	-10.172	-21.990	579.0	-3.798
2	2	1.568	6.524	8.092	-0.970	0.000	-38.22	-10.704	-29.100	668.0	-4.356
	AVERAGE						**-27.76**	**-11.97**	**-21.36**		**-5.66**

Schedule and Pipe Insulation

Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	1.695	1.876	3.571	-0.882	0.000	-34.23	-19.807	-26.460	212.0	-12.481
0	2	1.862	3.752	5.614	-0.710	0.000	-27.60	-11.227	-21.300	432.0	-4.931
1	1	1.924	3.262	5.186	-0.651	0.000	-25.28	-11.153	-19.530	432.0	-4.521
1	2	1.678	5.138	6.816	-0.877	0.000	-34.32	-11.400	-26.310	579.0	-4.544
1	0	1.820	1.386	3.206	-0.761	0.000	-29.48	-19.183	-22.830	212.0	-10.769
2	0	1.987	2.772	4.759	-0.592	0.000	-22.95	-11.063	-17.760	432.0	-4.111
2	1	1.739	4.648	6.387	-0.819	0.000	-32.02	-11.366	-24.570	579.0	-4.244
2	2	1.496	6.524	8.020	-1.042	0.000	-41.06	-11.499	-31.260	668.0	-4.680
	AVERAGE						**-30.87**	**-13.34**	**-23.75**		**-6.28**

Schedule and Thermal Blanket

Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	1.532	1.876	3.408	-1.045	0.000	-40.55	-23.467	-31.350	212.0	-14.788
0	2	1.671	3.752	5.423	-0.901	0.000	-35.03	-14.247	-27.030	432.0	-6.257
1	1	1.726	3.262	4.988	-0.849	0.000	-32.97	-14.545	-25.470	432.0	-5.896
1	2	1.505	5.138	6.643	-1.050	0.000	-41.10	-13.649	-31.500	579.0	-5.440
1	0	1.646	1.386	3.032	-0.935	0.000	-36.23	-23.569	-28.050	212.0	-13.231
2	0	1.783	2.772	4.555	-0.796	0.000	-30.86	-14.876	-23.880	432.0	-5.528
2	1	1.561	4.648	6.209	-0.997	0.000	-38.98	-13.836	-29.910	579.0	-5.166
2	2	1.343	6.524	7.867	-1.195	0.000	-47.08	-13.187	-35.850	668.0	-5.367
	AVERAGE						**-37.85**	**-16.42**	**-29.13**		**-7.71**

Schedule, Thermal Blanket and Pipe Insulation

Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	1.478	1.876	3.354	-1.099	0.000	-42.65	-24.680	-32.970	212.0	-15.552
0	2	1.606	3.752	5.358	-0.966	0.000	-37.56	-15.275	-28.980	432.0	-6.708
1	1	1.660	3.262	4.922	-0.915	0.000	-35.53	-15.676	-27.450	432.0	-6.354
1	2	1.449	5.138	6.587	-1.106	0.000	-43.29	-14.377	-33.180	579.0	-5.731
1	0	1.586	1.386	2.972	-0.995	0.000	-38.55	-25.082	-29.850	212.0	-14.080
2	0	1.716	2.772	4.488	-0.863	0.000	-33.46	-16.128	-25.890	432.0	-5.993
2	1	1.501	4.648	6.149	-1.057	0.000	-41.32	-14.668	-31.710	579.0	-5.477
2	2	1.295	6.524	7.819	-1.243	0.000	-48.98	-13.717	-37.290	668.0	-5.582
	AVERAGE						**-40.17**	**-17.45**	**-30.92**		**-8.18**

Pipe Insulation + Thermal Blanket, Thermostat Control (Tset=65°C)

Usage events		Energy consumption			Impact on energy consumption				Monthly savings		
# Showers	# Baths	Standing losses (kWh)	Usage energy (kWh)	Total energy (kWh)	Standing losses (kWh)	Usage energy (kWh)	Standing losses (%)	Total energy (%)	Change in monthly EWH energy (kWh)	Monthly HH energy usage (kWh)	Change in household energy usage (%)
0	1	2.092	1.876	3.968	-0.485	0.000	-18.82	-10.892	-14.550	212.0	-6.863
0	2	2.087	3.752	5.839	-0.485	0.000	-18.86	-7.669	-14.550	432.0	-3.368
1	1	2.090	3.262	5.352	-0.485	0.000	-18.83	-8.309	-14.550	432.0	-3.368
1	2	2.073	5.138	7.211	-0.482	0.000	-18.86	-6.265	-14.460	579.0	-2.497
1	0	2.096	1.386	3.482	-0.485	0.000	-18.79	-12.226	-14.550	212.0	-6.863
2	0	2.093	2.772	4.865	-0.486	0.000	-18.84	-9.082	-14.580	432.0	-3.375
2	1	2.076	4.648	6.724	-0.482	0.000	-18.84	-6.689	-14.460	579.0	-2.497
2	2	2.058	6.524	8.582	-0.480	0.000	-18.91	-5.297	-14.400	668.0	-2.156
	AVERAGE						**-18.84**	**-8.30**	**-14.51**		**-3.87**

Appendix C

Usability study documents

Post-Task Questionnaire

I thought this task was…

1 – Very difficult
2 – Somewhat difficult
3 – Neither difficult nor easy
4 – Somewhat easy
5 – Very easy

The task could be made easier by:

____
____
____
____

System Usability Scale

	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

Consent & Recording Release Form - Adult

I agree to participate in the study conducted and recorded by the University of Stellenbosch.

I understand and consent to the use and release of the recording by University of Stellenbosch. I understand that the information and recording is for research purposes only and that my name and image will not be used for any other purpose. I relinquish any rights to the recording and understand the recording may be copied and used by University of Stellenbosch without further permission.

I understand that participation in this usability study is voluntary and I agree to immediately raise any concerns or areas of discomfort during the session with the study administrator.

Please sign below to indicate that you have read and you understand the information on this form and that any questions you might have about the session have been answered.

Date: _________

Please print your name: ____

Please sign your name: ____

Thank you!

We appreciate your participation.

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