The Development, Implementation, and Application of Demand Side Management and control (DSM+c) Algorithm for Integrating Micro-generation System within Built Environment

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NOMENCLATURE

Symbols

i	the i^{th} time step
j	the j^{th} demand
k	total control steps on a certain demand
Demand[j][i]	the j^{th} demand at the time step i, W
Supply[i]	the available total supply at the time step i, W
Kctrl	total control steps for demands with similar priority
$\alpha[j][k]$	control factor applied over the j^{th} demand at the k^{th} control step
$E[n][i]$	the n^{th} environmental variable at time step i
$E_{low}[n]$	the lower setting point for the n^{th} environmental variable
$E_{high}[n]$	the higher setting point for the n^{th} environmental variable
Ne	total number of environmental variables
$t_{ngtv,\max}$	maximum negative shifting time, s
$t_{pstv,\max}$	maximum positive shifting time, s
N_{TS}	total number of shifting steps
n_{incr}	shifting increment
t_{start}	start time, s
t_{end}	end time, s
$t_{ini,start}$	the initial start time, s
$t_{ini,end}$	the initial end time, s
NewDemands[i]	new total demand at time step i, W
Nd	total number of demands
NewDemandsAfterShift[j][i]	the j^{th} demand profile after being shifted at time step i, W
$A_r(k)$	the net residual area at the k^{th} shifting step
$A_{r\text{-}min}$	the minimum residual area
nControlStep[j]	the control steps of the j^{th} demand
T_{lower}	lower temperature setting point, °C
T_{upper}	upper temperature setting point, °C
T_{DSM_ON}	ON temperature setting point for DSM purpose, °C

T_{DSM_OFF}	OFF temperature setting point for DSM purpose, °C
$T(t)$	inside temperature at time t, °C
$T_{amb}(t)$	ambient temperature at time t, °C
$K(t)$	thermostat binary state (0 for off; 1 for on) at time t
COP	coefficient of performance
P_e	electricity power required by a demand system, W
ρ	average density, kg/m^3
c	average thermal capacity, J/(kg °C)
V	volume, m^3
U	average U value, W/(m^2 °C)
A	surface area, m^2
Δ	dead band of temperature setting points, °C
X_+	upper setting point, °C
X_-	lower setting point, °C
$\dot{Q}(t)$	volume flow rate of water at time t, m^3/s
T_{inlet}	inlet water temperature, °C
P_D	CHP engine power after considering the de-rating factors
P_R	CHP engine-rated power, W
η_T	de-rating coefficient of the temperature factor
η_H	de-rating coefficient of the altitude factor
P_{el}	CHP real power generated, W
η_G	efficiency of the CHP generator
$cos\ \Phi$	power factor of the CHP generator
P_{th}	CHP thermal energy rate generated, W
R_{HtP}	heat-to-power ratio
η_G	efficiency of the CHP heat exchanger
$\dot{V}_F$	volume flow rate of the fuel input
LHV	low heating value, J/m^3
η_{el}	CHP electricity efficiency
$\eta_{overall}$	CHP overall efficiency
GHG	amount of green house gas emission, kg/s

ρ_F	fuel density, kg/m^3
EF_{CO2}	emission factor equivalent to CO_2 level
$C\%$	carbon proportion of fuel
$\dot{Q}_L$	thermal flux on load side, W
$\dot{Q}_S$	thermal flux on source side, W
$\dot{W}$	power consumption by compressor, W
$TCAP$	Total Capacity, W
$ODBT$	Outdoor Drybulb Temperature, °C
$IWBT$	Indoor Wetbulb Temperature, °C
Q_{actural}	heat pump capacity at other conditions, W
Q_{norminal}	heat pump capacity at nominal condition, W
$Power_{\mathrm{actural}}$	power consumption at other conditions, W
$Power_{\mathrm{nominal}}$	power consumption at nominal condition, W
C_{Qh}	Correction factor for heat pump capacity at heating mode
C_{Ph}	Correction factor for heat pump power consumption at heating mode
C_{Qc}	Correction factor for heat pump capacity at cooling mode
C_{Pc}	Correction factor for heat pump power consumption at cooling mode

ABSTRACT

Recent legislation and building regulations aim to reduce the energy demands of buildings and include renewable and low carbon based micro-generation technologies. Due to the intermittent nature of renewable energy systems and fluctuating demand profiles at the domestic level, matching the demand with a volatile supply of low operating efficiency, as is the case with some low carbon energy systems, at the local level, becomes a big challenge for the widespread implementation of zero/low carbon energy systems. The research undertaken centres on the potential exploitation of demand side resources to provide the solutions to the issues addressed above.

This thesis focuses on the development, implementation, and application of a bottom-up Demand Side Management and control (DSM+c) algorithm to create greater flexibility in demand and better facilitate the integration of renewable and low carbon energy technologies within the built environment, without significantly compromising user satisfaction. This DSM+c algorithm can be applied to both strategic and operational levels.

The strategic level DSM+c algorithm is suitable for the development and analysis of DSM approaches. The measures of load shifting and demand side control are available to specify the DSM options upon loads. The results, in terms of demand/supply match, energy export/import, and environmental impact etc., before and after having applied DSM+c algorithm upon loads, are quantified when linked with Renewable (RE) & Low Carbon (LC) energy supply systems. The DSM+c algorithm at strategic level has been embedded within a decision support platform, MERIT. MERIT is a demand-supply matching tool for assessing the feasibility of renewable energy systems. This allows engineers to develop appropriate demand supply control strategies.

The operational level DSM+c algorithm is capable of controlling loads based on the available supply at a certain time, through the assistance of information gathered from simulation or via real-time measurement. The control impact of the operational level DSM+c algorithm upon internal environmental parameters can be quantified. A virtual platform for implementing the DSM+c algorithm is established, within which the information of demand, supply, and internal environmental parameters, are obtained through simulation and input to carry out the process of the DSM+c algorithm. Furthermore, an Internet-enabled Energy System (IE-ES) platform for implementing these control actions upon individual loads in a practical environment has been developed.

Finally two types of case studies are presented respectively, showing how the DSM+c algorithm plays a key role within the whole decision-making procedure in a project and how it is applied to an individual appliance at operational level. The thesis concludes with recommendations of potential applications for this work and prospective further development.

CHAPTER ONE INTRODUCTION

This chapter briefly presents challenges and issues associated with the current energy demand/supply structure. Actions on both demand and supply side are suggested to improve the current fossil-fuel dependent energy structure move towards a zero and low carbon one. Within this research, measures of demand side management (DSM) are discussed. In particular, a novel concept of active DSM at the micro level is addressed, the aim of which is to improve energy efficiency on the demand side and energy utilisation from renewable and low carbon resources. Furthermore, the idea of scaling the applicability of micro DSM up to a larger level through a bottom-up approach is also proposed. In addition, a brief outline of various chapters of this thesis is provided.

1.1 Challenges Ahead

The relationship between humans, environment, energy and economics is inherently complex (Zahedi, 1994) and many conflicting viewpoints and thoughts abound. The ideal aim which citizens would like to achieve is to optimise all the objectives of each aspect within this complicated system while meeting expectations, minimising the impact on the environment and achieving efficient energy utilisation at an affordable cost.

Buildings are a platform within which people, energy, environment and economics interact extensively (Clarke, 2001), and as such, they perfectly represent the conflicting relationships arising from these interactions. It is generally accepted that buildings are the most important man-made contribution to today's world, as they impact on every aspect of our lives. Unfortunately, since their initial construction, these energy-hungry devices do not stop consuming energy until they reach the end of their lives and are demolished. This appetite for high energy consumption is not only associated with buildings themselves, but also with the devices/goods inside them. Previously, it has been shown that the energy consumption of the building sector is rather high, which accounts for nearly half of the total energy consumption in the UK (CIBSE Guide F, 2004). This is also expected to increase further because of global population growth, the increasing number of buildings, and the ever-improving standards of living.

In a global context, in order to meet ever-increasing energy consumption needs within the built environment sector, many fossil-fuel-fired power plants have been constructed and even more are expected in the near future, particularly in developing countries, such as China and India. This means that thousands of tons of increased GHG emissions will be emitted into the atmosphere. If future energy supply scenarios like this do occur, it will be the current population who will begin to suffer the consequences. In order to mitigate this, there is a need to take positive action at the current time to address this issue before it is too late to do so.

The evolution of the energy demand and supply structure has been responsive to the requirements of a specific period of development. Historically, people were more concerned about meeting the energy demand with affordable energy supplies with little or no consideration of the impact on the environment. Therefore during this period, the driving factor was the ability to generate as much energy as possible in the most economic manner. This resulted in the construction of large centralised fossil-fuel-burning power plants. The economic scale became the most influential factor during this period resulting in a cheaper electricity unit price the bigger the power plant. It should be pointed out that the efficiency of such power plants is relatively low, with only around 30% of the primary energy being used effectively (Kelly 2006). Gradually, people realised that a supply-following-demand energy structure has its limitations and the disadvantage of not being sustainable from an energy perspective. The limitations of a centralised energy supply model became apparent in that guarantee of supply could not be ensured due to the possibility of demand overload, specifically in countries with growing economies. A practical solution needs to be found to address this issue.

Today, economic, sustainable development has gradually become the main priority when implementing further energy infrastructure development. Nowadays, the public are increasingly aware of the significant consequences for the environment using the traditional energy supply method; this being one of the principal objections to the continued use of fossil fuels, even if they are relatively inexpensive. Current research is focusing on the development of new technologies to aid the implementation of a sustainable energy infrastructure. At the same time, policy-makers are developing policies and strategies aimed at encouraging greater awareness uptake of energy efficiency and the use of green/low-carbon energy supplies to meet demand. To meet an ever-increasing energy demand without compromising the atmospheric environment, particularly in less developed countries, clean and low-cost systems and techniques have to be employed and energy efficiency must be improved.

Conflicting viewpoints exist regarding climate change and other energy issues but one thing is acknowledged, that being the urgency for mitigating the associated greenhouse gas emissions. Several technology options are available to tackle this problem: fossil fuel de-carbonisation and sequestration; the switch to new and renewable sources of energy (Gross et al, 2003); the deployment of demand side measures to reduce and reshape demand profiles including effective energy efficiency and load management, are just to name a few (Clarke, 2004).

1.2 Energy Demand within Residential Building Sectors

A significant proportion of energy utilisation in any nation is used to meet the energy demands of buildings, especially those associated with the residential sector. Currently, domestic, commercial and public buildings consume nearly half (46%) of all energy used within the UK, of which, 63% is consumed by residential households (CIBSE, 2004). Domestic energy consumption has also increased by 32% since 1970 and by 19% since 1990 (Shorrock and Utley, 2003). This is due to several factors, including the increase in the number of households, population growth, increased usage of appliances, increasing household disposable income, etc. The energy demand within the residential sector can be specifically classified into space heating, hot water, lighting and household appliances. Recent figures show space heating and hot water accounting for 84.2% of energy use within the domestic sector in 2004 (Shorrock and Utley, 2003). It is interesting to note that between 1970 and 2000, energy consumption associated with lighting and appliances increased by 157%. However, this end use represents a relatively small percentage of the total delivered energy, equating to 13.2%, in 2004 (Shorrock and Utley, 2003).

Current standards of living result in modern homes containing more household appliances than our grandparents ever dreamt of having. Household items such as cookers, microwaves, washing machines, dishwashers, fridge-freezers, digital TVs and computers etc. are taken for granted, and in many cases multiple units can be found within a single household. The amount of energy used by appliances has increased by 9% since 1990; the influential factors include the increase in the total number of appliances bought and used by households and the increasing number of households. UK households spend around £5billion per year on electricity to power lights and appliances, which accounts for about a quarter of UK electricity consumption. According to the latest Digest of UK energy statistics (BERR, 2008), the total electricity consumption within the domestic sector is around 115 TWh in 2007, 29% of total electricity consumption. The evolution of ownership of different appliance types is shown in **Figure 1-1** (Shorrock and Utley, 2003). It can be seen that the ownership of all frequently-used domestic appliances is increasing, some at a rapid rate, i.e. rechargeable electronic products; and some of which have already reached their saturation level i.e. fridge/ freezers.

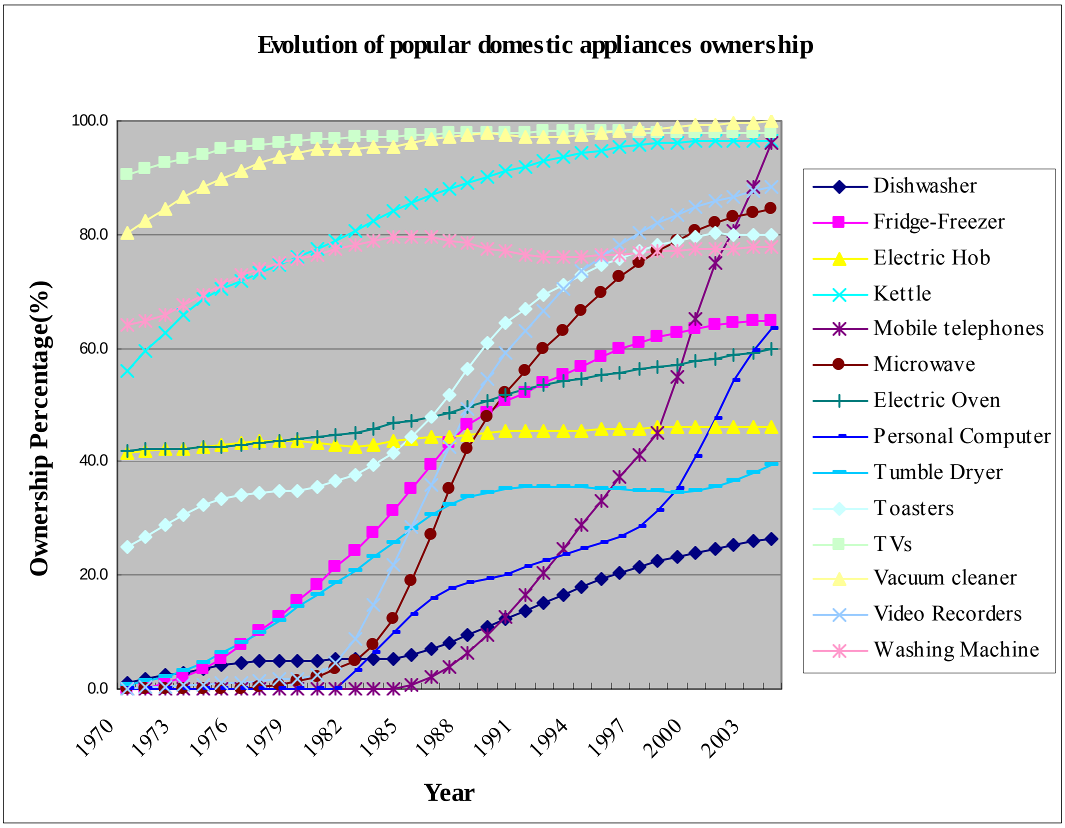

Figure 1-1 Evolution of the Ownership of Popular Domestic Appliances

Typically, the higher the household income, the higher the number of different appliances owned by the householder. Ownership of home computers reached 45% of UK households in 2000. Nearly a third of all householders had access to the Internet via their home computer. The energy consumption of lighting has increased by 63% between 1970 and 2000 and by 11% between 1990 and 2000. This increase has mainly been accounted for by the shift from rooms lit by single ceiling luminaires towards multi-source lighting, e.g. ceiling lights in addition to halogen-based wall and table lamps. The introduction of energy efficient light bulbs in the early 1980s has in some ways controlled the rate of increase in lighting demands.

A continuing upward trend in domestic electricity consumption is an obvious and deeply worrying sign. In fact, the electricity consumed by household domestic appliances in the UK doubled between 1970 and 2002 (DTI, 2003a) and is anticipated to rise by a further 12% by 2010 (MTP (Market Transformation Programme) 2005). This rise is not solely associated with the increasing number of devices within houses, but also with human behaviour resulting in wasted energy that would have otherwise been saved. Reducing this wastage is a challenge that can be addressed either by increasing public energy efficiency awareness or through the implementation of systems to help people manage energy use effectively without compromising their comfort levels or environmental expectations.

Furthermore, inefficient appliances can cost considerably more to operate during their operational life than energy-efficient appliances newly introduced to the market. The energy use associated with standby power for some electronic appliances can also be an influential factor in increasing domestic energy consumption. It is estimated that 1% of the UK's total energy consumption is associated with the standby status of domestic appliances, which is the equivalent of 6% of the total domestic electricity consumption (Energy Saving Trust, 2006). In addition to appliances and occupancy behaviour, the energy performance of the building envelope is equally important and should also be assessed, e.g. levels of insulation and air tightness.

1.3 Focuses of Current Energy Policy

Current UK energy policies targeted at the built environment address two aspects of the problem of potentially damaging environmental emissions associated with energy utilisation. These are: i) they enact greater energy efficiency measures; and ii) they introduce the adoption of new and renewable energy technologies. The drivers behind this include: the recent EU Directive on the Energy Performance of Buildings (EPBD) (EU, 2002); the UK government's White Paper on Energy Policy (DTI, 2003); and the Scottish Executives' SBS (Scottish Building Standards) on the standards for new buildings (SBSA, 2007). These policies stress the importance of building regulation in helping to bring about the improvements required.

The EPBD (EU, 2002) instructed that by the end of 2005 all EU member states should have brought into force national laws, regulations and administrative provisions for setting minimum requirements for the energy performance certification of buildings. Such certification applies to all new build and existing buildings subject to major renovation.

Simultaneously, the UK Energy White Paper (DTI 2003b) begins to address this issue in the context of an important challenge we are facing, climate change, and the linkage with the ever-increasing levels of carbon dioxide (CO_2) emissions due to human activities. UK energy policy development is focusing on a number of factors. These include: the widespread uptake of low carbon technologies (like CHP or micro-CHP systems); the adoption of new renewable and low carbon energy technologies; and substantive improvements in energy efficiency. These not only aim to reduce greenhouse gas emissions to target levels to mitigate the potential damages associated with global warming, but also in certain situations may provide a measure of energy security (Hawkes and Leach, 2007; Hawkes and Leach, 2005).

The Scottish Building Standards (SBS), an executive agency of the Scottish Government, is responsible for the development and implementation of new standards and regulations for buildings in Scotland. In recent documentation, it requires that at least 10% of the annual heating demands for new buildings come from on-site renewable energy technologies, such as solar, wind or biomass energy (SBSA, 2007).

1.4 Energy Efficiency

Energy efficiency has been identified as having a vital role in restraining the growth of domestic energy use. Improving energy efficiency is one of the cheapest, cleanest, and safest ways to decrease energy usage (DTI, 2003b). Within buildings, energy is often wasted as a result of poor levels of insulation, poor control of heating, ventilation, air conditioning and lighting, and the installation/operation of inefficient plants/appliances.

1.4.1 Buildings

Improving the energy performance of buildings has mainly focused on how to improve the insulation levels within them. In the UK, most of the 26 million houses were built before 1980 and as such have no, or low, standards of insulation. However, recent efforts to improve insulation levels within buildings, has managed to suppress the rate of increase in domestic energy consumption. The targeted areas where greater suppression of heat/energy loss from buildings have been achieved, include loft insulation, cavity wall insulation, double glazing and hot water storage insulation. The levels of each improvement measure identified, is shown in **Figure1-2**.

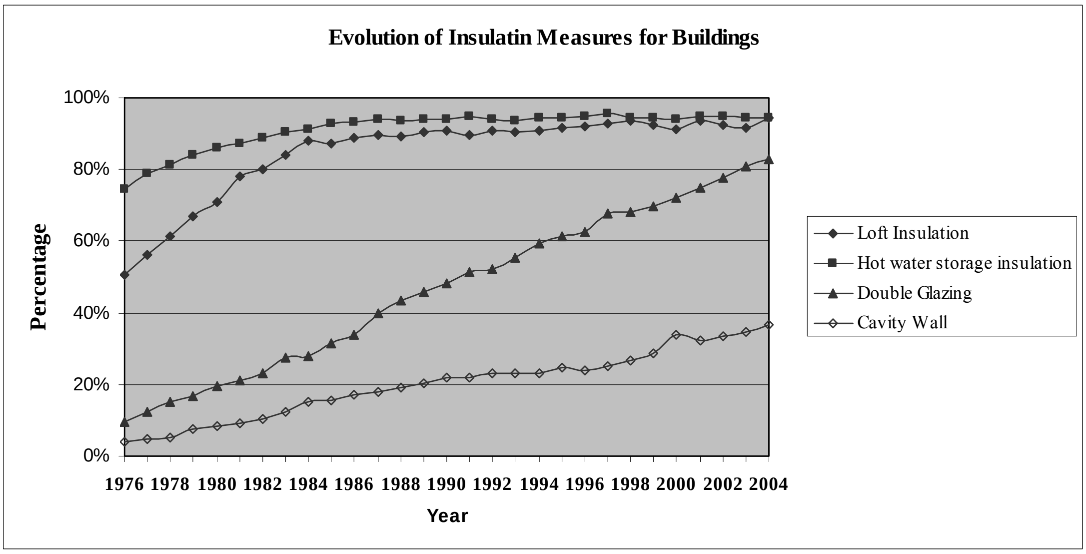

Figure 1-2 Evolution of Insulation Measures for Buildings

Insulation of hot water storage systems and loft insulation are the two most obvious and cost-effective measures to be implemented and have no/negligible maintenance requirements. As seen from **Figure 1-2**, these two measures are about to reach a level of saturation. In contrast, the penetration level of double glazing is increasing dramatically, and reached 83% in 2004 (DTI, 2003b). Due to the long payback period associated with the capital costs for installing cavity wall insulation and other limitations e.g. location, weather, etc. and the fact that financial support/incentives have been introduced within the last decade, the penetration levels of cavity wall insulation still remain low in comparison. As a whole though, most of the energy efficiency measures that can feasibly be applied are being implemented and are almost reaching their respective saturation levels.

1.4.2 Appliances within Buildings

Domestic appliances can be classified into four categories, i.e. cold appliances (fridge-freezer, refrigerator, upright freezer and chest freezer), wet appliances(washing machine, washer dryers, tumble dryer and dish washer), brown appliances (TV, video recorders, set top boxes and telephone chargers) and cooking appliances (electric ovens, electric hobs, microwaves, kettles and toasters).

Due to the increasing influence of appliance-based energy growth, several actions, including the implementation of energy labelling, have already been implemented to suppress it. Energy labelling is a measure introduced to enforce suppliers to provide more information on the electricity consumption of their devices in practice. This in turn is aimed at improving the energy efficiency of the appliance and user awareness of appliance-based energy consumption. According to the relevant regulations, energy labelling must be displayed on certain new household products displayed for sale, hire or hire-purchase (such as refrigerator, washing machine, dish washer, tumble dryer, and light bulb etc.). This helps customers take into consideration the running costs when choosing new appliances. It is hoped that this will influence the choice of appliance towards one with a better energy efficiency performance. However, early assessment on the effectiveness of this approach suggests customers are not always willing to become actively involved in such behaviour. There are two possible reasons for this. The first is cost of replacement, since the old appliance may still have a serviceable life and the price of a premature replacement is conceived as being much greater than what can be saved. The second reason is the lack of information provided to consumers in order to understand the energy labels on appliances. Hence, there is a need for further education and advice for consumers regarding the benefits of energy-efficient appliances and how to choose the best device for their intended use.

1.5 Bottom-up active Demand Side Management and control (DSM+c)

The aforementioned arguments indicate that energy policy and measures for improving energy efficiency (such as increased levels of insulation, the introduction of more efficient electrical appliances and smart energy management system); and new energy supply technologies, including renewable (RE) and low carbon (LC) energy technologies, have great potential to positively reduce energy and associated carbon emissions form the building sector.

Society uses far more energy than is needed due to inefficient system control and 'energy-lazy' behaviour (DTI, 2003b). Much energy use is wasted in delivering energy services that are not actually used or required by users/occupiers. These include: the heating/cooling of unoccupied spaces and rooms; the overheating or overcooling to make up for temperature variations over larger floor areas; power consumed as a result of appliances in standby or off mode; and the purchase of needlessly energy-intensive appliances. If effective measures can be implemented to target these, it may be possible to achieve considerable energy savings. The number and type of appliances in use today is continually increasing. The ability to manage these various appliances so that they operate efficiently and effectively becomes a really challenging issue. If this type of operation can be achieved, great potential arises for savings in energy utilisation within the urban environment and ultimately this means more money for the users. According to Balaras et al. (2007), there has been a considerable rise in the number of small household air-conditioning systems within southern European countries in recent years. A change which creates considerable problems at peak load times has increased the cost of electricity, and which has lead to the disruption of the energy balance between demand and supply in those countries. Managing this kind of load can reshape the load profile, making it more favourable to utility or energy companies in order to improve the performance of existing power generating plants. When we add the increasing deployment of green/low-carbon energy technologies, the ability to maximise the utilisation of energy produced by these technologies and in turn synchronise this with the demand from different appliances, makes the challenge of matching demand and supply even greater.

Demand reduction approaches, such as cavity wall insulation, double glazing etc., can be regarded as ‘hard’ technical demand measures with the purpose of reducing the magnitude of energy demand during the operational period. Although these ‘hard’ reduction measures have already played an important role in suppressing the rate of demand increase, there are limitations in the ability of continued deployment to actually reduce demand, as some measures almost reach the saturation level. The ‘soft’ measures which focus on the management of various end-use devices have been largely neglected. Vast opportunities exist to make better use of, and lower, the energy consumption through better management and control.

Against this background, a novel active demand side management and control (DSM+c) approach is proposed in this thesis. Different from the traditional top down macro-level long-term utility-based DSM, this method uses the match results between demand and supply to decide the control actions to be implemented on the demand side. It also considers environmental variables (e.g. comfort temperatures, illumination levels, etc.) as a decision-making factor. By using this active DSM+c algorithm, the optimal control strategies for various appliances can be generated whilst maximum utilisation of energy supplied from RE or LC systems is guaranteed. At the same time there is no or negligible impact on end users/occupiers. The types of demand systems ideal for implementing the DSM+c algorithms are those associated with long time constants and typically identified as thermal loads e.g. space cooling/heating systems, washing machines, water heating, etc.

1.6 Research Objectives

The research aim is to develop, implement and apply this new, novel DSM+c algorithm at both strategic and operational level through a bottom-up approach, specifically to create greater flexibility in demand and better facilitate the integration of the energy generated from zero and low carbon sources within the built environment. The DSM+c algorithm specifies DSM parameters (i.e. demand priority, control method and duration, etc.) enacted upon selected loads. The optimal demand side management strategy can be generated through initiating the DSM+c algorithm against consideration of constraints from both supply and environmental variables. This algorithm has been integrated into a computational tool, called MERIT (Born, 2001), and successfully demonstrated. The major feature of this advancement in MERIT is to investigate and identify the best match of supply and demand when faced with various combinatorial options. Furthermore, these new algorithms have also been implemented within an Internet-resident monitoring and control platform towards real-time basis. Thus, the DSM+c algorithm can be used at both individual dwellings and larger community scales, and at both operational and strategic levels. It is demonstrated that this new method/approach will bring benefits to utilities, customers and the environment. For utilities, it can reduce peak load conditions and increase security and the supply reliability. For customers, it can reduce the energy use and hence provide financial savings, increase awareness of energy information and help users minimise energy wastage during everyday life. For the environment, it can save a significant amount of CO_2 emission through using more energy from green or low carbon sources. As such, it could be considered to be one of the most cost-effective measures, so far, to address the issues of environment, users, and energy suppliers.

1.7 Layout of the Thesis

This chapter shows the challenges and issues associated with the operation of the current energy system. The implications of measures enacted on the demand side in terms of policy, technology and management are described. The focus of the thesis is identified, specifically in relation to the activities required to address Demand Side Management and control (DSM+c).

Chapter Two presents a review of demand side management in various aspects, from design, programme implementation, through to evaluation of impact. Demand response and customer engagement are two main DSM approaches discussed in the thesis. The limitations of the demand response programs are discussed and their differences from the DSM+c algorithm proposed in this thesis are highlighted. In addition, the overview of load modelling and the development of communication technologies required for implementing DSM programmes are also presented.

Chapter Three illustrates the development of new micro-level DSM methods at both strategic and operational level. A generic DSM framework is established to accommodate different DSM options, such as load shifting and load control. In Particular, the algorithms for load shift at strategic level and demand side control at both strategic and operational level are described in great detail.

Chapter Four examines the enabling technologies both on the demand and supply side for the operation of a simulation-based demand side management algorithm. Combined heat and power (CHP) and heat pump models are described together with demand models such as a refrigeration system and water heating system.

Chapter Five describes the implementation of the DSM+c algorithm and relevant modules into a computational software tool (MERIT). It is also shown that the DSM+c algorithm at operational level has been implemented within Internet-Enabled Energy System (IE-ES).

Chapter Six presents the detailed procedures for verifying the DSM+c algorithm and the enabling demand and supply modules. A tailor-made verifying procedure is described to test the DSM+c algorithm (both strategic and operational level). For supporting demand and supply modules, an analytical method is proposed to verify the results from these models.

Chapter Seven presents two case studies used to demonstrate the applicability and functionality of the DSM+c algorithm at operational level. The first presents the application of the DSM algorithms at individual appliance level to investigate demand flexibility. Building upon the first case, the second presents the application of the DSM algorithms upon the individual appliance within a real-time small-scale renewable energy system, in order to study the demand-responsive performance.

Chapter Eight presents a case study to show the whole decision-making process for designing a low carbon multi-family building in Korea. The role that the DSM+c algorithm plays at the strategic level during the whole procedure is highlighted.

Chapter Nine summarises the research undertaken and highlights the main issues addressed; improvements to be made against the current research; and suggestions for the future work are also addressed.

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CHAPTER TWO   DEMAND SIDE MANAGEMENT REVIEW-THE STATUS QUO

This chapter mainly reviews the state-of-art research activities in demand side management (DSM). The background information of DSM is firstly described. Two macro-level traditional DSM options in particular (i.e. load management and on-site generation) are reviewed in detail from their objectives, methods, and current research status. The review of the appliance level DSM for various types of demands from statistical, simulated, and monitored sources is also reported. In addition, the issues of distributed generation are also illustrated. Finally, the specific work undertaken within this research, developing a micro-level DSM algorithm to improve the utilisation level of energy generated by building-integrated micro-generations, is presented.

2.1 Background

The term "Demand-Side Management (**DSM**)" did not exist prior to 1973. It appeared within an atmosphere of chaos in relation to an impending energy crisis and uncertainties, which prevailed at that time (Sioshansi 1995). It is widely regarded that during the 1970s a sequence of oil crises impacted upon the whole world. It led to a rapid rise in energy price, raised cost of power generation and subsequently higher electricity costs (Gellings and Chamberlin 1993; Sioshansi 1995). The quest for energy conservation became urgent within a climate of energy and financial crisis. Consumers, utility companies, and indeed society as a whole, have become aware of the importance of energy conservation. The concept of energy conservation and load management (**CLM**), which was the original name of DSM, emerged from that background at the beginning of the 1970s (Sioshansi 1994).

Due to the development of economics and technology, the demand for energy has steadily augmented from year to year. The old way to satisfy this increasing energy demand was to increase supply capacity by building more power generation plants, which was formally called Supply-Side Management (**SSM**) (Bellarmine 2000). The limited primary energy resources, a deteriorating environment, and unfavourable demand profiles were the three main constraints for the development of SSM strategies. It soon became clear that this type of approach was not suitable for sustainable development either from an environmental or an economic point of view.

Advances in technology have led to greater potential for more efficient energy utilisation and optimal energy/load management. The electrical and thermal demand profiles have become more and more unfavourable from the point of view of scale and peak time; the scale of the demand has increased and the peak is very high. In the future, if we are to rely solely on SSM, we would need very high capacity power generation plants or emergency power units solely committed to satisfying the peak demand during a very short period of time, which is not cost-effective. It has also been realised that modification to the way we use energy (including the time and amount of energy usage) in the demand side could not only save money but also satisfy the level of quality demanded by users of energy services. The agreement of controlling some loads when they are needed was reached by both the supply and demand side parties. Under this agreement, the term DSM officially came into being.

2.2 Utility-driven DSM

2.2.1 Definition

Traditionally most DSM programmes are driven by Utilities. Utility based DSM is defined as the planning, implementation, and monitoring of activities designed to influence and encourage customers to modify their level and pattern of electricity usage in such a way that the load profile can be modified by the utility company in order that it can produce power in an optimal way, i.e. changes in the time pattern and magnitude of a utility's load (Gellings and Chamberlin 1993; Gellings 1985).

2.2.2 Benefits

Utility-driven DSM programmes provide a number of benefits. From the utility perspective, it can reduce electricity consumption and defer the construction of new power plants and transmission lines. DSM can also bring economic benefits in the form of reduced capital expenditure, reduced operating costs, fuel savings, improved system efficiencies, and reduced losses. From the customer perspective, DSM can reduce energy bills and improve the service and comfort levels achieved.

2.2.3 Programmes

Most of the programmes falling under the umbrella of Utility-driven DSM include the following aspects (Gellings 1985).

- ***Load Management***

This entails having recourse to various economic and technical measures and maintaining the reliability level of the electricity grid. Load management programmes offer payments to participants to reduce their electricity usage when called upon by the system operator either for reliability or economic reasons. By adjusting or curtailing a production process, shifting load to off-peak periods, or allowing utility control of specific loads, customers can reduce the demand they place on the power grid. Participants are compensated for their willingness to reduce load through discounted retail rates or incentive payments tied to the specific loads made available to the system operator. Load management could reshape the load curve to achieve the purpose of cost-effective operations within electricity networks. At the same time it reduces the users' electricity bills.

- ***Strategic Conservation***

This is another popular demand-side option that gained support in the 1970s. "Strategic" is intended to distinguish between what is naturally occurring and what is utility-driven. Utility companies take economic and policy measures to encourage customers to become more involved in activities such as using advanced energy saving technologies, methods and devices to improve energy efficiency and thus reduce their energy consumption.

- ***New Uses***

Utilities actively promote new uses of electricity, in order to increase their profits. Electricity-using products provide either new services or improve the quality or desirability of a service over conventional alternatives. Generally, these products expand existing markets or open brand new markets. Examples include advanced heat pumps, home computers, energy auditing, energy-saving consultation and education etc.

- ***Electrification***

This type of DSM programme involves the replacement of some traditional out-of-date devices with electrified ones. Electrification is the term being employed to describe the new emerging electric technologies surrounding electric vehicles, industrial process heating, and automation. It offers the potential of significant productivity improvements and energy efficiency increases in manufacturing. Examples include robotics and industry automation, laser-based materials processing, and microwave heating and drying. These have a potential for increasing the electric energy intensity of the industrial sector. This rise in intensity may be motivated by reduction in the use of fossil fuels and raw materials resulting in improved overall productivity.

- ***Customer Generation***

This is a new type of demand-side management. Small-scale energy generation systems from either zero/low carbon energy sources or conventional fossil-fuel energy sources located on or near demand sites become popular and can play an important role to balance the demand and the supply from the conventional electricity grid. Most industrial customers and some large commercial customers have generation equipment on site, either for emergency backup or supplemental power. These energy generation systems can be treated as a type of demand side resource to help to meet the peak demand during grid critical periods.

This thesis attempts to develop a new approach to DSM at the micro level (i.e. appliance level) and from the bottom up by coupling load management and customer generation. The idea is to use load management measures at the appliance level to reshape the load profile, in order to better facilitate energy utilisation from on-site renewable or low carbon power generation sources. Therefore, the review focuses on these two main utility-driven DSM options: load management and on-site distributed generation.

2.3 Load Management (Demand Response)

Load management programmes of this nature, also known as a demand response programme, aims to manage the power on the demand side by using various economic and technical measures to reshape the load curve into the target curve (Paracha and Doulai 1998). It basically optimises the process/loads to improve the system load factor and normally is applied at macro scale (i.e. a large community or whole region). The load factor is the ratio of the average load to the maximum load within a certain period. The ideal value for the load factor is 1, which indicates that the average load is equal to the maximum load. However, in practice this is impossible to achieve and is always less than one (< 1.0). The lower this load factor, the greater the fluctuations within the demand profile. This results in increased capacity and/or cost for the operation of the supply side. Therefore measures are required to be implemented which improve the load factor. Load management is a suitable way of increasing the load factor, which is the process of scheduling the loads to reduce the electrical energy consumption and/or the peak demand at a given time. The following sections will review objectives, methods and current research status of load management.

2.3.1 Objectives (in load shape)

Six load shape objectives for load management programs are stated in the literature (Bellarmine 2000; Gellings and Chamberlin 1993; Gellings 1985; Nilsson 1994; Paracha and Doulai 1998), which are categorised under basic level (peak clipping, valley filling and load shifting) and advanced level (strategic conservation, strategic load growth and flexible load shape).

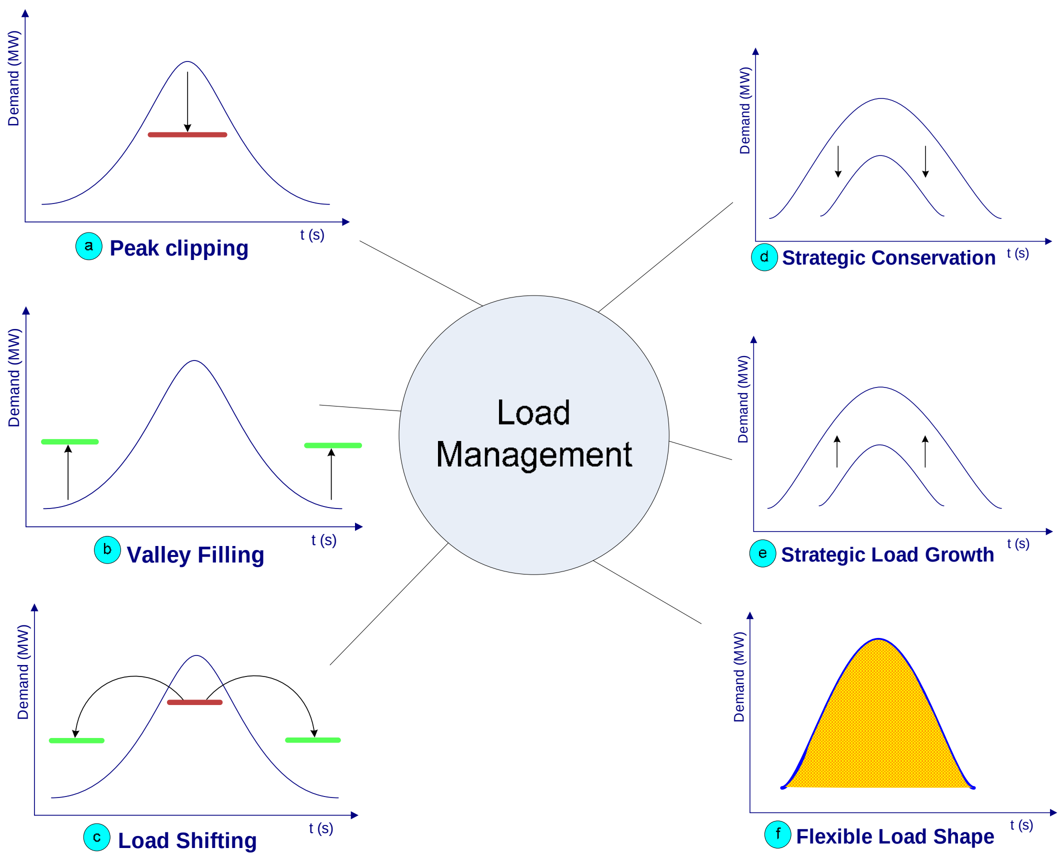

Figure 2-1: Load Shape Objectives for Load Management Program

- ***Peak clipping***

Peak clipping, one of the more traditional forms of load management, reduces the system peak loads during specific periods of time. Direct Load Control (**DLC**) is generally used to achieve peak clipping, which is most commonly practised by the utility having direct control over customers' appliances. It can be used to reduce operating costs and the dependence on critical fuels by economic dispatch. The shape of the load profile as a result of peak clipping being implemented is shown in **Figure 2-1 (a)**. Peak clipping becomes particularly vital for those utilities that do not have enough generating capacity to satisfy maximum demand during peak times. It can lower the service cost for utilities by reducing the need to operate at its most expensive unit and by postponing the needs for the future capacity additions.

- ***Valley filling***

Valley filling, another classic form of load management, builds the loads during the off-peak period. This may be particularly desirable where the long-run incremental cost is less than the average price of electricity. Adding properly priced off-peak loads under those circumstances decreases the average price. Valley filling can be accomplished in several ways, one of the most popular of which is electric-based thermal energy storage (water and / or space heating or cooling). The shape of a load profile through the valley filling technique is given in **Figure 2-1 (b)**. This technique can lower the cost of service by spreading fixed capacity costs over a longer base of energy sales and reducing the average fuel cost.

- ***Load shifting***

Load shifting, the last of the traditional forms of load management, can be regarded as having the effect of combining peak clipping and valley filling. The restructured shape of a load profile using load shifting techniques is also illustrated in **Figure 2-1 (c)**. This involves shifting loads from peak to off-peak periods without necessarily changing the overall energy consumption, through which peak clipping and valley filling can be achieved at the same time. Popular applications include the use of storage water heating, storage space heating, and cold storage.

- ***Strategic conservation***

Strategic conservation is a recent introduction and is regarded as one of the advanced load management options. It decreases the overall load demand by increasing the efficiency of energy use and leads to the load shape changes that result from utility-driven programs. Utility planners consider both naturally occurring actions and purposely-designed utility programmes to implement energy conservation and encourage efficient energy use. '*Strategic*' is intended to distinguish between naturally occurring and utility-stimulated. It reduces the demand not only during peak hours but also at other hours of the day. Examples include not only improvement in appliance efficiency but also those that occur naturally. The shape of a load profile through the strategic conservation technique is given in **Figure 2-1(d)**. This practice can reduce the average fuel cost and postpone the need for the future utility capacity addition.

- ***Strategic load growth***

Strategic load growth, another advanced load management option, concerns mainly the utility companies encouraging customers to adopt electro-technologies (electrification), either to replace inefficient fossil fuel equipment or to improve customer productivity and quality of life. This results in the increase of electric energy intensity and lowering the average cost of service by spreading the fixed cost over a larger base of energy sales, and thus benefiting both the utility companies and the customers. Increasing energy use during some periods, e.g. programs that encourage cost-effective electrical technologies that operate primarily during periods of low electricity demand, can be effective in achieving efficient plant operation. The shape of a load profile through the strategic load growth technique is shown in **Figure 2-1 (e)**. This reduces the average cost of service by spreading fixed cost over a long base of energy sales and benefits all the customers.

- ***Flexible load shape***

Flexible load shape, the last of the advanced forms of load management options, is a concept related to the reliability of energy supply with the possibility of variably controlling customers' equipment. The programmes involved could be variations of interruptible or curtailable load control; concepts of pooled, integrated energy management systems; or individual customer load control devices offering service constraints. The shape of a load profile through the flexible load shape technique is illustrated in **Figure 2-1 (f)**. Utilities can realise both operating and future fixed costs by allowing dispatch flexibility to reduce or postpone demand for selected customers.

2.3.2 Classifications of Load Management Programmes

Load management programmes involve reducing loads on a utility's system during periods of peak power consumption or allowing customers to reduce electricity use in response to price signals. Most of the conventional load management programmes can be categorised based on two dimensions (RMI 2006). The first dimension features how and when utilities call on programme participants to shed load.

Customers are called upon for either emergency/reliability conditions or for economic purposes. The customers will be paid for reducing their electricity demand during system contingencies. Economic programs offer consumers incentives to reduce loads during non-critical periods when the cost of delivering services exceeds some specific limit. The second dimension shows how utilities motivate customers to participate. It can be classified into load response and price response programs. For load response programmes, a utility offers customers payments or incentives for reduction of demand during specified periods. Straight communication signals (telephone, power line, pager and Internet) may be used to notify participants of reliability or economic events in exchange for direct utility payment. Participants either receive participation payments as a bill credit or discount rate for their participation in the programmes, or are rewarded in monetary terms for their performance, depending on the amount of load reduction achieved during critical conditions of power system management. It includes direct load control, interruptible/curtailable load tariffs and emergency demand response programmes etc. On the other hand, they may use pricing signals as an indirect way to more accurately reflect the cost of providing power as a function of time. Electricity tariffs are not flat, so the rates fluctuate following the real time cost of electricity. In price response programmes, customers voluntarily reduce their demand in response to forward market prices (Kirschen 2003). This type of LM programme includes Time-Of-Use rates, Critical Peak Pricing and Real Time Pricing etc. Different LM programmes in terms of these two dimensions are shown in **Figure 2-2**.

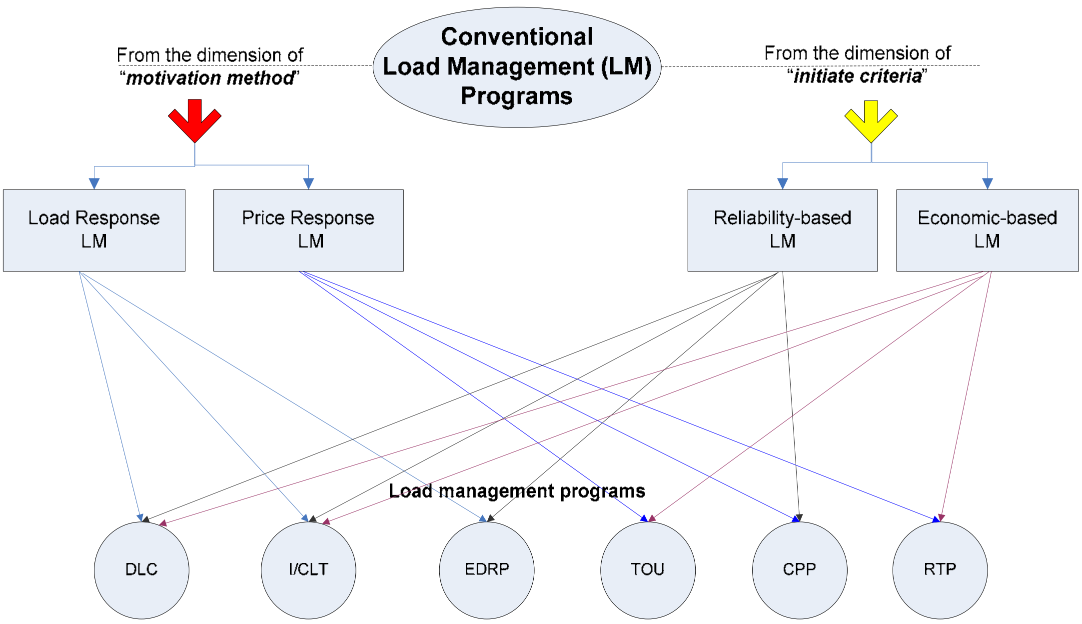

Figure 2-2: Classification of Load Management Programs

2.4 Current Status of Load Response (LR)

2.4.1 LR Type

- ***Direct Load Control (DLC)***

DLC programmes are primarily targeted at small commercial (<100kW peak demand) and residential customers. Customers sign up for the programme to allow utilities to shed remote customer loads unilaterally by directly switching different equipment on or off with short notice as subject to a certain mutually agreed contract. Typical remotely controlled equipments include air conditioners and water heaters. The agreement contract specifies the maximum number of events per year (e.g. up to 30) and the maximum duration of any given event (between 2 and 8 hours, but typically 4). The utilities provide incentive payment to customers as a reward, e.g. fixed monthly payments credited to the customers' utility bill, plus a one-time participation payment. Very little advance notification will be given prior to initiating an event (3 minutes or less). Most DLC programmes allow the customer to override an event if they experience discomfort, but some programmes impose penalties for overrides (Wright and Martinez 2003).

Load switches or "smart" thermostats are required to implement DLC programmes (Nadel 1992). Load switches cycle the AC compressor or completely shut down other loads such as lighting and water heating. Smart thermostats are programmable, communicate and used to raise temperature-setting points; and reduce customer load automatically during peak reduction events. Utilities typically pay upfront for the cost of these devices/ technologies and offer these to the customers free of charge. These technologies are relatively inexpensive, quite reliable and capable of achieving up to 60% load reduction per site for small customers (RMI 2005).

- ***Interruptible/Curtailable Load Tariff (I/CLT)***

Customers participating in **I/CLT** programmes sign an interruptible/curtailable load contract with utilities, which agree to switch off major portions or even a facility's entire load as and when requested by the utility. I/CLT programmes mainly target medium (100~500kW peak demand) to large customers (>500kW peak demand). The utility must notify customers before an interruptible/curtailable event takes place. Advance notice is typically given minutes to hours ahead as a minimum, but some programmes notify participants up to a day ahead. Similar to DLC programmes, the utility must specify upfront, the maximum number of events and durations per year. Participants receive lower electricity bills during normal operation, as well as additional incentives for each event. Severe penalties can be enforced for non-performance/compliance. The interruptible load rates are normally applied to commercial and industrial consumers, such as office buildings, universities and industrial plants etc. The load reduction can be achieved by introducing a demand limiter, which is installed by the customer, and the utility sends control signals to interrupt the contract amount if such need arises. Some large commercial and industrial facilities install back-up generators to supply power to critical loads in case of unexpected interruptions in power. The utility benefits by way of a reduction in its peak load and thereby saving costly reserves, restoring quality of service and ensuring reliability. The customers benefit from reduction in their energy costs and from incentives as identified in the contract (Tuan 2004).

- ***Emergency Demand Response Programme (EDRP)***

In EDRP, participating customers are paid incentives (almost 10 times the electricity price in the off-peak period) for measured load reductions during emergency conditions (Fahrioglu and Alvarado 2000). Although EDRP would cause an amount of uncertainty in the peak reduction, the customers, particularly some large consumers, like to participate in this type of programme. The high participation rate of this programme is due to two main reasons: high incentives and no penalty for not reducing their consumption (DoE 2006).

2.4.2 LR Strategy

The development of load management strategy is vital to the successful design and implementation of the various large-scale, utility-driven load management programmes. Different objectives in terms of system reliability, cost and customer impact are specified by utilities for different types of programmes. As addressed in the previous section, some types of load management programmes (such as DLC, I/CLT and EDRP etc.) are managed by utilities whilst others (such as TOU and RTP etc.) need the voluntary involvement of customers.

During the last three decades, DLC programmes received much more attention from researchers than others. Most DLC programmes have been analysed from the supply side, offering schemes to achieve single or multiple objectives, such as minimising the system operation costs (Chen et al. 1995; Hsu and Su 1991), maximising the reduction of system peak load, maximising utility’s profit (Ng and Sheble 1998), minimising system peak load (Cohen and Wang 1988) and minimising the discomfort caused to customers (Bhattacharya and Crow 1996). Cohen and Wang (1988) proposed a method for scheduling the load control using dynamic programming. It is based on an analytical model of the load under control, which gives it the advantage of allowing any length of time for the control periods and any cycle rates. The method can be used for different utility objectives including minimising production cost and minimising peak load over a period.

Various methodologies were applied to optimise the DLC scheduling, such as linear programming (Kurucz, Brandt, and Sim 1996), dynamic programming (Cohen and Wang 1988) and fuzzy logic (Bhattacharya and Crow 1996) etc.

Hsu and Su (1991) pointed out that DLC must be coordinated with unit commitment, which schedules generators in short term by taking account of start-up costs and time delays, in order to achieve maximum operational cost savings. Chen et al (1995) presented an effective method for DLC dispatch with the objective of minimising system operational costs. The method was applied to successively dispatch multiple DLC groups. It coordinated a DLC group with the available supply-side options. In addition, the impact of DLC on unit commitment was illustrated and an extension to include capital cost consideration was also addressed.

Kurucz et al (1996) developed a linear programming (**LP**) model to optimise the amount of system peak load reduction through scheduling of control periods in commercial/industrial and residential load control programmes at Florida Power and Light Company. The LP model can be used to determine both long and short-term control scheduling strategies and for planning the number of customers who should be enrolled in each program. Results from applying the model to a forecasted late 1990s summer peak day load shape are reported. It is concluded that LP solutions provide a relatively inexpensive and powerful approach to planning and scheduling load control. Also it is not necessary to model completely the general scheduling of control periods in order to obtain near best solutions to peak load reduction. In order to achieve maximum cost benefits, a DLC dispatch schedule should be coordinated with utility economic considerations such as unit commitment and economic dispatch.

Conventional cost-based DLC ignores the rate structure offered to customers. The resulting cost savings may cause revenue loss. A profit-based DLC using linear programming was introduced by Ng and Sheble (1998) to examine generic direct load control scheduling. Based on the cost/market price function, the approach aims to increase the profit of utilities. Instead of determining the amount of energy to be deferred or to be paid back, the algorithm controls the number of groups per load type to maximize the profit by shifting the load from low to high profit margins.

DLC strategy was also studied in a multi-objective framework (Jorge, Antunes, and Martins 2000) and presented a multi-objective decision support model which allows the consideration of the main concerns that have an important role in DLC: minimise peak demand as perceived by the distribution network dispatch centre; maximise utility profit corresponding to the energy services delivered by the controlled loads; and maximise quality of service in the context of remote load control.

2.5 Price-Based Demand Response (PBDR)

2.5.1 PBDR Classification

The PBDR programmes are based on dynamic pricing rates in which the electricity tariffs are not flat. They are designed to lower system costs for utilities and bring down customer bills by offering high price during expensive hours and lower prices during inexpensive hours. The load shape objective is to flatten the demand curve by reducing peak loads and/or shifting load from peak to off-peak periods. According to Charles River Associates (2005), the rates include Time of Use (TOU), Critical Peak Pricing (CPP), Extreme Day Pricing (EDP), Extreme Day CPP (ED-CPP), and Real Time Pricing (RTP).

- **TOU**

TOU rate is the basic type of PBDR. The electricity prices differ in different blocks of time. Generally, the rate during peak periods is higher than the one during off-peak periods. The simplest TOU rate (Gellings and Chamberlin 1993) has two time blocks: the peak and the off-peak. The rate design is aiming towards reflecting the average cost of electricity during different periods. Economy 7 tariff in the UK (Tan and Kirschen 2007) is a good example.

- **CPP**

CPP rate contains a pre-specified higher electricity price superimposed on TOU rate or normal flat rate. The CPP rate (DoE 2006) is called during system contingencies or high wholesale electricity prices for a limited number of days or hours per year.

- **EDP**

Similar to CPP, EDP rate (Charles River Associates 2005) has a higher price of electricity and differs from CPP in the fact that the price is in effect for the whole 24 hours of the extreme day, which is unknown until a day-ahead.

- **ED-CPP**

ED-CPP rate (Charles River Associates 2005) contains two types of rate, which are invoked under different conditions. During extreme days, the CPP rate is called for peak and off-peak periods. Whilst for other days, a flat rate is being used.

- **RTP**

RTP is hourly fluctuating prices reflecting the real cost of electricity in the wholesale market (Moholkar, Kilinkhachorn, and Feliachi 2004). Customers are informed about the prices on a day-ahead or hour-ahead basis. The electricity price varies continuously (hour by hour) based on the utility's load, power market and power producers who participate in satisfying the demand. Customers can buy their power on this spot market for the best available price and savings can be substantial. Implementing a RTP programme requires significant technology investment, including automated interval metering, along with more complex price forecasting, communications and billing systems. Automated RTP control technology for customers is recommended to maximise performance and savings. At the moment, it is unclear whether RTP programmes are more cost-effective than other types of LM programmes. There are some obstacles in terms of the aspects of technologies, incentive to consumers and utility companies, supportive policies and regulations, and pricing schemes (Albadi and El-Saadany 2008). However, many economists are convinced that RTP is the most direct and efficient LM method suitable for competitive electricity markets and should be the focus of policymakers (Bloustein, 2005).

2.5.2 Customer Response to PBDR programs

There are typically three types of customer response to different PBDR programmes (DOE, 2006).

- Customer reduces his electricity usage during critical peak periods, when prices are high without changing consumption pattern during other periods. Customer may experience temporary comfort loss. This response is achieved, for instance, when thermostat settings of heaters or air conditioners are temporarily changed.
- Customers respond to high electricity prices by shifting some of their peak demand activities to off-peak periods. As an example, they shift some household activities (e.g. dishwashers, washing machines, tumble dryers) to off-peak periods. The residential customers in this case will bear no loss and will incur no cost. However, this will not be the case if an industrial customer decides to reschedule some activities and rescheduling costs to make up for lost services are incurred.
- Customer adopts on-site generation equipment to match the demand. Customers who generate their own power may experience no or very little change in their electricity usage pattern; however from the utility perspective, electricity usage patterns will change significantly, and demand will appear to be smaller.

2.5.3 Evaluation of PBDR Programmes

There are several indicators used to judge how successful the implemented PBDR programmes are (Albadi and El-Saadany 2008).

The first indicator is the actual peak demand reduction. As this is an absolute value, it is necessary to normalise this value to the percentage peak demand reduction. Thus this relative value can be used to compare different programmes with similar situations.

In addition to peak demand reduction, the performance of PBDR programmes is measured using two parameters associated with elasticity: the price elasticity of overall electricity consumption and elasticity of substitution. The former one represents the sensitivity of customer demand to the price of electricity. This is defined as the ratio of the percentage change in demand to the percentage change in price (David and Li 1992). It would cause a temporary loss of comfort. The elasticity of a substitution measures the rate at which the customer substitutes off-peak electricity consumption for peak usage in response to a change in the ratio of peak to off-peak price. For residential customers, no energy service loss or further cost would be incurred. However, it was not the case for commercial and industrial customers, as described in Section 2.5.2. This is an important factor for load shifting measures. Similar definitions can also be found. According to Kirschen et al (2000), elasticity is decomposed into self-elasticity and cross elasticity. Self-elasticity measures the demand reduction in a certain time interval due to the price of that interval. Cross elasticity measures the effect of price of a certain time interval on electricity consumption during another interval.

Another aspect of DR programmes evaluation is customer acceptance and enrolment in the programme. Without customer participation, PBDR programmes will certainly fail to achieve their objective of reducing peak demand.

2.5.4 Utility Experiences (mainly in US) on PBDR Programmes

- **EDF, France**

Electricite De France (EDF) operated the most successful example of TOU pricing programme. The programme was applied to industrial customers in 1965 and introduced to residential customers in 1965 on a voluntary basis. Currently, it is estimated that one third of its customers (30million) are on TOU pricing (Charles River Associates 2005).

In 1993, EDF introduced a CPP pricing programme called Temp (Charles River Associates 2005) in which the year was divided into three types of days: Tempo Blue, Tempo White, and Tempo Red. 300 days of the year were Tempo Blue in which electricity was cheaper than the normal TOU prices. Tempo White days were 43 and they were at slightly higher rates compared to that of normal TOU. Tempo Red days were only 22 and they were the most expensive. Customers could know the colour of the next day by several means (such as consulting the Tempo Internet website; subscribing to an email service that alerts them of the colours to come; using a data terminal; using a vocal system over the phone; checking an electrical device provided by EDF that could be plugged into any electrical socket.).

- **Gulf Power Company, US**

Gulf Power Company implemented an experimental programme in Florida with TOU pricing (Charles River Associates 2005). Within the programme, customers were provided with smart thermostats that automatically adjust the temperature and other loads depending on a price signal. Normal TOU prices were applied 99% of all hours in the year. In the remaining 1% of the hours, the utility had the option of charging a critical peak pricing more than the normal peak period prices. This programme results in 42% peak demand reduction during critical peak periods. In a recent survey, the programme received a 96% satisfaction rating.

- **California's Pricing Experiment, US**

The experiments were carried out by the state of California to test customer response to a variety of pricing options, including TOU and CPP rates (Charles River Associates 2005). Customers on TOU and CPP rates pay a higher price during the five-hour peak period that lasts from 2pm to 7pm on weekdays and a lower price during the off-peak period, which applies during all other hours. Two sets of peak/off-peak prices were designed for each TOU and CPP rate to allow for precise estimation of the elasticity of demands. Analysis of data from the California experiment indicated that it was very effective for CPP rate customers to reduce peak demands. Customers were likely to reduce air conditioning usage during higher peak price periods, and shift laundry, dishwashing and cooking activities from some peak period usage to lower cost off-peak periods.

- **Chicago Community Energy Cooperative, US**

A market-based RTP pilot programme for residential customers was implemented by Chicago Community Energy Cooperative and the local electricity utility (Barbose, Goldman, and Neenan 2004). The RTP rate was decided on a day-ahead basis. The project was designed to estimate the magnitude of customer response to hourly energy pricing and understand the drivers of responsiveness. This was a three year project started in 2003.

The results of customer loads in the first year implied that participants responded to the higher prices they faced during the peak periods (Barbose, Goldman, and Neenan 2004). An electricity price elasticity of -0.042 was estimated over the full range of prices. 25% of aggregated demand reduction was achieved during the notification period. Over 80% of the participants reported that they modified their air conditioning usage, while over 70% of them modified their clothes-washing pattern. Results were also showing that multifamily households as a group were more price-responsive than single-family households. From survey results, customer satisfaction was very high in this programme. 82% of the participants thought that the programme was "quick and easy". 20% of customers' monthly bill was saved. This project has shown that residential customers were a viable market for RTP. As residential load was a key contributor to system peak, it was important to deploy RTP rate structure in the residential sector market.

- **Georgia Power, US**

Georgia Power operates one of the largest and possibly the most successful RTP programmes in the world (Barbose, Goldman, and Neenan 2004). It was estimated that during emergency conditions, 17% of demand was reduced by its customers, freeing up 800MW of capacity. It began with a two-year controlled pilot in 1992, with the objectives of increasing competitiveness, improving customer satisfaction by giving customers more control over their bills, and curtailing load when needed to balance demand and supply. The programme was mainly targeted for commercial and industrial customers. Both day-ahead and hour-ahead programme were implemented within the project. The structure of RTP rate was two-part rate: "baseline" standard rate and the rate difference between the standard rate and the hourly real time pricing rate. Georgia power also offered price protection products for both limiting the risk associated with high price and restricting the windfall reaped during periods of low prices. There was no evidence found that these price protection products dampened price responsiveness of customers.

The results of this programme had shown that manufacturers with highly energy-intensive processes, such as chemical, pulp and paper companies, were generally the most responsive customers. And also the education for customers to understand the benefits of RTP rate was the key to a successful dynamic price demand response programme. The satisfaction level of customers was measured from the feedback received through various levels of meetings held with customers.

2.6 Limitations of LR and PBDR

There are, however, several drawbacks that need to be addressed within utility-driven demand response programmes reviewed above.

- Most of the demand response programmes are carried out through top-down approaches. Either the condition of the grid network or the price signal within the electricity market is the main indicator to trigger load management programmes. It is difficult to use this approach to identify the actual DSM resources that would bring less impact upon users.

- All the above-mentioned load control strategies take the benefits of the supply side as a main consideration. For instance, some strategies aim to increase the profit of utilities, whilst others try to reduce the power system peak load, in order to defer the construction of new power plants or avoid operating emergency generators. But these strategies do not actively reduce energy demand.

- Conventional DSM programmes are effective in reshaping the load curve, which limits the energy usage in peak time and encourages its use during off-peak periods. Instead of reducing energy demand, those strategies actually encourage the usage of energy during the period when the electricity price is low, when sometimes the usage may not be necessary. This makes no contributions to decreasing existing high-levels of GHG emissions, and potentially makes the problem even worse.

- Most of the designed control strategies are only suitable to one type of demand device. With a large amount of appliances deployed, either electric water heaters or air conditioners, this makes it impossible to accommodate additional types of appliances installed in the demand side. The lack of flexibility restricts the load strategy from being rolled out into further areas.

- The comfort on the customers' side is not the first priority. As previous experiences show, many users suffer from uncomfortable environments/ conditions, which is one of the main reasons why user participation rates in some DSM programmes remains quite low.

- The feedback from some demand response programmes is considered, but usually in a qualitative way. There is always a delay period to consider the customers' satisfaction level compared with the time when the actual control actions were enacted. It would be nice if there were some new ways to quantify the control impact and make control actions on real time basis, in order to minimise the inconvenience to the users.

2.7 Micro-level DSM (Customer Side)

2.7.1 Background

A novel concept of DSM at the micro level is proposed in this thesis to overcome the drawbacks of the conventional top-down DSM approach. Here, micro-level DSM means that demand side management and control is carried out upon various appliances within single household or individual buildings. The objectives at system level can be achieved through a bottom-up approach. It is not only suitable for load management at an individual dwelling level, but can also be used in large-scale applications. In addition, with the rapid growing of small-scale embedded generation at the domestic level, the supply profile becomes more volatile. The time variance of supply from renewable energy resources, which generally does not match the load profile, may lead to congestion or energy surplus (Kupzog and Roesener 2007). Usually these distributed generation devices are scattered throughout the customer base. It is a challenging task to co-ordinate all these sources and integrate them within the power system. Micro-level DSM systems would play an important role in maintaining the reliability of the whole power system and better utilise energy from distributed generation systems. It is possible to couple the customer-side embedded generation into the local demand network via a micro-level DSM system, as it manages the loads from each individual house. The micro-level DSM system can be scaled up to system level via the bottom-up approach in order to analyse the performance of the whole power system.

For each micro-level DSM system, three major objectives are to be achieved: improve the efficiency of energy use; increase the utilisation of energy produced by renewable or low carbon energy systems; and minimise the impact upon users. These objectives should be reached simultaneously. Micro-level DSM would play an important role in improving efficiency of energy use by controlling demand systems better and avoiding unnecessary energy waste. Through reshaping the demand profile, more energy generated from RE/LC sources can be facilitated.

A certain extent of demand flexibility exists within the consumption process for every end-use device. Normally end-use devices ‘use’ electricity to provide a ‘service’ to the user (Schweppe, Daryanian, and Tabors 1989). Different appliances have different flexibility in their own energy consumption processes. For example, the flexibility for electric-based heating and cooling appliances (i.e. refrigerator, air conditioner and electric water heater etc.) is high, as temporary power disconnection for them does not critically impact on the service/function they are expected to deliver. For some appliances like washing machines and dish-washers etc, energy usage and service may both be rescheduled to another period, which could be acceptable for the customer as long as the service has been delivered as required. For other appliances, such as lighting and cooking etc., services may be reduced in quality or amount, but neither service nor energy usage can be rescheduled without inconvenience to the consumer. While for other devices, such as entertainment devices (TVs, VCRs and HiFis etc.), the flexibility is low since switching off will have a huge impact on the users. Empirical evidence suggests that introducing demand flexibility could result in increasing the tolerance level of users when supply power for a device is disconnected. However, little research has been carried out to study the tolerance levels of customers when different types of appliances are controlled. A good DSM system undertakes switching actions upon appliances without the notice of the user (Stadler and Bukvic-Schafer 2003).

2.7.2 Current Status of Appliance-level DSM system

- ***Historical demand***

Newborough collected and analysed the electricity demand of individual dwellings and the main types of domestic appliances within UK households (Newborough and Augood 1999). Various methods of modulating these electricity demands have been proposed, such as 1) to size, and control the operation of, electrical heaters fitted within appliances in a more load-conscious manner; 2) to utilise some form of integrated control to ameliorate the effects of coincident demands emanating from individual appliances during peak periods; 3) to apply thermal storage techniques; and 4) to simply avoid using electricity for heating purposes where a suitable gas-fired alternative exists. Up to 60% of peak demand reductions are found when only the load-conscious control algorithm is applied to individual cooking and washing appliances without adversely affecting their performance. The data used and the results obtained from the investigation are for a specific experimental case, which is not a general case. The impacts of load management actions upon users are not considered in a quantitative way.

- ***Individual demand modelling***

Another aspect of research interest in developing an appliance-level DSM system is through demand modelling. Generally speaking, it is difficult to derive reasonably accurate models for the consumption behaviour of potential DSM loads due to the individual characteristics and the stochastic behaviour of each single process.

However, among all residential appliances, electrical heating and cooling appliances, which contribute significantly to the total DSM loads, can be described using a generic class of conceptual electricity storages (Kupzog and Roesener 2007). Different accuracy levels for these types of load models can be found in the literature. Models based only on historical data have been developed by Virk and Loveday (1994), and Tomiyama, Daniel, and Ihara (1998). However, they are not adequate for DSM purposes, as they tend to represent the power system and their loads in a "normal" state meaning that no effects of load control actions are taken into account. Walker and Pokoski (1985) suggested an empirical model based on regression analysis of historical models and lifestyle. Again, it is not adequate and outside the scope to apply DSM. Only a physically based load model is suitable for a micro-level DSM system, as it allows simulation of the individual dynamic load performance, i.e. the so-called "pay-back" effect and the effects on environmental variables that are used to assess impact on consumer comfort. It is possible to find a great number of individual load models reported in literature, as in Lee and Wilkins (1983), Chong and Malhami (1984), Chong and Debs (1979), Gomes and Martins (1995), Molina et al. (2003), Asawari and Moholkar (2005). These models are based on energy balances between the external and internal environment. Aggregation may be achieved in a bottom-up approach based on individual load models.

In addition, Ning and Katipamula (2005) developed set-point control strategies for aggregated thermostatically controlled appliances (**TCAs**), mainly refrigerators, heating, ventilation and air conditioning units (**HVACs**) and electric water heaters (**EWHs**), in a competitive electricity market. By varying the TCA thermostat settings, the TCA power consumption can be shifted from the high-price period to the low-price period to reduce the peak-load and energy cost. Runmin, Nehrir, and Pierre (2007) proposed a voltage-control strategy for utility-side load management of aggregate residential EWHs, in order to improve system stability and security, as well as equipment utilisation rate. Through controlling the operating voltage of EWHs, the total power demand of aggregated EWHs loads during peak time can be controlled. Although these models are developed for controlling aggregated appliances, the principle behind these models can also be applied to individual units.

- ***Monitoring and control communication system for load management purpose***

The other aspect of micro-level DSM research is the monitoring and control communication platform. Traditionally, radio-controlled switches installed in various appliances are a popular way to perform one-way direct load management. During periods of peak electricity usage, the switches are activated by a radio signal sent by utilities. The common approach is to disconnect loads in a specific order and keep them disconnected as long as needed. In cases when disconnection periods are very long there is an option of load rotation, reconnecting already disconnected devices after a certain time has elapsed whilst disconnecting others. However, the impact of load control upon users' comfort is not considered in an accurate and dynamic way. Therefore, two-way communication is required to acquire some information on demand side impact. Different types of monitoring and control communication systems based on various communication media are proposed in the literature. Here, several typical systems were listed as follows.

Asawari and Moholkar (2005) present a Computer-Aided Home Energy Management (**CAHEM**) system, shown in **Figure 2-3**, which enables the implementation of price-responsive load management for the residential sector. It consists of a computerised load control implemented with the help of X10 appliance controllers. X10 is the oldest home networking protocol that communicates over the power line within the house. The computerised load control includes load models, user interface, and a load shifting algorithm. A controller sends the control signal over existing electric wiring to the receiver modules dedicated to each appliance. The receiver modules control the appliances depending on the control command received from the main controller. The user can request the status of each appliance. Therefore, a two-way transmission of power line signals can be achieved through this system. The main drawback of using the X10 power line carrier is its signal strength, which is low and can be subject to failures due to noise on the power line. Extra devices, such as noise filters and phase couplers, are needed to resolve the problem, which would add more cost to the whole system.

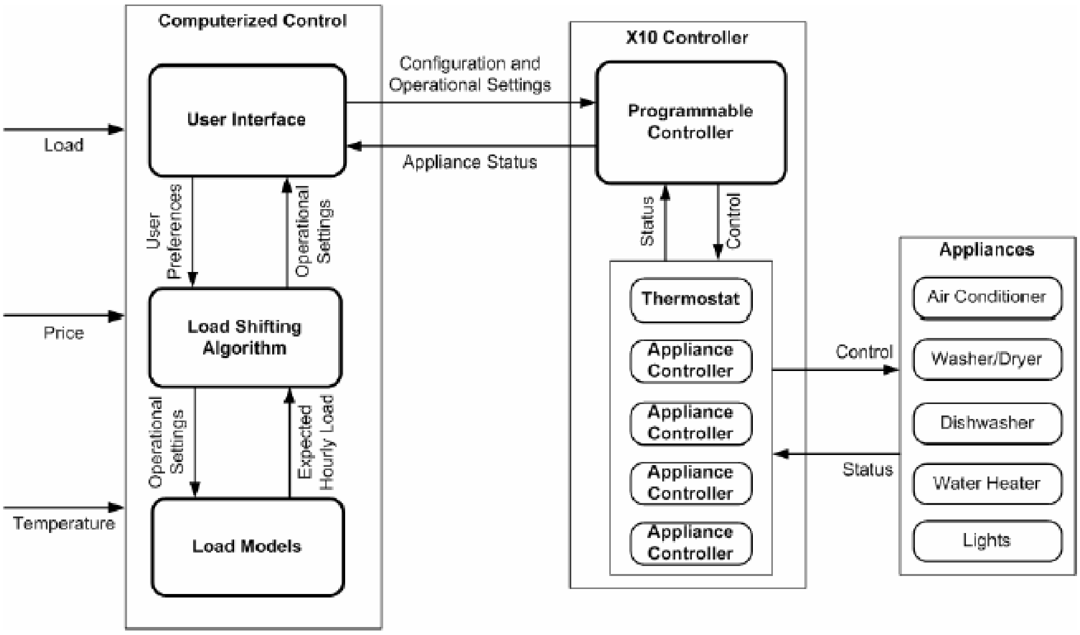

Figure 2-3: CAHEM Diagram

Low-cost, flexible and powerful monitoring and control systems are required in this field. The structural elements of possible systems for residential energy consumers should include: wired or wireless network architecture/protocols, sensors, actuators and software systems to monitor and control home devices. A mixed-technology web-based monitoring and control system is proposed as a pilot study between Intel Folsom Innovation Centre and the Sacramento Municipal Utilities District (SMUD) by (Williams et al. 2006). The target is to allow users to view and control energy data via a home web address with a graphical user interface. The primary entertainment display (TV) is connected to the computer for viewing purposes. Home automation and other specialised software are installed to collect, normalise, store and display information from temperature sensing devices and a whole house energy meter. Internet access was used to transfer data to a centralised database and to provide remote access to data and control systems. Wireless and power line technologies were used for meter and control system communications. Through using various types of technologies it provides better opportunities to try more cost-effective, suitable and accurate sensors for designing an optimal and sophisticated control strategy. The total whole system costs may come down significantly, as the system is adopted at large scale.

Molina-Garcia et al. (2007) demonstrated the application of a Wireless Sensor Network (**WSN**) to electrical power management, which brings new opportunities to small customer consumption control. The system, shown in **Figure 2-4**, has a set of several sensors and actuator nodes, which report the information of energy consumption for the load, as well as environmental variables, such as temperature, humidity and light intensity. The data of these parameters will be transmitted to the sink node as soon as they are known. Data travels through the wireless network by means of a succession of hops (from node to node) until the destination is reached. The load control algorithm, aimed for selecting the optimum load control strategies, will be executed in a PC after the required data is received by the sink node. Once the control actions have been generated, the control commands travel back through the wireless network until they arrive at the nodes where the control actions are performed. The consumption data and forced actions within this individual building may be transmitted through any communication network (such as Internet, GPRS, UMTS and Wi-Fi etc.) to the electrical or energy service company for historical records and further refining the load control strategy.

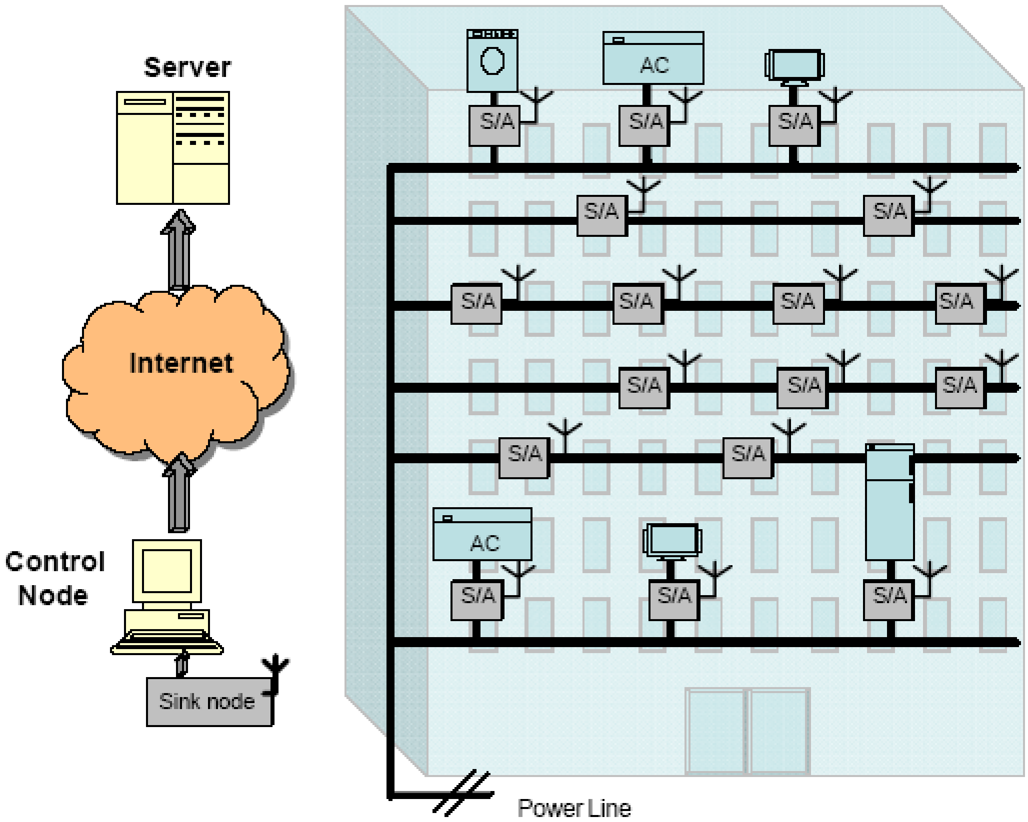

Figure 2-4: Diagram of WSN System

Ha, Lamotte, and Huynh (2007) proposed a multi-level optimisation mechanism for customer-side load management. Agent management of energy is used to carry out the distribution of the energy of the housing by proposing a dynamical threshold of the total energy consumption for each household. Agent is a sort of interface, which is allowed to gather information from and execute control actions upon demand devices. The home automation system coordinates the energy consumption in the house by using service flexibilities. Depending on the satisfaction feedback from customers, obtained through home automation systems, the limit of power consumption of the household can be modified by the management Agent. Through this mechanism, the comfort of users is considered dynamically with the satisfaction of the constraints from energy production capabilities. The proposed solution makes it viable for private households to automatically adjust their consumption in order to satisfy power constraints and consequently to participate in a DSM system.

Similar to Ha's system, a multi-agent home automation system for power management is presented by Abras et al. (2008). The system is built upon a multi-agent prototype. Each agent is integrated into a power resource or equipment, which may either be an environmental variable (such as temperature, humidity or luminosity) or a service (washing, cooking, heating or cooling). Every agent coordinates and cooperates its action with each other in order to reach an overall near-optimal solution. The control algorithm implemented within the system can be decomposed into emergency mechanisms and anticipation mechanisms. The former one protects from constraint violations, whilst the latter computes the best future set-points under the comprehensive consideration of predicted consumptions, productions, and user criteria. Thus, the presented system is capable of adapting the power consumption to available power resources according to user comfort and cost criteria.

Hong et al. (2008) proposed an Internet-enabled energy system (**IE-ES**) for demand side management within the built environment. The system consists of device monitoring and control modules, data server modules and service-oriented application modules. It monitors the power demand being experienced and the supply that is currently available, together with the environmental variables. It is believed that the best way to collect these essential data is to use wire/wireless Internet communication using standard TCP/IP protocols, which is more accurate and dynamic. Also the Internet provides an important medium with low cost and high coverage for distributing information without time and location constraints, which is feasible to be used for real-time distributed monitoring and control of various devices within the built environment. The system is even able to operate a certain service (such as DSM) using the data from linked simulation models when certain demand or supply devices are not available. Therefore, the proposed IE-ES is low cost, generic, flexible, and powerful, which is adopted to perform the verification study for the developed DSM algorithm in this thesis. Detailed description of this system is illustrated in Chapter Six.

Other technology, such as a Grid Friendly Controller, has been developed in Pacific Northwest National Laboratory (**PNNL**), US. It can detect impending grid instability by monitoring low-frequency signatures (PNNL 2006). In the future, such devices may be fitted to domestic consumers to provide load-shedding at times of excessive power-system stress, such as congestion or energy deficit. It can help to achieve the balance between energy supply and demand.

The above review of both simulation and real systems shows the variety of DSM that can be applied at the small scale. Most models are set up based on the current power system network. DSM plays an important role in improving energy efficiency on the demand side. Most of the energy during peak time can be avoided through better control strategies, and most systems consider the impact of load control upon user comfort levels, another aspect beneficial to the supply side. The load control actions are initiated when the power system condition is violated and cost of energy production becomes too high.

2.7.3 Distributed Generation Issues

With the recent growth in small-scale distributed generation, also known as embedded generation, there is increased interest in the utilisation of energy generated from resources such as small-scale PV, wind turbines, micro-CHP and heat pumps, etc. In current power systems, the balance between electrical power generation and demand is usually maintained by measures on the generation side following expected load charts. Although the concept of supply side management has proved to be adequate in the past, recent developments in renewable and low carbon energy systems are adopted to invoke major changes in future power network management. The volatile characteristics of supply from RE and LC sources put extra pressures on the current power system. Demand side management is a suitable means to solve the balancing problem when integrating a high fraction of renewable energy sources into the electricity grid.

In the past, customer side generation, such as PV, back-up generation, was regarded as DSM resources. They were used to play some role in supplying demands when conventional power generation was unable or far too expensive to meet the demand. According to Byrne et al. (1994, 1996) and Perez et al. (1993), the most popular renewable technology successfully integrated with DSM potential and recommended by utility providers was PV systems. Most researchers focused on the technical and economical aspects of PV-DSM systems. Perez et al. (1993) stated that PV output closely matched utility system peak loads during the summer period when solar energy was also available. Various PV-DSM systems such as rooftop, non-dispatch enabled PV-DSM (without storage) and dispatch enabled PV-DSM (i.e. with storage) etc., could be found in the literature (Byrne et al, 1994, 1996). Dispatch enabled PV-DSM systems integrating battery banks were the most popular ones, and could maximise the power available during the utility's system peak demand period. It was used mainly for the purpose of peak shaving.

A cost-benefit analysis of PV-DSM systems (Byrne et al. 1996) demonstrated that PV was far more viable than had been previously thought. The study was carried out in the U.S where peak demands occur on hot summer days due to high utilisation of air-conditioning equipment, and at the same time abundant solar exists. The peak in PV output, however, occurs prior to the peak in demand, so by including modest storage facilities (i.e. a dispatch enabled PV-DSM system) these peaks can be aligned with one another and thereby offer significant peak shaving benefits to utility providers. The cost-benefit approach includes both the energy value (i.e. the systems ability to save energy) and the capacity values (i.e. the reduction in peak demand), in addition to other factors such as modularity and fossil fuel price protection. Modularity refers to the ability of matching incremental increases in load with equivalent capacity increments. Fossil fuel price protection refers to the protection offered by renewable technologies against fuel price volatility and future environmental legislation. The economic potential of such a demand-side measure was also illustrated for the application to commercial buildings in the USA (Byrne et al. 1996).

However, research in to the coupling of renewable energy sources with load management strategies is a new topic. Only a couple of papers talk about this new approach (McKenna et al. 2007; Kamphuis et al. 2005). The integration of large-scale renewable energy systems into the current power network through DSM strategies was the main focus. McKenna et al. (2007) focus on the development of a control strategy on the demand side to maximise the use of wind energy supply from a wind farm in Ireland. The energy supply is also supplemented with a small-scale hydro-electricity plant. The controllable loads in this case include water pumping, wastewater treatment, offices and street lighting. The analysis is conducted in the absence of a financial incentive for the participation and with the inclusion of a carbon tax as an incentive respectively. A real-time application of matching power supply and demand is demonstrated by Kamphuis et al. (2005) via the use of software agent technology. Software agents are used as the representatives of power producing and/or consuming installations. The bottom-up coordination, market algorithms and agent technology are used with algorithms from micro-economic theory for real-time matching. A real-world field-test was conducted to prove that the operation of a number of distributed installations to reduce real-time imbalance in a commercial portfolio appears to be possible at a given capacity level.

2.7.4 Research Undertaken in This Thesis

As can be seen, both of the above two applications, coupling distributed generation sources with demands, are analysed at system level. If more and more energy produced by distributed generation is exported to the electricity grid, it would make the grid unstable and even induce brown/blackouts. It is a dilemma. On one hand, due to environmental concerns, distributed generation should be encouraged to increase its fraction in our current energy system make up. On the other hand, less exporting of distributed generation energy is suggested from a grid condition point of view. Therefore, it is vital to maximise the utilisation of the energy produced by embedded generation at the local level and reduce the burden on the power system. Unfortunately, few references are found discussing the flexibility of the demand profile at individual household levels which can be utilised to develop load control strategies, in order to better facilitate the energy produced by small-scale RE & LC energy supply systems, which will be the main focus of this thesis.

RE systems refer to technologies like photovoltaic (PV), wind turbine (WT), and solar collectors etc. LC systems refer to technologies such as heat pumps (HP) and combined heat and power (CHP) etc. These are all suitable to be applied to single buildings. Due to the characteristics of RE and LC technologies, how to satisfy the demand and maximise the use of these technologies in much more efficient ways are major issues. RE systems are normally intermittent and dependent on the factors such as weather, time and location. Without proper control, LC systems operate inefficiently and can be expected to emit more GHG for the same supply level as conventional ones, which would do harm to the local air quality, due to fluctuating and unfavourable demand. It is necessary for an algorithm to deal with the demand profile and make it become favourable for RE and LC energy supply systems. Therefore, new DSM algorithms should be certain, which are able to perform the load shedding strategies on domestic appliances and smooth the load profile for favourable building-integrated energy generation device operations without compromising the comfort of users.

2.7.5 Encapsulate DSM Knowledge within a Decision-making Tool (MERIT)

A unique computational decision-making tool, called MERIT (Born 2001; Smith 2002), is adopted as a platform to integrate the DSM algorithm developed in this research. MERIT has been developed by ESRU within the department of Mechanical Engineering at the University of Strathclyde since 2001. One of the main reasons for choosing this tool is that it is a demand-supply matching tool aiding with the design of hybrid energy systems, particularly from RE and LC sources. There is a range of renewable energy models available, including PV, wind turbine, flat-plate collectors for water heating, which is able to perform the simulation of different types of RE supplies. Another reason is that it allows the analysis of energy systems based at any location over any chosen time scale from a day to a year with a user-specified number of time steps per hour. Furthermore the software structure of MERIT is clear, flexible and generic, which makes it easy to add another new model into the existing platform. New RE or LC supply models (such as heat pump and micro-CHP etc.) can also be developed and added into the existing supply portfolio. Demand models for the requirements of simulation-based DSM systems can be developed and integrated within the demand side without disturbing the existing functionality.

So far, as there is no other existing general tool to perform DSM strategy analysis, MERIT could be considered a suitable candidate after having been incorporated with DSM algorithm. This algorithm specialises in the analysis of the impact of various DSM measures upon the performance of the energy system at full-scale level (both micro and macro). The reason for this is to enable decision-makers to design DSM scenarios and select the best strategy for better facilitating the integration of RE or LC supplies, which in turn could reduce the supply capacity and further decrease the investment cost. An optimal load management strategy may be achieved based on certain available supply systems. The algorithm has not only been verified within the software tool (MERIT), but also within several case studies through incorporating the algorithm into an Internet-enabled energy system (Hong et al. 2008) in practice.

2.8 Summary

This chapter reviewed the status of demand-side management from both a utility and customer-based perspective. The research gap and issue pertaining to this are also presented in the review. The need for a computational based DSM tool required for designing and selecting the strategies to smooth the demand load profile when a high fraction of the energy supply is from distributed generation has been demonstrated. The following chapters will discuss the detailed DSM algorithm and the relevant low carbon energy supply technologies. This thesis will mainly propose the DSM methodology for hybrid energy systems (e.g. REs or/and LCs-based) and implement its algorithm at various levels (from strategic to operational application) under a computational tool platform.

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CHAPTER THREE DEMAND SIDE MANAGEMENT AND CONTROL (DSM+c) ALGORITHM

This chapter describes the ***DSM+c*** *methodology developed for this study in detail. "****DSM+c****" is short for* ***Demand Side Management and control****, which is regarded as a new concept of demand side management strategy. This algorithm considers the demand and supply at the same time for each time step over the simulation period and is able to generate the optimal demand control strategies under certain supply combinations. Two main* ***DSM*** *techniques load shifting (****LS****) and demand side controls (****DSC****) are illustrated in detail within this chapter. Different levels of* ***DSM+c*** *algorithm suitable for historical demand, simulated demand and monitored real-time demand are also addressed respectively.*

3.1 Background

Renewable (**RE**) and low carbon (**LC**) technologies have gained increasing popularity over the past few years, as indicated in the previous chapters. Due to the intermittent characteristics of RE energy systems and the troublesome fluctuating demand profile at the micro-scale for the operation of LC energy systems, the problem of the mismatch of both magnitude and phase between the energy supply and the demand has become more obvious and increasingly significant. However, the match can be improved through efforts on both sides. Some researchers (Khan and Iqbal 2005; Rahman and Tam 1988; Weissbach and Kephart 2005) focus on measures on the supply side such as developing an optimal hybrid supply system through combining different RE and LC technologies to satisfy a specific demand profiles. One major drawback, however, is the low flexibility of this hybrid supply system which cannot accommodate all situations within the rapidly-fluctuating demand profile over a period of time. Further, whilst improving the storage system could be one solution, it is not economically desirable (Nieuwenhout et al. 2006).

The easiest, cleanest and safest way to improve the match between demand and supply is to deploy demand side management measures on various loads, either reducing the demand or reshaping the demand profile. Traditionally, demand side management measures are mainly done on a macro-scale, driven by the energy utility companies. Most DSM programs were designed for the benefit of the companies themselves, to augment profit, as has already been addressed in the previous chapter. When the scale moves down to the micro level and the demand curve interval moves from being hourly-based to minute-based, the load curve becomes more dynamic and fluctuating (Born 2001). In terms of the users' behaviour, many activities are carried out randomly. The flexibility of this demand level needs to be studied, since it is necessary to ascertain to what extent it can be modified, through demand side measures, by either load shifting or load switching strategies, or both. An intelligent control system should be employed to control different categories of energy-consuming devices in order to manipulate the demand profile and follow the supply from RE or LC sources over the specified control period. Factors, such as internal environmental conditions, the performance of supply devices, the priority of the loads, users' satisfaction and users' behaviour, need to be balanced within the control system (Gajjar and Tajularas 1998; Newborough and Augood 1999). The DSM+c algorithm at the micro-scale takes all these factors into account and provides the capability to analyse and identify the best demand side strategies for the operation with various supply technology combinations.

3.2 Concept and Objectives

The concept of **DSM+c** involves using control devices to manipulate individual demands. The aim is to achieve a favourable aggregated demand for better energy supply system operation over a certain time period based on the availability of supply resources. The **DSM+c** algorithm developed in this thesis has been dedicated to this concept. This DSM+c algorithm is generic enough to be suitable for the demands from various sources, such as statistical demand, simulated demand and monitored demand. Based on the source of available demand data, different types of DSM+c algorithm will be invoked. Therefore, the DSM+c algorithm can be applied at different stages, from initial feasibility study, to detailed design stage, even to the operational level in practice.

The DSM+c algorithm can be regarded as a means to improve the demand/supply matching rate and thereby optimise the performance of energy supply systems such as RE and LC technologies etc. The objective of the DSM+c algorithm is to minimise the impact on users and at the same time maximise the match between demand and supply through identifying the best combinations of different demand side control options such as load shifting, load control (on/off control and proportional control) and load recover for various demand loads. Utilising these demand side measures will improve energy efficiency (e.g. by reducing the total demand magnitude), change the pattern of use (e.g. load shift), and achieve optimal switching strategies (e.g. on/off or proportional control) etc.

The objectives of DSM+c algorithm can be summarised as follows.

- To maximise the efficiency of energy use, so that energy wastage is reduced;
- To facilitate power from building-integrated renewables;
- To create optimal demand profiles for the operation of RE and LC energy systems.

To achieve these objectives, the main problem of the DSM+c algorithm to be solved is to find the minimum difference between supplies and aggregated demands for each time step when different control actions are applied. This can be described as the following **Equation 3.1**.

$$min\ Diff = \left| \underbrace{\left(Supply[i] - \sum_{j=1}^{n} \left(Demand[j][i] * \alpha[j][k] \right) \right)}_{k=1,\ ...,\ Kctrl} \right| \qquad \textbf{Equation 3.1}$$

subject to

$$E(n) = f\left(Demand(n), t\right)$$

$$E[n][i] \in \left[E_{low}[n], E_{high}[n] \right], \ \ \mathrm{n} = 1, ..., \mathrm{N}$$

where,

i: the certain time step;

j: the certain demand;

k: the control step on a certain demand;

N: the total number of environmental variables.

t: time, s;

Diff: the difference between demand and supply;

Demand[j][i]: the required power for the j^{th} demand at the time step i, W;

Supply[i]: the available supply at the time step i, W;

Kctrl: total control steps for demands with similar priority;

α[j][k]: control factor applied over the j^{th} demand at the k^{th} control step;

E[n][i]: the n^{th} environmental variables (E(n)) at time step i;

E_{low}[n] and E_{high}[n]: the set points for the n^{th} environmental variables;

Based on the DSM+c parameters defined (such as priority, method and duration etc.), the DSM+c algorithm will generate the best control combination for the demand loads without compromising users' comfort and will, at the same time, optimise the operation performance of supply-side systems.

The following sections illustrate the different forms of DSM+c algorithm based on the various resolutions of available demand data, ranging from hourly statistical data for strategic level application, to minutely/secondly detailed simulation data or real-time monitored data for detailed design analysis purposes and even for operational level in real practice.

3.3 The Strategic Level DSM+c Algorithm

The strategic level DSM+c algorithm refers to the application of DSM+c measures upon hourly or half-hourly statistic/historical demands. It is capable of managing both energy and load based on the comparison of demand and available supply resources and generating optimal DSM strategies. The demands under this level are time-series data known in advance. The internal environmental data relevant to the demand is normally not available. To consider the impact of DSM+c measures upon the demand environment or users' convenience, empirical experiences with demands (such as energy pattern, the duration of demand being controlled, etc.) are employed.

Several demand side measures, such as energy efficiency, load shifting and demand side control, can be used under this level of DSM+c algorithm. These measures are classified into two fields: energy management and load management. Energy management refers to managing the demand over a certain period. Energy Efficiency (**EE**) and Load Shifting (**LS**) are the two main measures. EE is a DSM measure which replaces existing low energy efficiency demand devices within higher ones. This could result in levelling down the magnitude of total demand profile. It maintains the same level of energy services with less energy consumption and has almost zero impact on users' convenience. LS is another DSM option which maintains the same energy consumption as before and shifts energy services to another period where either the price is low or the energy is sufficient. This could bring some inconveniences to users, as normal pattern of energy use is changed. Demand Side Control (**DSC**) is the main method used for load management strategy, which controls the loads when required at each time step. This could results in significant impact upon users and demand environment. Therefore, the maximum control duration for a specific load need to be considered within this strategic level DSM+c algorithm, in order to reduce the impact to its minimum.

The general logic behind this strategic level DSM+c algorithm can be described as follows. The available DSM+c options specified for each demand are checked in the first place. Depending on its potential impacts on the demand side, the DSM+c options available from zero/low impact level to high impact level are: EE, LS and DSC respectively. The demands with the EE option (if defined) will be controlled first, followed by the demands with the LS option (if defined), while the demands with the DSC option (if defined) are dealt with lastly. The match results between the demands and supplies using the DSM+c algorithm are presented both in the form of a graph and data. A flow chart representation of the control logic is shown in **Figure 3-1**.

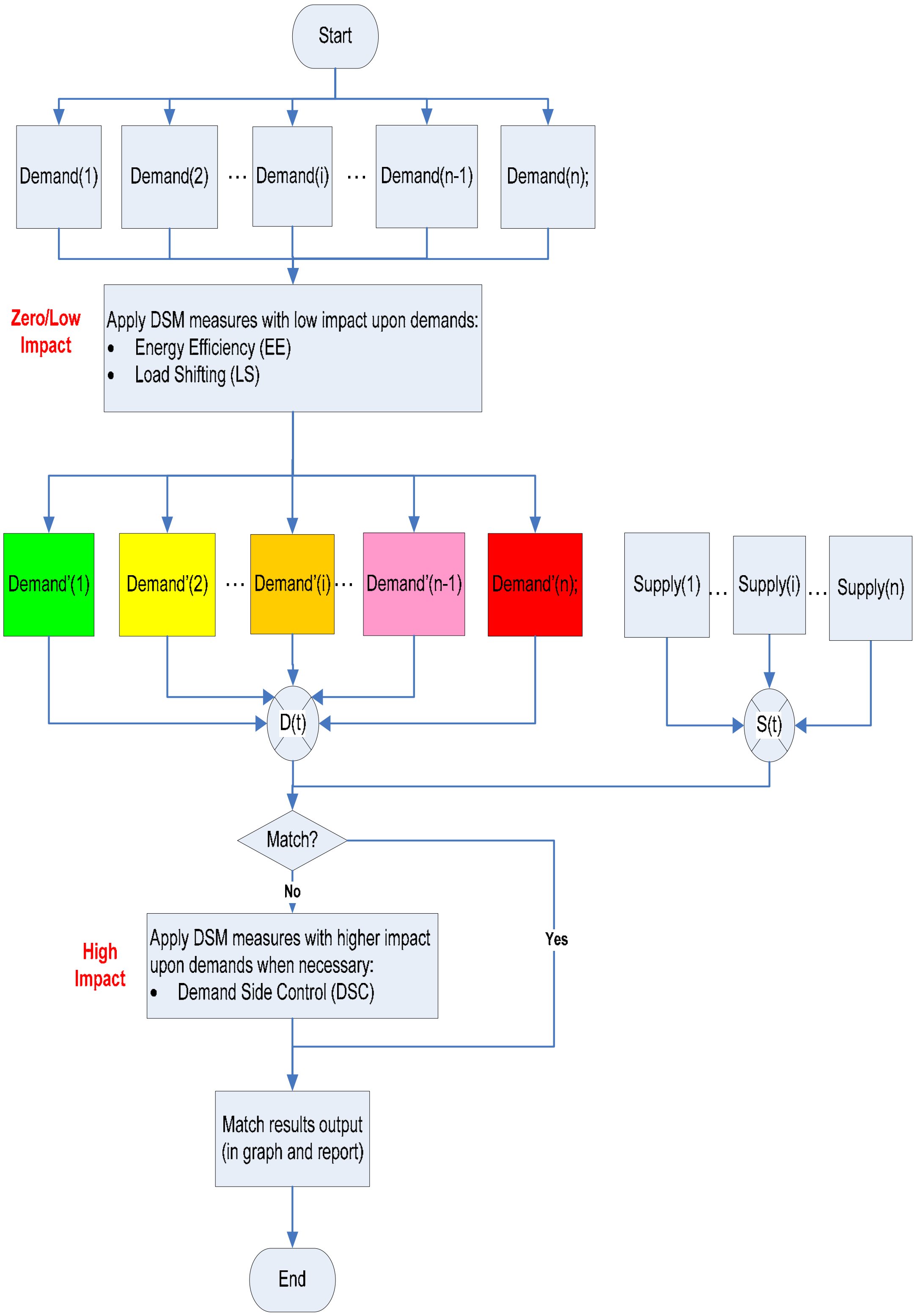

Figure 3-1: General Control Logic for the Strategic Level DSM+c Algorithm

For demands with an EE option, a specific reduction rate throughout the control period is applied, which reduces the magnitude of the demand to a certain level. A good example of this is the replacement of the existing incandescent light bulbs with high energy efficient ones.

For demands with an LS option, similar to the EE option, the strategic level DSM+c algorithm manages these throughout the entire specified control period. Based on the same level of energy use, a demand-specific shifting algorithm is employed to find out the maximum shared area with the supply profile.

For demands with a DSC option, the strategic level DSM+c algorithm examines the demands at each time step and compares them with the supply at the same time step. A proper control action is applied based on the comparison results.

This thesis is focused on the LS and DSC options, which are illustrated as follows.

3.3.1 Load Shifting (LS) Algorithm for RE and LC Systems

LS is not a new concept, but a novel attempt to apply upon demands to achieve better match with the time-varying stochastic supply from RE and LC energy systems. Traditionally LS is a popular classic DSM measure for changing the use patterns of an appliance and shifting the load from an on-peak period to an off-peak period (Gellings and Chamberlin 1993). In terms of the context of this study (involving RE and LC technologies), the supply from RE energy systems depends on the time and location, and the performance is also vital to the operation of LC energy systems. Shifting the existing loads to the period with sufficient supply is very important because changing the pattern of use might affect the daily behaviour of the users. This would not affect the whole capacity of the power and would maintain the level of energy consumed. Popular applications include water heating, space heating, clothes washing and drying, and customer load shifting. The idea behind load shifting is to identify a time period in which the shared area between the demand and the supply is at its maximum, and then to allocate the selected shifting demand to that period.

There are several parameters relevant to LS which should be defined.

- **Shiftable or non-shiftable**

  This depends on the properties of the demand. Some loads with fixed operating durations such as washing machines, microwaves, and dishwashing machines etc. are shiftable (Newborough and Augood 1999), whereas other loads, for instance lighting, cannot be shifted.

- **Load flexibility (whole or partial)**

  Another parameter to be defined is the flexibility of demand profile. The demand profile for a certain load represents the energy use pattern during its operating period. Here the question of whether the total demand or only part of it can be shifted during the control period poses itself. The answer significantly affects the load shifting strategy. The options are available to define part of the demand through the start time to the end time of the profile are provided.

- **Shifting increment**

  This parameter defines how the specified load is shifted, which will affect the results of the match between the total demand and supply curve. The optimal match results of a certain combination of demand and supply are different if the loads are shifted with a smaller increment. It is more accurate to shift the loads at lower times. However, this means it would take longer to obtain the results.

- **Shifting boundary and Shifting direction**

  The last two parameters to be considered in the load shifting strategy are the shifting boundary and shifting direction. Sometimes it is not permitted to shift the load freely within the specified period, and this may only be shifted within a certain period or shifted in a certain direction (forwards or backwards). The extreme case is that it can only be shifted in a certain direction and within a certain period. Therefore, the boundary and direction parameters are provided for users to define the load shifting strategy. Maximum positive shift time ($t_{pstv,\max}$) defines the maximum time for the load shifting in a forward direction compared to the current point. Maximum negative shift time ($t_{ngtv,\max}$) specifies the maximum time for the load shifting in the backward direction from the current point.

The detailed algorithm for **LS** is shown in **Figure 3-2**. From the flowchart, the general rationale for the **LS** strategy can be seen clearly. The algorithm starts by checking the properties of all the selected demand profiles in order to find out which demand profile(s) is set as a whole or partially shiftable property and which demand profile(s) is non-shiftable. Then appropriate actions are carried out for the demand with different properties.

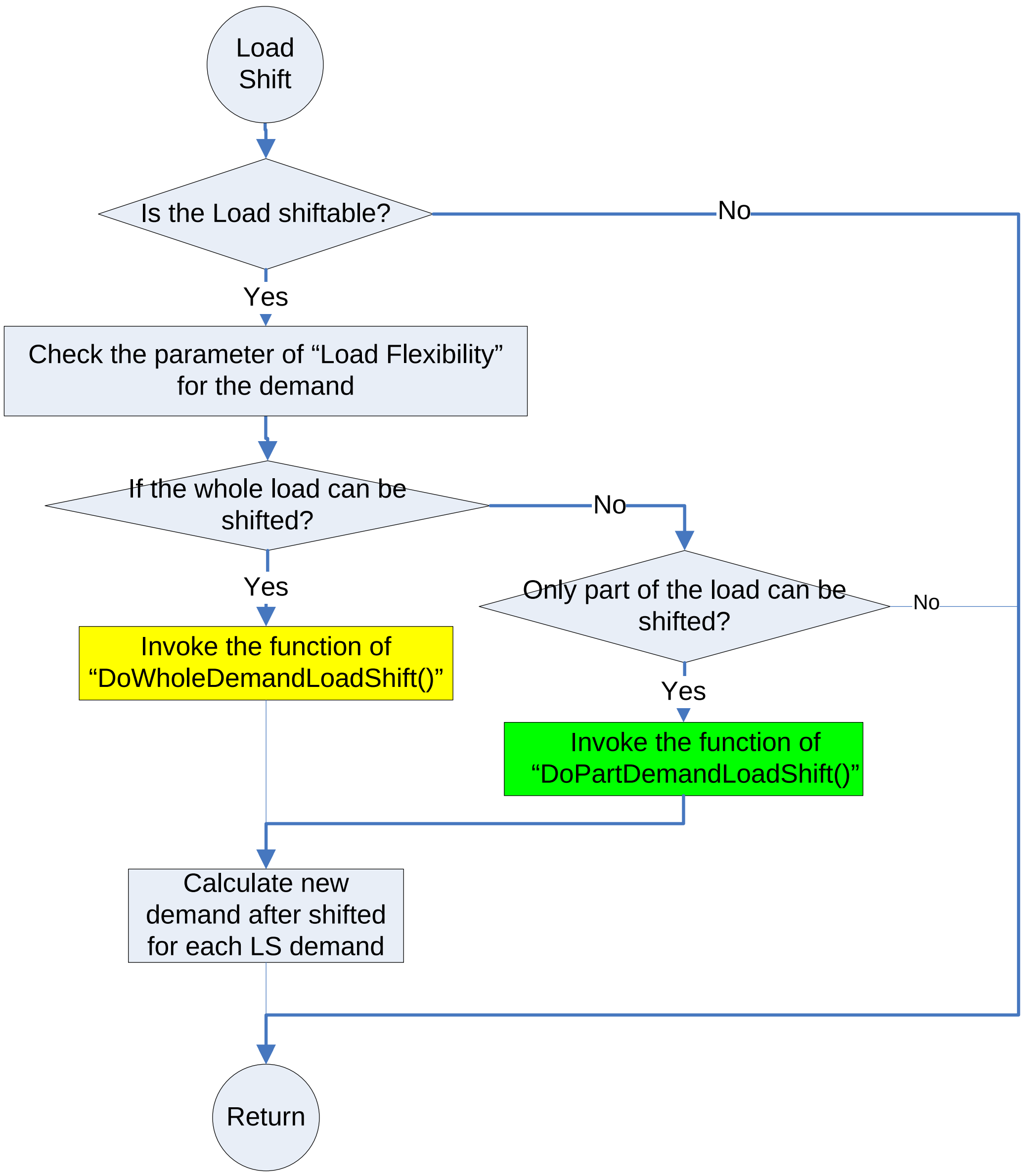

Figure 3-2: Detailed LS Algorithm

For those demands with *whole load shiftable* features, the next step is to calculate the total shift steps using the parameters $t_{pstv,\max}$ and $t_{ngtv,\max}$ which can be specified by the users.

The first important factor for **LS** to decide is the total shifting steps (N_{TS}). This can be determined by shifting duration and shifting increment (n_{incr}), shown in **Equation 3.2**. n_{incr} can be specified by the users.

$$N_{TS} = \frac{Shifting\ Duration}{n_{incr}} = \frac{|t_{end} - t_{start}|}{n_{incr}}$$ **Equation 3.2**

where,

N_{TS} = the total number of shifting steps;

n_{incr} = the shifting increments at every time step.

The shifting duration is determined by two variables: start time (t_{start}) and end time (t_{end}). t_{start} and t_{end} differ based on whether the maximum negative and positive shifting steps are defined, shown in **Equation 3.3** and **Equation 3.4**. Assume the controlled period is specified from *0* to *T*. *T* is the end of the whole control period. For loads that are able to be shifted as a whole, t_{start} and t_{end} are the initial start time ($t_{ini,start}$ = *0*) and end time ($t_{ini,end}$ = *T*). For part-shifting loads, t_{start} and t_{end} is decided by $t_{ini,start}$, $t_{ini,end}$, $t_{pstv,\max}$ and $t_{ngtv,\max}$. $t_{ini,start}$ and $t_{ini,end}$ are the initial start and end time. $t_{pstv,\max}$ and $t_{ngtv,\max}$ are maximum positive and negative shifting steps.

$$t_{start} = \begin{cases} 0, & \text{When the maximum negative shifting step is not defined;} \\ t_{ini,start} - t_{ngtv,\max}, & \text{When the maximum negative shifting step is defined.} \end{cases}$$

Equation 3.3

$$t_{end} = \begin{cases} T, & \text{When the maximum positive shifting step is not defined;} \\ t_{ini,end} + t_{pstv,\max}, & \text{When the maximum positive shifting step is defined;} \end{cases}$$

Equation 3.4

Another important factor for the **LS** algorithm is the shifting boundary, which can be user-determined by specifying the parameters of maximum positive shifting steps $t_{pstv,\max}$ and maximum negative shifting steps $t_{ngtv,\max}$. If the options are not specified, the default values of the shifting boundary start from *0* and continue through to the end of the whole period (*T*).

Depending on the flexibility of the load (whether wholly-shiftable, partially-shiftable or non-shiftable), the algorithm executes the processing logic. This is illustrated as follows.

For loads with wholly-shiftable features, there are two possible situations. One is that part of the demand profile remains inside the shifting boundary. In this situation, new demand is simply replaced by the original demand at the previous shifting increment steps after being shifted, which is shown clearly in **Figure 3-3** (e.g. the *points 1* and *1'*). Another situation is that part of demand goes beyond the shifting boundary. Under this condition, the demand is displaced to the demand at the start time of load shifting, which is also shown in **Figure 3-3** (e.g. the *points 2* and *2'*).

For loads with partially-shiftable characteristics, the situation is a little more complex. After having specified the part of the demand profile to be shifted (see **Figure 3-4**), the new demand profile is achieved by subtracting the specified demand to be shifted from the original demand profile (see **Figure 3-5**). Based on this new demand profile, there are also three situations which can arise in terms of the results of the demand after being shifted. The first situation is that the demands are placed within the shifting boundary at the particular shifting time, such as the points 1' and 3' in **Figure 3-6**. The second situation is that the demand is outside the shifting boundary, in that case the extra part of the demand outside the range needs to be moved automatically to the start of the shifting period by the algorithm, which can be seen clearly in **Figure 3-7,** e.g. point 3'.

The last one is that demands are outside the shifting boundary, and will remain the same as before, such as points 2 and 2' shown in **Figures 3-6** and **3-7**. In respect of loads that are non-shiftable, the demands have to be left unchanged.

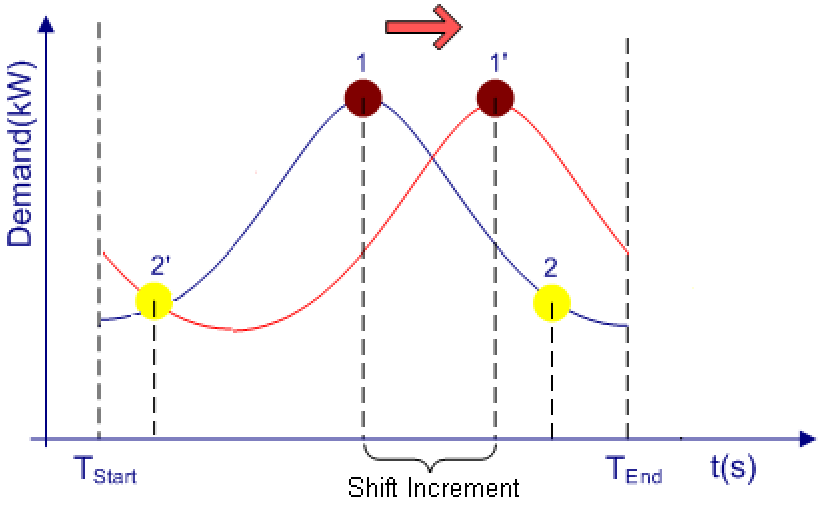

Figure 3-3: Diagram for Whole Load Shift

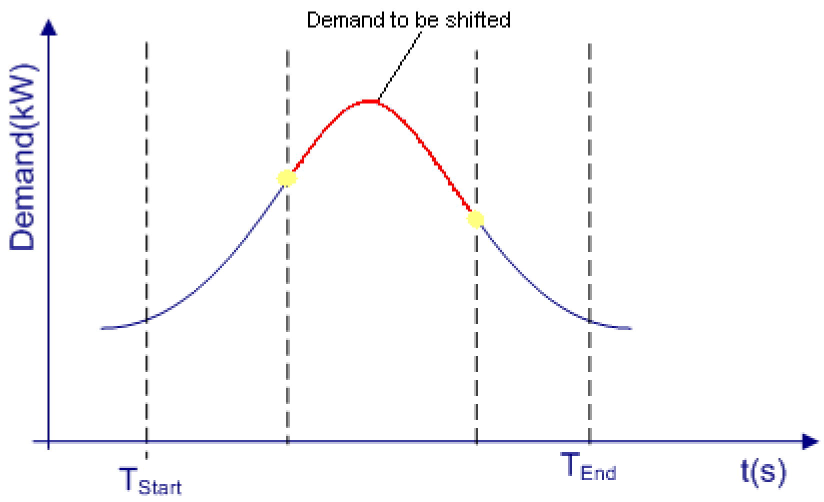

Figure 3-4: Demand Profile before Partial Load Shifting

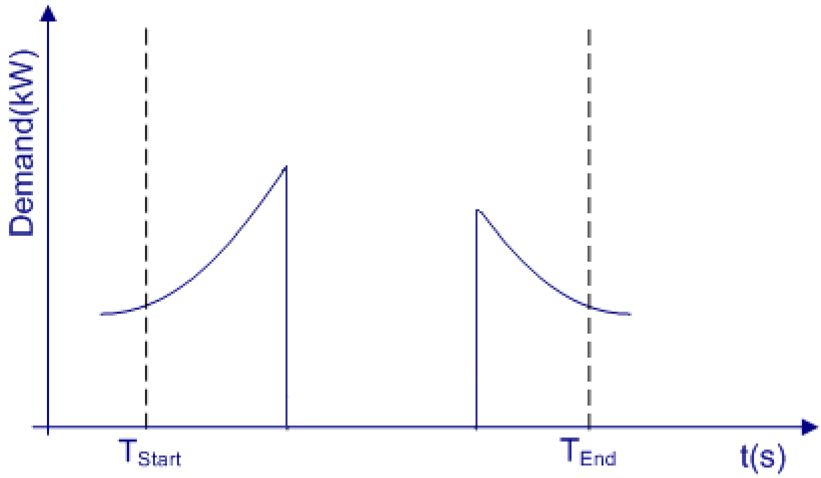

Figure 3-5: New Demand Profile after Subtracting the Profile to be Shifted

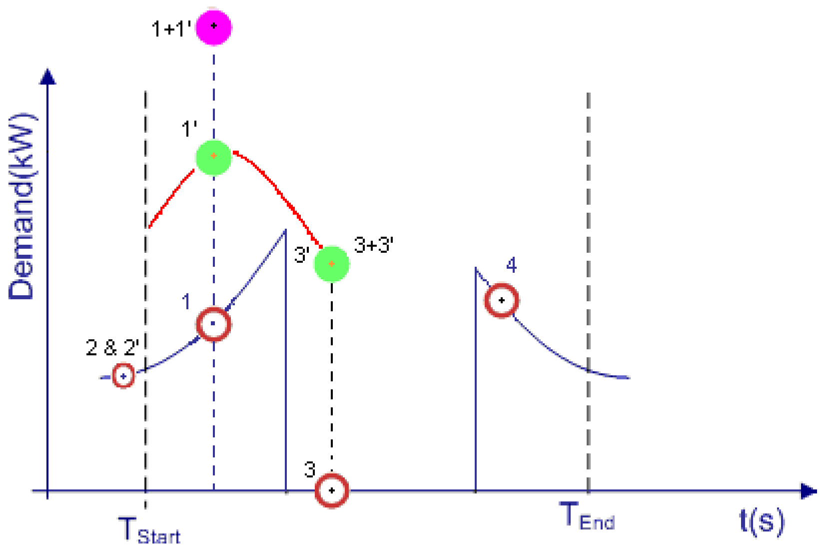

Figure 3-6: Partial Load Shifting within the Boundary

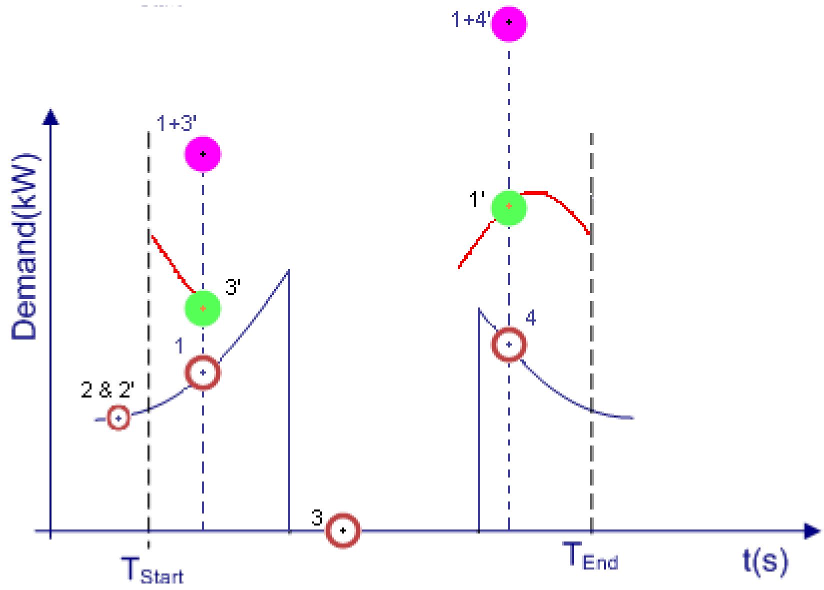

Figure 3-7: Partial Load Shifting outside the Boundary

The total demand at each shifting increment step is determined using **Equation 3.5**. It sums up all the sub-demands after the **LS** at certain time.

$$NewDemands[t] = \sum_{j=1}^{n} NewDemandsAfterShift[j][t], \qquad \textbf{Equation 3.5}$$

where,

n = the total number of demands,

NewDemands[t] = new total demand at time step t;

NewDemandsAfterShift[j][t] = the jth demand profile after being shifted at time step t.

The residual area between the new total demand profile after being shifted and the total supply profile for this shift time step is calculated using the following **Equation 3.6**. The result of the residual area is stored in a one-dimension vector, the size of which is defined by the total shifting period.

$$A_r(k) = \int_0^T NewDemands[t]dt - \int_0^T Supply[t]dt, \qquad \textbf{Equation 3.6}$$

where,

$A_r(k)$ = the net residual area.

After having obtained all the results of the residual area for each shifting time step, the minimum residual area $A_{r\text{-}min}$ can be known from vector $A_r(k)$ in **Equation 3.7**.

$$A_{r-\min} = \min\left(A_r(k)\right). \qquad \textbf{Equation 3.7}$$

The shifting time is marked when the minimum residual area is found and the demand values re-assigned to the new demand after being shifted. Also through the value of shifting time at the minimum residual area, the direction and the steps to be shifted based on the current demand position can be derived. Thus, it is possible to obtain the optimum shifting strategies for the demand profiles in order to maximise the match between the energy from renewable or other energy resources and the demand profiles. The detailed flowcharts for the algorithms of whole load shift and part load shift are illustrated in **Figures 3-8** and **3-9**. It can be seen that each module starts the procedure by quantifying the shifting steps based on the specified control period and the shifting increment. It follows with a loop (controlled by total shifting steps) nested with another inner loop (controlled by the specified control period). With these two nested loops, it is able to identify the post-shifted total demand and residual area between the supply profile and the new after-shifted demand profile for each time step.

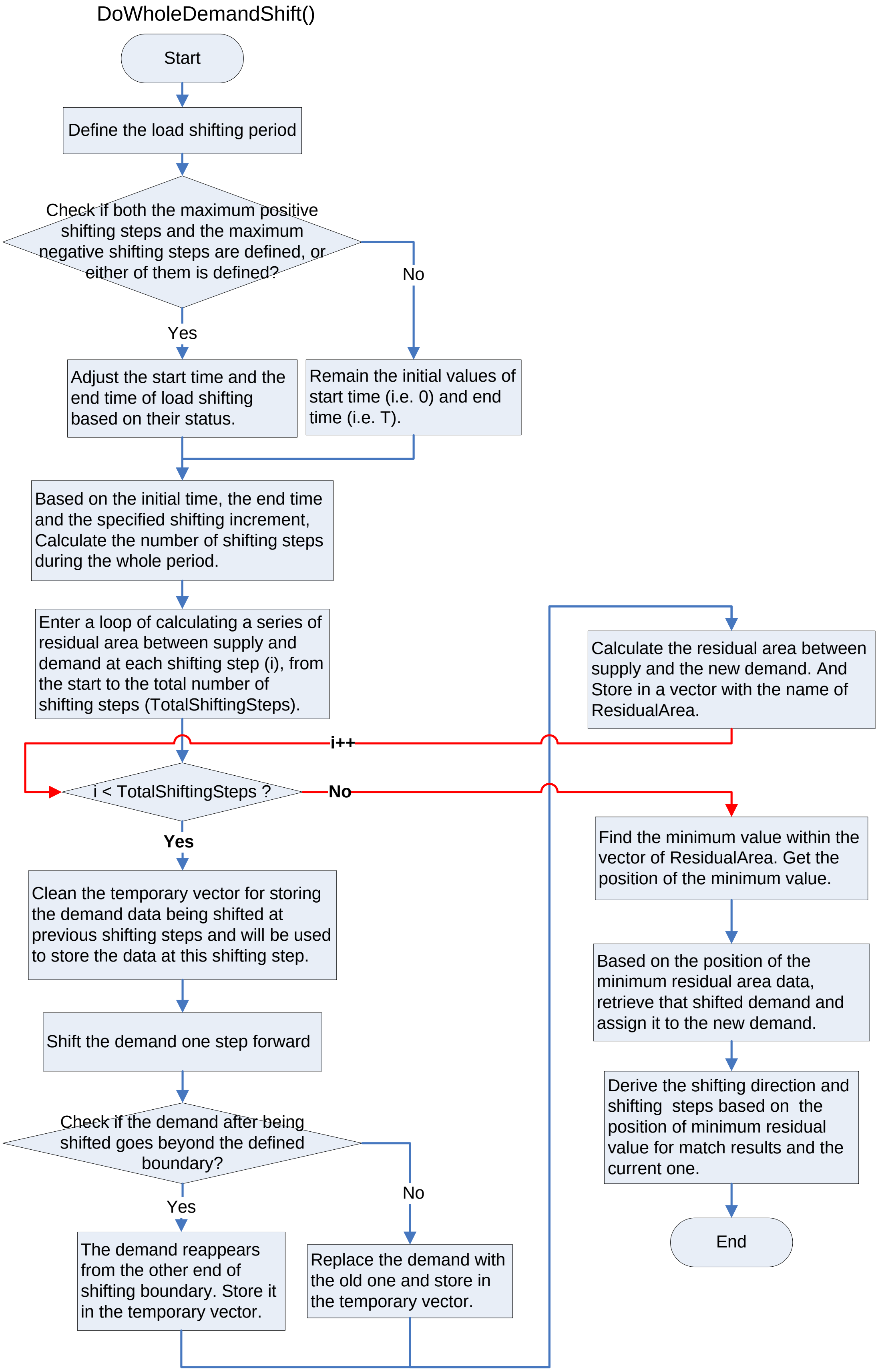

Figure 3-8: Detailed Algorithm for Whole Load Shifting

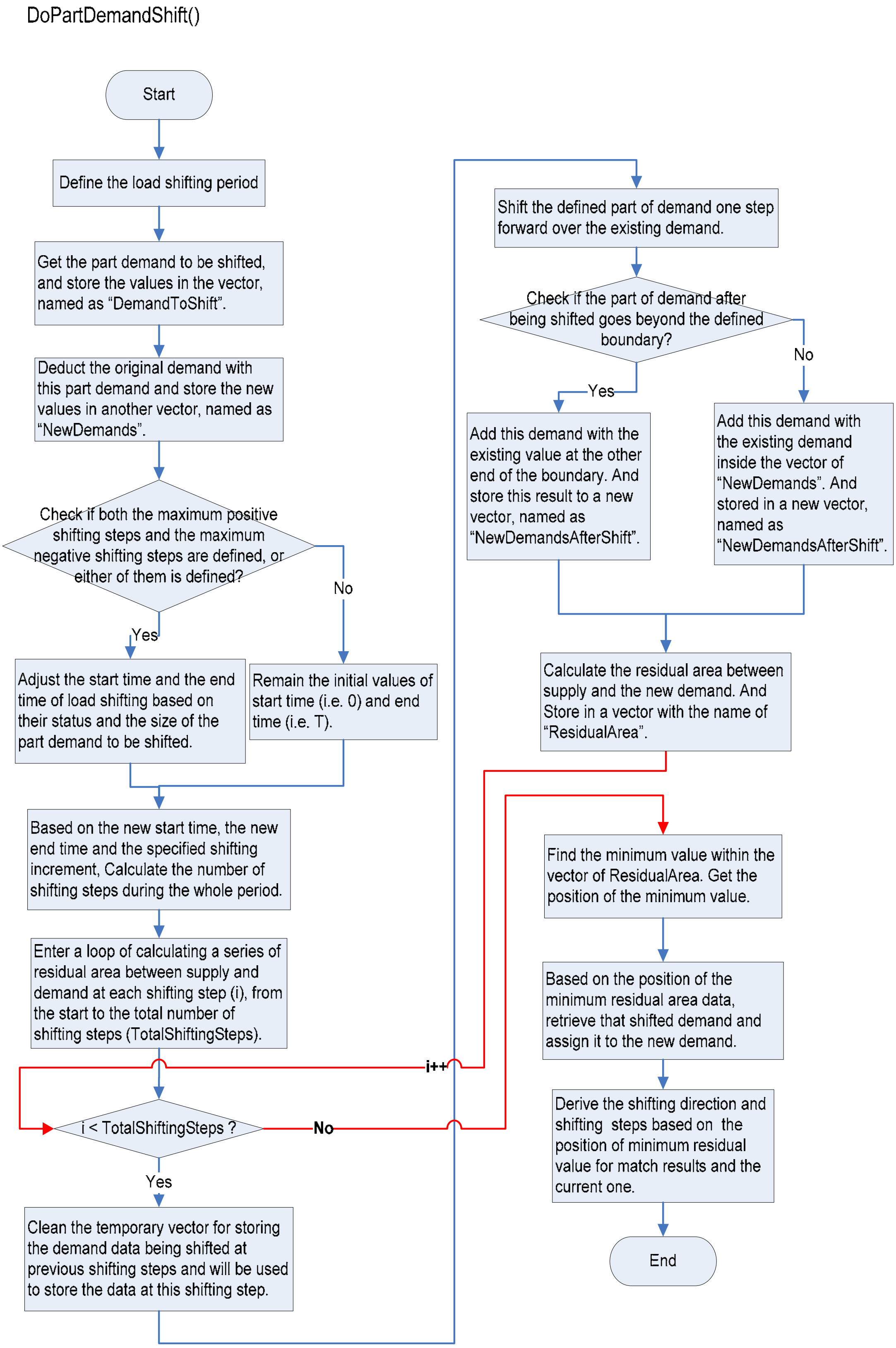

Figure 3-9: Detailed Algorithm for Partial Load Shifting

3.3.2 Demand Side Control (DSC) Algorithm at Strategic Level

DSC is the other major DSM method for manipulating the energy demand profile from appliances through different combinations of switching strategies, either on/off or proportional control. In general, direct load control (**DLC**) (Molina et al. 2003), regarded as the forerunner of DSC, is used to reduce the demand during the peak period based on the conditions of the electricity grid and the electricity price signal. In terms of the context of this study (involving RE and LC supplies), the capability and flexibility of controlling the loads are vital when there is not enough supply from RE or other LC sources during a certain period. Popular applications on demand side to apply DSC method include water heating, space heating/cooling, refrigeration systems and customer load control etc. The idea behind DSC is to find out the best switching strategies for loads with minimum impact on users' convenience, in order to achieve the minimum difference between demand and supply. It can improve the energy match between demand and supply from intermittent sources and reshape the demand profile towards more favourable for the operation of LC-based energy supply systems. At the first place, all demands are prioritised from high control availability, medium control availability to low control availability and even no control at all. And the control methods, either on/off or proportional, will be specified for each individual load. At the strategic level, this algorithm is also required the parameter of control duration to define how long the load can be controlled if necessary, as the internal environmental data is normally not available at this level. Based on the amount of available supply, appropriate decisions will be made upon the demands. Despatch when demand is equal to supply. Charge the battery or thermal storage when surplus deficit is found. For the condition when the total demand is greater than the total available supply, the strategic level DSC algorithm will be invoked to control demands.

3.3.2.1 DSC Parameters

As discussed above, three DSC parameters are introduced to perform DSC study at strategic level.

- **Load Priority (LP)**

LP is one of the most important parameters to be defined in the strategic level DSC algorithm. It refers to the control availability for a certain load. That is to say, it allows the loads to be controlled in the order of the specified LP, from high control availability to low control availability, and even no control at all. LP is set according to the impact on the users' side. The higher the LP, the less impact it may have on users. There are four levels of LP available from which to choose: high, medium, low, and no control. If a certain demand profile is defined as ***high LP***, it means that it has high availability for it to be controlled. Therefore, if at that time, supply is less than demand, this demand profile can be controlled in the first place. If the demand is defined as ***medium LP***, it has medium control availability. If the total demand is still greater than the supply after having controlled the demands with ***high LPs***, the demands with medium control priority will be considered next. The same rationale applies to the demands with ***low LP***. For the loads which have no control priorities, they cannot be controlled at any time in the whole control period, even if the supply is less than the demand, as if it is controlled, it will affect users the most. Therefore, emergency supplies need to be considered at that time.

- **Control Method (CM)**

CM is another parameter to be defined in the strategic level DSC algorithm. This essentially decides how the demands are controlled. There are two main control methods available: on/off control and proportional control. For the loads with proportional control, the percentage of maximum available control limit can also be specified. Some loads (such as refrigerators etc.) can be switched on or off. Some loads (such as lighting or electric-based thermal systems) can be adjusted proportionally. Others can be switched both on/off and proportionally. In a word, CM depends upon the properties of the loads themselves.

- **Control Duration (CD)**

Another parameter, defined in the DSC algorithm at the strategic level, is **CD.** CD is the maximum period that a certain load can be controlled, which is designed to consider the pay back effect (Kurucz et al 1996) of the demand after being controlled. It indicates the time available for controlling without affecting the comfort of the users. This value can be achieved either from empirical experience or by calculations using simulation models or through monitoring the relevant environmental variables on a real time basis. The latter two ways are discussed in later section for operational level DSM+c algorithm. In this section, the empirical way is adopted which is suitable for demands when the relevant internal environmental data are not available. This is the case at strategic level. For demands, only hourly or half-hourly time-series data is available. Therefore, the parameter of CD is introduced to cope with this situation. If the expected control time for a certain demand is beyond the maximum control duration, it cannot be controlled at the next time step (even if control is still required). The definition of CD is based on the maximum tolerance time of users for the particular demand being controlled. It is preferable that the control time for any particular demand is less than the maximum control duration.

3.3.2.2 DSC Parameters for Domestic Appliances

In order to use the DSC concept in the real world situation, it is vital to study DSC parameters as they have a direct impact on the results of different control strategies. The better DSC parameters are defined, the better results DSC strategy can obtain. An example is set for analysing the demand from various frequently-used household appliances. Some appliances, such as refrigerators, air conditioners, electric heaters for space heating, and electric immersion heaters etc., are ideal for load management applications (Lu and Katipamula 2005). They are thermostatically-controlled and have inertial features. Normally, these appliances contribute greatly to the total household energy use. According to the DTI (2003), more than 80% of energy is consumed by thermostatically-controlled appliances (TCAs) within the residential sector in the UK. These TCAs have high control availability because of their long responding time and low impact on users, and they are the main research interests in this thesis. Depending on the increasing level of impact on users, some appliances with fixed energy-use patterns have the medium control priority, such as washing machines, dishwashers, clothes dryers, etc. (O'Sidler 2002). Other appliances such as vacuum cleaners, hairdryers etc., can be labelled as low control level. And yet other appliances for IT and entertainment use, such as desktop computer, TVs and DVD players, have no control availability at all. Appliances with different LP, CM and CD are shown in **Table 3.1**.

Table 3- 1: Various Control Priorities, Methods and Durations for Residential Appliances

Load	Control Method		Time	Priority
	On/Off	Partial		
Hot water	√	√	Hour/Min	High
Washing machine	√	√	Hour/Min	High
Tumble dryer	√	√	Hour/Min	High
Dishwasher	√	√	Hour/Min	High
Fridge/Freezer	√		Min	High
Towel rails	√	√	Min	High
Elec. Apps. (with chargers)	√	√	Min	High
Lighting	√	√	Min/Sec	High
Elec. Apps. (heating)	√	√	Sec	High
Electric oven/hob	√	√	Min	Medium
Slow cookers	√	√	Min	Medium
Elec. heating	√	√	Min	Medium
Air-conditioning	√	√	Min	Medium
Elec. blanket	√	√	Min	Medium
Microwaves	√		Sec	Medium
Extractor fans		√	Sec	Low
Hairdryers		√	Sec	Low
Elec. Apps. (instantaneous)	√			No control
Entertainment	√			No control

3.3.2.3 DSC Algorithm (Load Control)

Figure 3-10 illustrates the flowchart for the load control module in detail. The philosophy of this module is to control various loads as little as possible in order to meet the available total supply at certain time. The module automatically sorts the selected demands into three clusters: cluster one (high control availability), cluster two (medium control availability) and cluster three (low control availability). The algorithm will perform the control actions under the decreasing order of the control priorities, that is to say, from cluster one, to cluster two, and finally cluster three. After having controlled demands within cluster one, the algorithm sums up all the demands (including demands of other clusters both controlled and uncontrolled) to find the new total demand and compares this with total supply. If the total demand is still greater than the total supply, it will move to another cluster and repeat the procedure above. If the total demand is less than supply, it will terminate the control at the current time and move to next control step.

If there is more than one demand within one cluster, the DSC algorithm treats them equally, applies the possible control factors upon each demand within the same cluster and finds the best control combination to achieve the minimum difference between the available supply and new total demand. For instance, if the total number of demand cluster with high control availability is two, then a function with the input parameter of the total number within this demand cluster, **DSC(2)**, as demonstrated in **Figure 3-11**, will be called to realise the demand side control capability. After this function is executed, the total demand will be recalculated. If the new total demand is less than or equal to the supply, it will terminate the control process and continues to the next time step. If the new total demand at this stage is still greater than the supply, the control for the demand cluster with medium availability is required until the total demand is less than or equal to the total supply. A similar mechanism is subsequently applied to the demand cluster with low control availability.

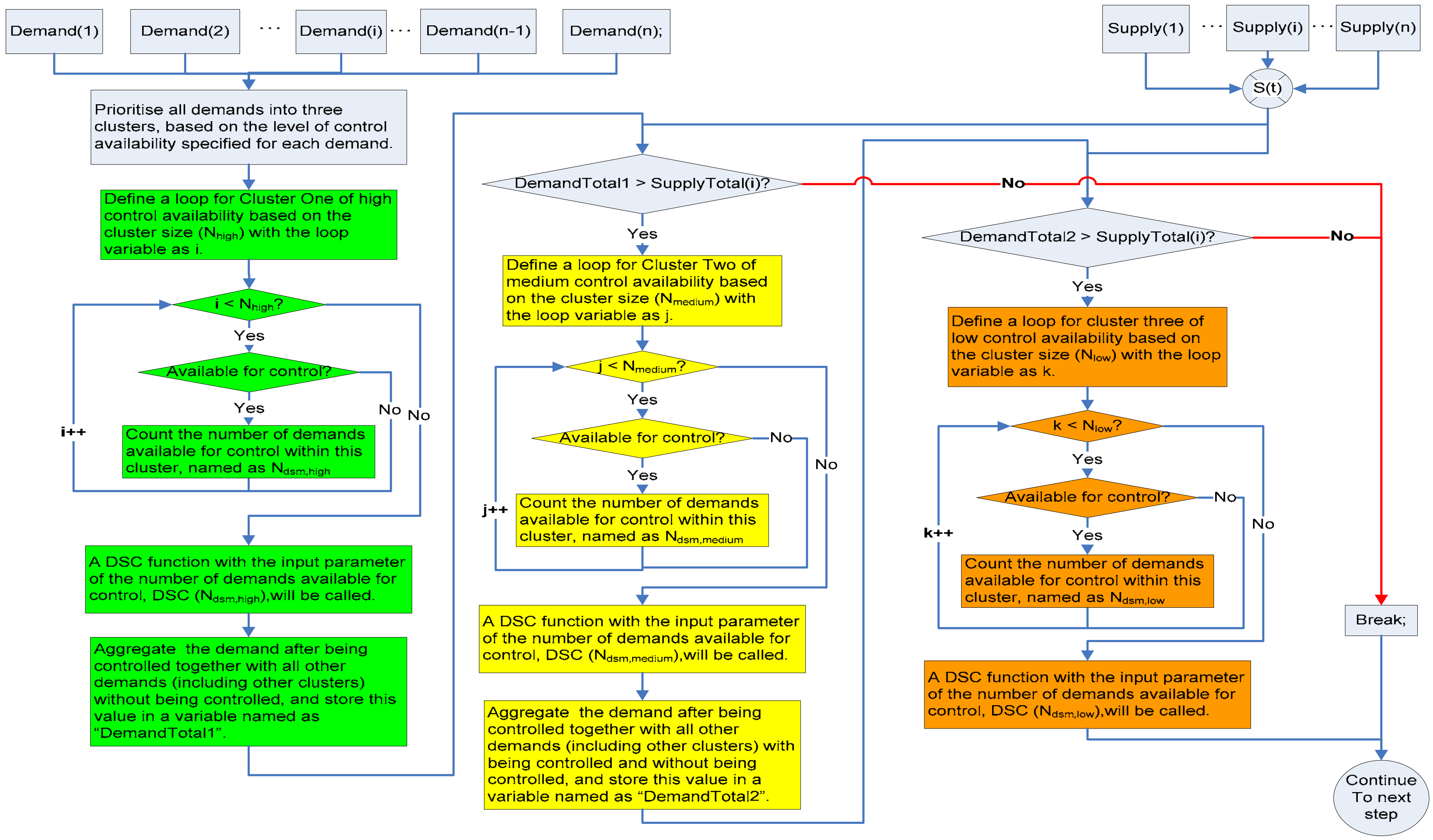

Figure 3-10: Flowchart for the Load Control Module

Within the sub-routine for the demands having the same priority level, the total number of control steps need to be determined first. For demands with on/off control, the control steps are only **2** (either on or off). For demands with proportional control, the control steps can vary depending upon the accuracy of the proportional control that users need. In this study, the control steps for proportional control are set as **10**, which is sufficient from an engineering point of view. A variable with a one dimension array *nControlStep[n]* is introduced to store the control steps of each demand profile. With the load control method being specified, the value of every element in the *nControlStep[2]* can be identified as in **Equation 3.8**. The total number of control steps can be determined using **Equation 3.9**.

$$nControlStep[j] = \begin{cases} 2, & \text{On/Off control;} \\ 10, & \text{Proportional control.} \end{cases}$$ **Equation 3.8**

where, j = 0, 1, …, n-1, if there are *n* demand profiles.

$$TotalControlSteps = \prod_{j=0}^{n-1} nConstrolStep[j]$$ **Equation 3.9**

The control duration, specified by users, is also considered within the sub-routine. It can be regarded as a restriction factor limiting the control action upon loads. The load cannot be controlled at a certain current time step even when the demand is greater than the supply, if this load has been controlled at every time step during a certain previous control duration. This special variable is designed for the statistical/historical demands, which lack relevant environmental information. The value of control duration under this situation is mainly derived from empirical study. If it is necessary to quantify the control duration accurately and dynamically, a demand model or real-time monitoring devices should be employed, which will be discussed in the next section. The rules regarding the control duration can be summarised as follows.

RULE ONE: For CM with on/off control, if the demands at the time steps of the previous control duration are all controlled, then the demand at the current time step can not be controlled even if the supply is less than the demand;

RULE TWO: For CM with proportional control, if the demands at the time steps in the previous control duration are all controlled with the maximum control limit, then the demand at the current time step can not be controlled even if supply is less than the demand.

In order to obtain the best controlling strategy among all the demand profiles, all possible control combinations for DSC demand profiles are enumerated exhaustively. The balances between total demand and total supply are calculated at each controlling step. Then the searching algorithm is employed to identify the smallest one among all the balances and retrieve the specific controlling strategy for every demand profile according to this minimum balance value. Based on these optimal controlling strategies, the demand profiles are recalculated and the new demand results are obtained for a particular type of control priority level. The new demand outcome is compared with the remaining supply source available in order to decide whether the control for a lower type of priority level should be carried out or not.

The detailed flowchart for the whole sub-routine relating to a typical case with two demands having the same control priority for instance, is shown in **Figure 3-11**. As can be seen, two loops, which are controlled by the control steps (nControlStep(0) and nControlStep(1)) for each demand respectively, are nested to calculate the total demand after DSM and its balance with the supply under all the possible combinations of control actions for both demands. Depending on the control method specified for the demand, different sub-modules (either the on/off or proportional algorithm) will be initiated within the inner loop. For the on/off control algorithm, as shown in **Figure 3-12**, the control action upon the demand at the current time step is dependent upon the status of this demand during the previous control duration. If this demand at all time steps within the previous control duration was controlled, the demand at the current time step cannot be controlled even if the control action is expected. In this way, the impact of controlling the demand is considered. A similar philosophy is also applied to the proportional control algorithm as shown in **Figure 3-13**. When the loops are terminated, all the balances between the total demand and the supply have been calculated and stored in a vector. Then a function of "*FindMinBalance*" is called to find out the control action under which the total demand is closest to the supply. The results are retrieved and applied to the demand at the specific time step. This procedure is continued until the end of the control period. The previous listed algorithms are only for two demands, for the purposes of demonstration only. The whole DSM algorithm is flexible and generic and has the capability to adjust itself to suit the different number of demands.

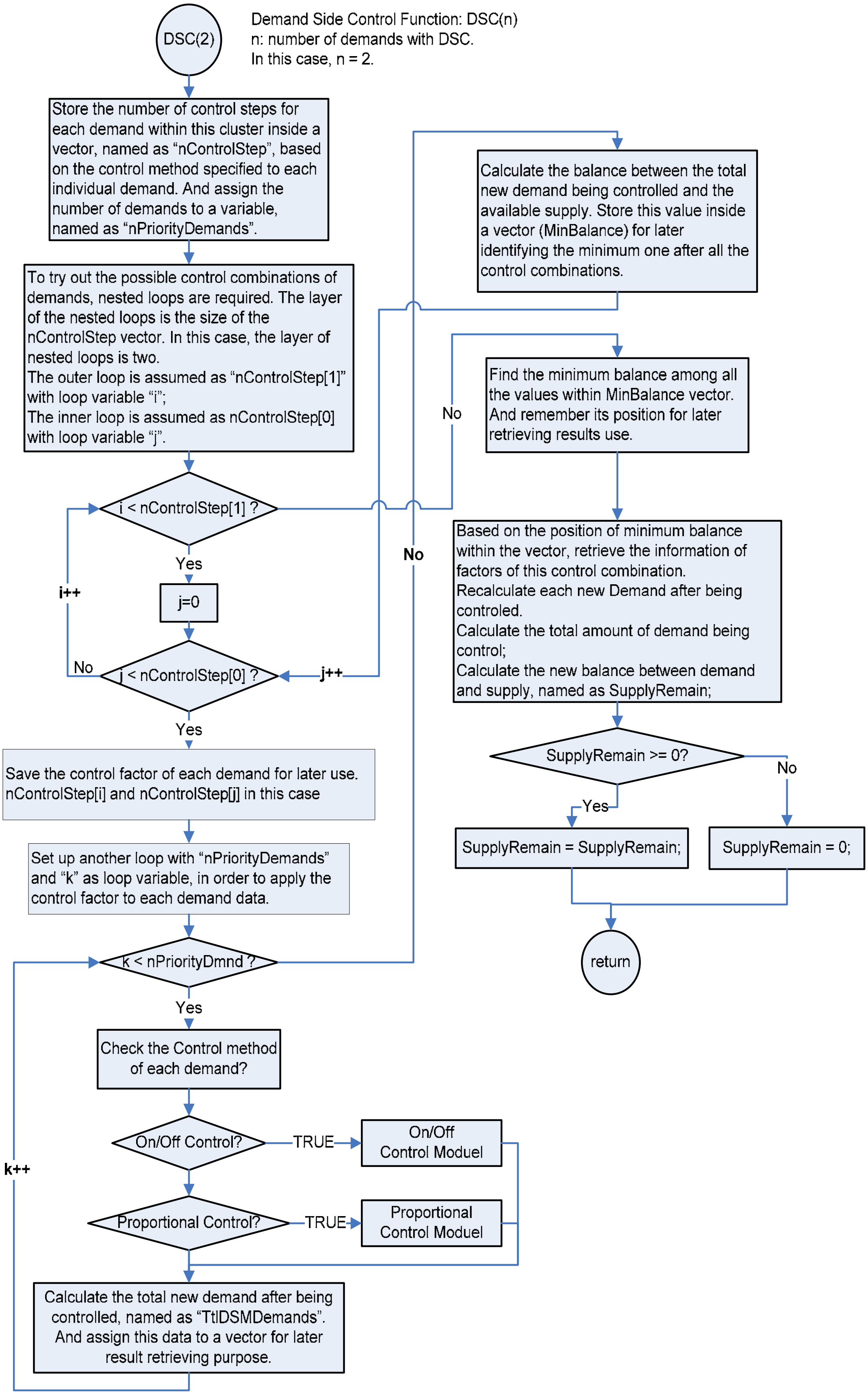

Figure 3-11: Details of the DSC(2) Algorithm

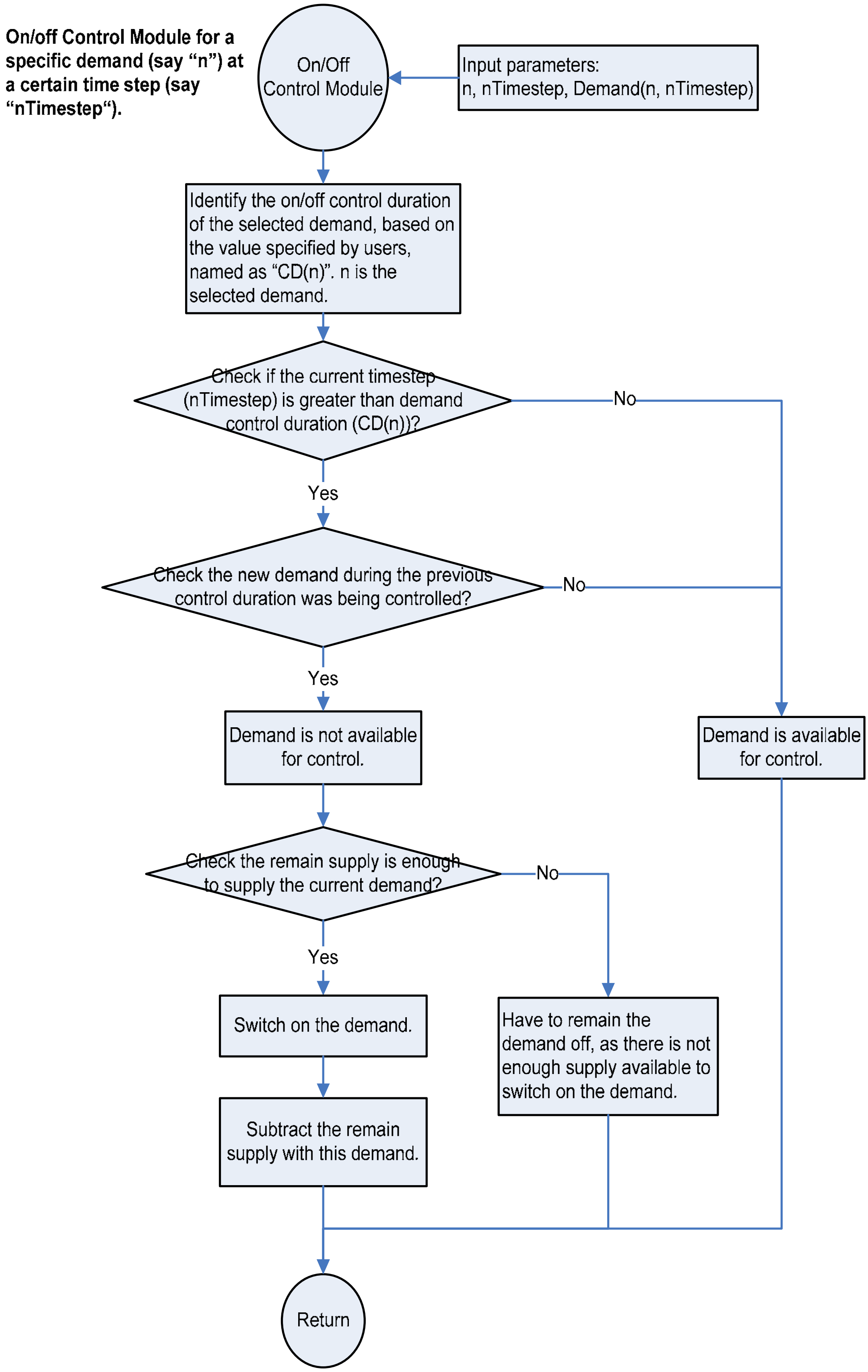

Figure 3-12: Detailed Algorithm for On/Off Control

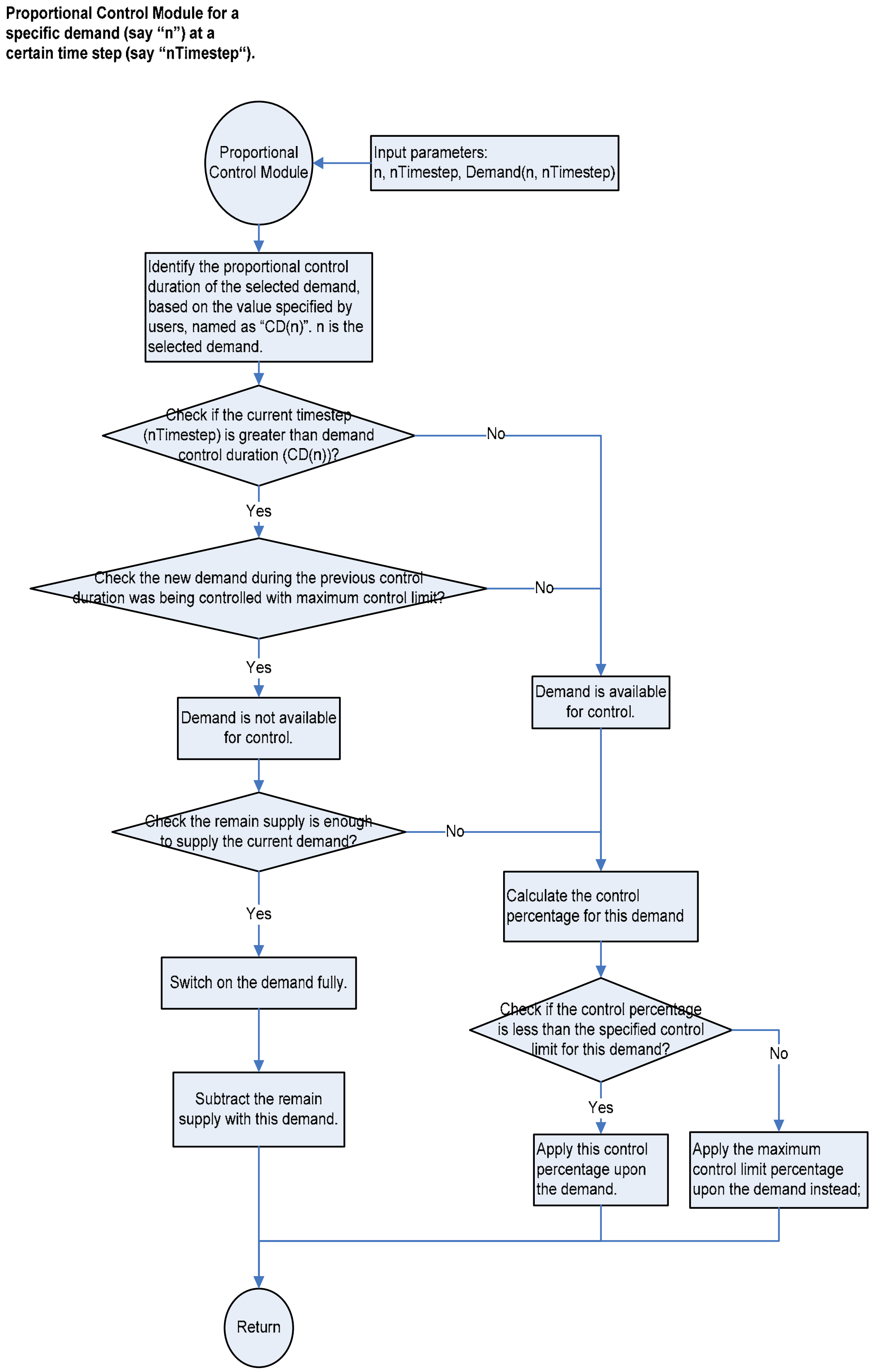

Figure 3-13: Detailed Algorithm for Proportional Control

3.4 Towards Operational Level DSC Algorithm

As discussed previously, the DSC algorithm is only invoked when total demand is greater than total supply. The control duration for a certain load is employed to consider the pay-back effect. In order to judge whether the demand at the current time step can be controlled or not, knowledge of whether it has been controlled during the previous control duration is required. In the previously-stated control rules, the demand cannot be controlled at the current time step unless the load at all previous control durations was also controlled. The value of the control duration generally is obtained from empirical study and is constant in DSC analysis during the specified control period. This is not the common case, since the control duration sometimes changes with the relevant environmental conditions and with the time as well. Therefore, a modification to the DSC algorithm is required in order to identify the control duration for a certain load throughout the control period.

3.4.1 The Operational Level DSC Algorithm

Based on the strategic level DSC algorithm illustrated in previous sections, the modified DSC algorithm based on the algorithm at strategic level, also called the *operational level DSC algorithm*, is developed to meet the purpose of quantifying the control impacts. This operational level DSC algorithm is capable of quantifying the post-control impact upon the micro environment (this mainly refers to the users' comfort level) after controlling the loads either through simulation or real-time monitoring via sensors. This is a vital issue, as the post-control impact indicates the extent to which users will accept the control actions. It also provides a framework for evaluating the expected demand side control strategy. The operational level DSC algorithm connects supply and demand in much more technical detail and smaller time steps than the one at strategic level.

To develop the operational level DSC algorithm, electricity-based thermal demand models (discussed in **Chapter Four**) or sensors/actuators are required. Electricity-based thermal demand models are used to identify relevant environmental variables through simulation, while sensors/actuators are employed to measure the environmental conditions or control the devices on a real time basis. The operational level DSC algorithm takes environmental variables (either through simulation or real-time monitoring) into account. Therefore the optimised control actions on the loads (e.g. minimising the users' impact) can be achieved. The control logic of the operational level DSC algorithm is shown in **Figure 3-14**. It composes of two aspects: energy aspect and micro-environment aspect.

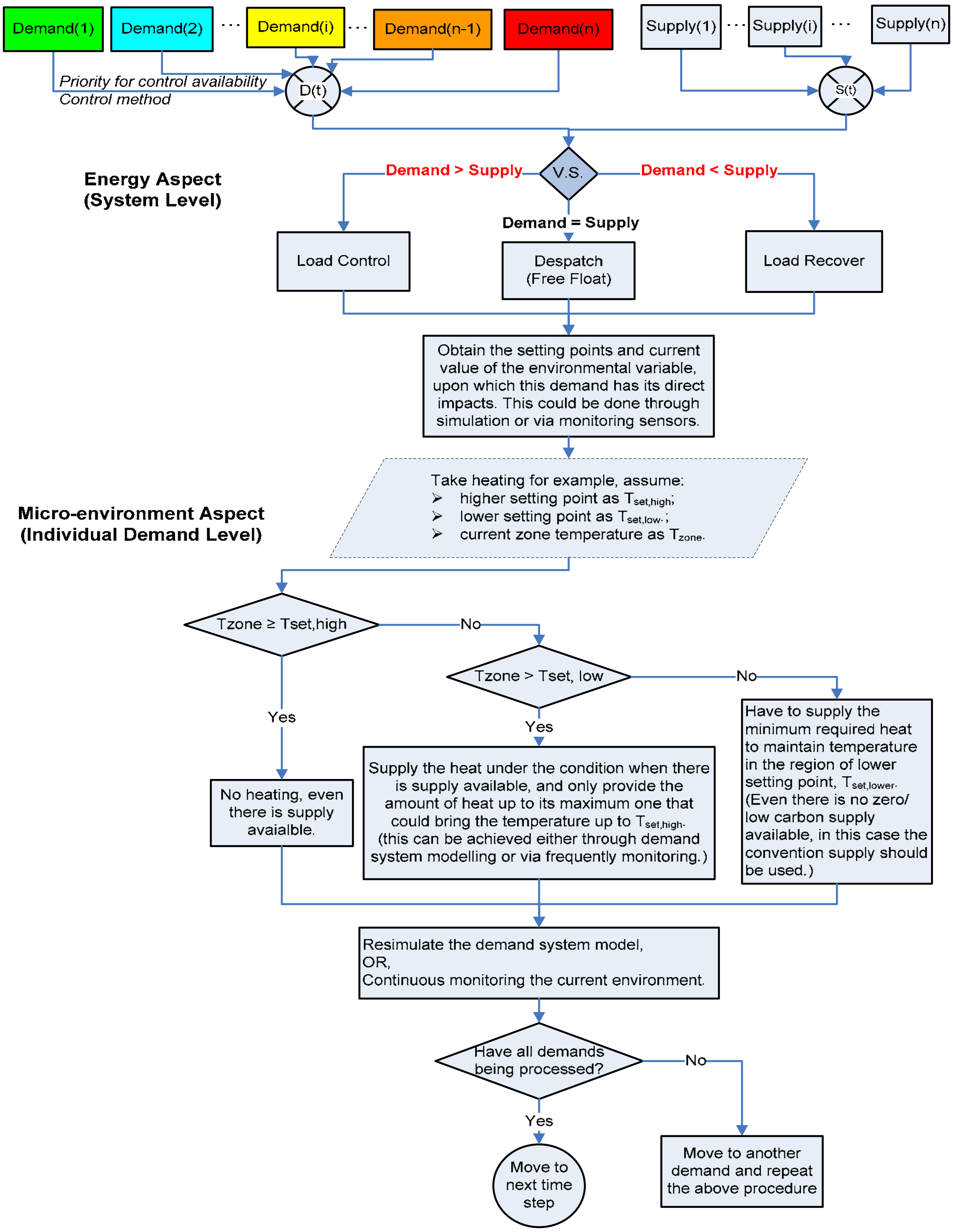

Figure 3-14: Control Logic for the Operational Level DSC Algorithm

3.4.2 Energy aspect of operational level DSC algorithm

Comparing this with the strategic level DSC algorithm described in **section 3.3.2.3**, the similar patterns are adopted in terms of energy aspect at system level, shown in **Figure 3-14**. The difference is that for cases when total demand is less than total supply, a load recovering module is introduced here. The main function of this module is to recover some loads when surplus supplies are available. It prioritises the demands into three clusters under the ascending order from low to high control availability. And it recovers the demand cluster with low control availability first of all, when there is surplus supply at the current time step. Depending on the total demand recalculated after recovering the load, the algorithm compares the new total demand with the total supply. If the total supply is still greater than the new total demand, it moves to the next demand cluster with higher control availability to be recovered until the total supply is less than the total demand.

3.4.3 Micro-environment aspect of operational level DSC algorithm

For the micro-environment aspect, internal environmental variables (such as temperature, humidity, and illumination level etc.), upon which the demand system has direct impact, are used as indicators to make sure whether the actual action can be applied. The value of the main internal environmental variable at the current time step can be achieved either through simulation of demand system model or via real-time monitoring sensors. Having checked this value with the set-point values, appropriate control actions will be taken. This can maintain the internal environment variables within an acceptable range (users' specified comfortable zone) and at the same time some loads can be controlled or recovered without sacrificing their convenience.

It is important to select suitable environmental variables as decision criteria. The more influential the variable and the more variables involved, the more sophisticated and realistic demand side control actions at the operational level will be generated. In order to make it simple and easy to understand, this study mainly considers a single environmental variable for each load within the operational level DSC algorithm, as at this stage the attention is paid to the DSC concept.

3.4.4 Operational level DSC algorithm for simulated demands

Within this section, a simplified refrigeration system model is chosen as an example to demonstrate the procedure of the operational level DSC algorithm for simulated demands. The refrigerator model itself is described in **Chapter Four** in detail. For RE supply, a small scale wind turbine (500W capacity) is selected as an option. The matching results between the wind turbine supply and the simulated refrigeration demand before applying DSC algorithm are shown in **Figure 3-15 (b)**. From the graph shown in **Figure 3-15 (c)**, it can be seen that the demand after applying DSC algorithm is reshaped with the available supply source, on the condition that the temperature within the cabinet is controlled within a specified thermostat range. However, from the new demand profile after DSC, it is seen that the profile in red in **Figure 3-15 (c)** is fluctuating, which results in the refrigerator going on/off frequently. This is likely to shorten the life of the refrigerator, and potentially damage its compressor.

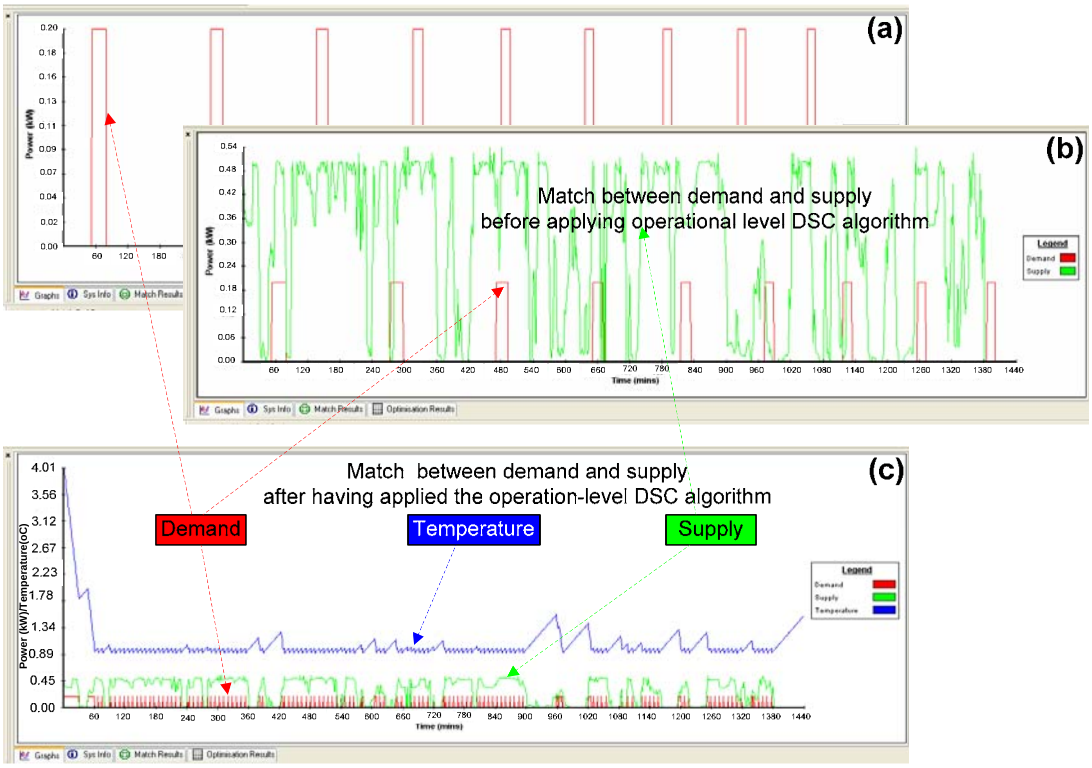

Figure 3-15: Match Results before and after the Dynamic DSC Algorithm

In order to improve the spiky demand profile after DSC, *DSM_OFF_Temp* and *DSM_ON_Temp* are introduced to optimise the thermostat control settings for the refrigeration system.

DSM_OFF_Temp is a virtual set point just under the original upper thermostat setting. It is used as a reference point for the load control module. The control logic is similar as the logic of on/off with a dead band, except when the temperature is between the upper thermostat set point and the *DSM_OFF_Temp* point. In that case, the temperature at the previous time step is compared with the one at the current time step. Take this refrigeration system for instance, if the temperature trend is going down, no control will be applied to the load until the temperature reaches the *DSM_OFF_Temp* point. If the temperature is increasing, it means the refrigerator is off and will remain so until it reaches the upper thermostat setting point.

DSM_ON_Temp is another virtual set point just over the original lower thermostat setting. It is used as a reference point for the load recovery module. The control logic is similar to the one, except when the temperature is within the range between the

DSM_ON_Temp point and the lower thermostat setting point. For that particular range, the temperature changing trend is examined by comparing the results between the temperature at the current time step and the one at the previous time step. Again, taking the refrigeration system as an example, if the temperature trend is increasing, no recovery action will be applied to the load until the temperature reaches the *DSM_ON_Temp* point. If the temperature is decreasing, it means the refrigerator is on and that status will remain until it reaches the lower thermostat setting point.

The modified thermostat of this refrigeration system for the operational-level DSC algorithm is shown in **Figure 3-16**. Thus, the spiky demand caused by the load control and recovery module is improved. The new result is shown in **Figure 3-17** as follows.

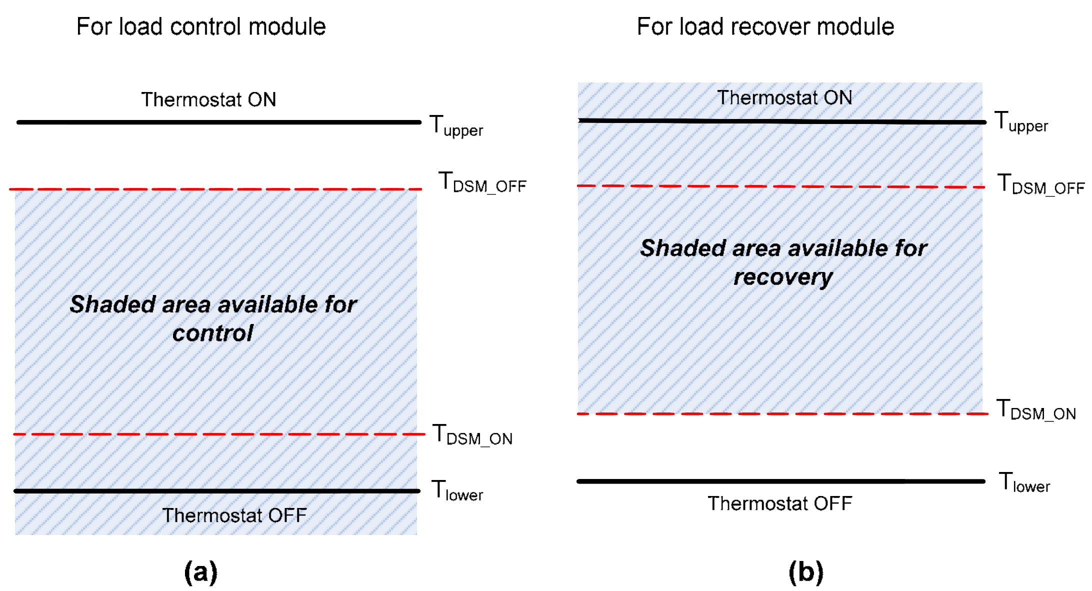

Figure 3-16: Modified Thermostat Control Logic of Refrigeration System for the Dynamic DSC Algorithm

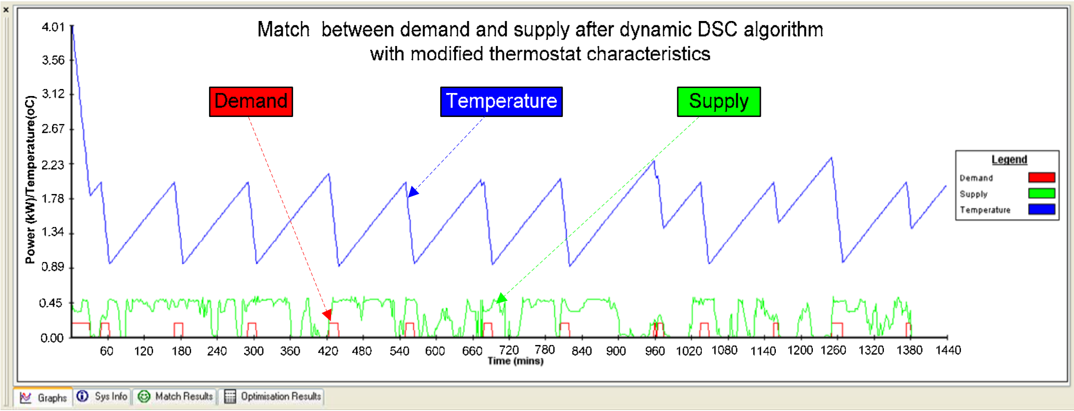

Figure 3-17: New Match with Modified Thermostat Control Logic

3.4.5 Operational level DSC algorithm for real-time monitored demand systems

For real-time monitored demands, both the demand data and relevant environmental variable are measured through selected sensors on a real time basis. These data are stored in EnTrak (Kim 2004), an SQL-based energy database system developed by ESRU, University of Strathclyde. At the same time, the interfacing module, developed within MERIT, accesses the EnTrak database and retrieves the data. The environmental data from EnTrak, acting as an indicator, is compared with the initial settings specified by the users. Based on a comparison of results, the control actions which can be applied on a certain load will be determined simultaneously. Furthermore, the algorithm converts the generated control actions upon a certain load at each time step into the actuator-recognisable messages. Then the messages trigger the actuators to control the appliances within the system, either switching on or off, or proportionally, in a specific percentage, or remaining at the same status as before. The dynamic DSC algorithm for monitored demands is integrated within an internet-enabled energy service system. The detailed implementation is described in Chapter Five.

3.5 Summary

This chapter has illustrated the concept and objective of DSM+c. The DSM+c algorithm is a new concept of demand side management, which can not only assist management decisions at strategic level, but which also has control capability under operation level. Both strategic level DSM+c algorithm and operational level DSC algorithm have been developed and discussed in this chapter.

3.6 References

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CHAPTER FOUR ENABLING DEMAND AND SUPPLY TECHNOLOGIES

This chapter describes the rationale behind and development of the supporting interface of dual-form energy system, electricity-based thermal demand models (such as heating and cooling systems, etc.) and supply models (such as CHP, heat pumps etc.) as a complement to the implementation of the DSM+c algorithm.

4.1 Supporting Interface for Demands and Supplies

The main objectives of the **DSM+c** algorithm, as discussed in **Chapter Three**, are to facilitate power from building-integrated renewables (RE) and other low carbon (LC) emission resources, avoid export from or import to a centralised energy supply infrastructure, and create optimal demand profiles for LC and RE operations. Some renewable supply technologies such as photovoltaic (PV), wind turbines and solar collectors are commonly used for the production of electricity and thermal energy to meet demands. These technologies are highly dependent on climate conditions, geological locations and time (Jenkins 2001), and their output is intermittent and unreliable. When these intermittent renewable technologies are used in a sustainable energy supply system, it is important to consider how well-matched the profiles of demand and supply are, and to seek the best possible match. Suitable methods for modelling the energy generation from these intermittent technologies have already been discussed by Born (2001), who integrated these supply models into a platform, called MERIT. MERIT as described in **Chapter Two Section 2.7.5** is a tool to analyse the match between supplies and demands.

In order to provide a reliable energy supply (electrical or thermal), the outputs of the above-mentioned intermittent renewable sources may be supplemented by various other means. These may include low carbon emission technologies such as combined heat and power (**CHP**) and heat pumps (**HP**) etc. Favourable demand profiles are required for LC system operations, as LC system will give the best performance when it runs at a constant designed load (HVCA, 2008). If the demand profile is fluctuating, this will decrease the overall efficiency of LC devices and in the case of those LC systems driven by fuels, more CO_2 emissions will be generated and released to the atmosphere. The DSM+c algorithm is developed for the purpose of creating an optimal demand profile for the operation of LC supply devices.

Further to the discussion in Chapter Three, the control impact upon consumers' environment requires serious consideration, as it is relevant to the customers' acceptance of DSM+c actions. To quantify the control impact, demand models of space heating/cooling system, hot water storage and refrigeration system are required. These electric-based thermal systems are ideal for applying the DSM+c algorithm, as observed in Chapter Three. The inertial nature of this type of system enables it to have higher control availability and lower impact on user comfort, as well as the potential for introducing zero/low carbon energy systems to supply these demands.

As may be noticed, two energy forms (electrical and thermal) are usually involved in low carbon emission technologies and demand systems. CHP, for example, is a high energy efficiency device generating electrical and thermal energy at the same time. A HP supplies thermal energy and simultaneously consumes the electricity. Electric-based hot water storage provides hot water for daily usage and at the same time consumes the electricity. Air conditioner is another example, it supplies the thermal energy required for the space and simultaneously needs electricity. To handle these dual energy systems, a multi-functioning platform is required, which should be capable to simultaneously match and dispatch both the electrical and thermal energy streams.

The Two-Match-View (**TMV**) structure has been developed in the aforementioned context to handle energy systems which involve both electrical and thermal energy forms. After the sustainable dual energy system model is specified and relative parameters are filled in, the simulation is conducted. The results in terms of both electrical and thermal energy for this particular energy system are stored, and two views for electricity and thermal energy are created respectively to show the results. In addition, supply can be classified into primary supply and auxiliary supply. Depending on the features of the dual energy system, it automatically detects whether it is demand or supply from the electricity and thermal viewpoints. A CHP system supplies both electricity and thermal energy simultaneously (**Figure 4-1**). A HP system supplies thermal energy while demands electrical energy (**Figure 4-1**). Another important point is that these two views are not independent but interact with each other dynamically, with any changes on one side automatically affecting the results on the other. The results on both sides are calculated simultaneously for each time step within MERIT.

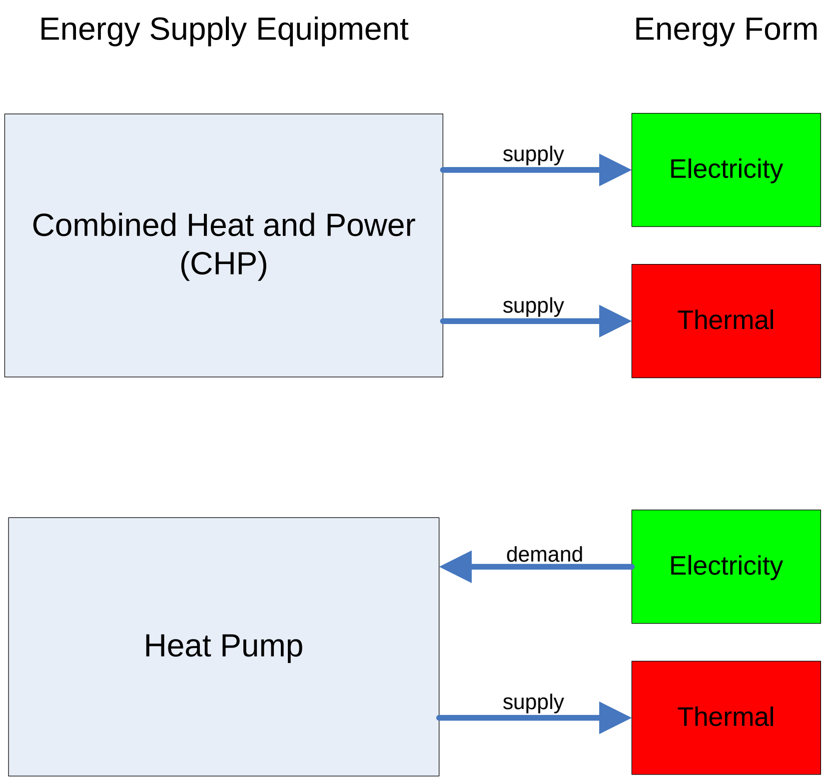

Figure 4-1: Diagram of the Two-Match-View Structure

Specially designed new indexes are proposed to assess the performance of LC energy systems. Born (2001) proposed the match assessment method for renewable energy systems and demand profiles. Basically, two matching elements, magnitude and phase, are used to decide how well the time-series profiles match. Within MERIT, several related indexes relevant to the match assessment are employed, i.e. inequality coefficient, correlation coefficient, shared area and match rate.

The existing assessment method needed to be improved when it was used to evaluate the demand-driven energy systems, such as CHP and heat pump energy systems. For these energy systems, the demand is followed. The match rate is usually relatively high and there is not much difference among all combinations between supplies and demands, making it difficult to judge which one is better by simply checking the figures of the match rates. Therefore, the existing criteria for assessing these systems are not sufficient, and some new indicators are required in order for the effective and efficient evaluation (Hong et al. 2007). As these energy systems operate at the partial load conditions most of the time, partial load performance of the energy system should be taken into account in the evaluation. The amount of times when the system operates at partial loads can be regarded as an indicator to show how well the system operates when it follows a particular demand profile over the simulation period. Other indicators such as fuel consumption, equivalent GHG emission, and overall efficiency over the simulation period, are also of great help in terms of appraising the operating performance of low carbon energy systems. The diagram for this multi-index assessment platform is shown in **Figure 4-2** that follows.

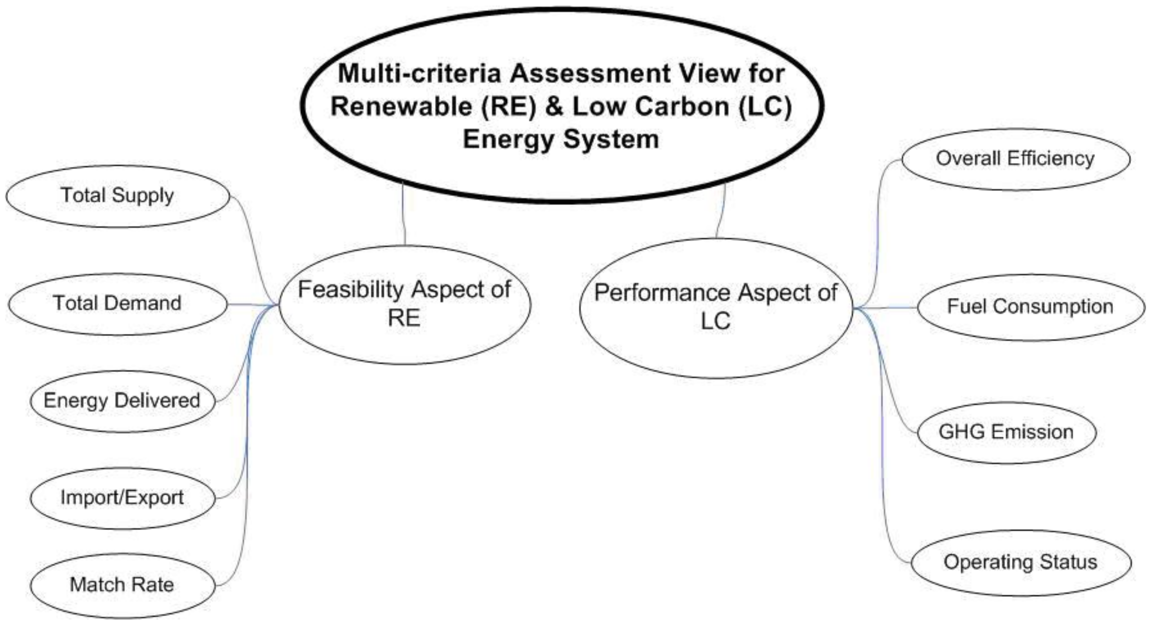

Figure 4-2: Diagram of Multi-Index Assessment Platform

The new multi-criteria assessment platform is built on the work of Born (2001), and is able to provide better evaluation of low carbon emission energy systems. It stores the possible combinations between calculated supply and demand profiles in order of precedence, recording them in the optimising table. Each combination is shown as one row in the table, which gives information in different columns, such as the amount of total demand and total supply over the simulation period, common criteria associated with feasibility aspect of RE and LC, and additional criteria relevant to performance aspect of LC etc. For each column, it provides the functionality of sorting in either ascending or descending order by simply clicking on the title of the column. Thus, the best combination based for certain criteria can be discovered, Therefore the platform is capable of analysing all the combinations based on their different criteria, and obtaining the best results.

Electricity-based thermal demand models and low carbon emission energy system models have been developed and integrated into the MERIT platform. The following section gives the detailed modelling procedures for heating/cooling demand systems and low carbon emission technology-based energy systems (especially the combined heat and power [CHP] system and the heat pump [HP] system).

4.2 Electricity-based Thermal Demand Models

Mathematic models of electricity-based thermal demand systems are required to quantify the control impact of the DSM+c algorithm on internal environment, as discussed in Chapter Three. Various demand models – both detailed and simplified - can be found. It is important to choose the appropriate one, as only some essential data, such as internal environmental parameters and energy consumption of the system, are required for DSM+c algorithm. The first priority of this study is to establish the connection between demand model and DSM+c algorithm. Component-based models are preferable, as they can be treated as a black box and replaced with a better one in the future. Based on the above considerations, the physically-based load modelling methodologies are adopted, as this appears to be one of the most promising approaches for the load modelling problem applied to DSM (Molina et al. 2003). According to Lu and Katipamula (2005), thermostatically-controlled appliances (TCAs) such as air conditioning systems and refrigeration systems, space heating systems, hot water storage etc., are ideal for the implementation of the DSM+c algorithm described in this thesis.

Physically-based domestic appliance models for heating and cooling demand purposes are developed in this study. Because the TCAs are similar, they can be modelled in similar fashion, this study focuses only on refrigerator and electric water heater storage models.

4.2.1 Cooling System Modelling

Popular cooling systems in residential dwellings include refrigerators for storing food and air conditioning systems, and both have a similar purpose. For refrigerator, it is to keep the box temperature at the desired level. Whilst for air conditioner, it is to maintain the room temperature at a certain level to keep the occupants within their comfort zone.

It is important to understand how the temperature for storing food, surrounding enclosures or occupants within, as well as the zone air, is lowered. Since the cooling device directly cools the air in the zone, it is the zone air temperature that falls first. As the food, surrounding enclosures or occupants within this system has a higher thermal mass than the air, there is a time lag between when the air temperature is reduced and when the temperature of the food or the surrounding enclosure or inside occupants is reduced over time as heat is extracted (Altwies and Reindl 2002). When the refrigeration equipment turns off, the air temperature shows a greater rise than the temperature of the articles being cooled.

The basic principle for the operation of cooling systems is to keep the temperature changes within a specified range. For the refrigerator, the stored food temperature should be maintained within the permissible safe range, which retards bacterial growth and avoids the risk of nutrient content loss (Altwies and Reindl 2002). For the air conditioner, the space temperature should not drift outside the users' thermostat settings, in order to avoid causing discomfort within the micro-environment (El-Ferik et al. 2004). However, due to thermal inertia of walls, a short-term small deviation from the specified range is not normally detectable by the user.

In this study, for reasons of simplification, refrigeration equipment, either a refrigerator or an air conditioner, is modelled as a 6-sided enclosure zone with a user-specified insulation level. The model focuses on the energy balance within the zone rather than on the refrigeration system itself. The refrigeration system is temperature controlled (Magoo 2003). For the refrigerator, the following assumptions are made:

1. The thermo-physical properties of all the materials are constant, and do not change with the temperature.
2. The temperature distributions only change with the time and are spatially uniform at any instant in time, which implies that the temperature gradients inside the zone are negligible.
3. For the purposes of simplification, a lumped parameter model is applied to the products and air inside the zone, which implies that the thermal properties of medium inside the zone is the average value of the stored products and air. It needs to be pointed out that this is not going to happen in reality. In practice, the thermal interaction between the stored products and the surrounding air is modelled as a convective heat exchange, which can be improved in the future.
4. The operating state of the whole system is controlled by a thermostat, the state of which depends on the temperature within the zone.
5. The impacts of the door opening times and duration upon the energy consumption of the refrigerator are not taken into consideration.

The main governing equation appears as **Equation 4.1** and this deals with the energy balance analysis within the zone.

$$\rho \cdot V \cdot c \cdot \frac{dT(t)}{dt} = U \cdot A \cdot \left(T_{amb}(t) - T(t)\right) - K(t) \cdot COP \cdot P_e \qquad \textbf{Equation 4.1}$$

where,

T(t) = inside temperature at time t, °C;

$T_{amb}(t)$ = ambient temperature at time t, °C;

K(t) = thermostat binary state (0 for off; 1 for on) at time t;

COP = coefficient of performance;

P_e = electricity power input required by the refrigeration system system, W;

ρ = average density within the zone, kg/m^3;

c = average thermal capacity within the zone, J/(kg °C);

V = total volume of the zone, m^3;

U = average U value of the zone structure, W/(m^2 °C);

A = the surface area of the zone structure, m^2.

On the left-hand side of the equation is the rate of temperature change inside the zone, which mainly depends on the thermal capacitance of the medium itself. If the thermal capacitance is low, the temperature inside the zone changes more quickly than if it were higher. On the right-hand side of the equation is the thermal interaction with the condition outside, mainly through conductance and convention; this is the main driver which causes the temperature increase inside the zone. The next parameter is the heat extracted from the zone, which depends upon the thermostatic state compressor power rating and the coefficient of the refrigeration system's performance. The evolution of the separate state K(t) is governed by a thermostat with the temperature settings (X_- and X_+), and the dead-band $\Delta = X_+ - X_-$. K(t) switches from 0 to 1 when K(t) reaches X_+ and from 1 to 0 when K(t) reaches X_-. No switching occurs otherwise, and changing the limits of thermostat settings allows the power consumption of TCAs to be regulated.

Several algorithms relating to this simplified cooling system (e.g. refrigerator) model are produced in **Figures 4-3**. It describes the logic of temperature-based on/off controller with a dead-band for the operation of refrigerator system, based on which its power consumption is calculated.

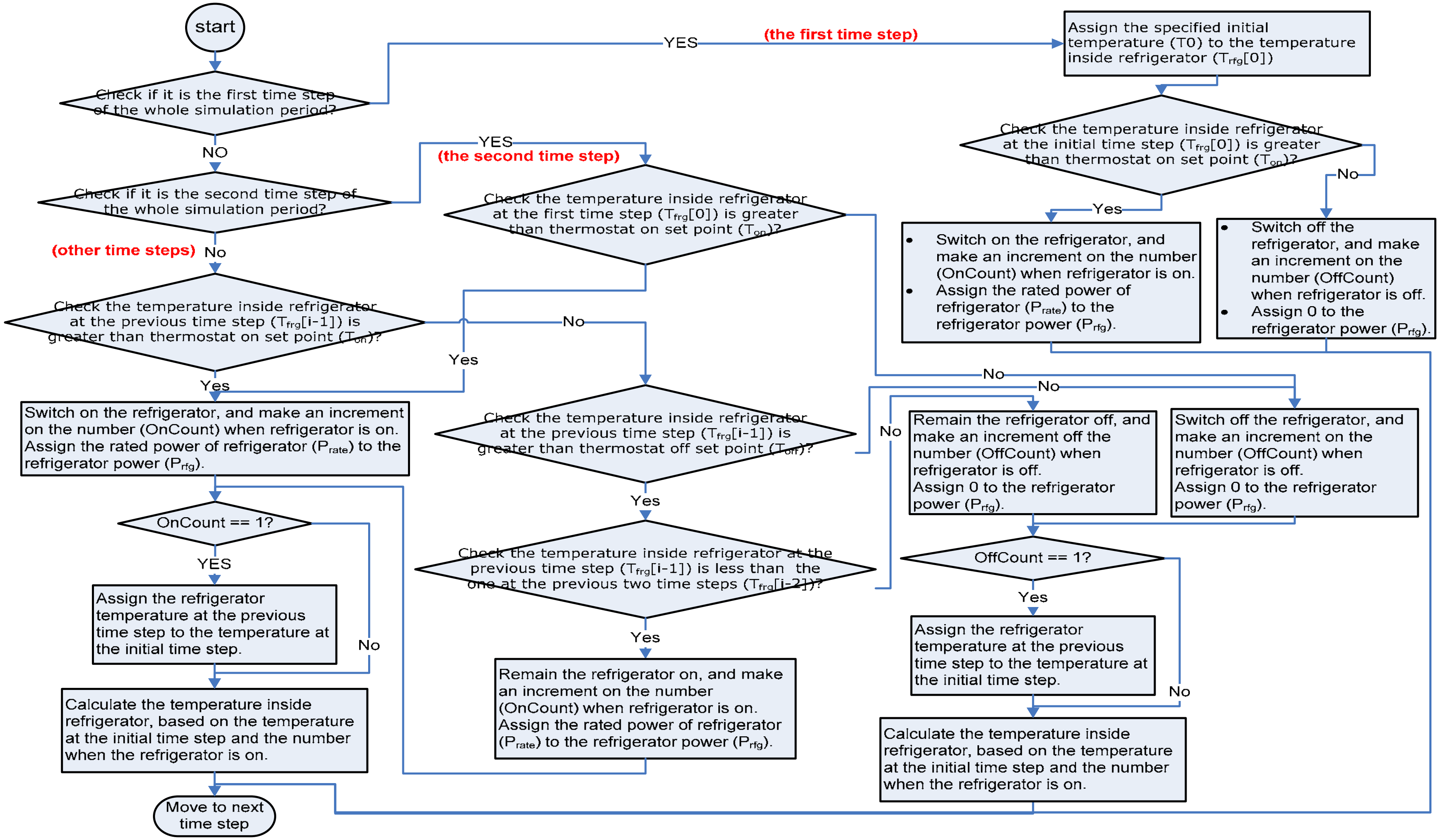

Figure 4-3: Algorithm for the Refrigerator Model

4.2.2 Heating System Modelling

There are two types of heating systems, air-based and water-based. Water-based heating systems are the main focus of this study. They are not only used for space heating purposes, but also for domestic hot water usage. The modelling of hot water storage (HWS) has received more attention than any other kind of energy storage, and the models developed for different kinds of hot water storage are well-documented in the literature (Fanney and Dougherty 1996; Fernandez-Seara et al. 2007; Kar and Al-Dossary 1995; Lacroix 1999; Laurent and Malhame 1994; Laurent et al. 1995; Molina et al. 2004). The physically-based hot water storage model discussed in this thesis was first proposed by Chong and Debs (Chong and Debs 1979), and is based on a linearised energy balance analysis, that makes the following assumptions:

1. The stratification of the hot water storage is ignored, which implies that it is fully-mixed at all times and thus, it can be identified dynamically by a single temperature variable.
2. Only one thermostat-based heating element is used within the water storage tank.

The main energy balance equation is shown in **Equation 4.2**.

$$\rho_w \cdot V \cdot c_p \frac{dT(t)}{dt} = K(t) \cdot P_e - \rho_w \cdot \dot{Q}(t) \cdot c_p \cdot \left(T(t) - T_{inlet}\right) - U \cdot A \cdot \left(T(t) - T_{amb}(t)\right) \quad \textbf{Equation 4.2}$$

Where,

T(t) = Inside temperature at time t, °C**;**

T_{amb}(t) = ambient temperature at time t, °C**;**

K(t) = thermostat binary state (0 for off; 1 for on) at time t**;**

$\dot{Q}(t)$ = volume flow rate of water at time t, m^3/s**;**

P_e = electricity power input of the heating element, W;

ρ_w = the water density, kg/m^3;

c_p = thermal capacity of the water, J/(kg °C);

V= water tank volume, m^3;

U = average U value of the hot water storage system, W/(m^2 °C);

A = the surface area of the hot water storage system, m^2;

T_{inlet} = the inlet water temperature, °C.

On the left-hand side of the equation is the rate of water temperature change within the storage tank, which depends mainly on the thermal capacitance and the mass of the water inside. On the right-hand side, the first part represents the heating power input to the tank, which mainly depends on the thermostat state and power of the heating element. The evolution of the separate state K(t) is governed by a thermostat with temperature setting, along the same lines as the cooling system, and changing the set point allows the regulation of the power consumption of TCAs. The second part indicates the thermal energy transfers to the new incoming water. The volume flow rate of the new water and the temperature difference between the new and old water inside the tank are two principal factors which affect the water temperature inside the tank. The last part concerns the heat loss to the environment, which depends on the thermal insulation level of the tank. This is another factor which causes the temperature decrease inside the tank.

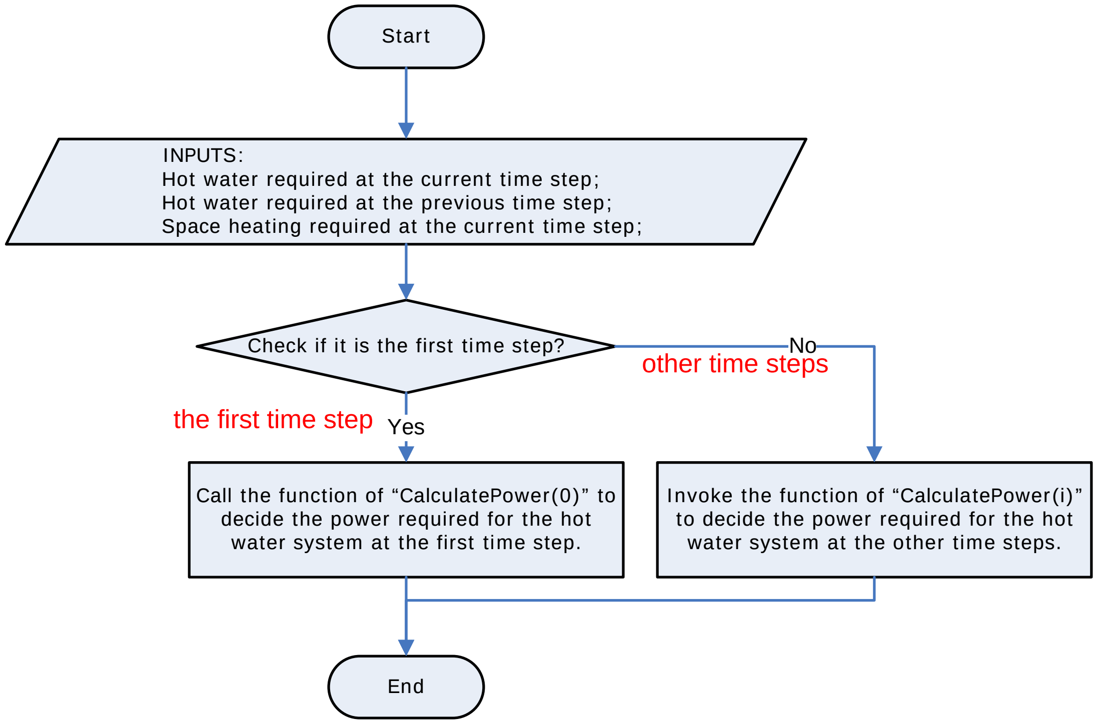

Figure 4-4: General Diagram of the Hot Water Storage Model

Figure 4-4 shows the overall logic behind hot water storage model. The main input parameter required is the demand profile throughout the simulation period, either for hot water or space heating or both purposes. The behaviour of HWS model at the initial time is different from the rest of the time, as there is no data at previous time to be considered. The model at initial time will be judged by its predefined parameters by users. Therefore two modules of calculating power consumption for these two particular situations are developed respectively. The detailed algorithms for these two modules, *CalculatePower(0)* and *CalculatePower(i)*, are shown in **Figure 4-5** and **Figure 4-6**. Through these two modules, the required thermal power can be quantified at each time step, further the electricity consumed by HWS can also be derived. The 4th order Runge-Kutta numeric method is used for solving the equation listed in **Equation 4.2**.

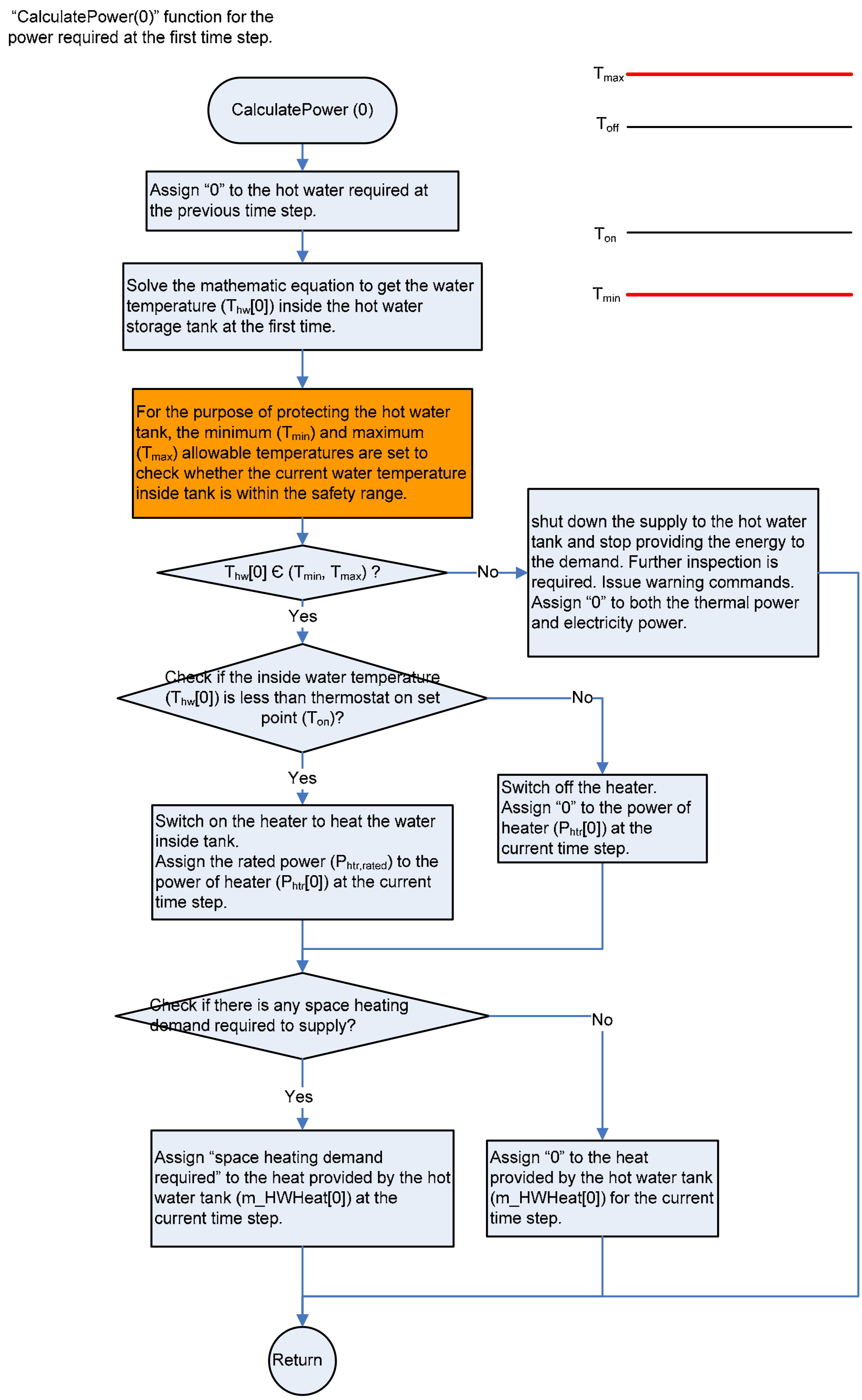

Figure 4-5: Flowchart for Calculating the Power Required for the Hot Water Storage at the Initial Time

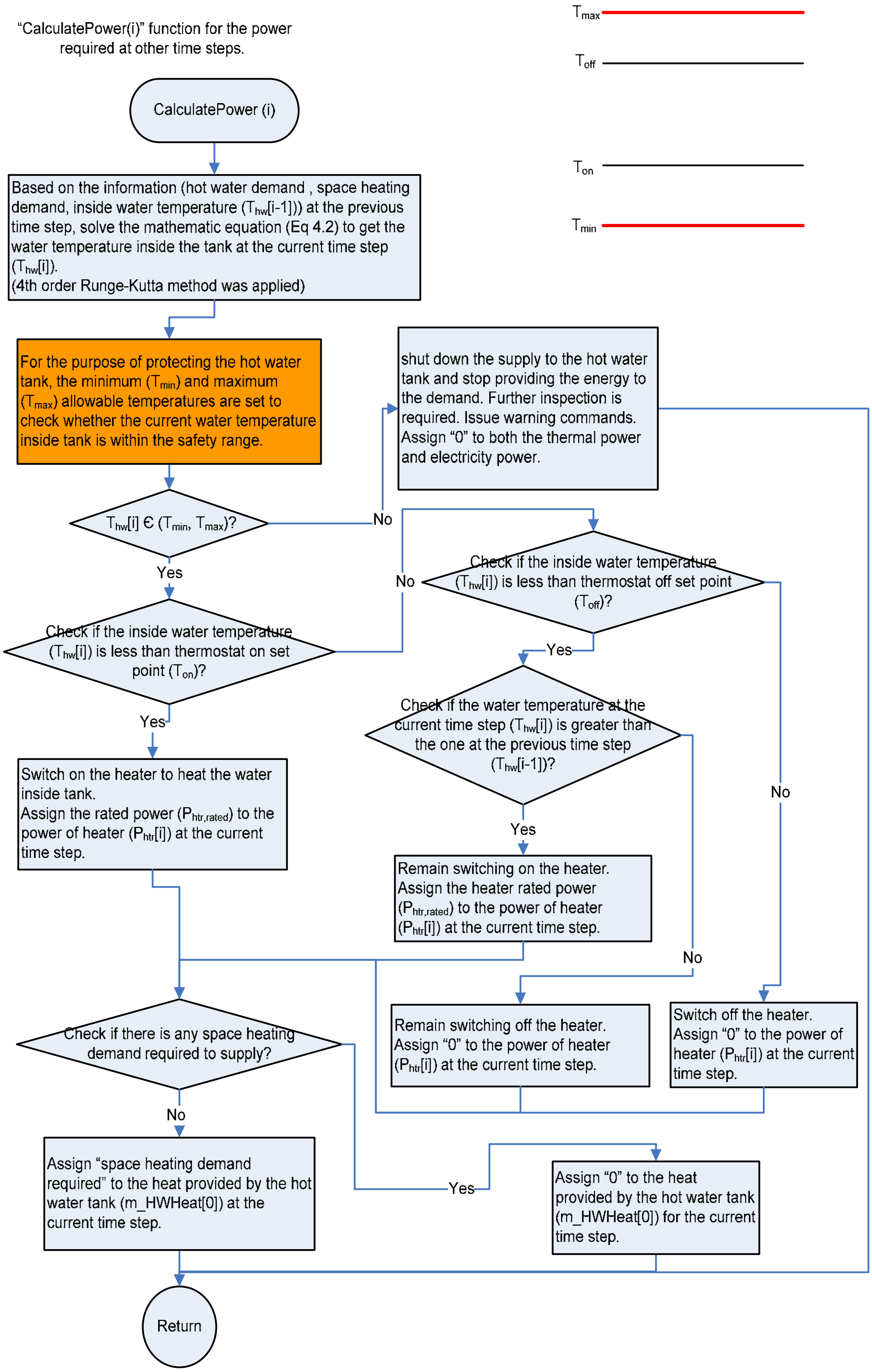

Figure 4-6: Flowchart for Calculating the Power Required for the Hot Water Storage Model at Other Times

4.3 Supply Models

To simulate the impacts of DSM+c algorithm upon the performance of renewable and low carbon supply systems, performance-based supply models for various technologies are required. These supply models are capable of modelling the performance changes before and after having applied DSM+c algorithm upon the demands. The main focus will be on the modelling techniques for LC energy sources, such as the CHP system and heat pump system [RE system (e.g. PV, wind turbine etc.) modelling has been already illustrated in Born's thesis (2001)].

4.3.1 CHP System

Combined heat and power (CHP) is an energy conversion device where electricity and thermal energy are produced simultaneously in one process (ASHRAE Handbook 2005). The electricity produced by CHP is called ***CHP electricity***. Accordingly, the thermal energy generated by CHP is called ***CHP heat***.

The generic model of CHP has been developed based on the existing generic generator model in MERIT, which allows the consideration of different types of CHP engines, part-load performance (of fuel consumption and heat to power ratio), minimum load to run CHP, de-rating factors for altitude and ambient temperature, the different types of fuel and their GHG emission (Smith 2002). The ability to follow the thermal or electricity loads, to run on the constant load, or to follow the largest demand, have also been taken into account.

This section describes the algorithm used to model the behaviour of different types of CHP systems (mainly small-scale or micro-scale) in different operating conditions. Several operation modes such as following the thermal loads, following the electricity loads, and running at constant loads, etc., can be selected to run the CHP system. The general procedure of the CHP module and details of these three modes are shown in **Figure 4-7**. The operating mode of CHP module is firstly checked. The CHP system will not operate, if none of the above-mentioned operating modes are specified. Based on a particular operating mode, different modules for calculating the performance of CHP system are activated.

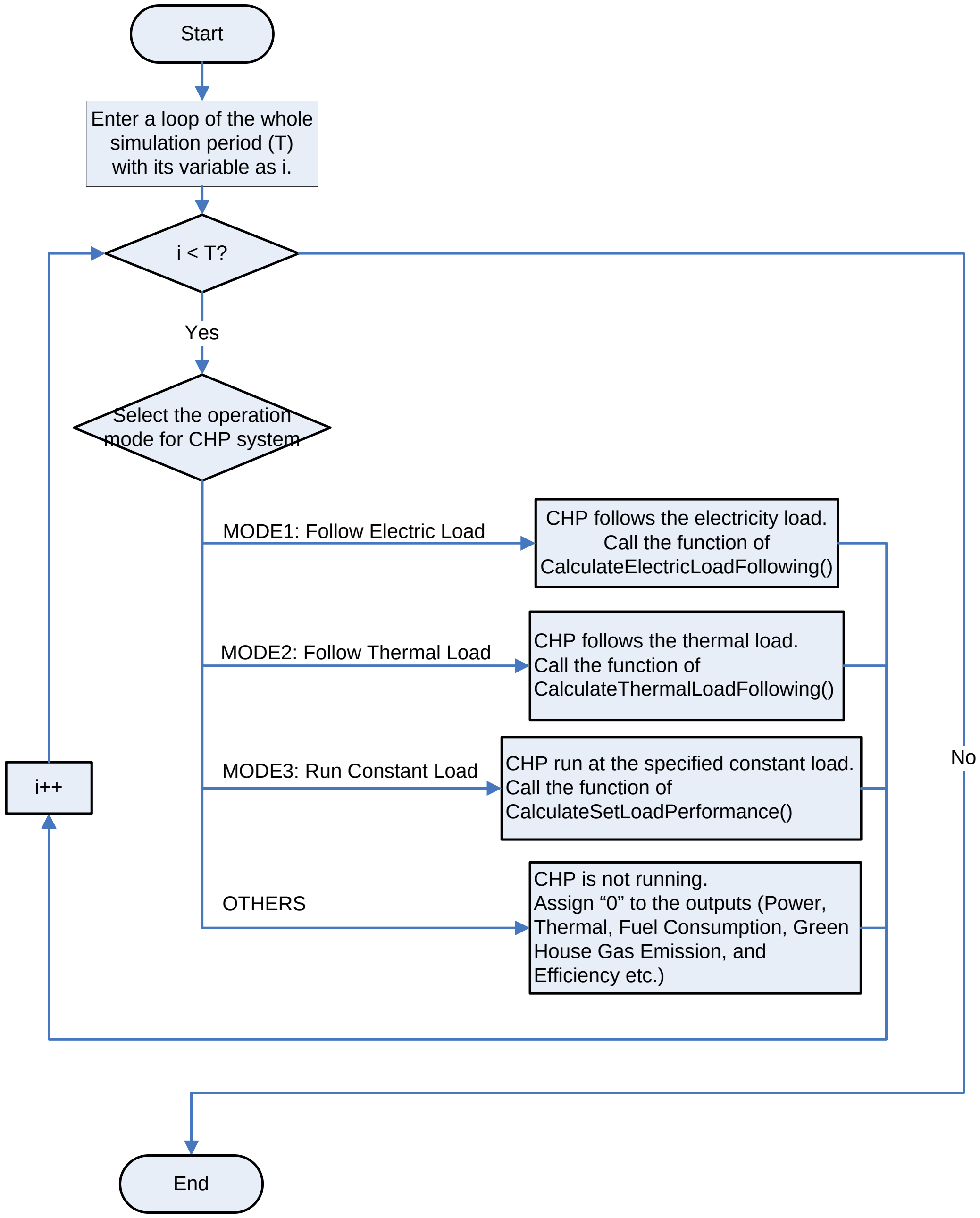

Figure 4-7: Diagram for Modelling CHP in MERIT

a. Constant-load-running Mode

Running at the constant load means that CHP is running at a certain equivalent fixed percentage of electricity loads during the entire simulation period. The de-rating factors, such as environmental temperature and altitude etc., are taken into account. The equation to calculate the maximum power of the CHP engine is shown as **Equation 4.3**.

$$P_D = P_R \cdot \eta_T \cdot \eta_H$$ **Equation 4.3**

where,

P_D = CHP engine power after considering the de-rating factors, W;

P_R = CHP engine-rated power, W;

η_T = de-rating coefficient of the temperature factor;

η_H = de-rating coefficient of the altitude factor.

In order to know the real power delivered to the end-users, the power factor and the efficiency of the generator must also be taken into account. The real power generated by CHP can, therefore, be calculated using **Equation 4.4**.

$$P_{el} = P_D * \eta_G * \eta_{el}$$ **Equation 4.4**

where,

P_{el} = CHP real power generated, W;

η_G = mechanical efficiency of the CHP generator;

η_{el} = electrical efficiency of the CHP generator.

In addition, the heat-to-power ratio, while operating at a fixed load condition, can be obtained by interpolating the available values at 100%, 75%, 50%, and 25% of the rated capacity. Then the by-product thermal energy at any particular time step can be calculated by simply multiplying the heat-to-power ratio and efficiency of the thermal exchange system, shown in **Equation 4.5**.

$$P_{th} = P_D * Load\% * R_{HtP} * \eta_{HX}$$ **Equation 4.5**

where,

P_{th} = CHP thermal energy rate generated, W;

Load% = percentage load;

R_{HtP} = heat-to-power ratio;

η_G = efficiency of the CHP heat exchanger.

For the same reason, fuel consumption at any particular percentage of the electricity load for each time step can be interpolated using the known fuel consumption values at 100%, 75%, 50%, and 25%. If the price of the fuel is given, the total cost of the fuel during the whole simulation period can be found. The overall efficiency and electric efficiency can also be calculated using **Equation 4.6** and **Equation 4.7**.

$$\eta_{el}\left(\%\right)=\frac{P_{el}}{\dot{V}_F * LHV}; \qquad \textbf{Equation 4.6}$$

$$\eta_{Overall}\left(\%\right)=\frac{P_{el}+P_{th}}{\dot{V}_F * LHV}; \qquad \textbf{Equation 4.7}$$

where,

$\dot{V}_F$ = volume flow rate of the fuel input, m^3/s;

LHV = low heating value of the fuel, J/m^3;

η_{el} = CHP electricity efficiency;

$\eta_{overall}$ = CHP overall efficiency.

In order to consider the environmental effects, the GHG emission is calculated based on **Equation 4.8** and **Equation 4.9**.

$$GHG=\frac{\left(P_{el}+P_{th}\right)*\rho_F * EF_{CO_2}}{\eta_{Overall} * LHV}; \qquad \textbf{Equation 4.8}$$

$$EF_{CO_2}=\frac{44 * C\%}{12}; \qquad \textbf{Equation 4.9}$$

where,

GHG = amount of GHG emission, kg/s;

ρ_F = fuel density, kg/m^3;

EF_{CO2} = emission factor equivalent to CO_2 level;

C% = carbon proportion of fuel.

The detailed procedure for modelling the CHP in the constant-load-running mode is illustrated in **Figure 4-8**.

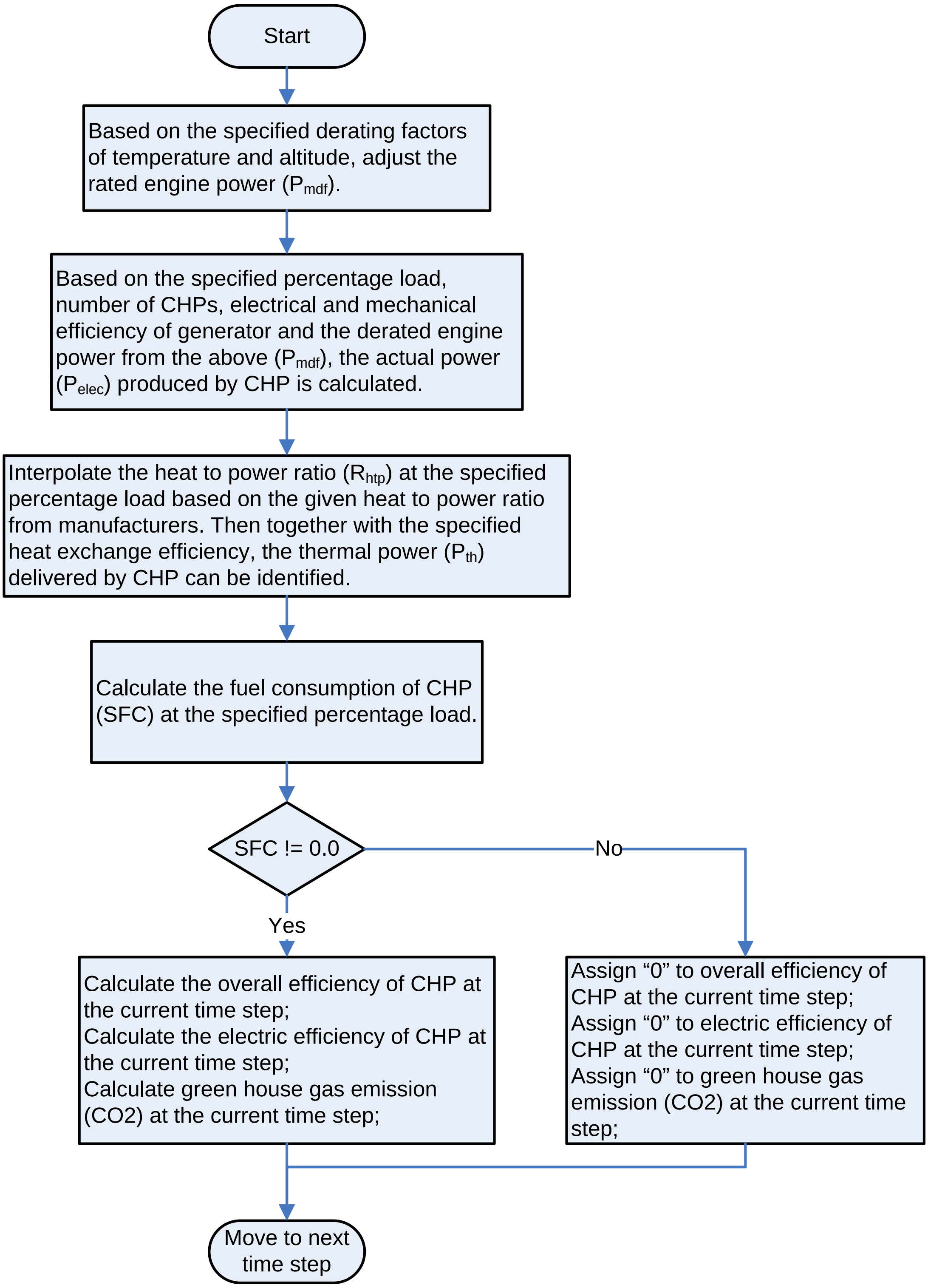

Figure 4-8: Procedure for Modelling the CHP in the Constant-Load-Running Mode

b. Electricity-load-following Mode

When the CHP plant is running in the electricity-load-following mode, the principal input parameter is the residual electricity demand at each time step.

After comparing the required residual demand with the rated power of the CHP plant, the electricity load percentage that is needed for the CHP plant to run at every time step will be determined. If the required electricity load is greater than the maximum rated power of the CHP engine, the engine will run at the maximum rated power, and the shortfall will be supplied from an auxiliary energy system, such as another CHP, generator, or battery etc. If the required electricity load is within the range of the minimum load and the maximum rated power of the CHP engine, the electricity load percentage is calculated as shown in **Equation 4.10**. If it is lower than the minimum load, the CHP engine will not operate.

$$Load\% = \frac{P_{el,rqr} / \left(\cos\varphi_G * \eta_G\right)}{P_D} \qquad \textbf{Equation 4.10}$$

Based on the information above, the fuel consumption and the heat-to-power ratio at a particular percentage load condition can be decided. In addition, the times when the CHP plant is running at different percentage loads can be counted, and can be used as one of the indices to assess the performance of CHP operation. Accordingly, the thermal by-product generated by CHP, fuel consumption, overall efficiency, electrical efficiency and the GHG emission within the simulation period, can be calculated by interpolating among the known values for 100%, 75%, 50%, and 25% of the electricity load. If values at other partial load percentages are known, these can also be used as additional reference points for interpolation. Usually, these values can be obtained from manufacturers' catalogue data (such as Cogenco etc.) or verification reports by US Environmental Protection Agency (EPA, 2003).

The detailed process is shown in context in **Figure 4-9**, which uses a flow chart to illustrate the algorithm.

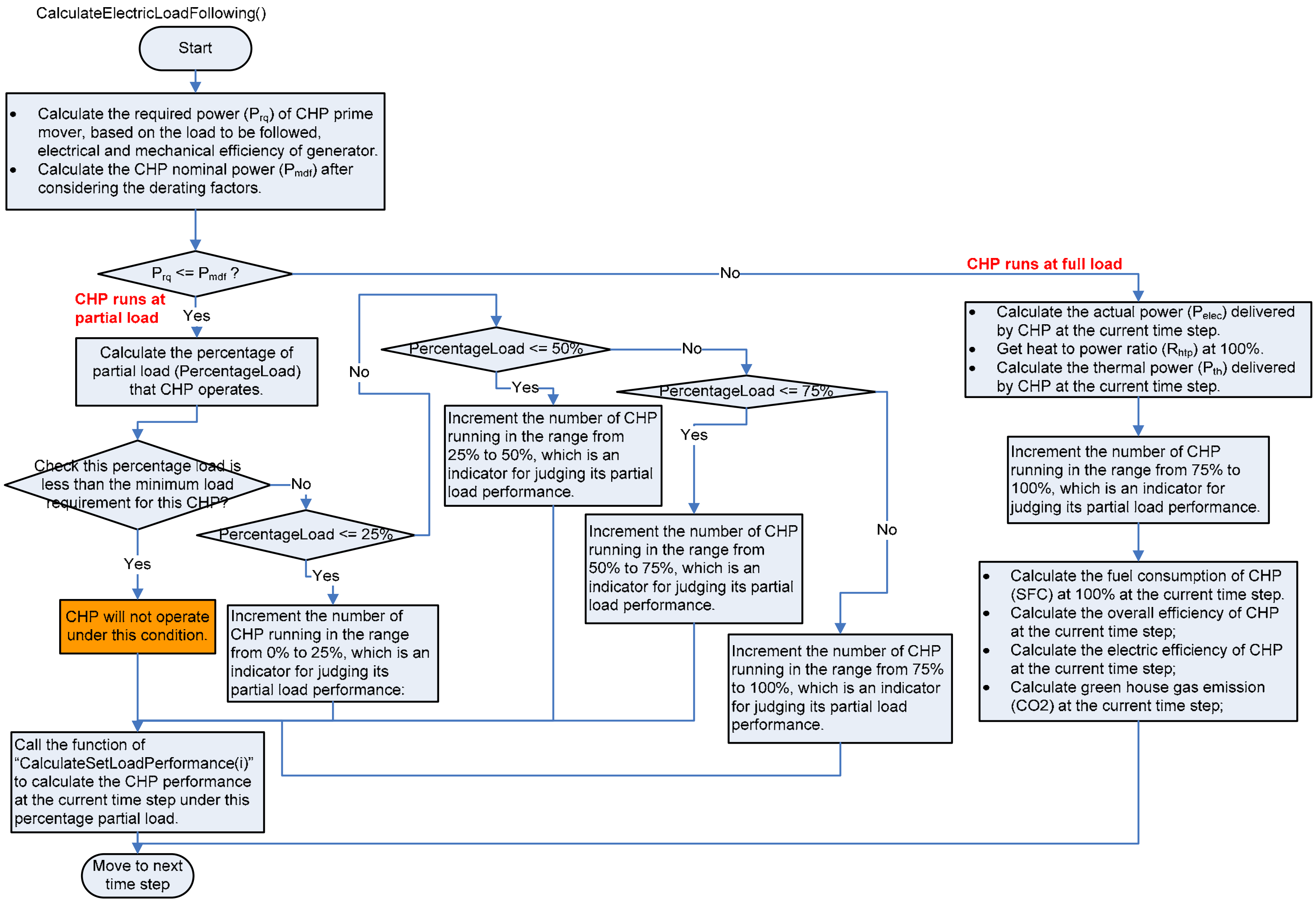

Figure 4-9: Detailed Modelling Process for CHP in the Electricity-Load-Following Mode

c. Thermal-load-following Mode

When CHP plant is running in the thermal-load-following mode, the required residual thermal demand for each time step needs to be known. As only the heat-to-power ratio at certain electricity load percentages is given, the most important thing in this situation is to decide the heat-to-power ratio at a particular required thermal load. The method used in this study is iteration. First of all, assume a specific heat-to-power ratio value while CHP plant operates within the range of 25% and 100% electricity load, and then use this assumed ratio to calculate the electricity demand at a certain time step. The percentage of electricity demand can then be calculated. Then decide again the heat-to-power ratio and compare this new value with the assumed value. If the difference is within the pre-defined tolerance range, this new value will be regarded as the heat-to-power ratio when the CHP plant runs to follow the required thermal demand. For the same reason, the outputs such as electricity by-products, overall or electric efficiency, fuel consumption, and GHG emission, can be calculated using the equations stated in the constant-load-operating mode. The algorithm for this mode is illustrated in detail in **Figure 4-10**.

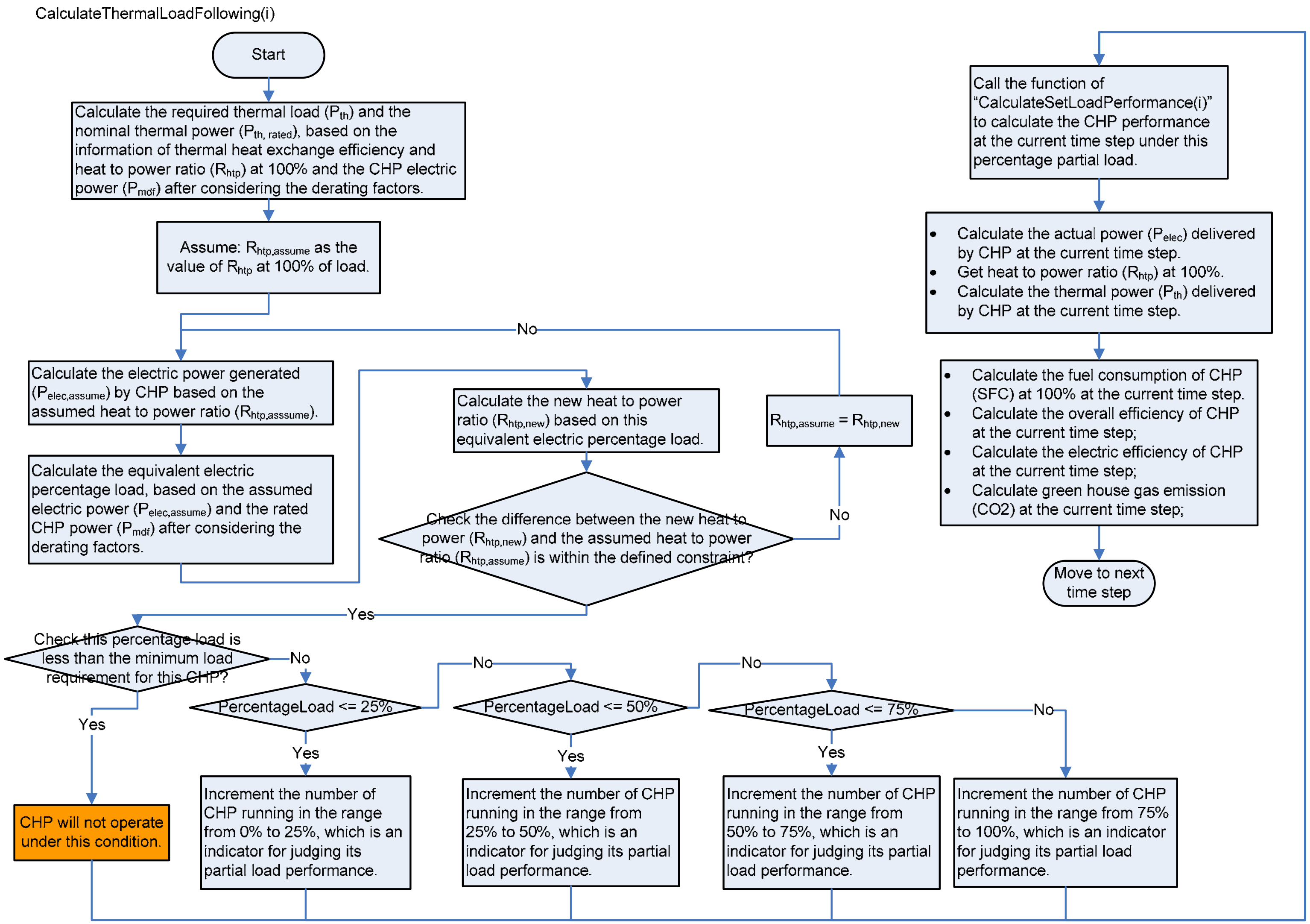

Figure 4-10: Algorithm for Modelling CHP in the Thermal-Load-Following Mode

4.3.2 Heat pump system

A heat pump is another potentially promising device for transferring energy from a low temperature source to a higher one with the cost of electricity usage (Wang 2001). It operates in two modes, both heating and cooling. In the heating mode, the heat pump works as follows: the heat from the heat source (either air or water or ground source water) exchanges with the cold refrigerant in a liquid state on the other side of the source-side heat exchanger, called an evaporator. The refrigerant is much colder than the temperature of the heat source. Therefore, heat flows into the refrigerant. This heat causes the liquid refrigerant to evaporate. The temperature of the liquid refrigerant does not increase greatly. The gaseous, low pressure and low temperature refrigerant then passes into an electrically-driven compressor, which raises the refrigerant's pressure and as a consequence, its temperature. This is then fed into a second heat exchanger on the load side, known as a condenser. This transfers heat to the air or water on the load side. When in cooling mode, the heat exchanger on the source side becomes the condenser, while the heat exchanger on the load side becomes the evaporator. This is accomplished through a reversing valve inside the heat pump. The basic diagram for the heat pump is shown in **Figure 4-11**.

For cooling:

$$\dot{Q}_L = \dot{Q}_S - \dot{W}$$ **Equation 4.11**

For heating:

$$\dot{Q}_L = \dot{Q}_S + \dot{W}$$ **Equation 4.12**

where,

$\dot{Q}_L$ = heat flux on load side, J/s;

$\dot{Q}_S$ = heat flux on source side, J/s;

$\dot{W}$ = power consumption by compressor, W.

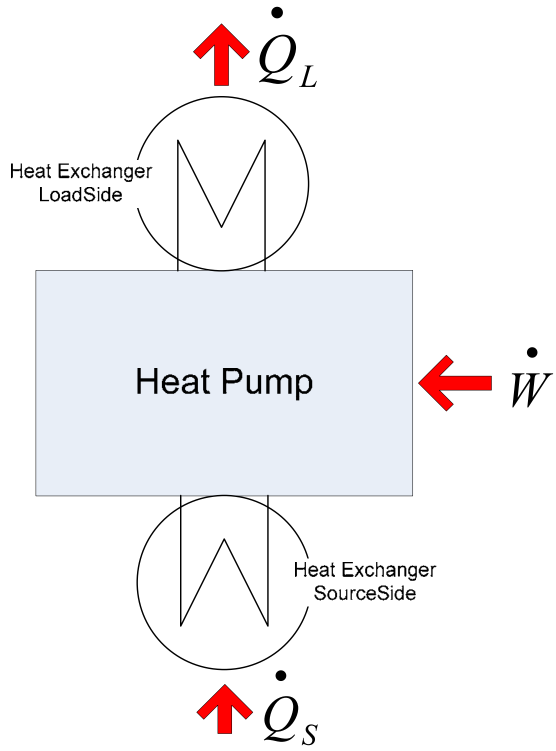

Figure 4-11: Basic Principle of the Heat Pump System

A number of heat pump models have been proposed by researchers over the years, ranging from detailed deterministic models to simplified performance-based models. Normally, the detailed deterministic models (such as the parameter estimation-based heat pump model developed by Jin (2002), are complicated models requiring numerous generally unavailable inputs and require longer simulation times. This makes them unfavourable when comparied with the strategic level simulation tools like RETScreen (2007) and MERIT, and even with detailed building simulation tools like TRNSYS (2007) and EnergyPlus etc. Performance-curve-based models for heat pumps, such as curve fitting (Shenoy 2004; Tang 2005) and the interpolation algorithm in TRNSYS, are popular and have been widely-used in recent years because of their easily accessible inputs and fairly accurate simulation results. These treat the heat pump as a black box and the system performance is predicted using the equations generated either through curve fitting or via interpolation from the manufacturer's catalogue data. In addition, it is accepted that the models based on the manufacturer's catalogue data tend to fail when operating beyond the range of provided data. In Tang's (2005) thesis, 5% of error is addressed when matching with the catalogue data using the curve-fit model. This error will double or become even greater when matching with experimental data. Half of the error comes from the mismatch between the catalogue data and experimental data.

The heat pump interpolation model, described in this section, is generic. It can be used for an air source, water source or ground source heat pump, as long as the catalogue data is available. Based on the detail of the data provided, a corresponding dimension interpolation algorithm is required. For instance, if the catalogue data only depends on one variable (such as the outside dry bulb temperature), then a one-dimensional interpolation algorithm is used for obtaining the results, such as total capacity, sensible capacity and compressor power etc. If more input variables are provided, e.g. the indoor wet bulb temperature and entering dry-bulb temperature, a two-dimensional interpolation algorithm (William et. al. 2002) must be employed for simulation results. The same rationale is applied for more complicated catalogue data. It is easy to expand into a higher dimension interpolation algorithm. For this study, based on the available catalogue data (refer to **Appendix A** for details), a two-dimensional interpolation algorithm is employed for simulating the performance of the heat pump.

The algorithm interpolates between cooling performance measures, such as total cooling capacity and compressor power etc., based on the current values of the air flow rate, outdoor dry bulb temperature, and indoor wet bulb temperature. The total power consumed by the heat pump in the cooling mode should include the power associated with the indoor fan and the outdoor fan (if it is available) as well as the power associated with the compressor. It should be noted that the algorithm does not extrapolate beyond the data range provided in the manufacturer's catalogue data. If values outside the data range are provided, the model treats the data as the minimum or maximum values and the warning messages will be written into the result file. In addition, manufacturer's catalogue data requires conversion to SI units since the units vary for the input and output parameters.

The specification of heating performance data, such as total heating capacity and total power etc., is almost the same as for cooling performance data. The total power consumed includes the power associated with the indoor fan as well as with the compressor. The algorithm for the heating mode linearly interpolates between heating performance measures based on the current values of the air flow rate, outdoor dry-bulb temperature, and indoor dry-bulb temperature.

Table 4-1: Correction Factors for the TRANE Heat Pump Model

Heat pump model: TRANE WCZ036F		Air flow rate (in m^3/s)		
		0.460	0.519 (nominal)	0.590
Correction factors @ cooling mode	for total capacity (C_{Qc})	0.99	1.00	1.01
	for compressor power (C_{Pc})	1.00	1.00	1.00
Correction factors @ heating mode	for total capacity (C_{Qh})	0.99	1.00	1.01
	for compressor power (C_{Ph})	1.01	1.00	0.99

In reality, the heat pump does not always work in a nominal condition. In fact, most of the time it operates under other partial-load conditions. Therefore, correction factors are required in the simulation of the cooling/heating performance of the heat pump to adjust the performance data for operation in other conditions. Based on the available correction factors for specific input variables in the catalogue data ( ), the correction data for performance results are achieved through a linear interpolation method. Again no extrapolation is performed for input conditions that lie outside the data range. All the correction factors are dimensionless. Taking one heat pump model (WCZ060F100) manufactured by TRANE for instance, the nominal conditions are: air flow = 0.519 (in m^3/s), outdoor DB for cooling mode = 35 (in ^oC), indoor WB for cooling mode = 19.4 (in ^oC), outdoor DB for heating mode = 8.3 (in ^oC) and indoor DB for heating mode= 21.1 (in ^oC). The correction factors based on different air flow conditions are also available for both cooling and heating purposes within the catalogue data, as shown in **Table 4.1**. For the cooling mode, two correction values are provided: a multiplier for total capacity and a multiplier for total power. For the heating mode, two correction values are provided: a multiplier for total capacity and a multiplier for total power. These multipliers are used to identify the operating performance of the heat pump at other air flow conditions (0.460~0.590 m^3/s).

The heat pump capacity and power input at other conditions are adjusted using the following equations.

For the heating mode

$$Q_{\text{actural}} = Q_{\text{norminal}} \times C_{Qh} \quad \textbf{Equation 4.15}$$

$$Power_{\text{actural}} = Power_{\text{nominal}} \times C_{Ph} \quad \textbf{Equation 4.16}$$

For the cooling mode

$$Q_{\text{actural}} = Q_{\text{norminal}} \times C_{Qc} \quad \textbf{Equation 4.17}$$

$$Power_{\text{actural}} = Power_{\text{nominal}} \times C_{Pc} \quad \textbf{Equation 4.18}$$

Through this way, heat pump performance for both heating and cooling mode under various operating conditions can be predicted with fairly reasonable accuracy for the inputs for DSM+c algorithm.

4.4 Summary

This chapter has described the Two-Match-View (TMV) platform, which is able to accommodate the electricity and thermal side of a dual-form energy system simultaneously. Simplified mathematical models for electric-based thermal demand system and low carbon supply technologies (especially CHP, HP) have also been illustrated in this chapter, in order to enable the operation of the DSM+c algorithm and quantify its impact. The next chapter is mainly concerned with the discussion of the implementation and verification of the DSM+c algorithm, demand model, supply model and two match view within the computational tool, MERIT, already mentioned in **Chapter Two Section 2.7.5**.

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CHAPTER FIVE INTEGRATING THE DSM+c ALGORITHM AND THE MULTIPLE ENABLING MODULES WITHIN 'MERIT'

This chapter describes the detailed procedures for implementing the DSM+c algorithm and relevant modules into the quantitative computational software tool called MERIT. In addition, the implementation of DSM+c algorithm within Internet-Enabled Energy System (IE-ES), which is allowed to apply DSM+c algorithm under operational level, is also illustrated.

5.1 Introduction to MERIT

The MERIT system (Born, 2001) was developed in Visual C++ as a Multiple-Document-Interface (MDI) application within which windows, relating to the different aspects of demand, supply and surrounding environmental conditions, are used to define a supply/demand matching analysis. These aspects include the specification of weather and simulation period parameters, demands and RE/Auxiliary power delivery systems. **Figure 5-1** depicts the MERIT system structure, which consists of program manager, boundary conditions, demands, RE/Auxiliary supply systems and demand-supply match assessment. The user interacts with the program through the program manager interface, specifies connectivity settings for the local or remote SQL database, and gets data from the boundary conditions component and RE/Auxiliary supply systems components.

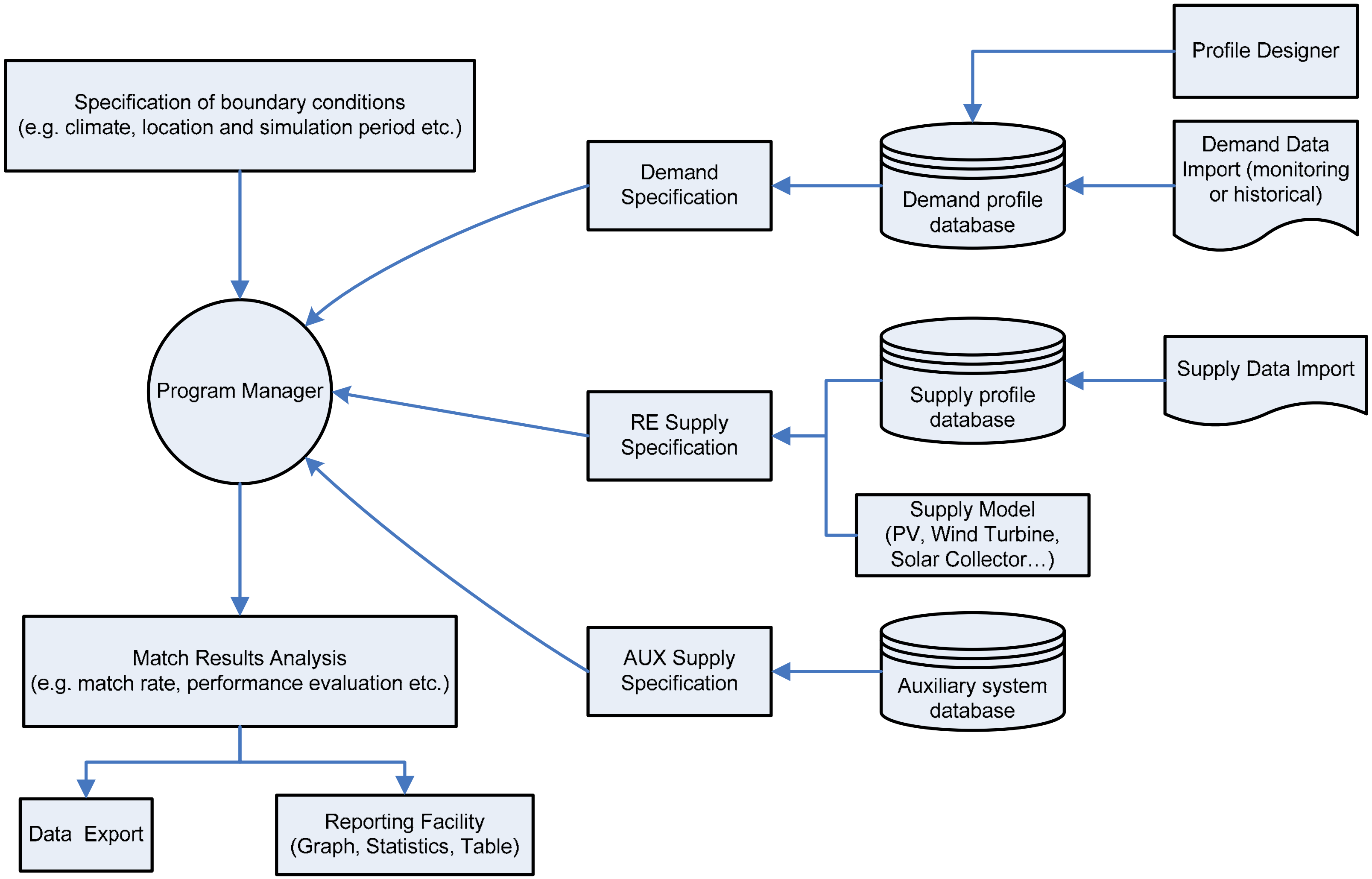

Figure 5-1: Original MERIT System Structure

The boundary conditions interface is used to specify the climate file at a certain location and during a certain simulation period. The demand profiles can be specified through loading the items available in the demand database. To establish the database, demand data is required. There are various ways to obtain such data, these being: from historical sources, calculated by a building simulation tool (e.g. ESP-r), from real-time monitoring devices, or having been designed by the use of a '*Profile Designer*' module in MERIT. The RE supply system module contains models of different possible renewable supply technologies. RE models can be selected from a model library through the database where performance data exists for a specific technology, or it can be imported. The method of defining the model of auxiliary supply system is similar to that for RE systems. However auxiliary systems are only activated when in combination with demands and RE supplies at the match stage. This is because their performance depends on how well RE supplies and demands are matched. Finally, all the inputs from the above components are used by the program manager in '*MERIT Work Space*', within which the mathematical processes are carried out to generate the outcomes (Born, 2001). All specified demands and supplies are shown in '*MERIT Match Space*'. Results are presented graphically and in tabular format in '*MERIT Report Space*'. These can also be exported to an external file using the match assessment component. The original interface of MERIT is shown in **Figure 5-2**.

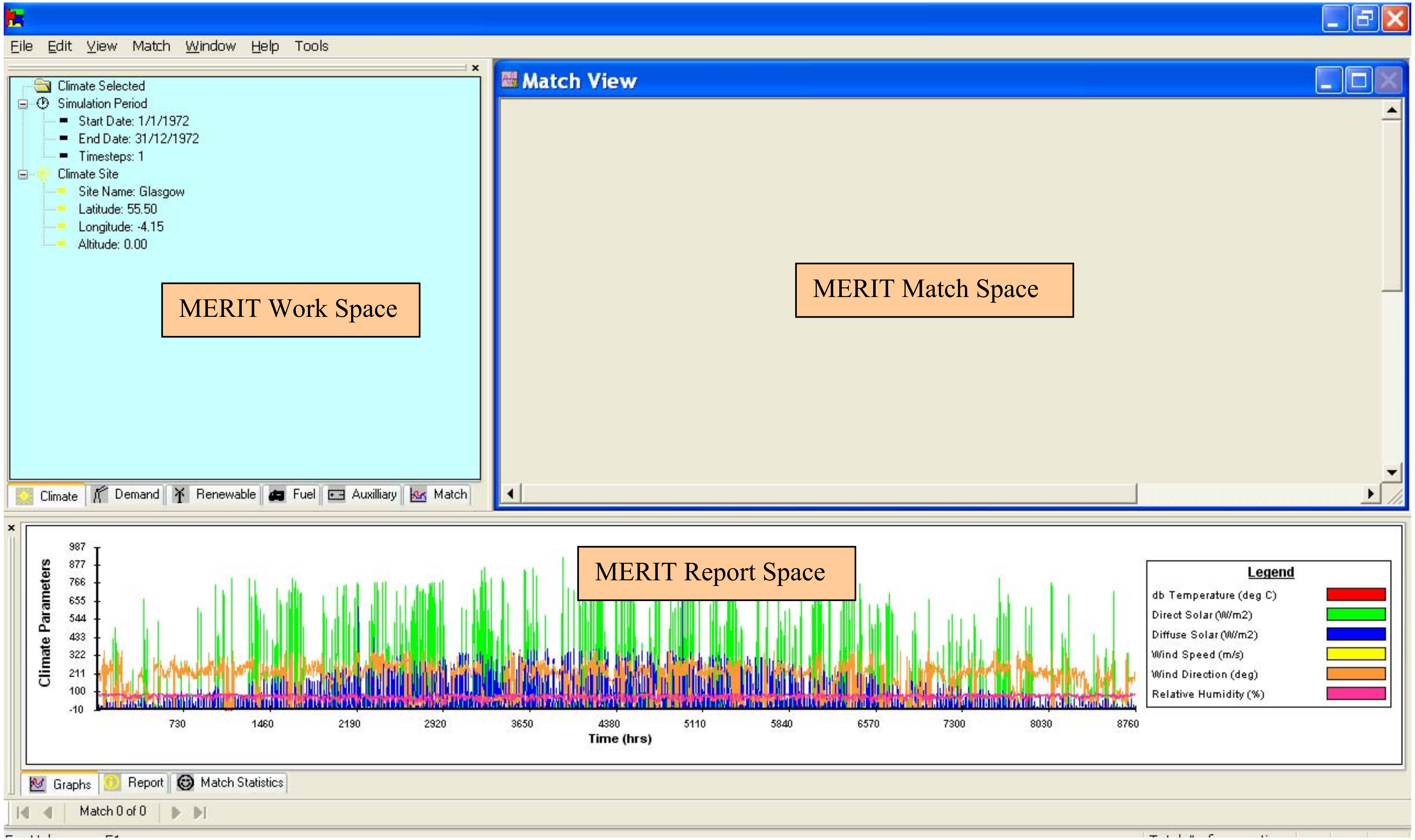

Figure 5-2: Original MERIT Interface

5.2 Implementation of New Modules within MERIT

The newly-developed components depicted with an orange colour in **Figure 5-3** have been successfully integrated into the MERIT system. These have been added in order to set up the inputs in the context of the DSM+c algorithm on both demand and supply side, carry out DSM+c analysis and illustrate the outcomes in various ways (i.e. graph, report and optimizing table). The new components consist of the DSM+c algorithm, demand models, low carbon emission energy system models (mainly CHP and heat pump), a multi-index assessment table for optimising the match results, and a dual match view (DMV) for dealing with systems that are involved in two energy forms.

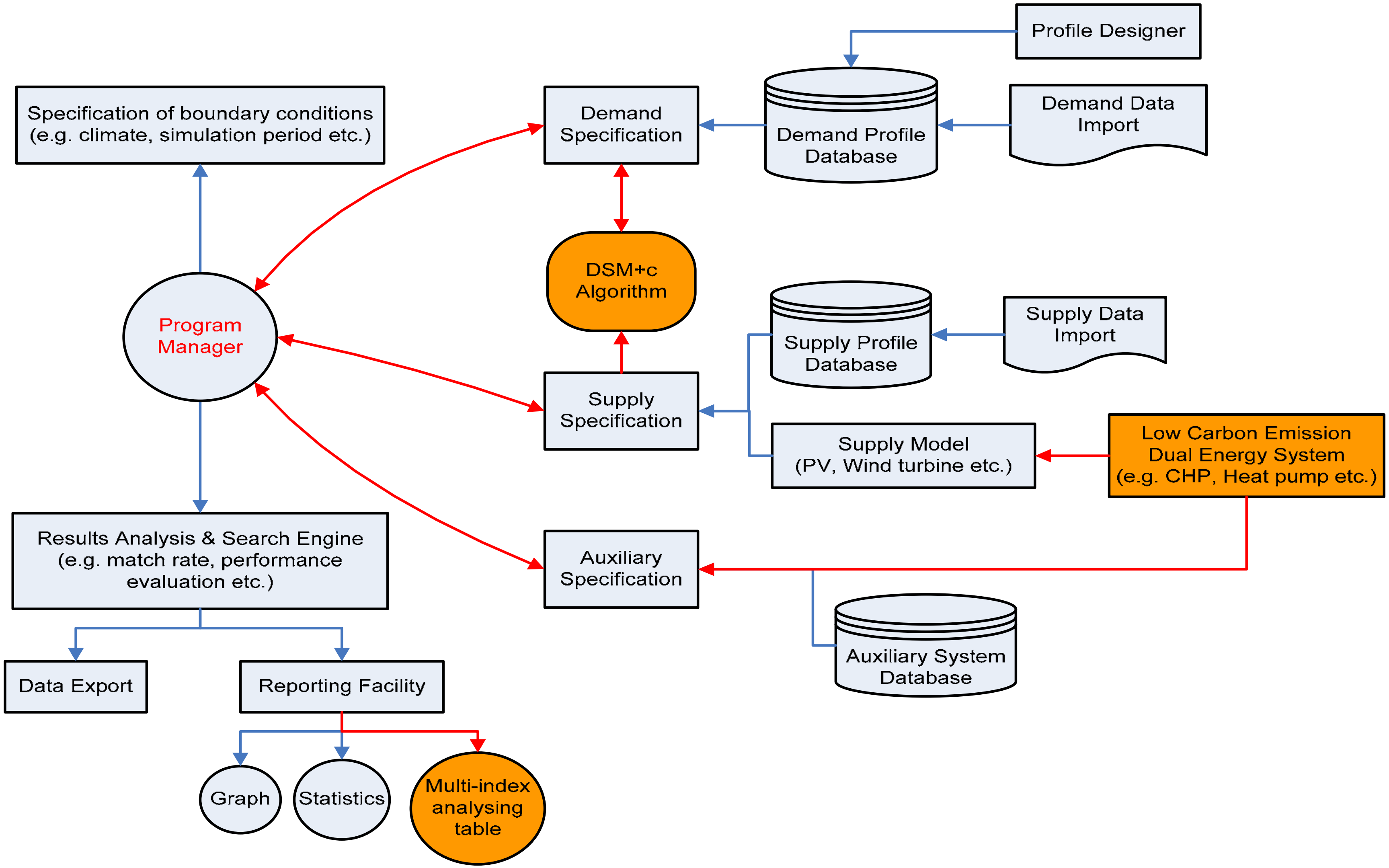

Figure 5-3: New MERIT System Structure

The key component is the DSM+c module, which functions as a bridge to connect the demand side with the supply side in order to optimise the match between demand and supply from renewables (RE) and low carbon (LC) sources without significantly compromising the user's satisfaction level on the demand side.

Other components shown in the figure provide support to the DSM+c module. The demand model (that may be either simplified or complex) is used to simulate the demand profile in order to quantify the control impact after having applied the DSM+c algorithm. This study focuses on the development of electricity-based thermal demand models, such as a refrigerator, hot water storage, and air conditioning system etc. LC energy systems are usually involved in two energy forms (thermal and electricity). For instance, some systems such as CHP can generate heat and power simultaneously. Others such as heat pumps supply thermal energy while simultaneously consuming electrical energy. In addition, depending on the operation mode of the chosen systems, some are set as primary supply while others are set as back-up supply devices. Therefore, this low carbon emission dual energy system module is associated not only with RE supply systems but also with auxiliary supply systems. The DMV interface is developed mainly for this purpose. The final developed component is the multi-index analysis table within the match assessment section. This allows users to examine the best combination between demand and supply in terms of certain index, such as match rate, fuel consumption, partial load operating performance, and CO2 emissions etc. The following sub–sections describe the implementation of each module in detail.

5.2.1 The DSM+c Algorithm Implementation

Two levels of the DSM+c algorithm were implemented within MERIT. These depend on the availability of internal environmental data such as temperature, humility, lighting level and acoustic level etc. A high level DSM+c algorithm was developed for demands lacking internal environmental information, while a more extensive low level DSM+c algorithm was designed for demands containing relevant internal environmental data (obtained either through simulation or via monitoring sensors).

To initiate the DSM+c analysis, DSM+c options for each selected demand should first be specified, as described in Chapter 3. A generic interface suitable for both high and low level DSM+c algorithms was developed. Within this interface, the DSM+c options are regarded as the properties of the demand, no matter what type of demand (either monitored, simulated or historical) it is. The property dialogue is the key interface for the DSM+c algorithm, and serves as a tie between users and the MERIT application. As discussed before, DSM+c options include: Energy Efficiency; Load Shifting and Demand Side Control (Hong et. al.2007). This study mainly focuses on the implementation of load shifting and demand side control options. **Figure 5-4** shows the parameter specification dialogue for the load shift option, where load flexibility, shifting increment and shifting boundary can be defined. **Figure 5-5** presents the interface of the parameter specification for the demand side control option, through which the DSM+c parameters such as priority, duration and methods can be specified.

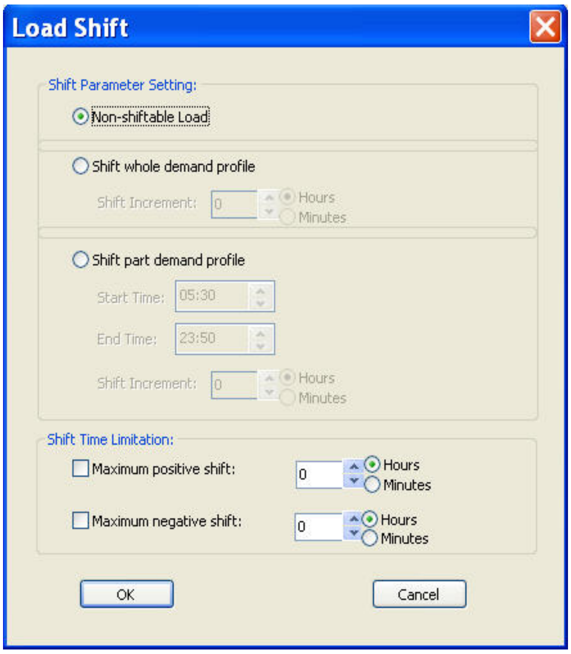

Figure 5-4: Parameter Specification Dialogue for the Load Shift

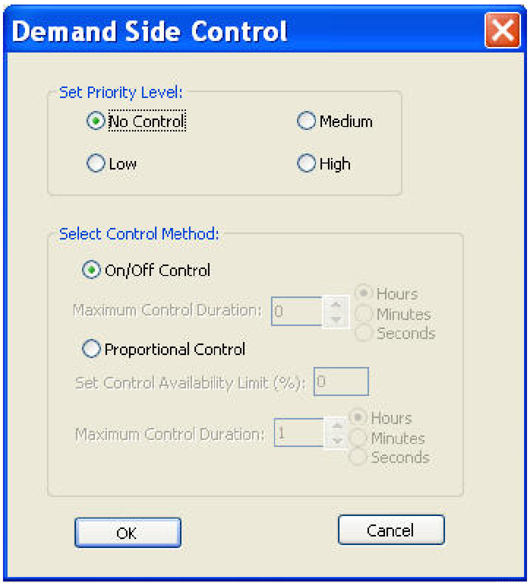

Figure 5-5: Parameter Specification Dialogue for the Demand Side Control

The symbol '***[c]***' and different background colour schemes are introduced for each demand button in '*MERIT Match Space*' to differentiate demands with or without DSM+c options and their priorities. A '***[c]***' symbol appearing at the end of the demand button name indicates that the demand is being specified with DSM+c option. The background colour for the DSM+c-option-specified demand button changes depending on the control priority specified, as shown in **Figure 5-6**. A red button means low priority for control, yellow means medium control level and green means high priority for control. A grey button indicates that no DSM+c property is specified regarding the demand or that there is no control availability at all.

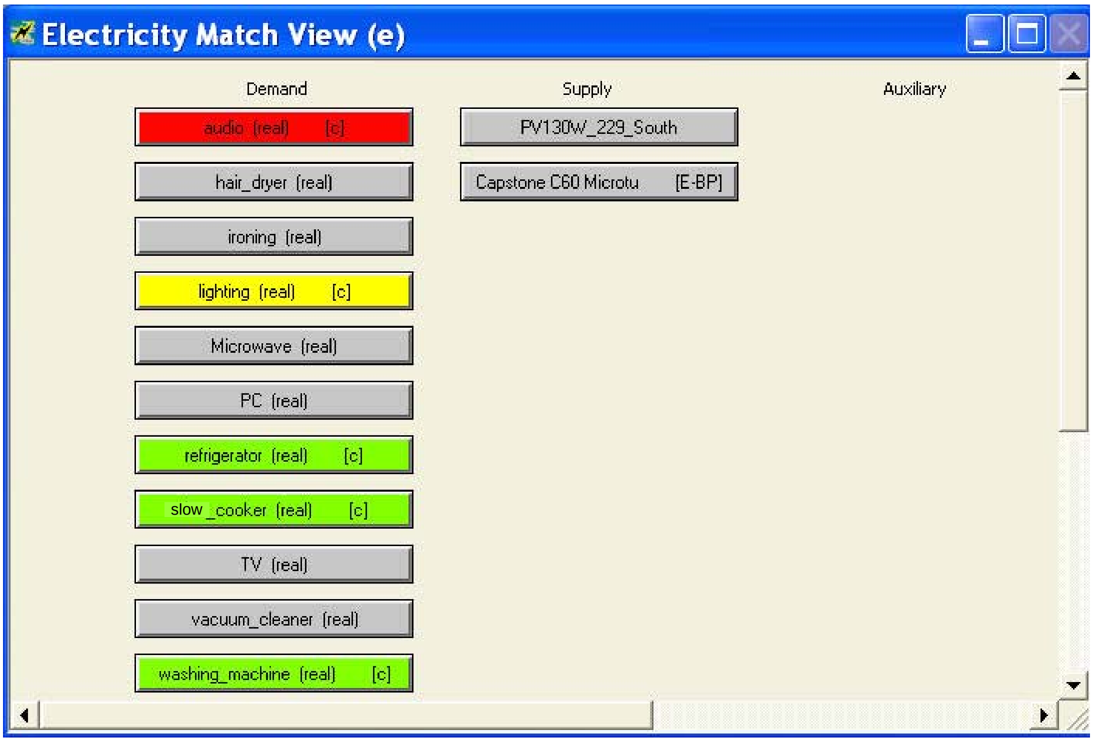

Figure 5-6: Diagram for Specified DSM+c Parameters in EMV

The DSM+c algorithm runs according to items selected in each column, i.e. different demands (with DSM+c) and supplies. Match results are presented graphically and in tabular format in the '*MERIT Report Space*'.

5.2.2 Implementation of Demand and Supply Models

Demand and supply models, as addressed in Chapter Four, allow users to quantify the control impact on the demand requirements and assess the operating performance of supply systems. The heating and cooling demand systems are selected for implementation within this thesis, because these are ideal for DSM+c applications due to their inherent thermal inertia. It is also important to implement supply systems such as CHP and heat pump, which are gaining popularity due to their lower carbon emissions when compared with conventional energy supply systems.

- ***Heating and Cooling System Models***

The heating and cooling system models developed here are physically-based simplified models this theory is discussed in detail in Chapter Four. The heating system model implemented in MERIT is an electric-based hot water storage system, which can be used for both hot water and space heating purposes. These are regarded as auxiliary devices in the MERIT context which deliver thermal energy but require electricity input. With the help of the DSM+c algorithm, the electricity demand can be modulated based on the availability of the RE supply and performance of the LC supply in an effort to try and meet users' need as much as possible. For the same reason the refrigeration model which is a typical cooling system is developed and implemented in MERIT. After specifying DSM+c parameters, optimised and energetically favourable demand profiles for RE and LC energy systems are generated. These make sure that the environmental conditions are maintained within the specified safety range. The main interfaces for these two systems are shown in **Figures 5-7** and **5-8**. The parameter inputs windows appear in detail in **Appendix B**.

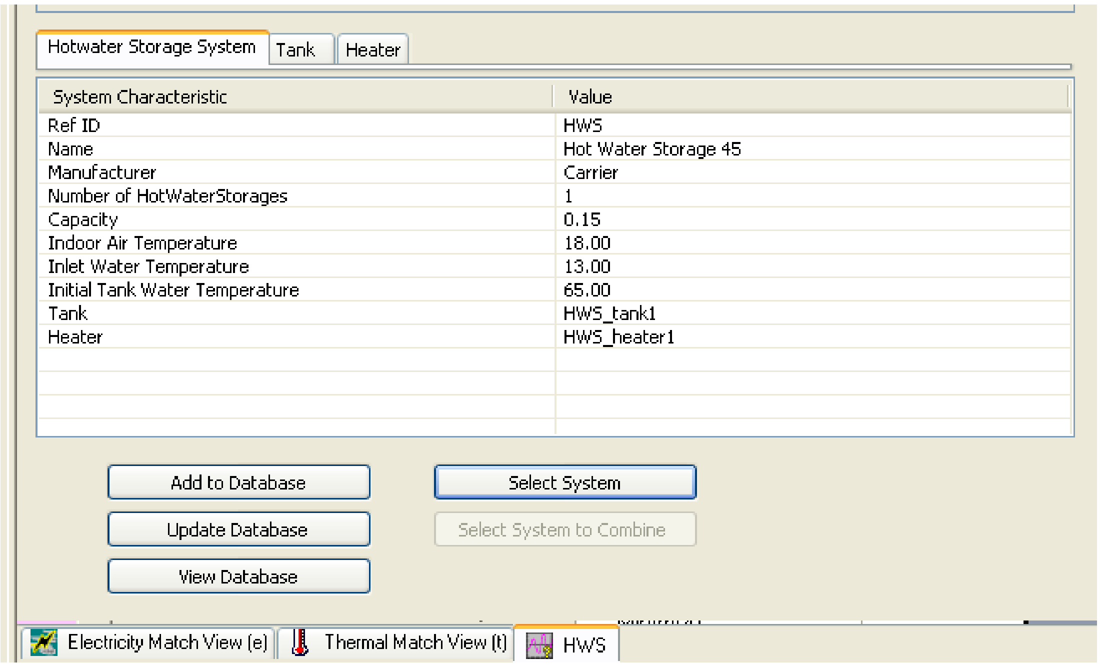

Figure 5-7: Interface for the Parameter Specification for HWS

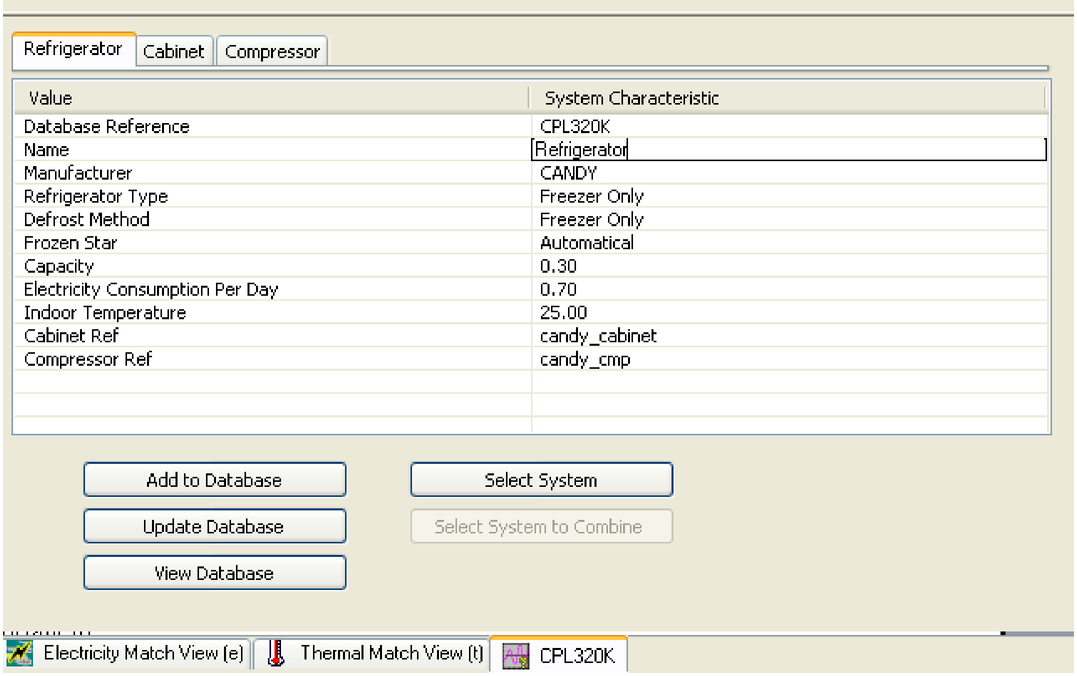

Figure 5-8: Interface for the Parameter Specification for the Refrigerator

- ***Heat Pump and CHP System Models***

The implementation of the heat pump and CHP system model is similar to the technique used by Born (2001) with RE/Auxiliary models (PV, wind turbine, flat plate collector and battery). The interface for each module is arranged in tab style, indicating various components within the system. One "master" tab contains general system information and reference information to other "slave" tabs. Through these references the master tab can connect with the rest of tabs. Thus a system with specific parameters can be set up. These models are simulated according to climatic conditions and manufacturers' specifications. Performance curves obtained from manufactures are used to identify the output or required energy at design conditions. At the same time, factors affecting performance at standard conditions are also considered when calculating the performance at other conditions other than design. The interface of the heat pump and CHP systems is shown in **Figures 5-9** and **5-10**. For more details see **Appendix B**.

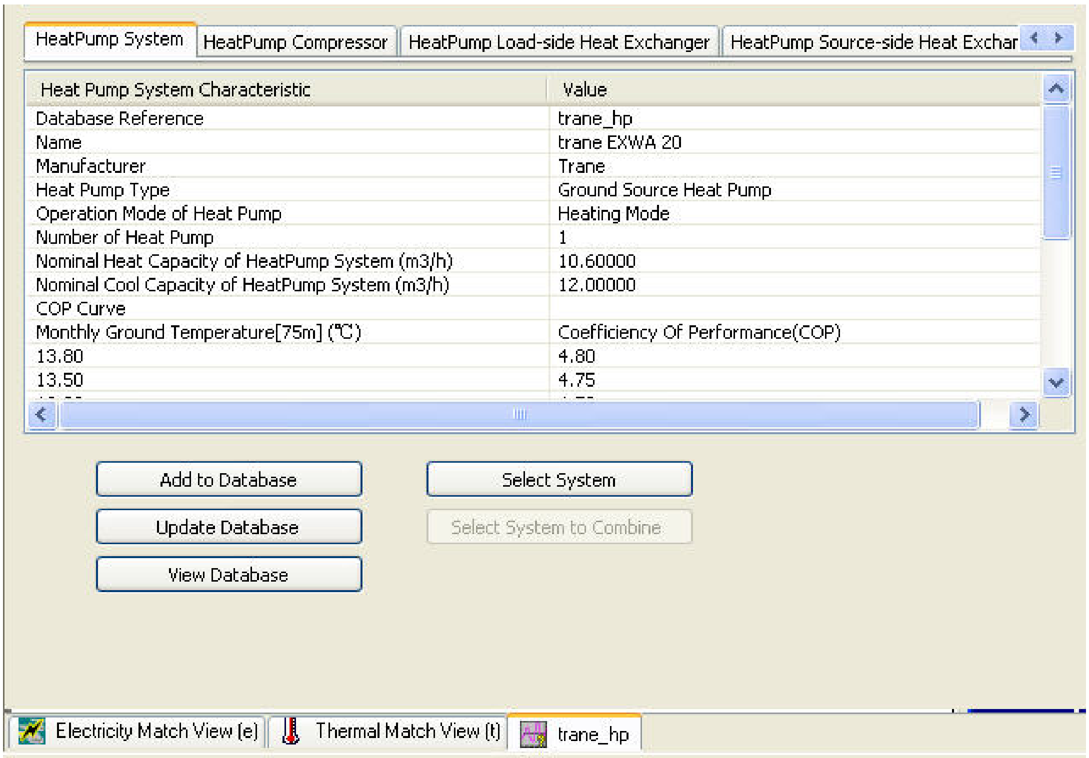

Figure 5-9: Interface for the Heat Pump System

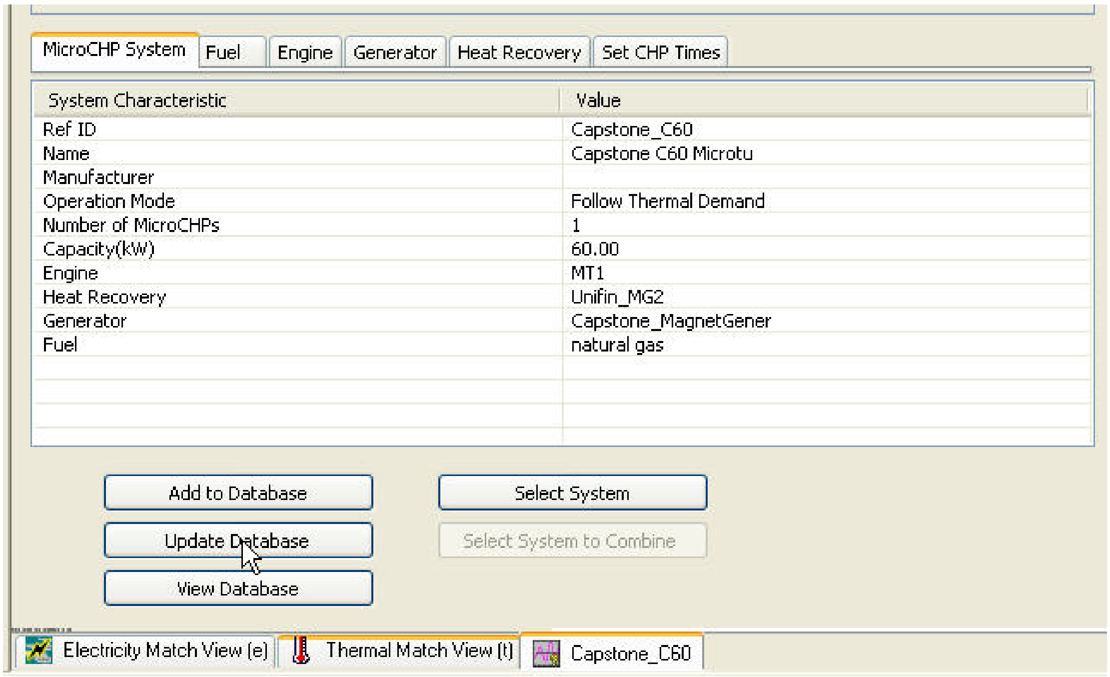

Figure 5-10: Interface for the Micro CHP System

5.2.3 Dual Match View (DMV)

In order to accommodate low carbon emission energy systems and to handle different energy forms simultaneously, the Dual Match View (DMV) has been designed and developed. Simply stated the DMV interface concept is to use two windows to represent thermal and electricity energy form respectively. The windows are mutually influenced by each other, with the events in one type of match view affecting the result in the other type of match view. It is suitable for some energy systems involving both electricity and thermal forms, e.g. CHP, heat pump, and electricity-based thermal systems etc. CHP for example can supply thermal energy and electricity at the same time as described in Chapter Four. Based on the choice of operation mode different layouts in two match views for CHP are set up. If the "***follow electricity load***" mode is selected the CHP is regarded as an electricity auxiliary supply system and thermal energy generated can be treated as an RE thermal by-product. However if the "***follow thermal load***" mode is chosen CHP is treated as a thermal auxiliary supply system and the electricity produced is an RE electricity by-product. Although one CHP is presented in two different windows, these are virtually connected with each other, so the changes made in one window result in a modification in the other window accordingly. Hence the algorithm is capable of handling this two-form energy system properly. The new interface for DMV is shown in **Figure 5-11**.

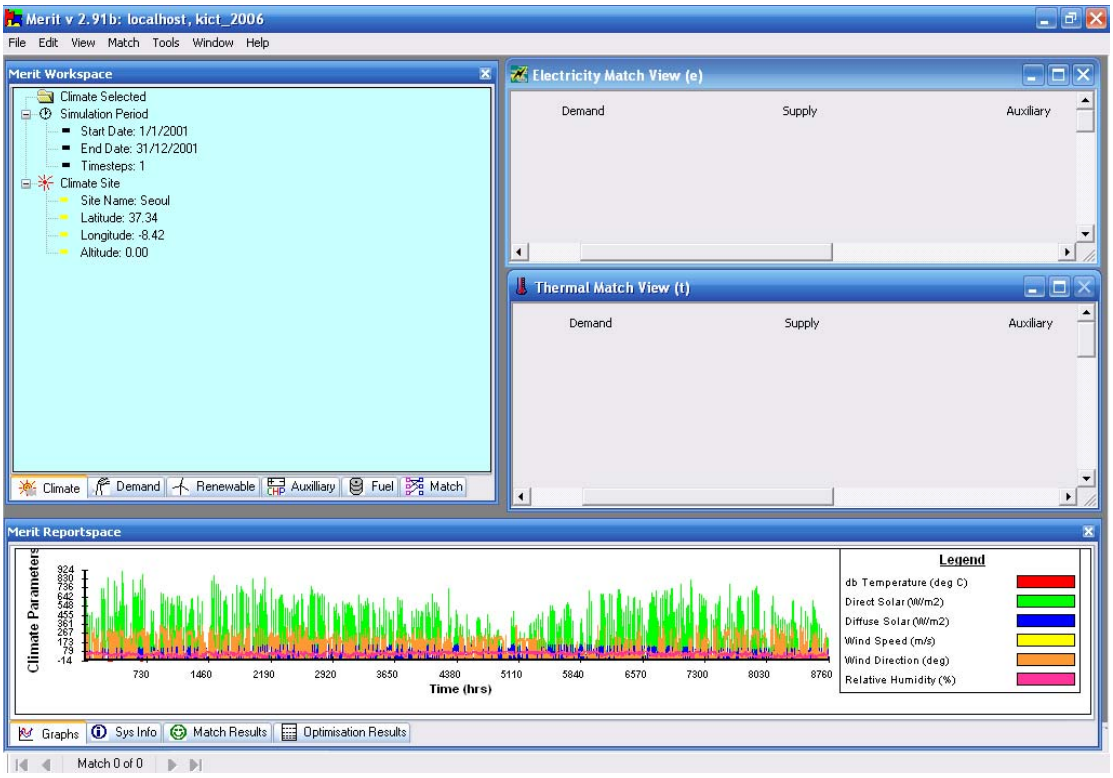

Figure 5-11: New Merit Interface with the Dual Match View

Compared to the original interface shown in **Figure 5-3**, the match view is divided into two parts which are the Electricity Match View (**EMV**), and the Thermal Match View (**TMV**) respectively. The EMV and TMV mainly show the specified items of demand and supply profiles. The example of the CHP and HP systems clearly illustrates the DMV concept as shown in **Figure 5-12**. When a CHP system is selected, a button is created respectively in the supply column under each energy form, representing the electrical and thermal energy produced by the CHP system. When a HP system is specified, one button in supply column under thermal energy form and the other button in demand column under electrical energy from are generated, indicating the thermal energy generated and the electrical energy required by the heat pump system.

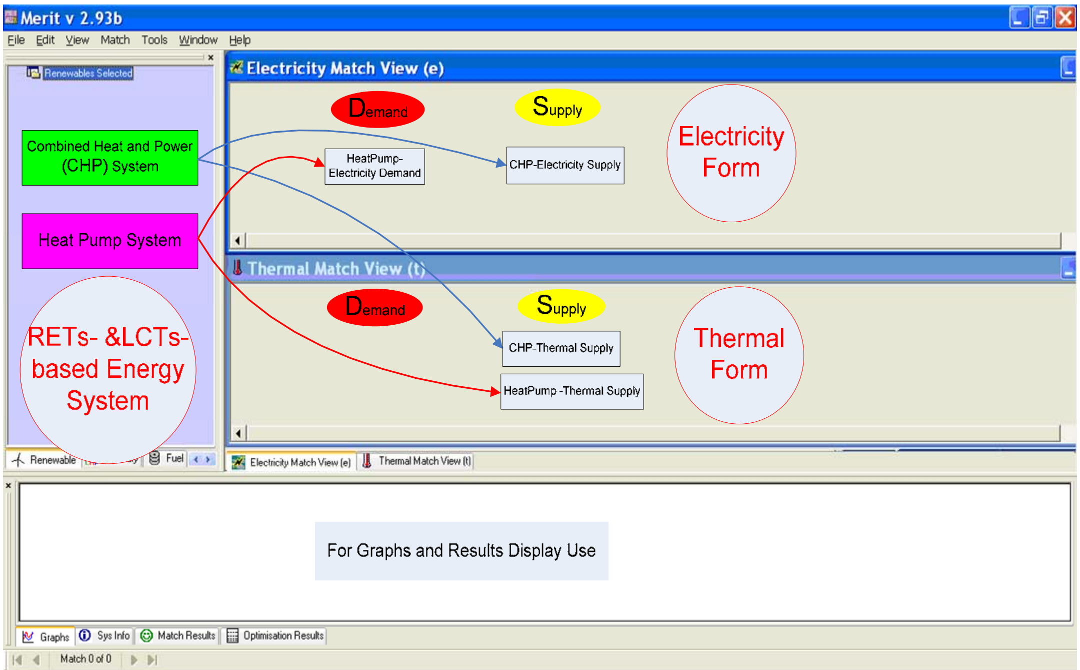

Figure 5-12: Example of the CHP and HP Systems in the New Merit Interface

5.2.4 Multi-index Assessment Table and Auto Search

A new tab '***Optimisation Results***' is developed to store the records of demand/supply combinations selected by users. A table with multiple index headings is embedded within this tab to save and present match results. The table is not static but re-sorts records by individual index. In this way users can identify the best combination between demand and supply in terms of a specific index. The indices include existing ones such as Total Demand, Total RE/Aux Supply, Match Rate (MR), Energy Delivered (EDL), Energy Surplus (ES), and Energy Deficit (EDE). Some new indices are also integrated within the table in order to assess both operational (including full and partial load) and environmental performance of low carbon emission energy supply systems. These additional indexes are Fuel Consumption, Fuel Cost, Average Efficiency, Electric Efficiency (if required), CO_2 Emission, and Number of Partial Load (25%~50%, 50%~75% and 75%~100% respectively). The interface for the optimisation table is shown in **Figure 5-13**.

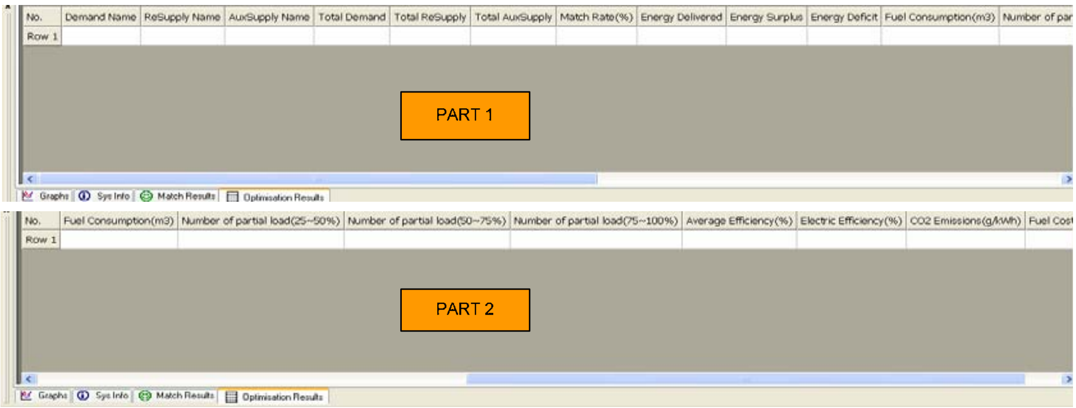

Figure 5-13: Interface for the Multi-Criteria Assessment Table

New items with and without DSM are added within the auto search facility thereby allowing users to search for best combinations among demands (with and without DSM+c) and supplies automatically. This is shown in **Figure 5-14**.

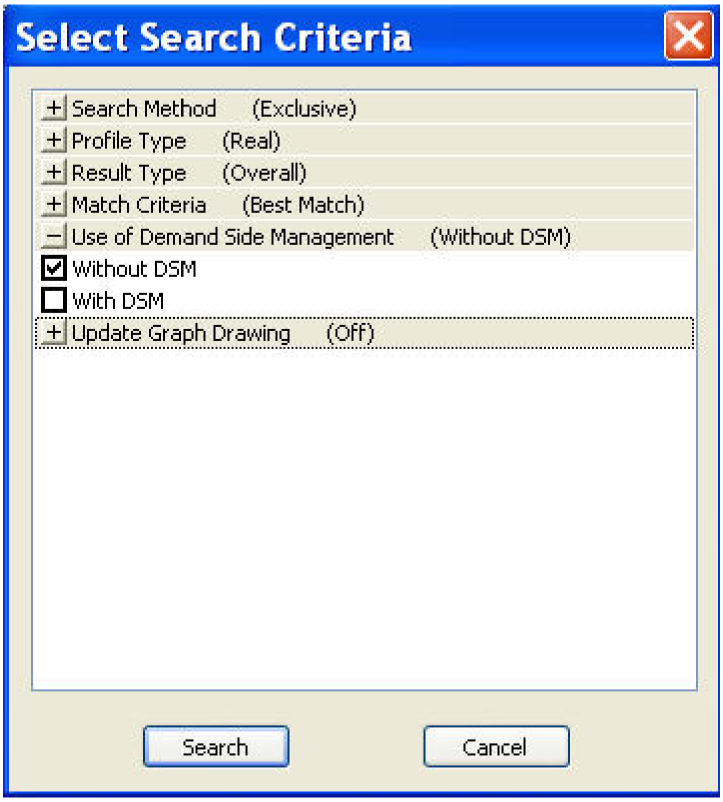

Figure 5-14: Auto Search Dialogue with and without the DSM+c Option

5.3 Implementation of Merit within Internet-enabled Energy System (IE-ES)

Previously implementation of the DSM+c algorithm within the software platform MERIT has been discussed. In order to allow the DSM+c algorithm to operate in real time, it is necessary to integrate MERIT into a real system which is capable of gathering information through real sensors and controlling real devices.

The majority of recent developments in building energy management systems (BEMS) and building automation systems (BAS) have followed the advances made in computer technology, telecommunications and information technology. Significant developments have been made in the standardisation of communication protocols (Chapman 1997) and in web-enabled controllers (McGowan 2000). These early-generation systems were developed using proprietary communication protocols and data structures (Wilkinson 2001). Latest advances in low-cost, high-performance PCs and the continuing widespread growth in high-speed, and high-capacity communication lines and networks, make next generation BAS and BEMS possible. Jiang (2005) points out that ideal BAS or BEMS should be inter-operable, open and expandable.

Due to advances in the Internet, the ability to acquire information and to control devices over the Internet is becoming desirable to the general public as well as professionals. It is feasible to use the Internet as a medium to build a web-enabled generic system to merge all aspects i.e. software, hardware and different communication protocols without time constraints. The infrastructure of the Internet is growing rapidly and globally thereby gradually enabling it to become an alternative of mass communication (Wang and Xie 2002). Using the Internet authorised users anywhere in the world can acquire requested data, monitor the whole intelligent building systems, and even control some devices within buildings. Through wired or wireless connection we are able to monitor home conditions and control appliances "3A" (Anytime, Any place within the same building, and at Any distributed location) to provide services such as indoor climate control, social care for vulnerable people, demand side management for saving energy etc. (Obaidat and Marchese 2006). In addition wireless connection can widen the application of device monitoring and controls because this releases people from complex wired work and allows for them to operate with a simple and convenient wireless monitoring and control network.

This makes it possible to implement the concept of an "***Internet-Enabled Energy System***" (**IE-ES**) which provides end users with the facility to access real-time data and to control the devices via a web browser or other customised client applications.

5.3.1 Internet-Enabled Energy System (IE-ES)

The IE-ES proposed in this thesis can accommodate the requirements mentioned above. It can be classified into three main parts. The first part is the monitoring/control sub-system on the building side. This consists of equipment, sensors, actuators and the gateway. The equipment can be HVAC devices, lighting, and other appliances. The sensors mainly monitor indoor climate conditions (such as temperature, humility, PIR, illumination, and CO_2/CO level etc.) and other activities (such as contact sensors, panic buttons, and fire detectors etc.). The actuators are the controllers which generate a control signal (on/off or proportional) to control equipment based on messages received from the gateway. The gateway is the core part of the building monitoring/control sub-system that connects devices, sensors and actuators together. It also plays a portal role in communicating with other systems over the internet by sending or receiving messages to/from other applications. Therefore it allows other applications to access the sub-system remotely either monitoring indoor climate conditions or controlling devices.

The second part is the remote server sub-system, called EnTrak (Kim 2004), which plays a key role as a data store, message response, and command centre. It comprises a database server (DB), dynamic control server (DC), and web server (WB). The DB, indicated as data storage, has its own format which is specially designed for an energy management system. Data from all sensors (wherever they are either in different places within a building or within different buildings at multiple sites) can be collected and saved in the DB via the Internet. The DB includes energy use data, energy generated by supply technology (either RE or LC) and environmental data from various sensors. The DB server is SQL-compliant so data inside the server can be retrieved by using SQL query commands (Molinaro 2005). The main function of the DC server is to process information as quickly as possible, because it is used to control devices. Unlike the DB which stores historical data from the building monitoring/control sub-system, the DC server deals with data on a real-time basis. The mechanism of the DC server is based on socket communication (Hunt 2002). A "socket" is a reliable and standard Internet Application Programming Interface (API) provided by the Operating System. Based on the "socket" connection among different software applications is achieved. This is called "socket communication". After the connection between the client and server is established by the socket information transfer in both directions is quick and straightforward. The WB server is the source of information. It waits for a request from the client (such as the web browser) for a file. After having received the request, it delivers specific web pages requested by the web browsers or other required files to applications via HTTP protocol over the Internet. All these servers communicate with each other and share information under the framework of EnTrak.

The third part of the system is client applications. These are terminals located on the other side designed for operators, energy managers, decision-makers or normal users etc. These software applications are located either locally or remotely. Users with appropriate authorisation have access to information inside the servers. Also the control messages generated by a special client are sent to the server and then passed to the building monitoring/control sub-system's gateway. This is an example of two-way communication. The web browser for example can be seen as a popular and widely-used client application. It can be used to present real-time energy information to decision-makers who are now able to gain clear and accurate information regarding the operation status and energy consumption of their building sites without phiscally leaving their offices. The energy conservation strategy can be invoked through analysis of the obtained information.

The overall structure of the whole system is illustrated as follows in **Figure 5-15**.

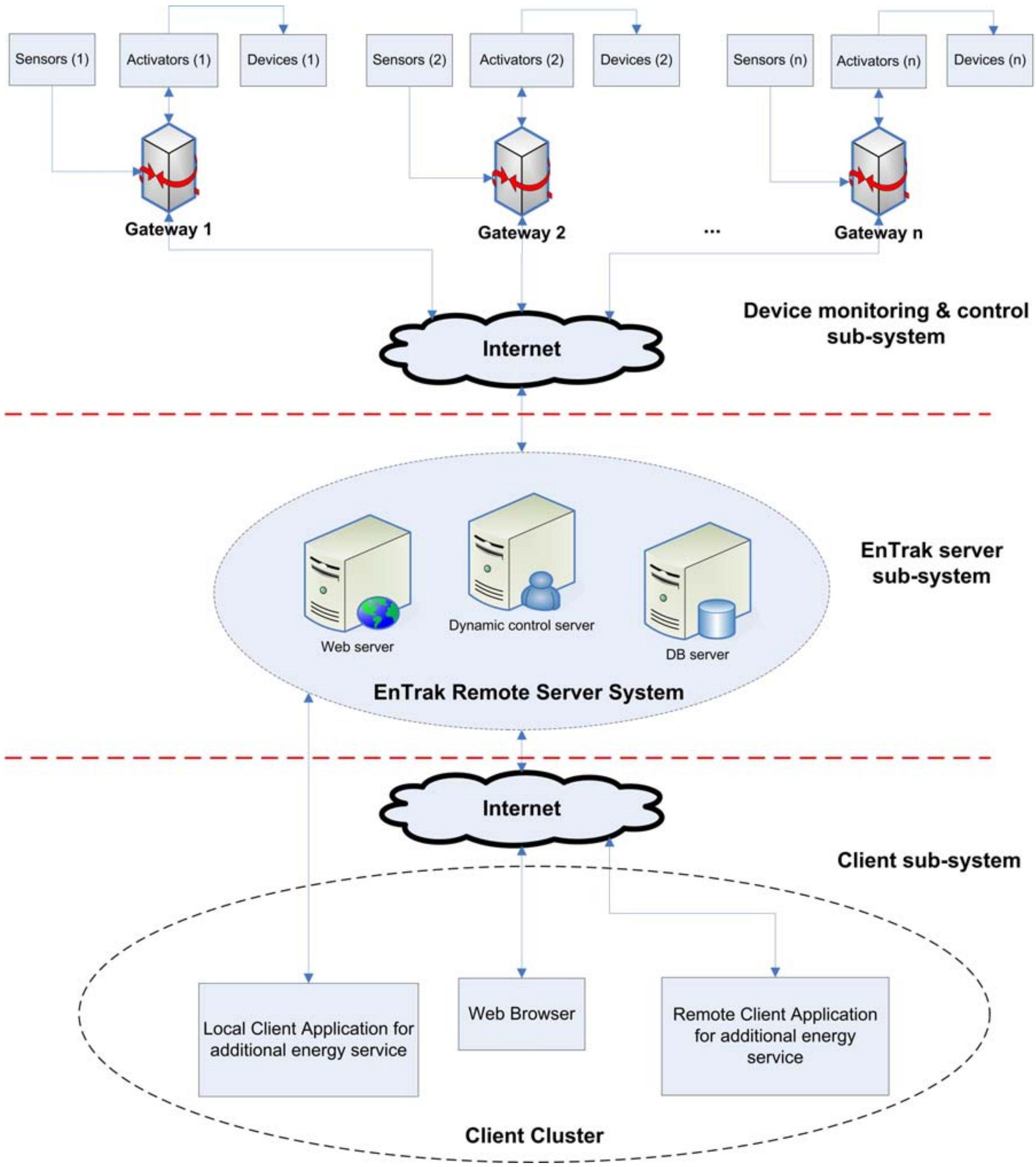

Figure 5-15: Basic structure of the IE-ES

The whole system is open, flexible, inter-operable and expandable with a clear structure. New functionality can easily be integrated into the system. Various protocols can be managed within the building monitoring/control sub-system, such as BACnet (Bushby 1997), LonWorks (Ziemerink and Bodenstein 1998) or TCP/IP (Leem et al. 2004). Sensors, actuators and the gateway can all be connected through wires or via wireless technology. A new server can be added into a remote server system if requested. Furthermore new client applications for providing new energy services to different end-users can be integrated into the system.

5.3.2 Integrating MERIT (DSM+c incorporated) into IE-ES

MERIT serves as a service-oriented client application within IE-ES. Two interfacing modules are required to embed MERIT within IE-ES and enable MERIT to perform a DSM+c study. One is the interfacing module for data access and the other is the module for real-time control. Depending on the location of the server system, these can be implemented either locally or remotely. The IE-ES after integration of MERIT is shown in **Figure 5-16**.

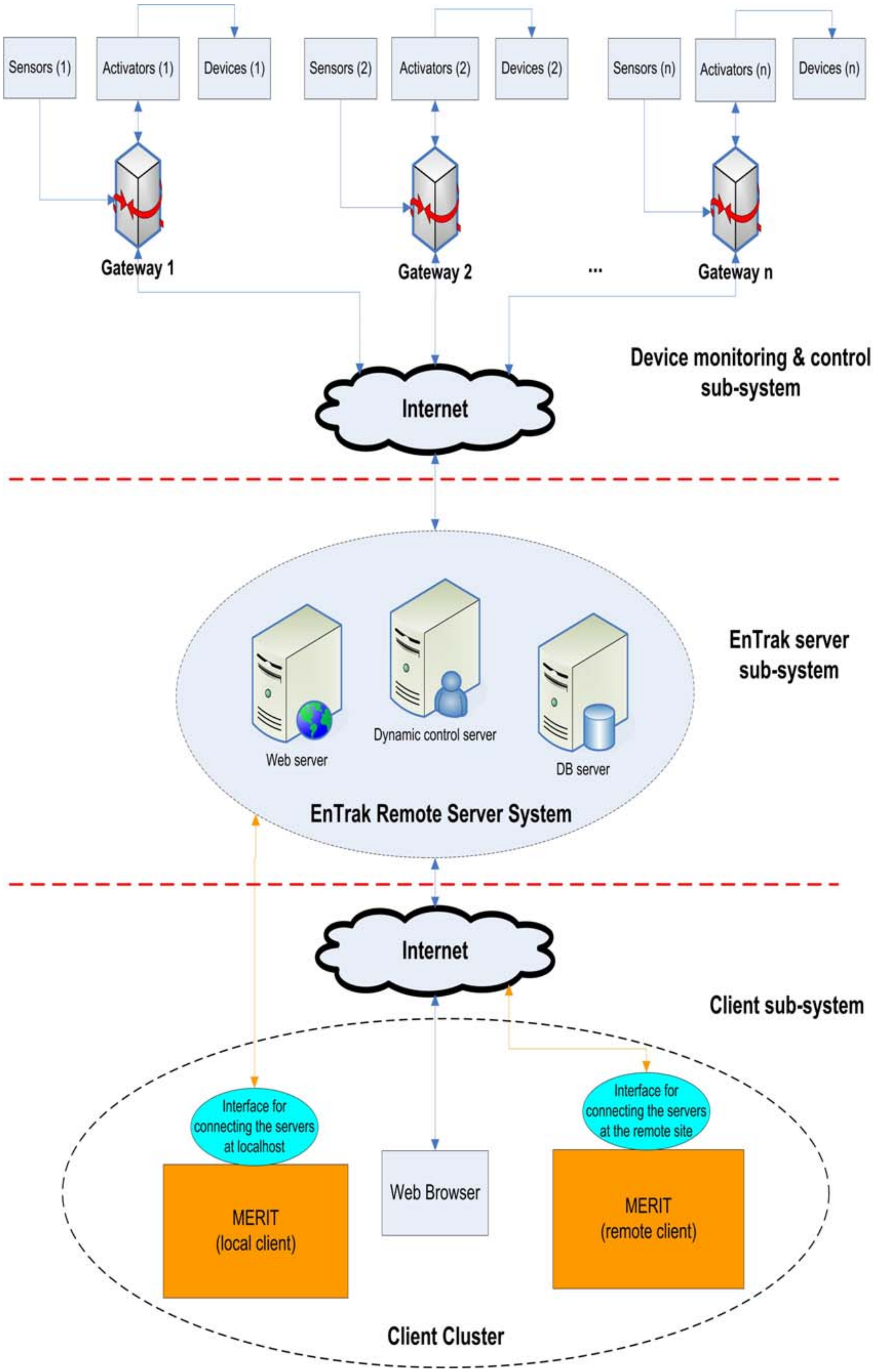

Figure 5-16: IE-ES Structure after MERIT Integration

5.3.2.1 Interfacing Component for Data Access

The interfacing component for data access provides functionality to obtain the specified internal environmental information (such as temperature, humidity, lighting level etc.) which can be used as inputs for the DSM+c algorithm. Through this interfacing component the DSM+c algorithm is able to communicate with the database server where internal environmental data is stored locally or remotely. It also checks the internal environmental data at real-time basis compares with set-points and issues appropriate control actions upon demand devices to maintain a certain level of environmental satisfaction.

The ODBC (Open Database Connectivity) method (Geiger 1995) which is one of the most popular Application Programming Interfaces (API) for communicating with various types of database is adopted to connect MERIT with the SQL-compliant DB server (EnTrak). There are several reasons for choosing ODBC, one being that it provides a consistent interface regardless of the kind of database server used. Secondly more than one connection can be realised by using ODBC and it reduces the workload of software development and improves both efficiency and software reliability. In most cases the ODBC configuration interface, ODBC functions for database operation and ODBC driver are required to establish connection with the data source. The ODBC client (MERIT) uses a language or vocabulary of commands to request data from or send data to the database server (EnTrak). The messages pass through the ODBC driver for that specific database server. The ODBC driver translates the messages into a format that the database server can understand. The database server then sends the results back to the ODBC driver which translates the results into a format that the ODBC client (MERIT) can understand. This structure is shown in **Figure 5-17** which illustrates how the three modules communicate with each other.

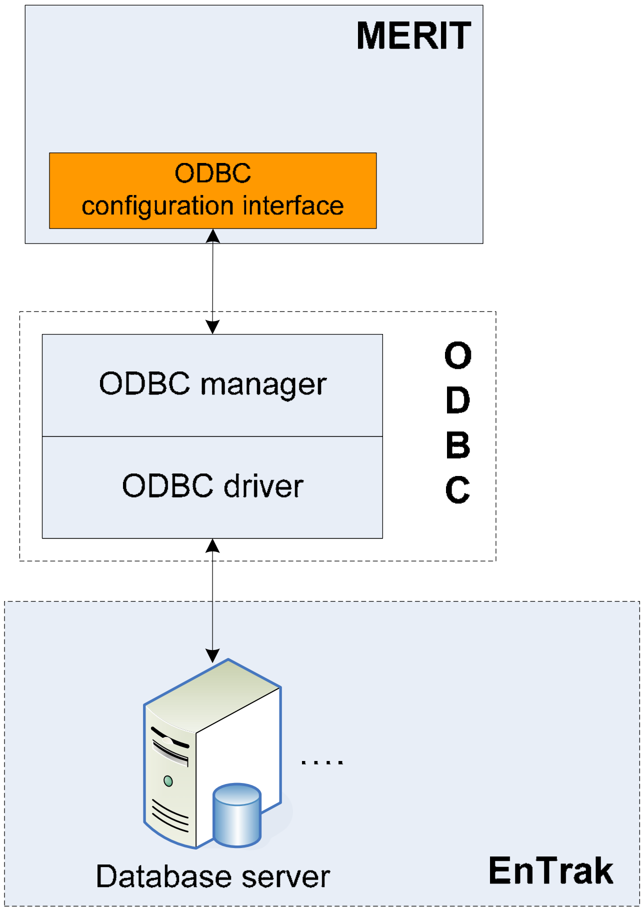

Figure 5-17: Structure for MERIT Communication with EnTrak through ODBC

Specific ODBC drivers are needed depending on the type of database server. In this case, the EnTrak database server is MySQL based. Therefore, the ODBC driver for MySQL (Sun 2008) i.e. MyODBC (the latest version is 3.51.23), needs to be installed.

To establish the connection between the MERIT application and EnTrak data source the ODBC module needs to be configured correctly. A configuration interface is developed within MERIT as shown in **Figure 5-18**. This allows users to input necessary information such as DSN (Database Source Name), ODBC driver name, IP address of the database server, database name, user name, password and port number.

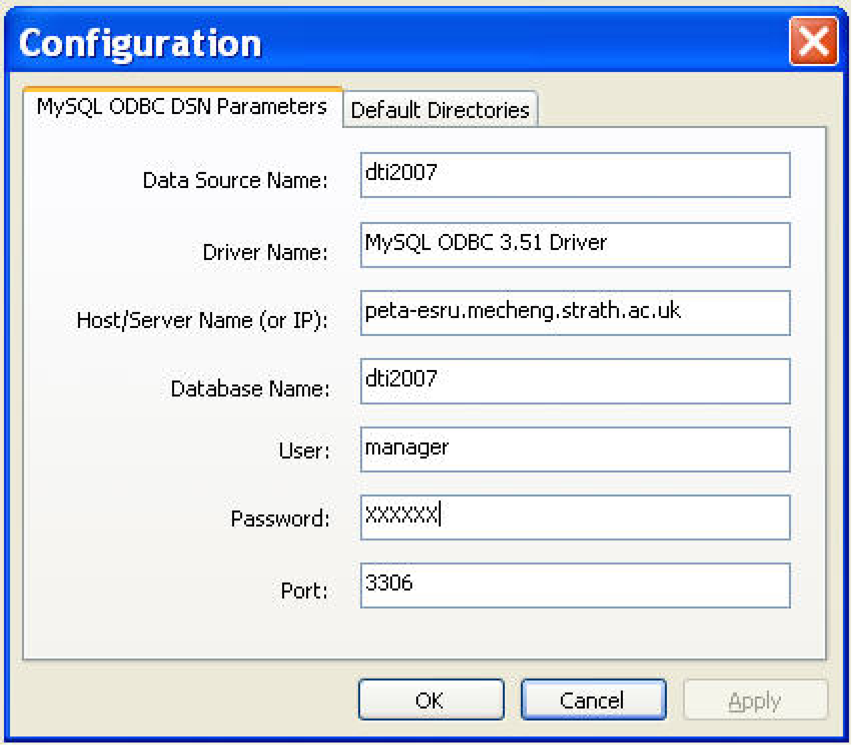

Figure 5-18: Parameter Specification Window for ODBC Connection

If the specified information in each field is correct the database name will be shown on the title bar of the MERIT main interface as shown in **Figure 5-19**. This indicates that the connection between MERIT and the database source EnTrak has been built successfully.

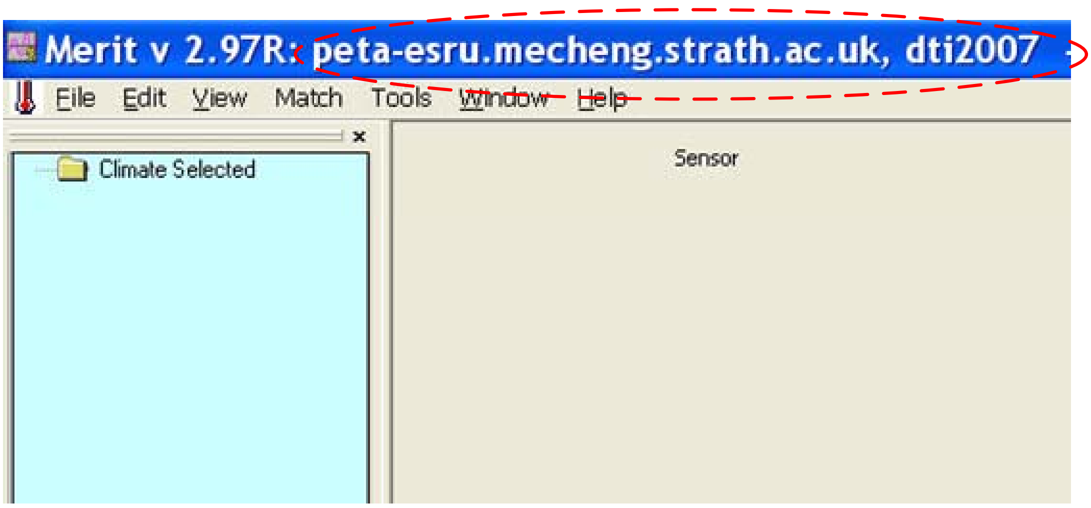

Figure 5-19: Relevant Information for Successful Connection

Otherwise relevant error information will appear. For example, if an incorrect database name is specified the error message box as in **Figure 5-20** pops up to advise the user to check the database name in the setting window.

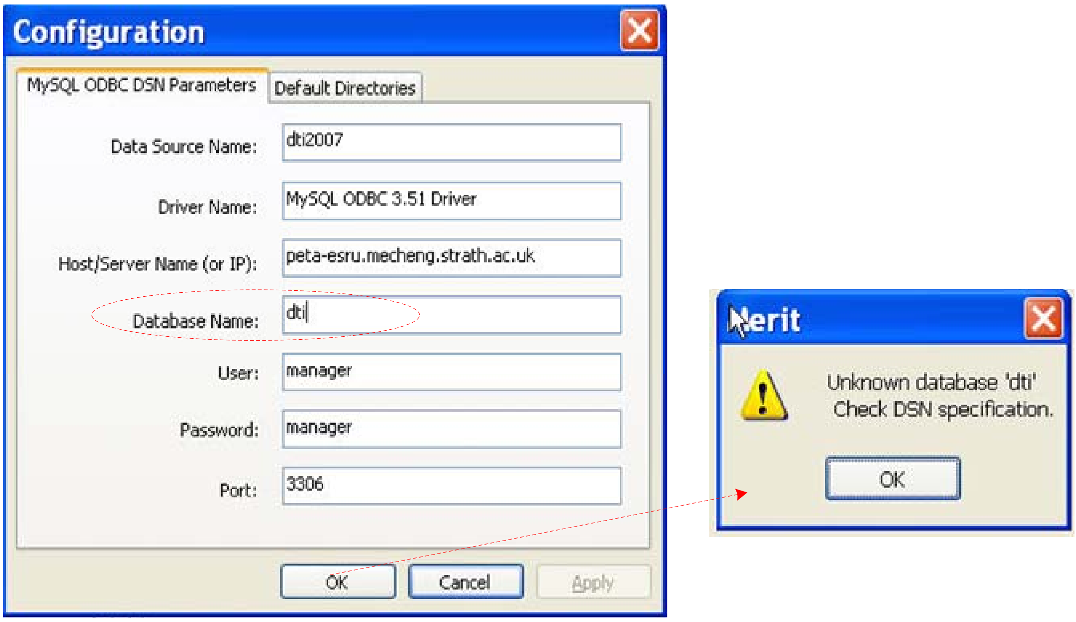

Figure 5-20: Message Regarding Incorrect Parameter Specification for ODBC Connection

MERIT was developed using C++ language through Microsoft Visual Studio IDE, therefore it is fairly easy to make the application ODBC enabled. A number of API classes and functions for ODBC are available in Microsoft Foundation Class (MFC) and are ready to use. Hence more effort can be placed on the design of the logic that allows for required information to be obtained. An algorithm is implemented to allow MERIT to obtain required information from the database server. This is shown in **Figure 5-21** as a flow chart.

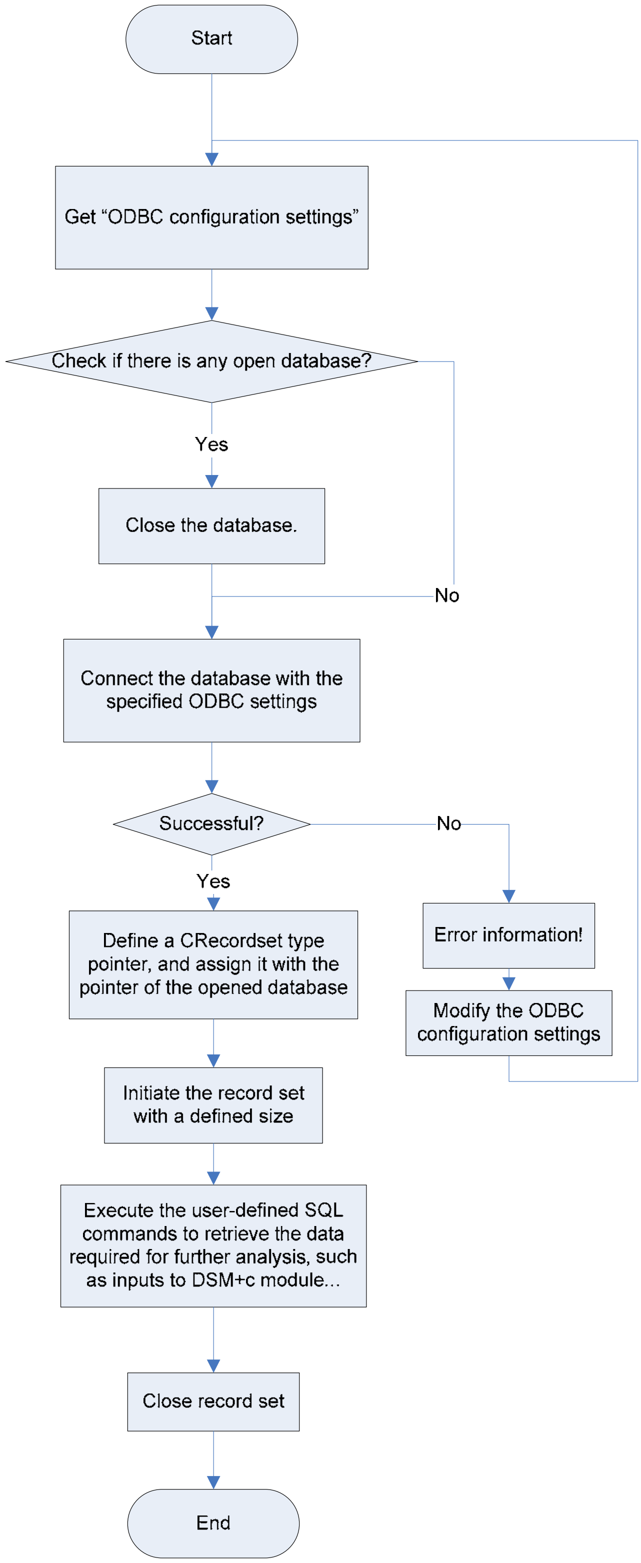

Figure 5-21 : Flowchart of Obtaining Data from the EnTrak Server

To prove that the implementation is successful an example is created to show data requests from the MERIT client by selecting a specific menu within MERIT and seeing whether the EnTrak server responds to the request correctly. Taking "load sensor" for example the objective is to show information of all sensors within the EnTrak DB server. After the item "load sensor" is selected it is connected with the database source and executes the specific SQL command to retrieve information about the sensor list from the DB server. Then all available sensors will show in MERIT. If one sensor is selected a button with the name of the sensor will be generated in the Electricity Match View. After the button is selected, another SQL command will be performed in order to retrieve data of that particular sensor based on the specified period. The results are shown in the graph section within '*MERIT Report Space*'. The detailed procedure is shown in **Figure 5-22**. As can be seen, all results are as expected. This confirms that the interfacing module for data access is able to request the specific information from the server and has been implemented within MERIT successfully. A similar procedure can be applied to access demand and supply information for DSM+c analysis.

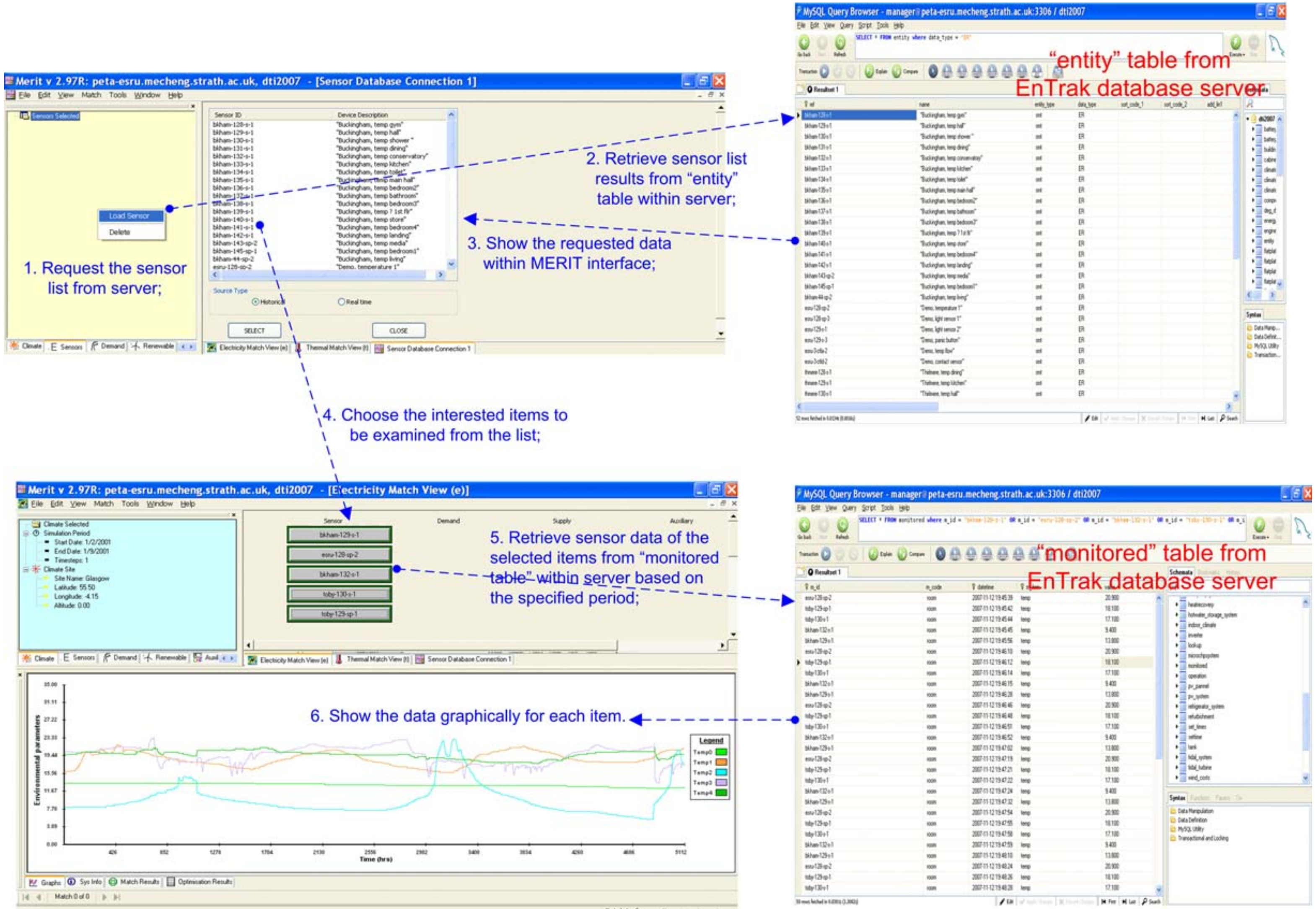

Figure 5-22: Diagram of Data Communication between MERIT and the EnTrak DB Server

5.3.2.2 Interfacing Component for Real-time Control

This real time control module allows MERIT to send control messages on a real time basis to the remote server, which converts them to device-recognisable control signals. This allows for the achievement of an optimised switching strategy among selected devices. The module is implemented in two stages. Like the interfacing module with the DB server connection between applications is established first after which pre-defined control messages can be sent/received.

To establish connection between any two applications installed in any two computers over the Internet a protocol suite needs to be used. There are several popular suites (Halsall 2005) which are available for this job e.g. NetBIOS Extended User Interface (NetBEUI) by IBM/Microsoft, Internetwork Packet eXchange/Sequences Packet eXchange (IPX/SPX) by NOVELL, AppleTalk by APPLE and the Transmission Control Protocol/Internet Protocol (TCP/IP) originally developed by the US Department of Defense (DOD). TCP/IP is also known as Internet protocol and is the most popular protocol suite over the Internet (Forouzan and Fegan 2002). A large percentage of networks nowadays are built upon TCP/IP since this has the desirable features of openness, flexibility and tolerance for multi-platform operating systems support from UNIX, LINUX to WINDOWS etc. The core parts of TCP/IP suites are normally unfamiliar to users. Socket as referred to earlier in **Section 5.3.1** provides an interface for the application to establish internet connection based on TCP/IP network system. It inherits advantages from its modulated programming which allow it to effectively handle the encapsulation and insulation of basic functional elements relevant to network communication. Thus, it accelerates the efficient development and effective use of various web applications. Currently sockets are widely adopted for network communication by many web applications such as IE, Netscape, Navigator and Outlook Express etc. (Quinton 1997). There are several widely-used socket APIs available, such as the BSD Socket, Transport Layer Interface (TLI) and Windows Socket Interface (Winsocks) (Comer and Stevens 1997).

For TCP/IP based network programming the client-server programming model adopted within this study is one of the most popular models (Kim 2004). The term ‘client-server’ describes the relationship between two computer applications. The client is a requesting program and the server is a program that awaits and fulfils requests from the client. They can be located within the same computer (local host) or at any two different sites over the Internet (remote host). In the socket context the client-server structure contains a socket server and socket client. Once two applications are ‘plugged in’ they are connected and ready to communicate. Messages are packed and sent as reliable TCP segments from source to destination. Two key parameters are needed for establishing the communication with the server: the IP address of the server and the port number. Similar to the telephone system the client calls the server using the specified IP address and the server’s port number. Once the server starts its status is that of listening for calls from clients. If an incoming call from the client is detected and accepted, the server will create a separate thread to handle the client. A thread here refers to a single sequential flow of control within a program. After the connection is authorised and accepted by the server the communication between the client (MERIT) and server (EnTrak) is considered to be successful. Messages can be sent/received to/from one another. After the communication is over the generated sockets need to be deleted on both server and client sides. The structure is shown in **Figure 5-23**.

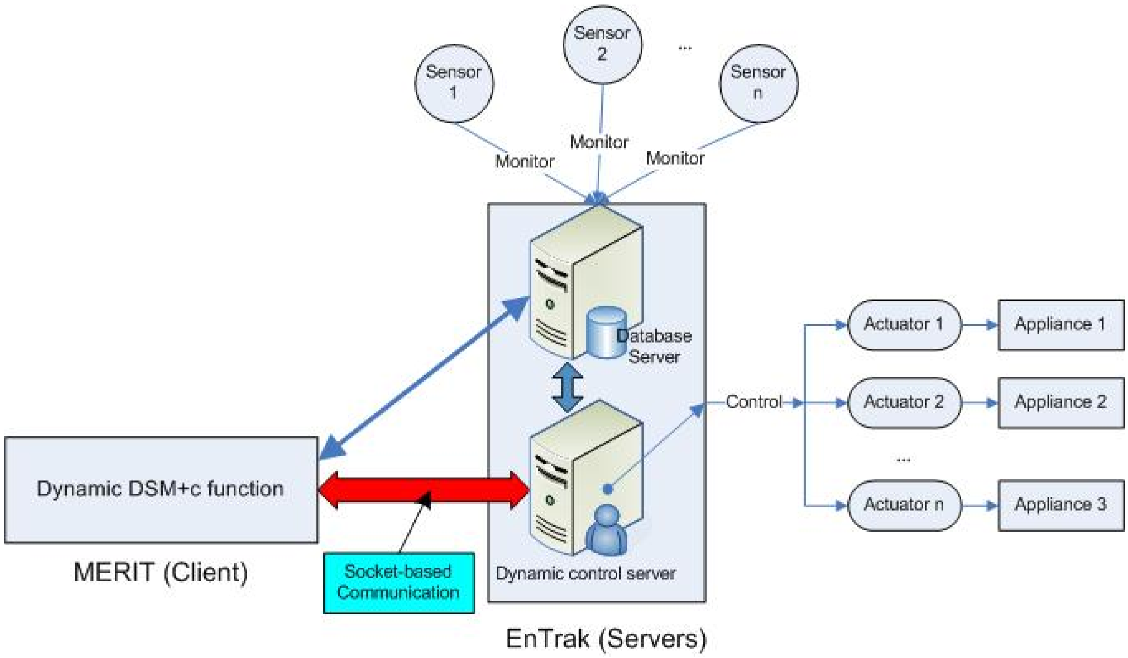

Figure 5-23: Structure for Socket Communication among MERIT, EnTrak, and Devices

The socket-based connection allows users to send their predefined messages to achieve the expected control upon devices on a real time basis and is different from the ODBC connection with the DB server which uses SQL commands to retrieve the requested data. After a connection is established and the server and client are able to communicate with each other the next important step is to design the format of the 'languages' they use. To make it possible for them to understand each other the conventions of the control messages should be designed in advance. Once the server can understand the meaning of the commands from the client it is able to send the right control signal to the correct device. The control message called the EnTrak-format message should contain information regarding the device ID and control action. The device ID is used to identify the device which is available for control. The control action could be on/off or proportional control for devices with a certain ID. If it is proportional control the percentage of control is also specified in the message. For example the message "Light 313 ON" means that the device "Light" with the unique ID 313 is controlled and the control method applied is "turning on". As an example for partial control, the message "Light 311 P 80" indicates that the device category is "Light" and the ID of the Light is

“311” and “P 80” means to turn on 80% of full device capacity. If the message is “Light 311 P 100” it means switch on the device fully.

To prove that implementation is successful another example is created. This mainly focuses on sending control messages from MERIT to the EnTrak server and further controlling devices on the building side on a real time basis. The detailed procedure is shown in **Figure 5-24**. It is used to confirm the interactions among MERIT, the EnTrak server and real devices as described. In the MERIT interface, buttons represent demand and supply devices. After specifying DSM+c parameters for each demand, demand buttons change colour from grey to green indicating high control availability. The system is then ready to perform DSM+c analysis. After combining demand with supply it is seen from the graph that MERIT generates the control messages based on the DSM+c algorithm subject to the conditions of demand and supply at each time step. The control message at a certain time step is packed and sent to the real time control server through the socket. The server then decodes the information received and distributes it to the gateway through the internet protocols (e.g. HTTP). Finally the gateway shown in the figure applies control actions to a certain device. All this happens almost on a real time basis and has been tested in the demonstration panel.

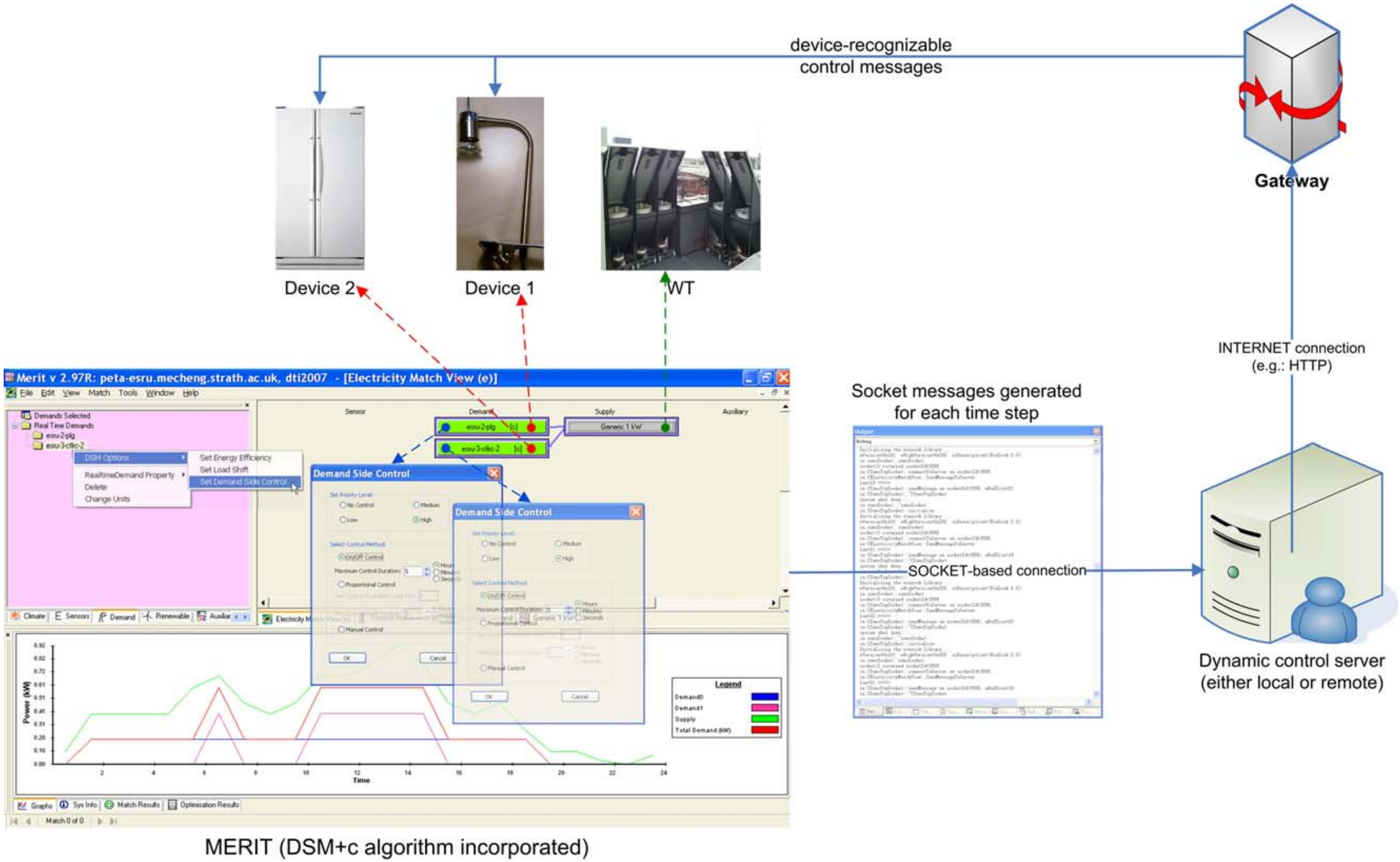

Figure 5-24: Diagram of the Control Message Flowpath between MERIT, EnTrak, and Equipment

5.4 Summary

This Chapter has illustrated how the DSM+c algorithm and relevant support modules integrate into MERIT. They endow MERIT with new functions, carrying out the DSM+c analysis for demands together with a renewable and low carbon emission energy system or a hybrid energy system. The detailed implementation of MERIT (incorporating the DSM+c algorithm) within Internet-enabled Energy System (IE-ES) has also been discussed/shown. This allows exploring viability of applying the DSM+c algorithm at operational level.

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CHAPTER SIX   VERIFICATION OF DSM+c ALGORITHMS AND SUPPORTING MODULES

This chapter describes the verification procedures for the DSM+c algorithms and support modules. Load shifting algorithm and demand side control algorithm are verified through a number of cases. All the cases designed have verified the outcomes from the DSM+c algorithm. For the support modules, analytical verification of electricity-based heating/cooling system models and heat pump model is carried out. It was proved that the results from the support models are in good agreements with the analytical solutions.

6.1 Introduction

The purpose of this chapter was to verify the developed DSM+c algorithm and to prove that the relevant demand/supply mathematical models generated correct results that are sufficient for the study undertaken in this thesis. Different verification methods are used to test the DSM+c algorithm and the support modules respectively. For the DSM+c algorithm, several cases are designed to test the outcomes from the DSM+c algorithm against their expected results (Bloomfield 1999). For the support modules, analytical method (Judkoff and Neymark 2006) is adopted to compare the outputs from the model to the results from the known analytical solutions. The following two sections describe the verification procedures in detail for the DSM+c algorithm and support modules.

6.2 Verification of the DSM+c Algorithm

As Bloomfield (1999) states, the main validation techniques that have been used for energy and environmental software programs are code checking, analytical verification, inter-program comparison, and empirical validation.

Due to the lack of comparable models and empirical data set, it is impractical to carry out the inter-program comparison and empirical validation for the developed DSM+c algorithm. In addition, the DSM+c algorithm deals with the discrete and stochastic demand and supply data. The outcome of the DSM+c algorithm is the manipulated demand, which is also discrete. There is no analytical solution to the

DSM+c algorithm. Therefore, it is not suitable to use analytical verification to carry out the validation for this algorithm.

The method adopted for this study is code checking by cases (Bloomfield 1999). Several cases are designed to compare the results from the operation of the code against the expected outcomes from these specified cases. It is important to make sure the designed cases are general. On one hand, the parameters required for the DSM+c algorithm at the strategic level, as described in Chapter 3, are time-series demand and supply data. Within these cases, the supply data in time series is generic which can potentially represent any type of energy supply technology, either RE or LC or grid network. The demand selected for DSM study is typical and time-dependent, not only representing the energy pattern of a load, but also contains as many as possible situations for testing the DSM+c algorithm. On the other hand, for the DSM+c algorithm at the operational level, the demand data and its relevant internal environmental data are obtained from demand models. The key point here is to verify the process of analyzing information among supply, demand and its relevant internal environmental parameters, based on which actions are taken under the logics described in Chapter 3. Similar to other cases, the time series data is used for the supply data. The demand model selected for this scenario is typical electrical-based refrigeration system, as described in Chapter 4. Its verification procedure is shown in Section 6.3.2 within this Chapter. This can also be replaced easily with other type of demand models when needed. Therefore, it can be said that the cases used within this Chapter are representative.

The following sections focus on the detailed verification procedures for the different parts of DSM+c algorithm (i.e. load shifting and demand side control). These are carried out using the designed cases under the decision-making platform, MERIT, where the DSM+c algorithm has been incorporated. The designed cases can be categorized into three types. The first type cases focus on proving the control methods (i.e. load shifting at strategic level and demand side control measure at both strategic and operational level respectively) for individual demand, in order to make sure they perform properly under a general demand and supply profile. The second type cases centre on testing the control order within the DSM+c algorithm for the multiple selected demands with different control priorities. And cases of the third type are created to verify the data exchange mechanism and control logics within the DSM+c algorithm at the operational level when interacts with supply and demand mathematical models at the run-time level.

6.2.1 Single Demand with Load Shift Only

This is a simple but general case to verify the load shifting algorithm. By selecting only one demand it is easy to see how the algorithm behaves and to check that the algorithm works as expected. As discussed in Chapter 3, depending on the load properties, the load shifting algorithm is classified into two parts: whole load shift and part load shift. The following sub-sections demonstrate the verification process of the load shifting algorithm in detail. A simulation period of one day (30^{th} April, 2002, Glasgow) is chosen. A demand profile with the name "washing machine" from a statistical resource and a renewable PV supply are used as an example to verify the functionalities of these two parts of the algorithm, i.e. whole load shift and part load shift.

Whole Load Shift

The demand which is defined as "shift whole demand profile" in Chapter 3 means the demand can move freely within the simulation period (every 24 hours if the simulation period is more than one day). The shared area between supply and new demand at each shift step is calculated. All the shared areas are compared and the maximum is retrieved as the best shift option. The original demand and supply match is shown in **Figure 6-1**. The green line is the pattern of energy generated by the PV panel based on Glasgow climate defined above. The red line is the demand profile. The match results between the demand and the supply before load shifting are reported in **Figure 6-2**. It can be seen that the shared area of these two profiles is 0.86kWh. After specifying the demand as "the whole load shift", the shared area at every shift time step is calculated using the algorithm and the results are listed in **Table 6-1**, from which it can be seen that the share area at the 4^{th} shift step (1.08kWh, highlighted in orange) is the largest among all others. This match result after the whole load shift is illustrated graphically and statistically in **Figures 6-3** and **6-4**, which is exactly the same as those calculated behind the interface (see **Table 6-1**). **Figure 6-5** shows the original demand and the demand after being shifted by the DSM+c algorithm.

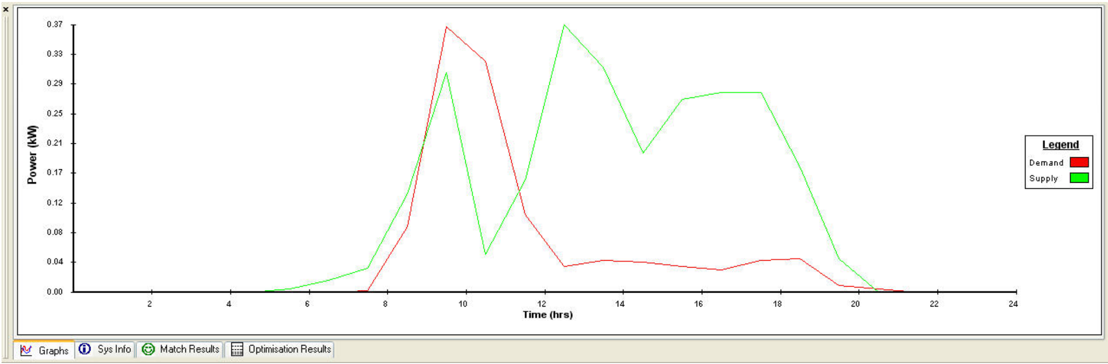

Figure 6-1: Demand/Supply Match before DSM+c

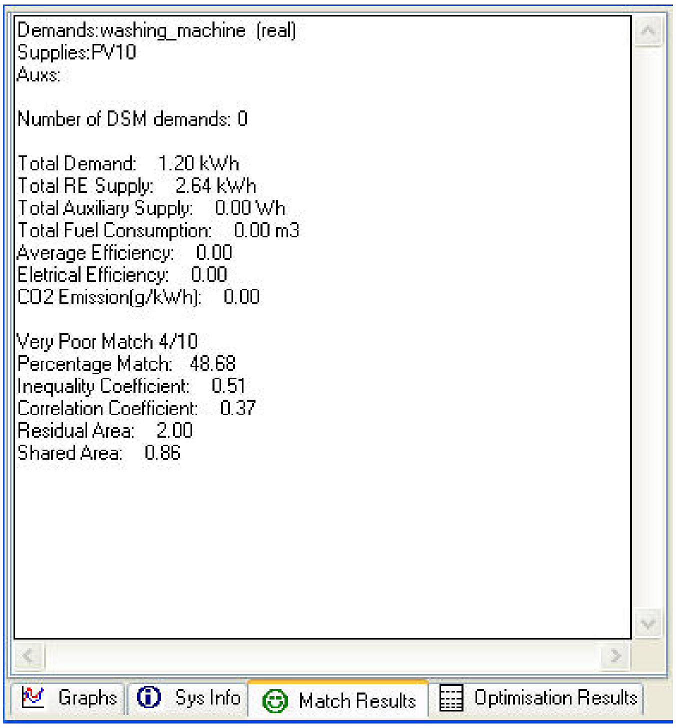

Figure 6-2: Match Statistics before DSM+c

Table 6-1: Share Areas at Every Shift Time Step

Shift Step	Demand/Supply Profile Shared Area (kWh)
1	0.860536
2	0.701149
3	0.883149
4	1.082091
5	0.874001
6	0.791937
7	0.834234
8	0.798562
9	0.596653
10	0.323299
11	0.153314
12	0.071314
13	0.040867
14	0.072773
15	0.120773
16	0.162867
17	0.197773
18	0.234773
19	0.277773
20	0.322773
21	0.359773
22	0.468773
23	0.604603
24	0.837438

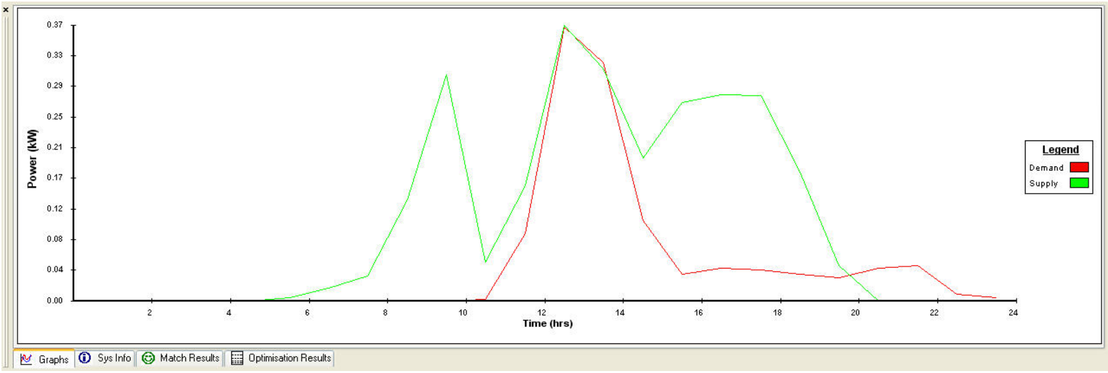

Figure 6-3: Demand/Supply Match after DSM+c

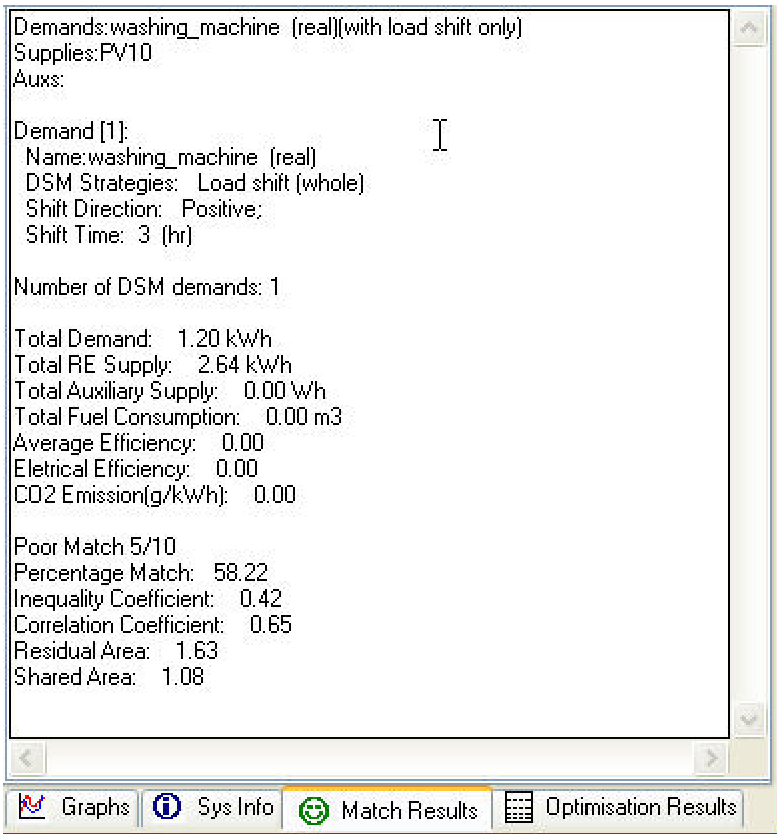

Figure 6-4: Match Statistics after DSM+c

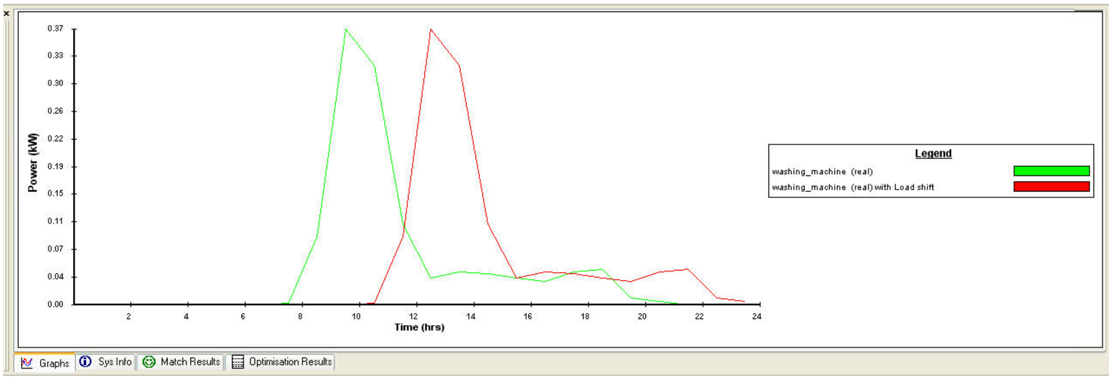

Figure 6-5: Demand before and after DSM+c

This whole load shifting strategy can be applied to appliances such as washing machine and dish washer etc. Through this algorithm the whole energy block required for operating the washing machine or dish washer can be reallocated to any period when the maximum match between the demand and the available supply is achieved.

Part Load Shift

The example of demand and supply profiles from the previous section is used here for the verification process of the part load shift. The load to be shifted is defined as from 9:00 to 11:00 based on the original demand profile, which means only two hours of loads are free to move along the simulation period. The purpose of the part load shift algorithm is to offset a specific load at each shift time increment (one hour in this case) along the time period, and find out the optimum shifting position, i.e. the one which has the largest shared area with the supply profile. **Table 6-2** shows the results of the shared area at each shifting time step. It can be seen that the 13th row highlighted in orange (i.e. 1.10kWh) is the one which has the largest shared area. The shared area before applying part load shift is the row in yellow (i.e. 0.86kWh). Therefore, the expected shifting strategy is to shift the original demand forward three shifting steps. The results are reported in **Figure 6-6** and shown in **Figure 6-7**. They are expected as can be seen. In order to compare the demand before and after part load shift, the comparison graph is also provided in **Figure 6-8**. The green line is the original demand and the red one is the demand after being shifted. As can be seen, the shifted load is moved one step forward and added upon the original demand.

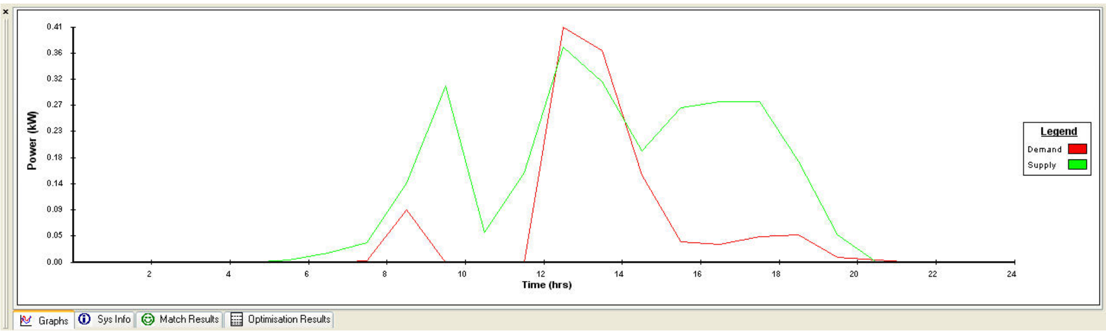

Figure 6-6: Demand/Supply Match after Part Load Shift

Table 6-2: Shared Area at Each Shifting Step for Part Load Shift

Shift Step	Demand/Supply Profile Shared Area (kWh)
1	0.392
2	0.392
3	0.392
4	0.397166
5	0.414867
6	0.446773
7	0.487603
8	0.578902
9	0.797532
10	0.860536
11	0.711149
12	0.97975
13	1.105939
14	0.921001
15	0.883936
16	0.980234
17	0.981562
18	0.790653
19	0.557299
20	0.430148
21	0.392
22	0.392
23	0.392
24	0.392

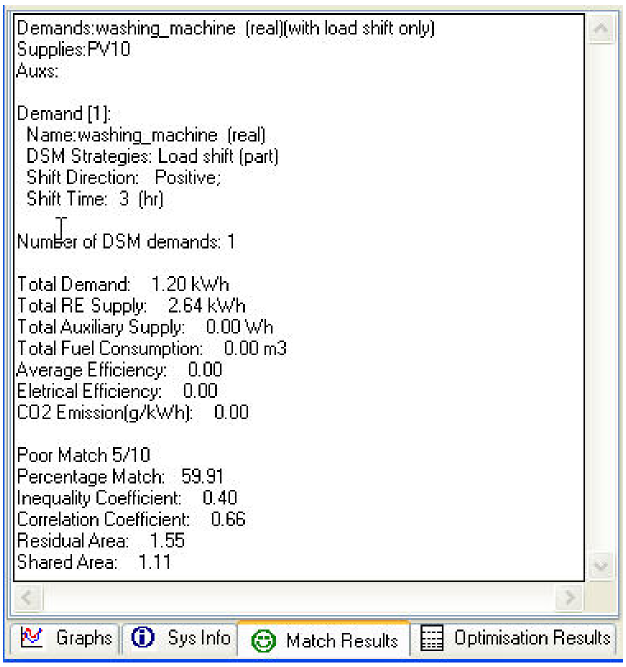

Figure 6-7: Match Results after Part Load Shift

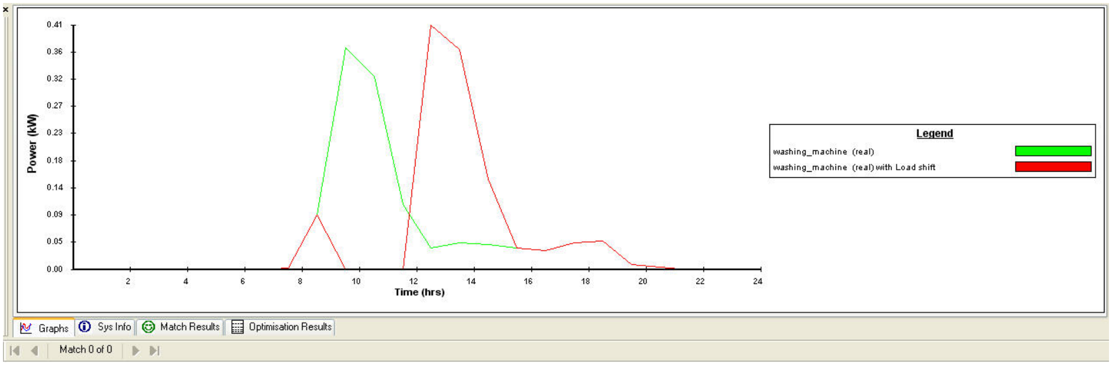

Figure 6-8: Comparison of Demand before and after Part Load Shift

Part load shifting strategy is suitable for the appliance when it can tolerate the separation of the whole process into several stages. A possible example in reality would be the operation of electricity-based hot water storage. If its insulation level is high enough, it is possible to shift part of the load to the period when the energy is available.

6.2.2 Single Demand with Demand Side Control Only

The logic of the DSC algorithm is to switch the load on or off fully or partially depending on the availability of supply and the feature of the demand device, without significantly violating users' conveniences or surrounding indoor environmental conditions. The verification includes the check of control logic and its impact upon users' convenience to prove that the results of the control method are as expected. The DSC algorithm takes the corresponding measures based on the relationship between the demand and supply. For instance, if the supply is less than demand, the measures of reducing demand, either fully or partially, should be taken. As far as the control impact is concerned, for historical time series demands only, if the demand at all the time steps is controlled during the previous control duration, the demand at the current time step cannot be controlled again, unless there is enough supply to satisfy the demand. For simulated or monitored demands, the control impact after DSC is considered by comparing the new environmental values with the initial setting point. Suitable load switching strategies are invoked according to the comparative results. The verification process for monitored demand has been described in Chapter 5. Section 6.2.3 within this Chapter describes the verification procedure for simulated demand in detail.

The historical demand profile of a slow cooker is selected as an example to show the verification process of the DSC algorithm. The DSC method of “Partial Control” is taken as an example to explain the verification process, as the other one (“On/Off” control) is its extreme case. Again, a one-day simulation period is selected. The control duration for this load is specified as 3 times of the time step in this case, which guarantees enough time is available for the load to be controlled when there is not sufficient supply available to meet the load. The maximum control availability limit is set as 50%, which means the control range for this profile is from 50 to 100%.

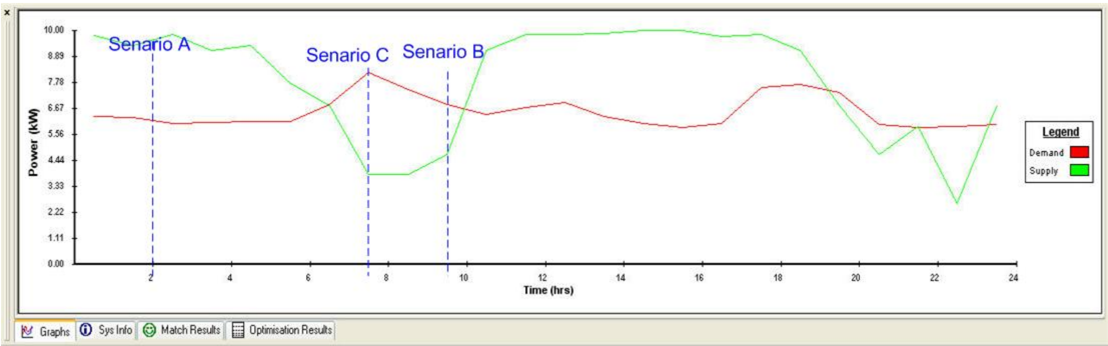

Figure 6-9: Demand/Supply Match before the DSC Algorithm

Figure 6-9 shows the match between demand and supply before applying the partial control algorithm. During the periods from 0700 to 1000, and from 1900 to 2300, the demand is greater than supply and the algorithm is expected to work only within these two periods. For the rest of the simulation time, the demands remain the same as before. The possible scenarios for this case are listed below.

Scenario A: Demand is less than supply and no control actions are taken;
Scenario B: Demand is greater than supply but is satisfied by supply after the deduction within the range from 0% to 50% including the border values;
Scenario C: Demand exceeds the supply and remains uncovered even after the maximum deduction (50% in this case).

Table 6-3 not only lists the data of supply and demand at each time step before applying DSM+c algorithm (as shown in **Figure 6-9**), but also enumerates the data of demand after applying DSM+c algorithm and its control percentage for each time step (as shown in **Figure 6-10**). Based on the control actions undertaken at each time step, the scenario information is also included in **Table 6-3**.

Table 6-3: Detailed Results before and after Partial Load Control

Time Step	Supply (kW)	Demand Before DSM+c (kW)	Demand After DSM+c (kW)	Control Percentage (%)	Scenario
1	9.806	6.348	6.348	0.0	A
2	9.377	6.310	6.310	0.0	
3	9.845	6.040	6.040	0.0	
4	9.183	6.079	6.079	0.0	
5	9.377	6.117	6.117	0.0	
6	7.749	6.117	6.117	0.0	
7	6.814	6.848	6.163	10.0	B
8	3.862	8.234	4.117	50.0	C
9	3.862	7.503	3.752	50.0	B
10	4.732	6.848	4.109	40.0	B
11	9.183	6.425	6.425	0.0	A
12	9.845	6.733	6.733	0.0	
13	9.845	6.925	6.925	0.0	
14	9.907	6.348	6.348	0.0	
15	10.000	6.040	6.040	0.0	
16	10.000	5.887	5.887	0.0	
17	9.755	6.040	6.040	0.0	
18	9.845	7.580	7.580	0.0	
19	9.183	7.733	7.733	0.0	
20	6.814	7.388	6.649	10.0	B
21	4.732	6.002	4.201	30.0	B
22	5.917	5.887	5.887	0.0	A
23	2.616	5.925	2.963	50.0	C
24	6.814	6.002	6.002	0.0	A

In order to check whether the algorithm works properly, the results at some time steps (t = 2, 8, 10) representing the three different scenarios after the application of DSC are studied. These are illustrated in **Figure 6-9** and highlighted in **Table 6-3**. It can be seen that the second time step highlighted in green at **Table 6-3** corresponds to Scenario A, i.e. the supply is greater than the demand. Therefore, the demands before and after DSC remain the same. The tenth time step, highlighted in yellow at **Table 6-3**, represents Scenario B. In this scenario, the demand can be met by the supply after a certain control percentage (less than the maximum control limit: 50%) is applied to the demand. In order to prove that the correct and optimised control percentage is applied, a detailed analysis at this specific time step is necessary. The results are shown in **Table 6-4**. There are ten control steps in total. Because the maximum control availability is 50%, those control amounts required above 50% remain the same as 50%. From the results, it can be seen that the control proportion of 40% (highlighted in orange) is the one that results in minimum balance between supply and demand, and at the same time, it ensures that the supply is greater than the controlled demand. This matches with the expected results in **Table 6-3**.

Table 6-4: Balance between Supply and Demand at a Certain Time Step for the DSC Algorithm (i=8)

Time step = 8, Maximum Control = 50%, Supply at this time step = 3.862kW		
Control Step	Control proportion	Balance between demand and supply (kWh)
1	0	2.116
2	0.1	1.431
3	0.2	0.746
4	0.3	0.061
5	0.4	-0.624
6	0.5	-1.308
7	0.6	-1.308
8	0.7	-1.308
9	0.8	-1.308
10	0.9	-1.308

At the eighth time step, even after the maximum control deduction (50%) on the demand profile, the demand is still greater than the supply (see **Table 6-3** highlighted in red), which falls into Scenario C. In a same way as the tenth time step, it is essential to see the detailed results at each control step. These are shown in **Table 6-5**. When the control availability is beyond 50%, it remains at 50% and the rest of the demand is unmatched. The minimum balance between the demand and supply is the one with 50% control proportion as highlighted in yellow in **Table 6-5**, and in accordance with the expected results in **Table 6-3**.

Table 6-5: Balance between Supply and Demand at a Certain Time Step for the DSC Algorithm (i=10)

Time step = 10, Maximum Control = 50%, Supply at this time step = 3.8624kW		
Control Step	Control proportion	Balance between demand and supply (kWh)
1	0	4.372
2	0.1	3.548
3	0.2	2.725
4	0.3	1.901
5	0.4	1.078
6	0.5	0.255
7	0.6	0.255
8	0.7	0.255
9	0.8	0.255
10	0.9	0.255

The demand/supply match after the DSC algorithm is illustrated in **Figure 6-10**. Relevant scenarios (A, B and C) are also marked in the graph. In addition, the demands before and after the DSC algorithm are compared in **Figure 6-11**.

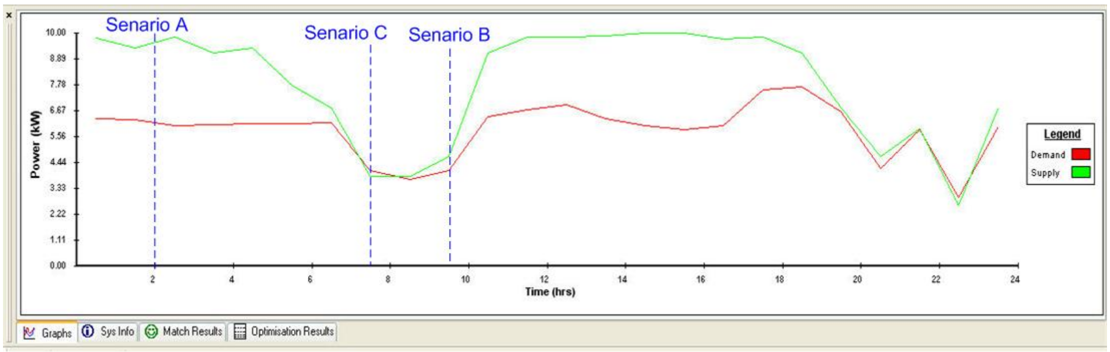

Figure 6-10: Demand/Supply Match after the DSC Algorithm

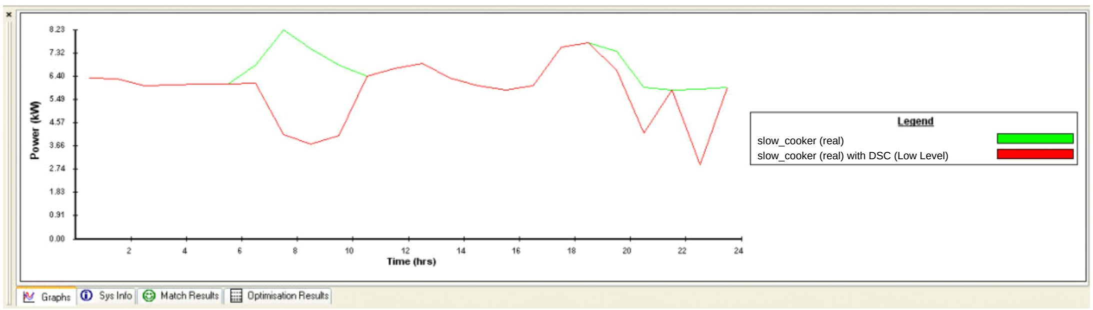

Figure 6-11: Comparison of Demand before and after the DSC Algorithm

The control duration is developed for the historical demands lacking relevant internal environmental data (such as internal temperature). The control duration specified through the interface is normally the integral times of the time step of the demand profile. Whether the demand at the current time step can be controlled depends on the supply at the current time step and the demand at previous time steps within the specified control duration, as described in Chapter 3 at section 3.3.2.3 regarding the control duration for DSC algorithm.

Taking the same example as above, in order to verify the rules regarding the control duration for historical demands defined in Chapter 3 at section 3.3.2.3 have been implemented successfully, three cases with different values of control duration are set and rerun the simulation above. From **Figure 6-12**, it is shown that the demand profile shape changes with various control duration settings. For the first graph, the control duration is one times the time step (i.e., 1*time step). At time step 8, the demand is fully controlled with the maximum control limit. Therefore, at the next time step 9, the demand cannot be controlled even though the supply may be less than the demand, with the outcome that the demand remains unmatched as shown in the graph. For the middle graph, the control duration increases to (2*time step). This takes the demands at the previous two time steps into consideration to decide the DSC actions with respect of the demand at the current time step. As the demands at the eighth and ninth time steps were controlled with the maximum control limit, the demand at the tenth time step cannot be controlled. This is shown in the 2nd graph of **Figure 6-12** as expected. At the bottom graph in **Figure 6-12**, the control duration becomes three times the time step unit (i.e., 3*time step). In this case the algorithm considers the status of the demands at the previous three time steps to decide the status of the demand at the current time step. As it can be seen, although the demands at the seventh, eight, and ninth time steps are controlled, the demand at the tenth time step is also controlled. The reason for this is that the control percentage of the demand at the seventh time step is 10%, which is below the 50% control limit. According to *RULE TWO* stated in Chapter 3 at section 3.3.2.3, the demand at the tenth time step can still be controlled. And this is confirmed by the bottom graph of **Figure 6-12**.

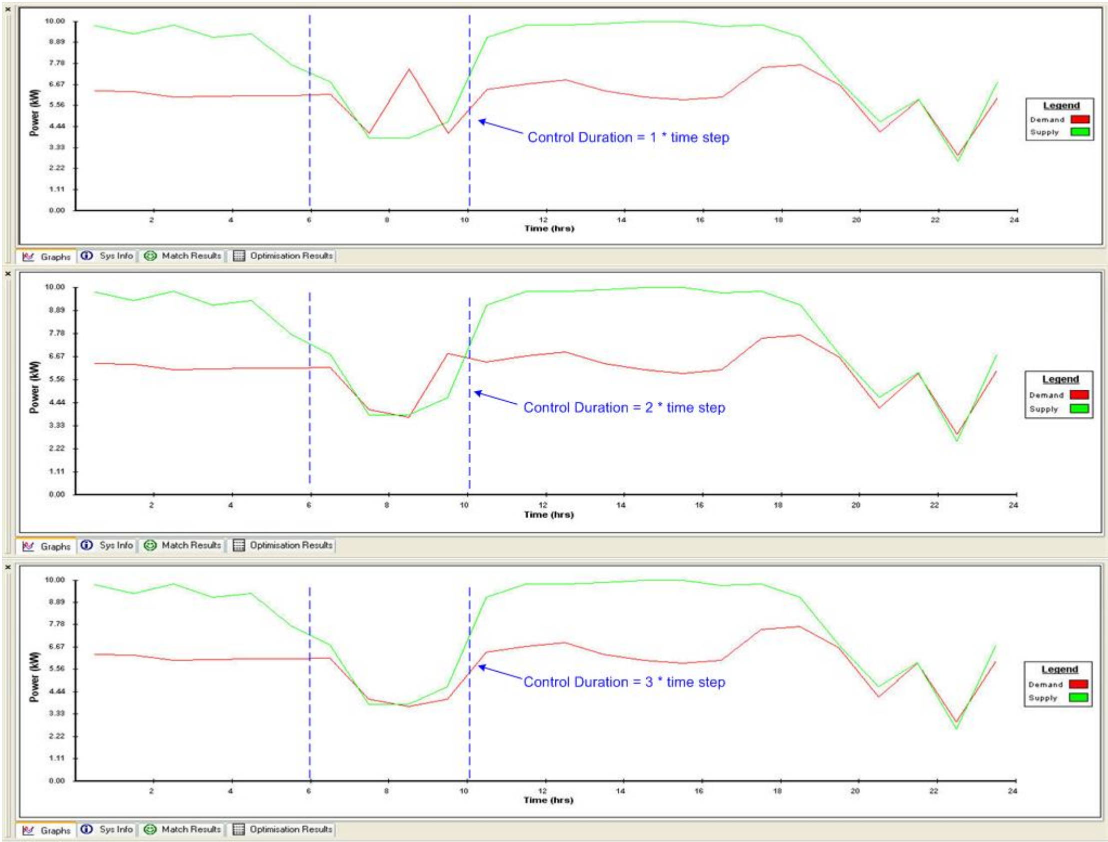

Figure 6-12: Match between Supply and Demand after DSC with Various Control Durations

6.2.3 Multiple Demands with Different Priorities

Another designed case to verify the algorithm is the scenario of multiple demands with different priorities (high, medium, low and no control). The purpose of this case is to verify when and in what order, the algorithm applies the specified control strategies to the selected demands. Four historical daily demands (i.e. from a refrigerator, slow cooker, vacuum cleaner, and TV) are selected for the verification of this case. A simulated profile from a generic 10kW wind turbine module is used as a supply source. The selected demands and supply are shown in **Figure 6-13** and the specified DSC parameters are listed in **Table 6-6**. The match before and after the control are shown in **Figures 6-14** and **6-15**.

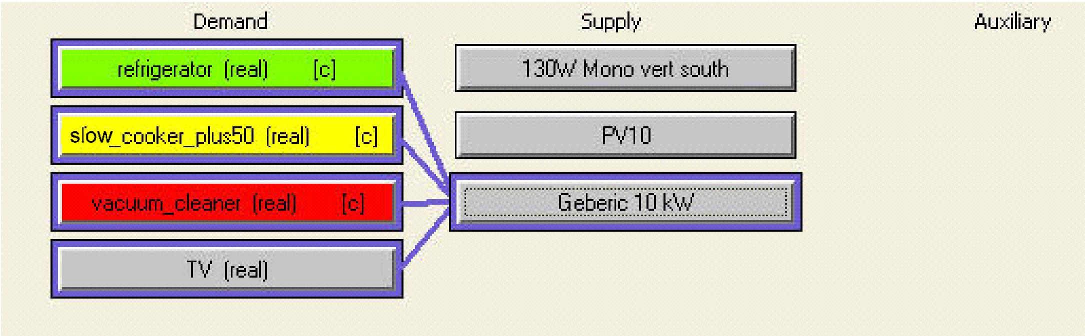

Figure 6-13: The Selected Demands and Supplies

Table 6-6: DSC Demand Settings

Demand Name	Priority for control availability	Control method	Control duration
Refrigerator	High	On/off	1 time step
Slow_cooker	Medium	Proportional (50%)	1 time step
Vacuum_cleaner	Low	On/off	1 time step
TV	No control	-	-

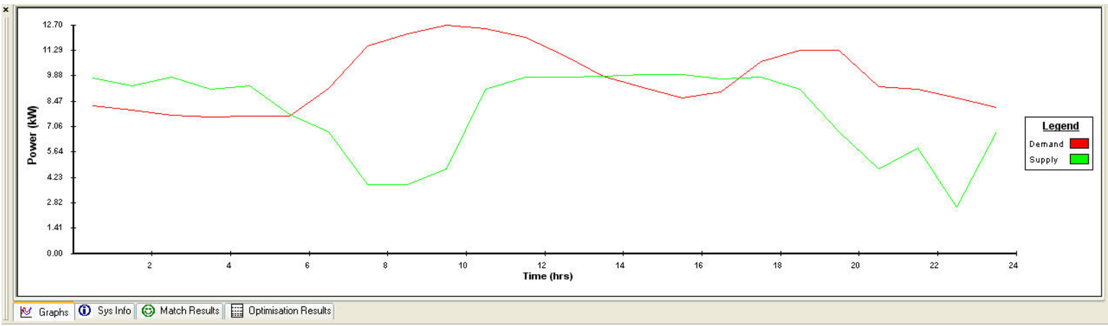

Figure 6-14: Demand-supply Match before the DSC Algorithm

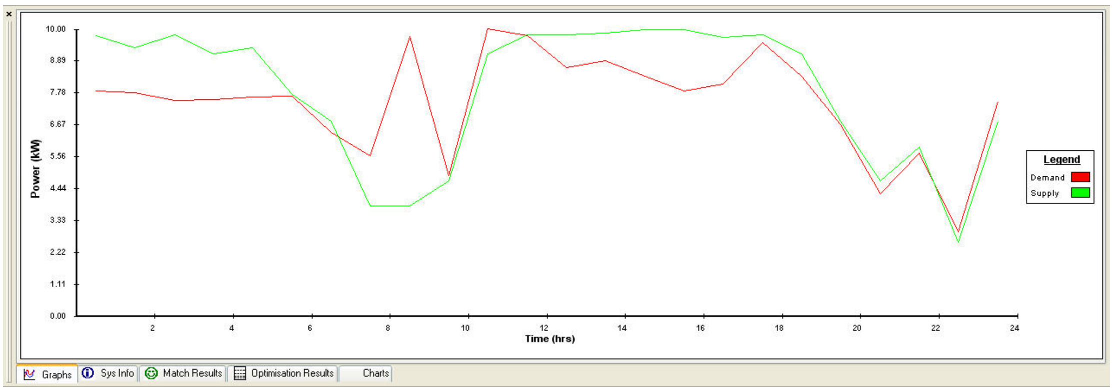

Figure 6-15: Demand-supply Match after the DSC Algorithm

Figure 6-16 shows the comparisons of each demand before and after having applied the DSC algorithm. There are two places (from 6 to 14; from 17 to 24) when DSC actions are taken because at these places demand is greater than supply. During the period from time step 6 to time step 14, all three demands are controlled to reduce the total demand so as to match the supply availability. And at time step 8, due to the limits of the control duration (i.e., 1 time step), the control is deactivated and the demands have their normal values in order to avoid causing inconvenience to occupants. In this case, the supply is not enough to satisfy the demand. At this specific 8th time step, back-up supply should be provided, such as power from the electricity grid or auxiliary devices.

At the second period from 17 to 24, the control order of multiple demands with different priorities can be seen **in Figure 6-16**. For instance, at time step 18, the refrigerator profile in red with its high control priority is switched off first. The new total demand is re-calculated, and after a comparison with the total supply, it still exceeds what is available. Next, the slow cooker demand in green with its medium control priority is controlled proportionally. The total demand is re-calculated and compared with the total supply again, and in this case the demand is less than the supply. As a result of this the demand in blue with a low control priority remains the same. It is concluded that the control order is correctly set and applied to this case study successfully.

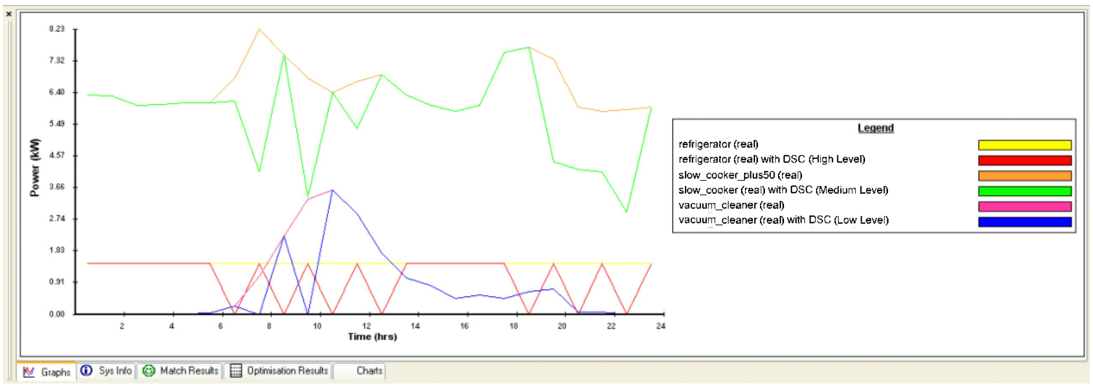

Figure 6-16: Demand Comparisons before and after the DSC Algorithm

6.2.4 Demand Model (Electricity-based Thermal Demand System)

The purpose of the verification process for this case is to test the robustness and correctness of the described DSM+c algorithm at operational level when combined with the demand model. Extra internal environmental variables (such as temperature etc.) obtained through simulation of the demand model are considered within the algorithm. Demand models mainly refer to the electricity-based thermal systems, such as heat pumps, air conditioning, thermal storage and refrigerators, etc. To perform the verification for the algorithm, an example of a simplified refrigerator model is selected as a representative for the demand model. The main parameters of the refrigerator are listed in **Table 6-7** and a wind turbine supply module based on the Glasgow climate is used for the supply profile. The demand profile of the refrigerator before applying the DSC algorithm, the supply profile, and the environmental conditions within the refrigerated place, can be simulated. These are shown in **Figure 6-17**.

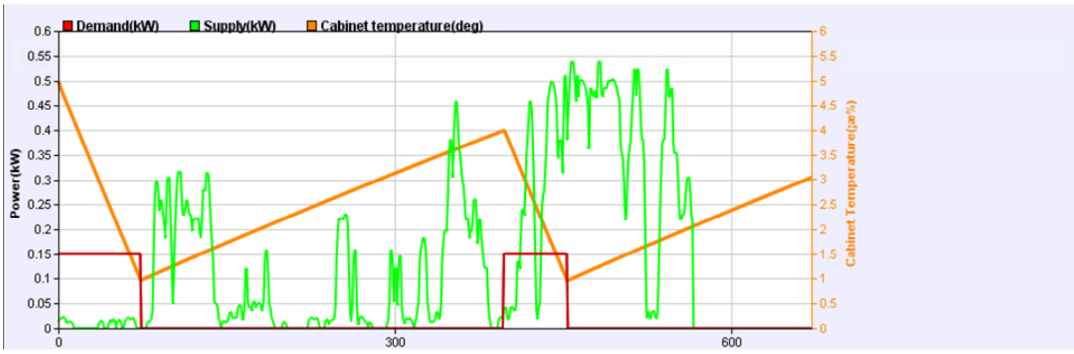

Figure 6-17: Match between Wind Turbine and Refrigerator Demand before DSC

Table 6-7: Parameters Specified in the Refrigerator Model

Name	Thermostat Temp (^{o}C)		DSM Temp (^{o}C)		Power (kW)	COP
	ON	OFF	ON	OFF		
Refrigerator	4	1	3.5	1.5	0.15	1.5

In this case, the cabinet temperature (T_{cab}) is adopted as an indicator for determining the compressor operation. The purpose of the DSC algorithm is to maintain the cabinet temperature within the range of set points. All possible eight scenarios that are based on the status of the cabinet temperature and the relationship between demand and supply are defined as follows.

Scenario 1: $T_{cab} \geq T_{up}$;

Scenario 2: $T_{cab} \leq T_{down}$;

Scenario 3: $T_{cab} \in \left(T_{down}, T_{up}\right)$ & $P_{demand} > P_{supply}$;

Scenario 4: $T_{cab} \in \left(T_{dsm\_up}, T_{up}\right)$ & $P_{demand} \leq P_{supply}$ & $T_{cab}^{i-1} > T_{cab}^{i}$;

Scenario 5: $T_{cab} \in \left(T_{dsm\_up}, T_{up}\right)$ & $P_{demand} \leq P_{supply}$ & $T_{cab}^{i-1} < T_{cab}^{i}$;

Scenario 6: $T_{cab} \in \left(T_{dsm\_down}, T_{dsm\_up}\right)$ & $P_{demand} \leq P_{supply}$;

Scenario 7: $T_{cab} \in \left(T_{down}, T_{dsm\_down}\right)$ & $P_{demand} \leq P_{supply}$ & $T_{cab}^{i-1} > T_{cab}^{i}$;

Scenario 8: $T_{cab} \in \left(T_{down}, T_{dsm\_down}\right)$ & $P_{demand} \leq P_{supply}$ & $T_{cab}^{i-1} < T_{cab}^{i}$.

Notes:

T_{cab}^{i-1} and T_{cab}^{i} refers to cabinet temperature at the (i-1) time step and the (i) time step.

T_{up}, T_{down}, T_{dsm_up}, and T_{dsm_down} are described in Chapter Three Section 3.4.4.

For scenarios 1 and 2, the cabinet temperature is outside the temperature range defined by the thermostats. Whatever the relationship between demand and supply, the actions of turning on or off the device have to be carried out to bring the temperature within the range, which are expected and shown in **Figure 6-18**.

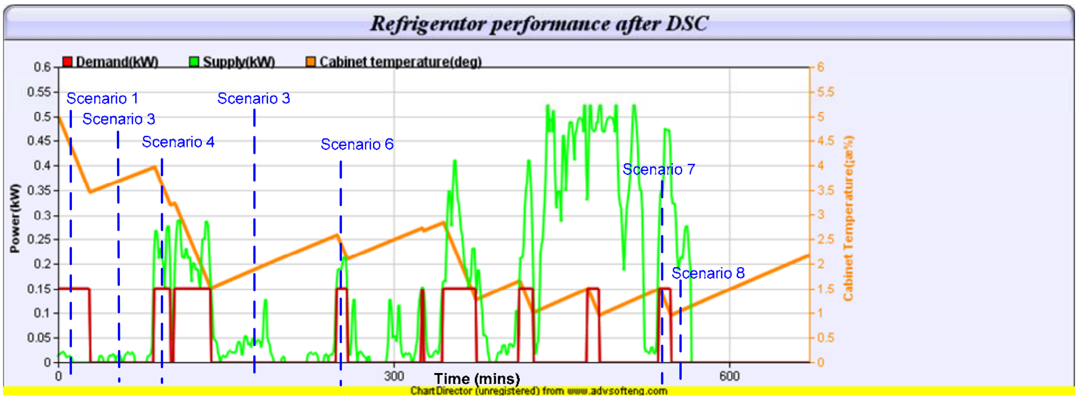

Figure 6-18: Match between Wind Turbine and Refrigerator Demand after DSC

For scenario 3, the cabinet temperature is within the range of thermostat set points and the demand is greater than supply. In this scenario, the action to reduce the demand, i.e. to switch off the refrigerator, is taken. This is confirmed in **Figure 6-18**.

In scenario 4, demand is less than supply and the inside temperature is kept between T_{dsm_up} and T_{up}. If the cabinet temperature is falling, the refrigerator should remain on until it reaches the set point of T_{dsm_up}. This is shown in **Figure 6-18**. For scenario 5, the only difference to scenario 4 is the cabinet temperature changing trend when compared with that at the previous time step. In scenario 5, the cabinet temperature is increasing rather than falling. The refrigerator should remain off until it reaches the set point of T_{up}. The same procedure can be applied to scenario 5.

Scenario 6 presents the case where the demand is less than the supply and the temperature is held in the range of T_{dsm_down} and T_{dsm_up}. It is expected that the refrigerator is on and maintains the temperature at the low level when the supply is available, which is marked in **Figure 6-18**.

In a same way as for Scenario 4, Scenarios 7 and 8 are defined to check whether the control algorithm works properly under the situation when the demand is less than the supply and the inside temperature is kept within the range of T_{dsm_down} and T_{down}. If the cabinet temperature at a specific time step is less than the cabinet temperature at the previous time step, the refrigerator should remain on. In the opposite case, if the cabinet temperature increases, i.e. $T_{cab}^{i} > T_{cab}^{i-1}$, the refrigerator should remain off until the temperature reaches the set point of T_{dsm_down}, although the supply is greater than the demand. The control logics of these scenarios are confirmed and shown in **Figure 6-18**.

6.3 Verification of Supporting Modules

The supporting modules include an electricity-based thermal storage system, a refrigeration system, a heat pump, and a CHP unit. As measured data for each supporting module are not available, analytical verification (Strachan et al. 2008) is adopted to carry out the process. For electric thermal storage system and refrigeration system, their outputs are compared to the results from known analytical solutions (Martin et al. 1994). For heat pump, the hypothetical tests are created to verify the ability to reproduce the behaviour as described by the manufacturers (Born 2001). The detailed procedures for these modules are described at next sections. For the CHP system, the detailed verification process, described by Smith (2002) is adopted.

6.3.1 Electric Thermal Storage System

In order to verify the hot water storage system model analytically, two tests are created. One test is set with no water withdrawal from the storage. The other one is set with constant water withdrawal. Based on the mathematical equations and numerical methods discussed in Chapter Three, the results generated by the model are compared against the analytical solutions under the same boundary and initial conditions.

Test 1: No water withdrawal ($\dot{Q}_v = 0$)

A simplified electric hot water storage tank model with the capacity of $0.15m^3$ was created. Due to the small capacity, the stratification inside the tank can be neglected (Kar and Al-Dossary, 1995). It is assumed that the water temperature inside the tank is even, whilst the ambient temperature around the hot-water storage system is assumed to be constant at 23 ^oC. The initial water temperature inside the tank is set as 65 ^oC, and the thermostat settings for switching the heater on/off are 60 ^oC and 68 ^oC respectively, with the dead band of 8 ^oC. The power of the heater is 4.5kW, and the time step is minute-based.

Two sections (free-floating and heating) are involved in this particular case. One is the heater-off stage, where the temperature inside the tank changes according to the conditions outside. The other is the heater-on period during which the water is heated by the electric resistant heater until the temperature inside the tank reaches the upper setting point of the thermostat. The simplified model results of each section are compared to the analytical solutions of the equation defined in Chapter 4 at section 4.2.2, and they are shown in **Figures 6-19** and **6-20**. An average deviation of 0.01% or less is observed from this comparison.

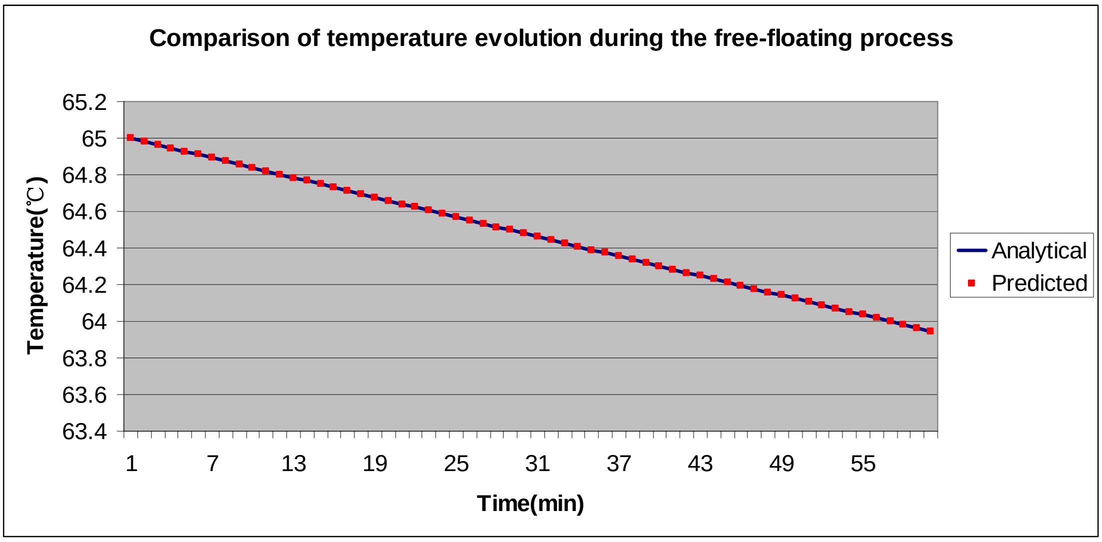

Figure 6-19: Comparison of Temperatures at the Free-Floating Stage

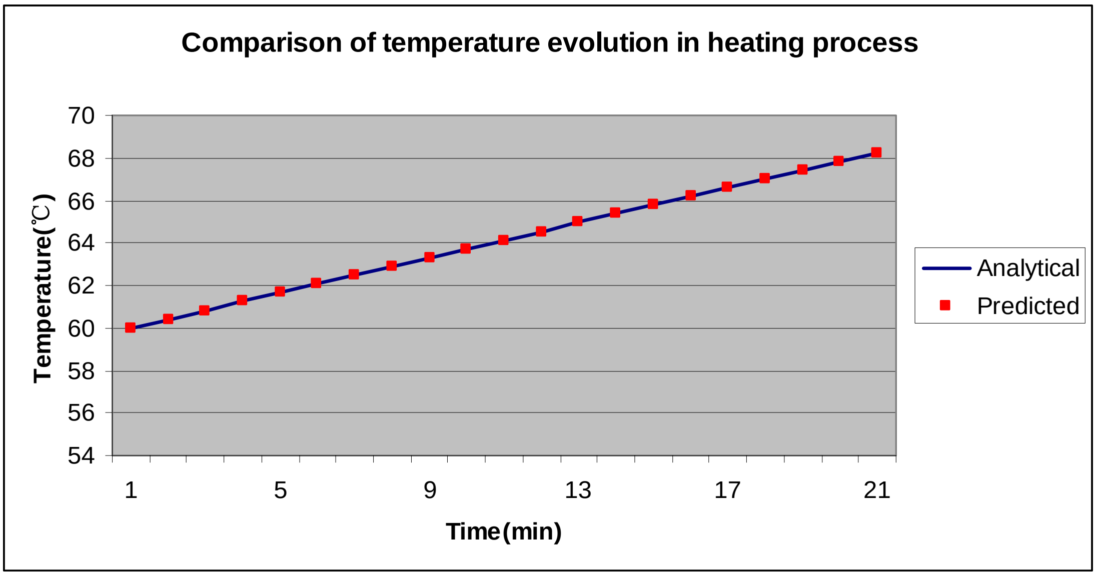

Figure 6-20: Comparison of Temperatures at the Heating Stage

Test 2: Constant water withdrawal ($\dot{Q}_v$ = constant)

In this test the daily water withdrawal is set to the constant value of 264 litres. In practice, the water withdrawal from the tank varies with time. Thus the analytical solution at each time step is different because the constant in the solution expression of the differential equations in Chapter 4 at section 4.2.2 changes with time. In order to identify if there are any problems with the implementation of the DSM+c algorithm at operational level, constant water withdrawal is chosen. In this case study it is assumed that the amount of water withdrawn from the tank is the same as the amount of water entering the tank. And the inlet water temperature in this test is assumed to be the temperature of tap water (13 ^{o}C). The other parameters (e.g. initial water temperature inside the tank, thermostat on/off setting points and heater power) are the same as those in Test 1. A similar verification method to that described in Test 1 is used in this test. The results of the temperature evolution within the tank are compared with the analytical solutions and shown in **Figures 6-21** and **6-22.** It can be seen that there is a good match between the hot-water storage model in MERIT and the analytical solutions.

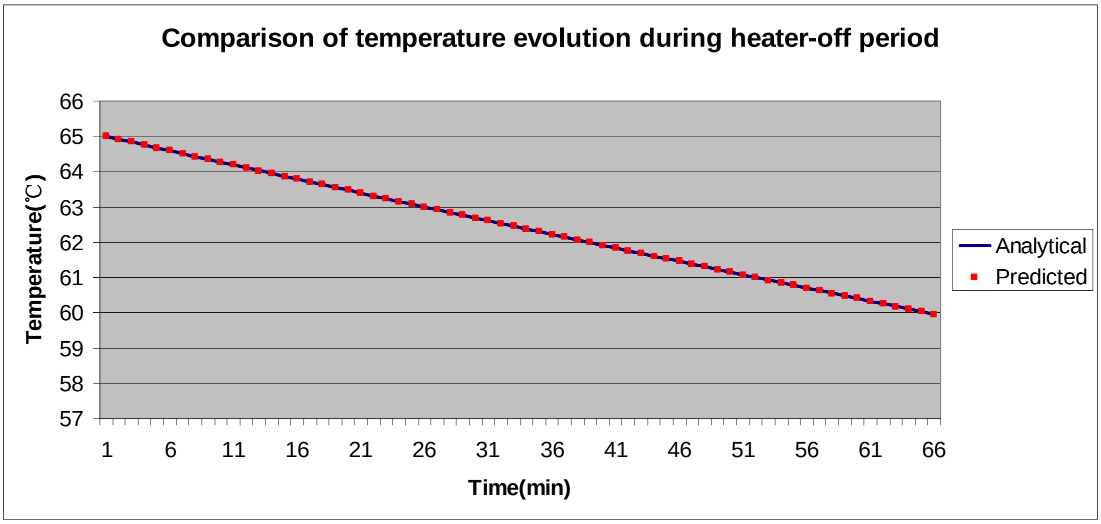

Figure 6-21: Comparison of Temperatures during the Heating-off Period

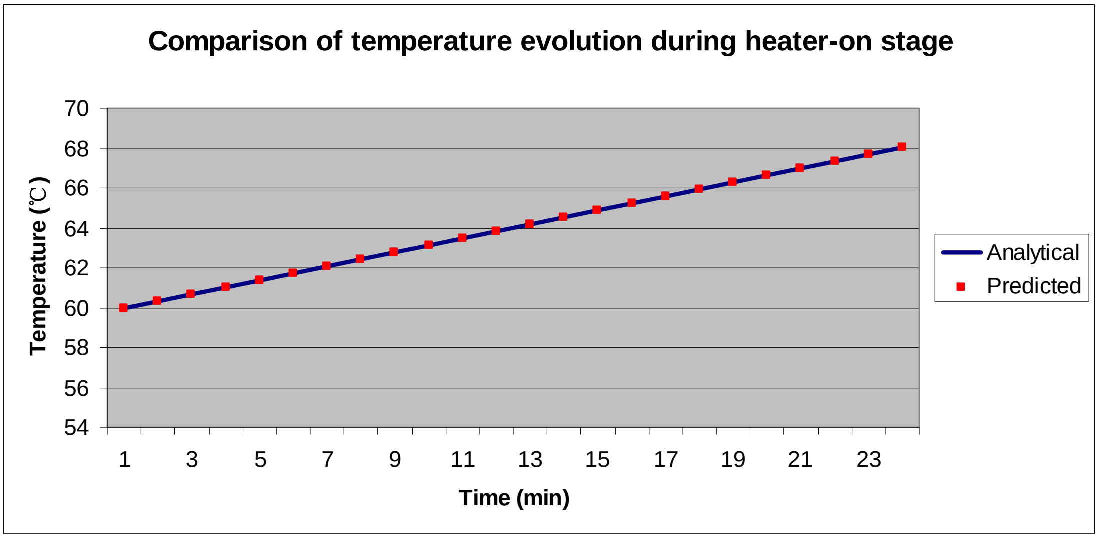

Figure 6-22: Comparison of Temperatures during the Heater-on Period

6.3.2 Refrigeration System

A similar analytical verification method as for the thermal storage system is also used to test the refrigeration system algorithm. The initial cabinet temperature is 6 ^{o}C, the thermostat setting is 5 ^{o}C (on) and 1 ^{o}C (off), with 4 ^{o}C dead band, and the compressor power is 150W. The whole volume of the cabinet is 0.3m^3 in this case and objects inside the cabinet occupies 1% of the space in this case. One refrigeration cycle is examined in this example because this will be adequate to assess the functionality of the DSM+c algorithm at operational level. The same procedure is applied for other cases. The predicted and calculated results are compared and shown in **Figure 6-23** (cooling period) and **Figure 6-24** (free-floating period). The predicted and calculated results are in good agreement and it is concluded that the model is capable of predicting the performance of a simplified refrigeration system.

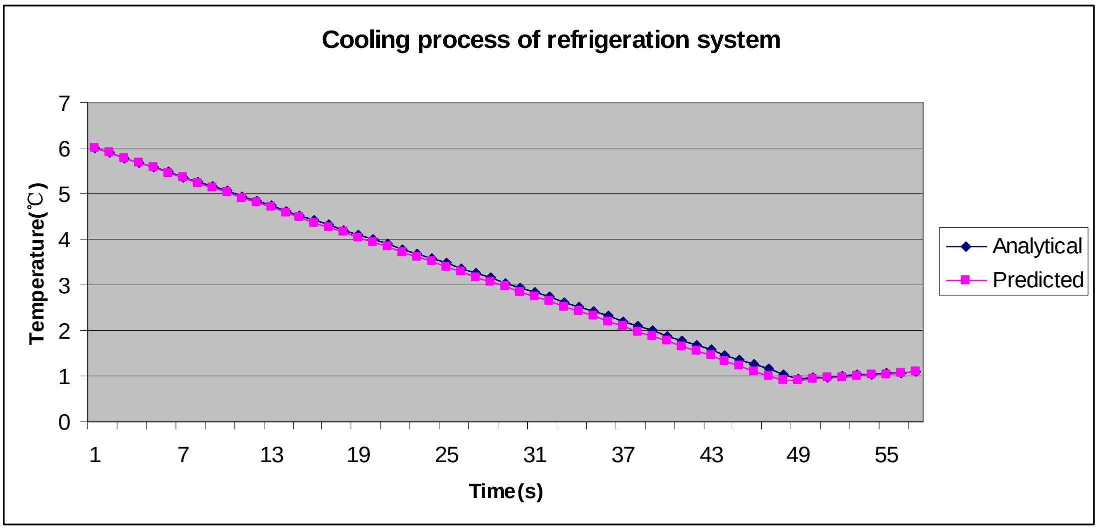

Figure 6-23: Comparison of Temperatures during the Cooling Process

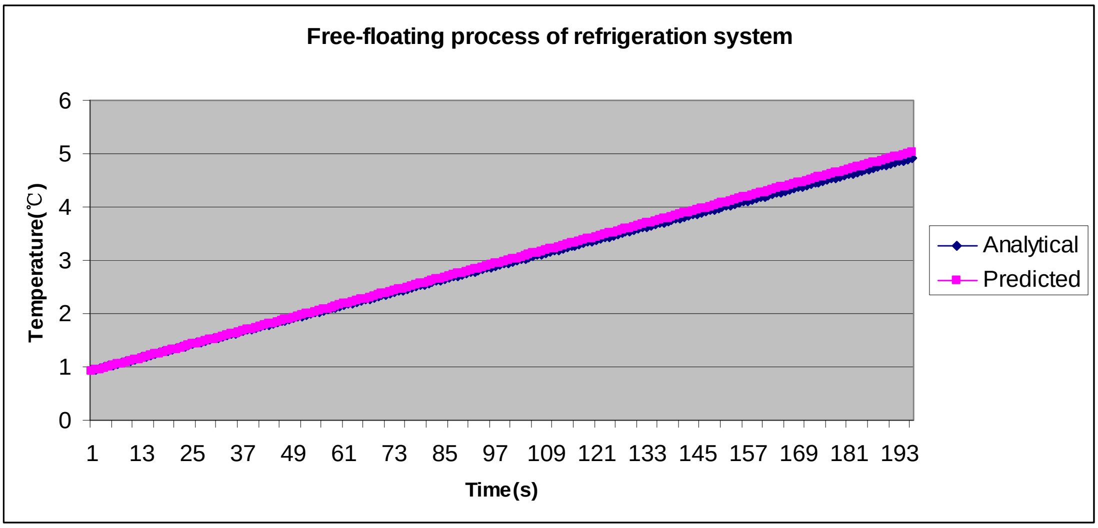

Figure 6-24: Comparison of Temperatures during the Free-floating Period

6.3.3 Heat Pump

The heat pump performance data under realistic operating conditions are not available and the model is verified by its ability to represent catalogue data obtained from a heat pump manufacturer (Trane 1997). The model implemented in MERIT is a two-dimensional interpolation algorithm (William et al. 2002) based on the HP manufacturer's catalogue data. The main purpose of this section is to determine whether the proposed algorithm is suitable for capturing the performance variations and profile of any other heat pump provided with catalogue data.

The model is tested against heat pump data manufactured from Trane (model number WCZ060F100-A). The same method can be applied to other types of heat pump models as long as the catalogue data is available.

The verification process is carried out in terms of the thermal power output and the electricity required. The predicted results of thermal power supply and electricity power demand, compared with manufacturer's thermal and electricity power catalogue data are illustrated in the following figures (from **Figures 6-25** to **6-28**). The consistency between predicted and actual results proves the suitability of using the implemented algorithm to simulate the heat pump performance.

Thermal supplied (Heating Mode)

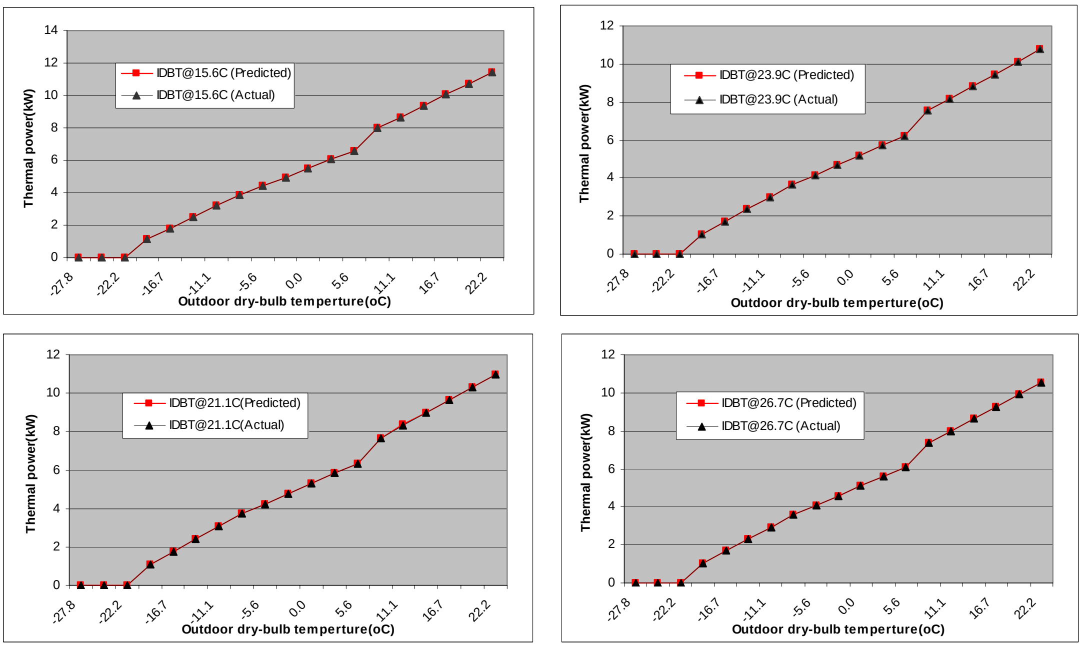

Figure 6-25: Comparison of Thermal Energy Supplied in the Heating Mode

Electricity power required (Heating Mode)

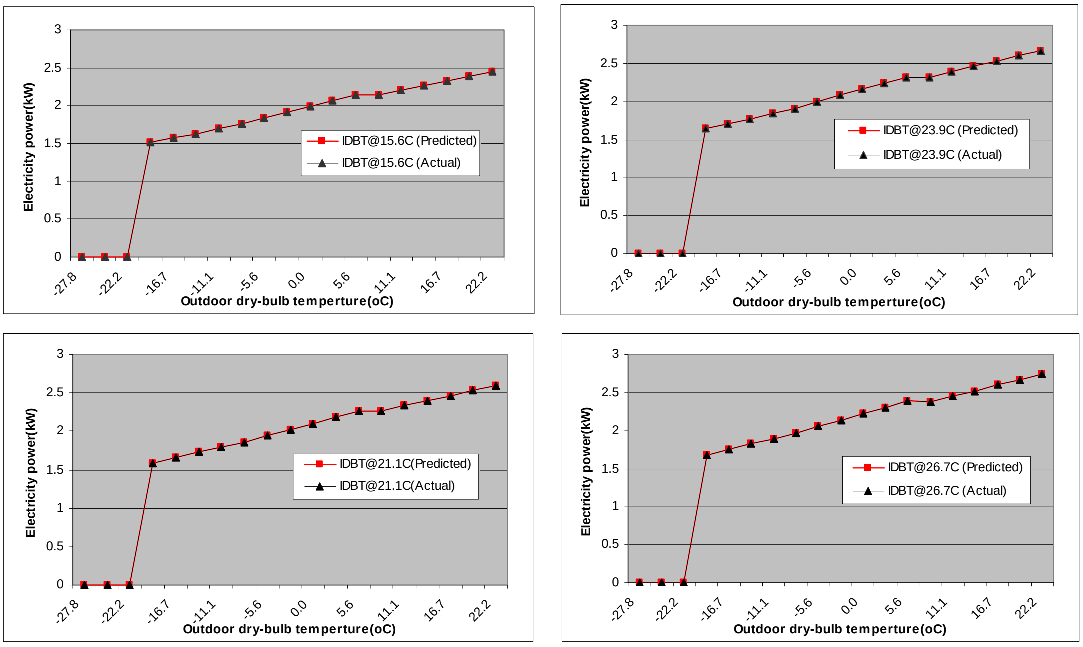

Figure 6-26: Comparison of Electricity Required in the Heating Mode

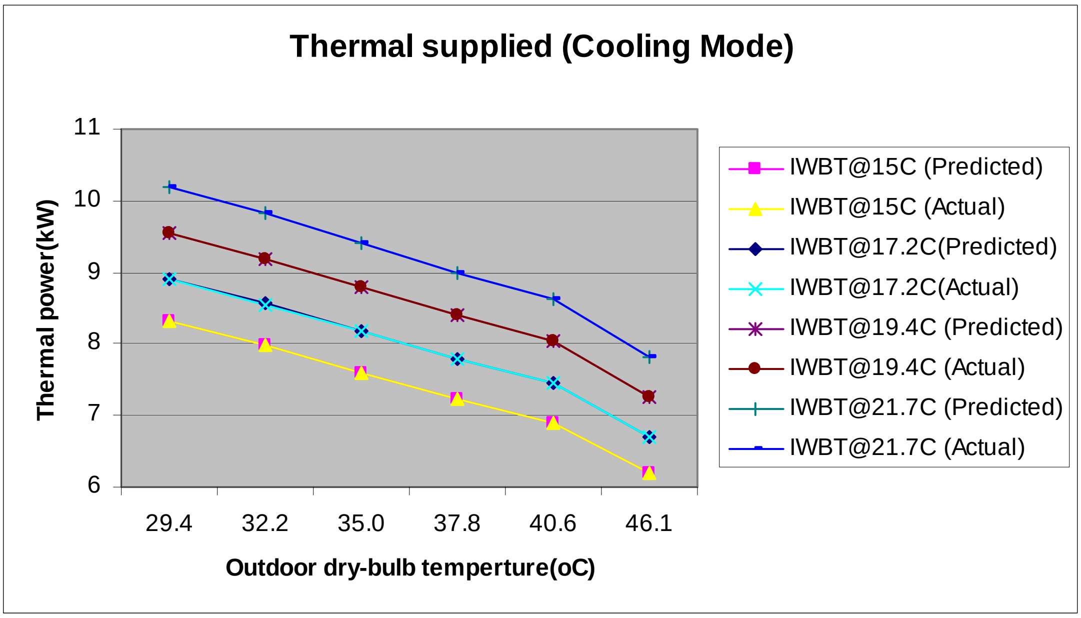

Figure 6-27: Comparison of Thermal Energy Supplied in the Cooling Mode

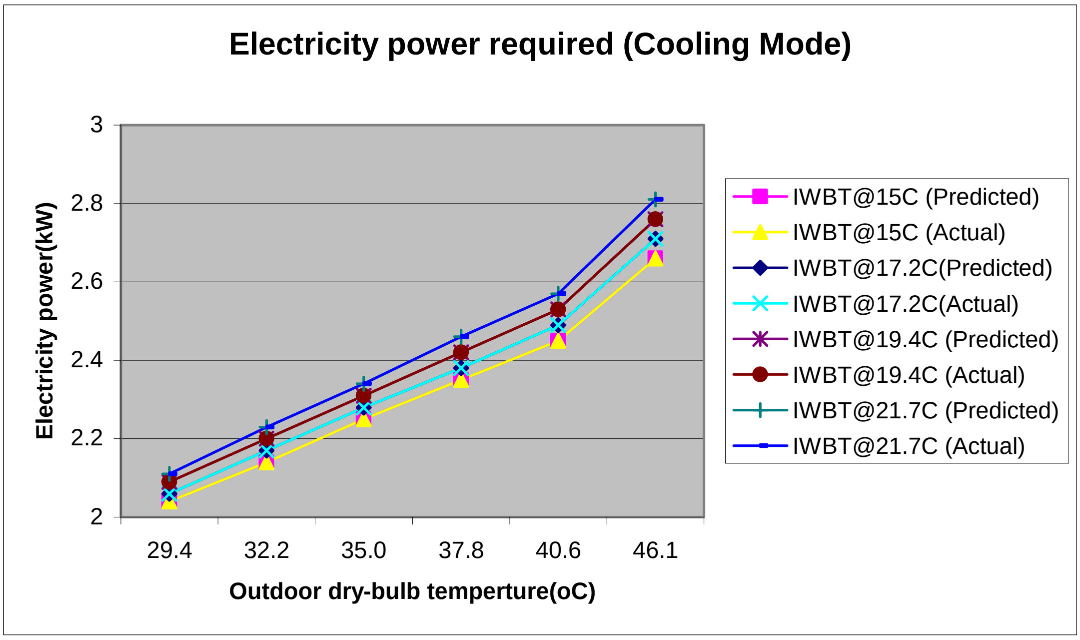

Figure 6-28: Comparison of Electricity Required in the Cooling Mode

In addition, the Root-Mean-Square (RMS) error for the total thermal capacity and power in the heating and cooling modes are shown in **Tables 6-8** and **6-9**. It can be seen that a RMS error is always less than 0.2% for all the specified heat pump outputs and it is therefore acceptable to draw the conclusion that the implemented two-dimension interpolating algorithm is capable of representing the heat pump performance in the cooling and heating modes.

Table 6-8: RMS Error for the Heating Mode

Performance Parameters	WCZ060F100-A AT 0.519m^3/s (TRANE)			
	Indoor Dry Bulb Temperature (^{o}C)			
	15.6	21.1	23.9	26.7
Thermal output RMS error (%)	0.15	0.16	0.18	0.14
Electricity input RMS error (%)	0.02	0.02	0.02	0.02

Table 6- 9: RMS Error Rate for the Cooling Mode

Performance Parameters	WCZ060F100-A AT 0.519m^3/s (TRANE)			
	Indoor Wet Bulb Temperature (^{o}C)			
	15.0	17.2	19.4	21.7
Thermal output RMS error (%)	0.11	0.10	0.11	0.13
Electricity input RMS error (%)	0.01	0.01	0.01	0.01

6.4 Conclusions

This chapter has described the procedures used for the verification of the DSM+c algorithm at both strategic and operational level. Two aspects of DSM+c algorithm have been verified: demand side measures for individual demand and the control logic for multiple demands. The results proved that the developed control logic and method are functioned as expected and have been implemented successfully.

This chapter has also described the analytical method adopted to verify the models of electric-based thermal storage system, refrigeration system and heat pump system. The objective was to verify that the developed models are giving the correct outputs that agree with the analytical solutions and the relevant catalogue data. The results were shown that the developed models have good agreements with the known analytical solutions and have the ability to reproduce the behaviour as described by the manufacturers. The next two chapters will apply the verified modules to the applications of DSM+c algorithm at both operational and strategic level.

6.5 References

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CHAPTER SEVEN CASE STUDIES ON OPERATIONAL APPLICATION OF DSM+c ALGORITHM

Two cases are described to demonstrate the feasibility of applying the DSM+c algorithm to the power supply for an individual appliance (i.e. electricity-based thermal demand) on a real-time basis through an Internet-enabled energy system (IE-ES). The first case focuses on the investigation of demand flexibility. The second case further illustrates the responsive performance of the demand under the utilisation of a certain pattern of energy supply produced by a renewable energy system. Both cases prove the viability of the application of this algorithm at operational level.

7.1 Case Study 1: Investigating the Flexibility of Demand

Electricity-based thermal demands, such as those of water heaters, space heating/cooling systems and refrigeration systems, are suitable for DSM study. The purpose of these demand devices is to maintain a certain thermal comfort level, i.e., water/air temperature or humidity of air, within a room or a tank. As inertial features of these types of demand systems, they have a certain extent of flexibility. Some research (Williams et al. 2006) has concluded that inefficient control and people's lack of awareness are the cause of a significant amount of energy wastage, and that an increase/decrease of 1 or 2 ^{o}C over a short period of time will not be noticed by users. This flexibility can be used for better operation of the demand devices and to facilitate the usage of intermittent renewable energy without violating user convenience. In this case, the focus is on the operation of a domestic refrigerator at different thermostatic settings, in order to evaluate their influences upon the energy and thermal performance of the refrigerator.

7.1.1 Experimental System

An experimental system is established to investigate the performance of a domestic refrigerator under various pairs of thermostat setting-points using the developed DSM+c algorithm. The architecture of this experimental system is shown in **Figure 7-1**. It is comprised of two parts: hardware and software. The hardware includes the demand device, sensors, actuator and gateway, while the software contains the central database server system (EnTrak) and service-oriented application (MERIT, incorporated with the DSM+c algorithm).

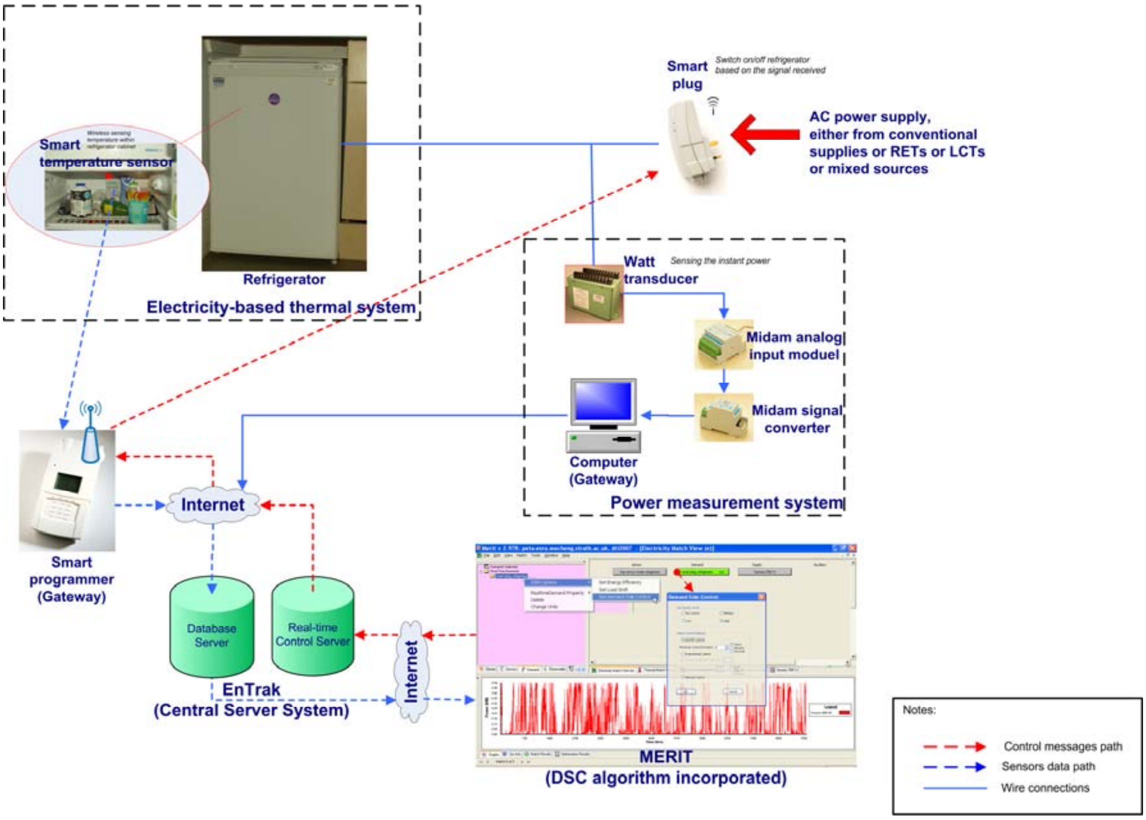
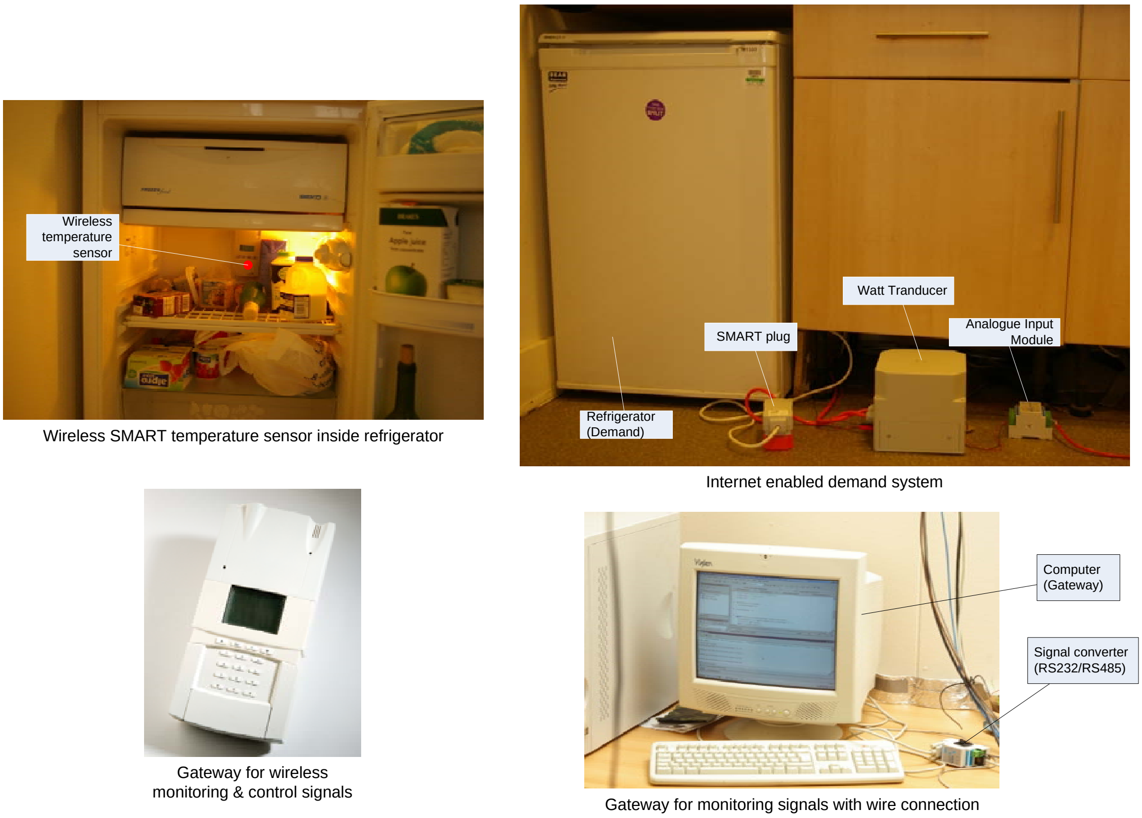


Figure 7-1: Experimental System for Refrigerator Control

- ***Hardware***

Most of the hardware devices used for the system are listed in **Figure 7-2**. A standard domestic refrigerator (RB12, [Beko Refrigeration plc, 2000]) is chosen as the tested demand device for this case study, as shown in the graph. The refrigerator is located in the kitchen on the third floor of the James Weir building at the University of Strathclyde. Two wireless SMART temperature sensors, manufactured by ADAM Communication Systems International Ltd (2007), are employed to monitor the temperature inside and outside the refrigerated cabinet respectively. The inside temperature sensor is attached to the inner wall of the refrigerator, shown in **Figure 7-2**. This monitors the temperature continuously and avoids the inner temperature extending beyond the prescribed range. Also, a watt meter is embedded in the main power supply circuit to monitor the power consumption of the refrigerator compressor and light. The plug of the refrigerator is replaced with a SMART plug (ADAM Communication Systems International Ltd, 2007), shown in **Figure 7-2**. This enables the refrigerator to be switched on/off according to the control signal received. In order to prove the proposed system is flexible and sufficiently generic to be able to accommodate different kinds of protocols, both wire and wireless communications are used within the system. The transmission of power consumption data is realised through a wired connection. The devices include analog input module Midam 500 and signal converter Midam 200, distributed by Mikroklima s.r.o (2007). The Mdiam 500 accommodates different ranges of analog inputs (±150mv, ±500mV, ±5V, ±10V etc.) for accommodating the outputs of different sensors. The Midam 200 enables the outputs from analog data sensors to be converted into RS232-type signal through ethernet cable, which can be connected to a normal computer. The computer serves as a gateway device, which sends the data to the central database server for further processing. Another type of gateway is the SMART programmer, shown in **Figure 7-2**. This manages the monitored signals from wireless temperature sensors and sends the control command to the wireless SMART plug as requested. The wireless network is based on proprietary RF technology (available 433.23~434.25MHz, also available as 868~870MHz and 902~928MHz). The SMART programmer (ADAM, 2007) not only sends the acquired temperature data to the central database server through the Internet, but also receives the control signal from the application to execute the actuator through the Internet.



Wireless SMART temperature sensor inside refrigerator

Internet enabled demand system

Gateway for wireless monitoring & control signals

Gateway for monitoring signals with wire connection

Figure 7-2: Key Hardware Components of the System

- ***Software***

The software is the brain of the system, combining all the devices organically and enabling them to perform the specified task. There are two principal applications in the system, the central database server (EnTrak) and the service-oriented application (MERIT). EnTrak stores the monitored data with a specified time interval. Depending on the type of monitored data, the time interval is different. For example, for the refrigeration system, the time interval for the compressor power of the refrigerator is specified as second-based, in order to capture transient power behaviour. For temperature, it is specified as minute-based data, as the temperature is updated by minutes. MERIT, incorporated with the DSM+c algorithm, acquires the specific data from EnTrak, processes them, generates the control commands, and sends back to execute the control upon the demand device through the Internet. All these functions happen on a real-time basis.

7.1.2 System Working Procedures and Scenario Description

As far as this case is concerned, the purpose is to investigate the impact of refrigerator performance under short-term changes in thermostat settings. This can be realised through adjusting the upper and lower thermostat setting values within the DSM+c algorithm. The key variable is the temperature inside the refrigerated place. This is monitored continuously using the wireless temperature sensor by which the refrigerator is controlled. The sampling frequency also can be specified, one minute in this case, which is accurate enough to detect changes. Subsequently, the data, together with the outside temperature, is transmitted to EnTrak through the SMART programmer gateway via the Internet. At the same time, the power consumption data is monitored using the watt transducer and sent to EnTrak though another gateway, the normal computer. MERIT then accesses EnTrak and acquires the latest data in terms of temperature and power consumption. The data are processed by the DSM+c algorithm within MERIT. The control logic is straightforward. If the inside temperature is beyond the thermostat cut-in point, the SMART plug is on, i.e., the compressor is in working status. If the temperature is lower than the thermostat cut-out point, the compressor is off. If the temperature is between the thermostat cut-in and cut-out points, the temperature in the previous time step needs to be taken into consideration when deciding the on/off status of the compressor. After the data are analysed, the control commands are generated based on the condition inside the refrigerator, and are initiated to control the refrigerator through the SMART plug on the demand side. Through the above procedure, the change to the thermostat settings within the refrigerator can be examined.

Several scenarios are designed to study the impact of changing the thermostat setting point upon the performance of the refrigerator. ***Scenario A*** monitors the normal operating condition of the refrigerator using the system introduced above. For convenience, the thermostat is set in the middle of the temperature range. The watt transducer and temperature sensor are used to measure the power consumption and temperature inside and outside the refrigerator respectively, the purpose being to understand the refrigerator’s thermal and electric energy performance under a certain original embedded thermostat control setting.

According to ASHRAE (2006), the reference temperature for a domestic refrigerated compartment of 5 ^{o}C is recommended. It is acceptable to store the food within a range of 3 ^{o}C variations of this referenced point, i.e. from 2 ^{o}C to 8 ^{o}C (FSA 2007). Based on this general guidance, two more scenarios, which use their own external control system by replacing the original control system in *Scenario A*, are proposed. The new control system is comprised of a wireless temperature sensor inside the refrigerator and the SMART plug as mentioned above. The SMART plug switches the refrigerator on/off depending on the value from the inside temperature sensor, in order to maintain its temperature within a certain safety range. Threshold temperature points can be configured inside the DSM+c algorithm in MERIT. Thus, different cut-in and cut-out temperature setting points can be specified within the DSM+c algorithm. In ***Scenario B***, the refrigeration system is controlled by the status of the temperature sensor inside the refrigerator, with the setting of the cut-in temperature at 5.5 ^{o}C and the cut-out temperature at 4.5 ^{o}C; energy supply is from the electricity grid. Similar to *Scenario B*, ***Scenario C*** is also controlled by the status of the internal temperature sensor and is powered from the grid. The difference from Scenario B is the temperature setting points, with the cut-in temperature at 6 ^{o}C and the cut-out temperature 4 ^{o}C. The detailed settings of these scenarios are listed in **Table 7-1**.

Table 7-1: Detailed Parameter Settings for Scenarios A, B and C

	Temperature-based control		Energy supply
	Cut-in point(^{o}C)	Cut-out point (^{o}C)	
Scenario A	thermostat (middle position)		Grid
Scenario B	5.5	4.5	Grid
Scenario C	6.0	4.0	Grid

7.1.3 Results and Discussion

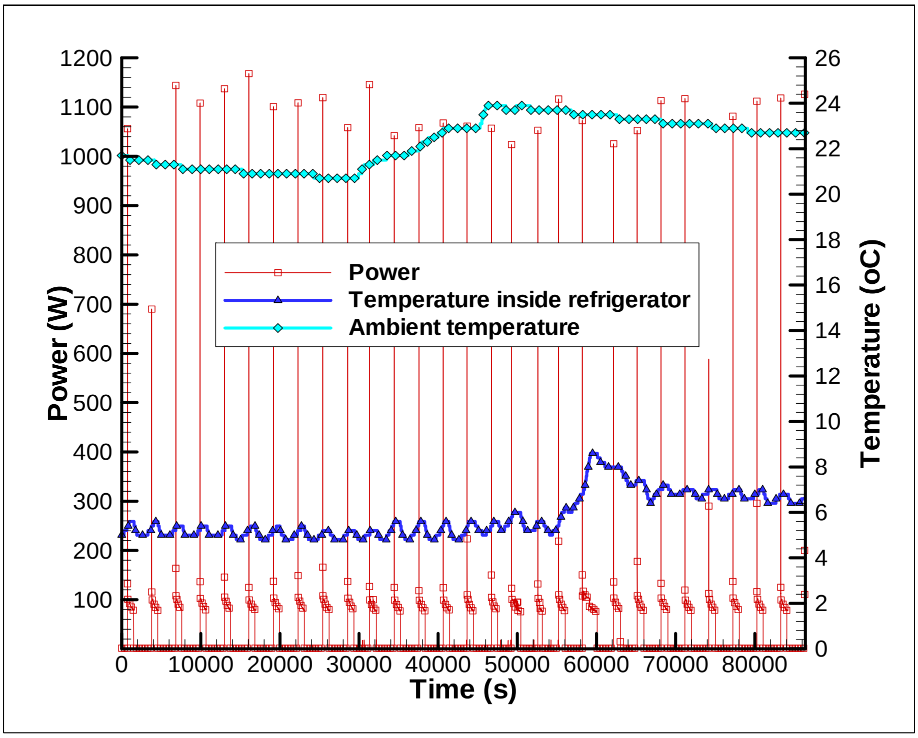


Figure 7-3: Daily Monitoring Results for Scenario A

Figure 7-3 shows the monitoring results in terms of compressor power, cabinet temperature, and ambient temperature for *Scenario A* within a normal weekday. From the pattern of the compressor power profile, it is clear that the refrigerator is controlled not only by the basic thermostat control but also by a cycle rate control. The cycle rate control indicates how often the compressor is turned on during a certain period of time. This enhances the temperature control performance. As can be seen, the cabinet temperature is well controlled. Among all normal cycles, there is only a small temperature swing of 0.8 ^{o}C. The temperature swing is calculated by adding the temperature differential, system lag, and system over-shoot. When the inside temperature reaches the cut-in point, the basic thermostat control is applied. This can be derived from the fact that the longer compressor operation period is found at the point around 16:00 (60000 s) as per **Figure 7-3**. Furthermore, under this scenario, the number of cycles of the compressor is 28. The starting current of the compressor is 6~10 times more than the normal operating current. Although the starting duration is short (only 1 or 2 seconds), a large number of start-ups will reduce the compressor life and energy efficiency. The energy consumption within one cycle is around 0.021kWh, resulting in 0.60kWh daily energy use. The ratio of energy delivered to temperature reduced is 0.0268kWh/ °C.

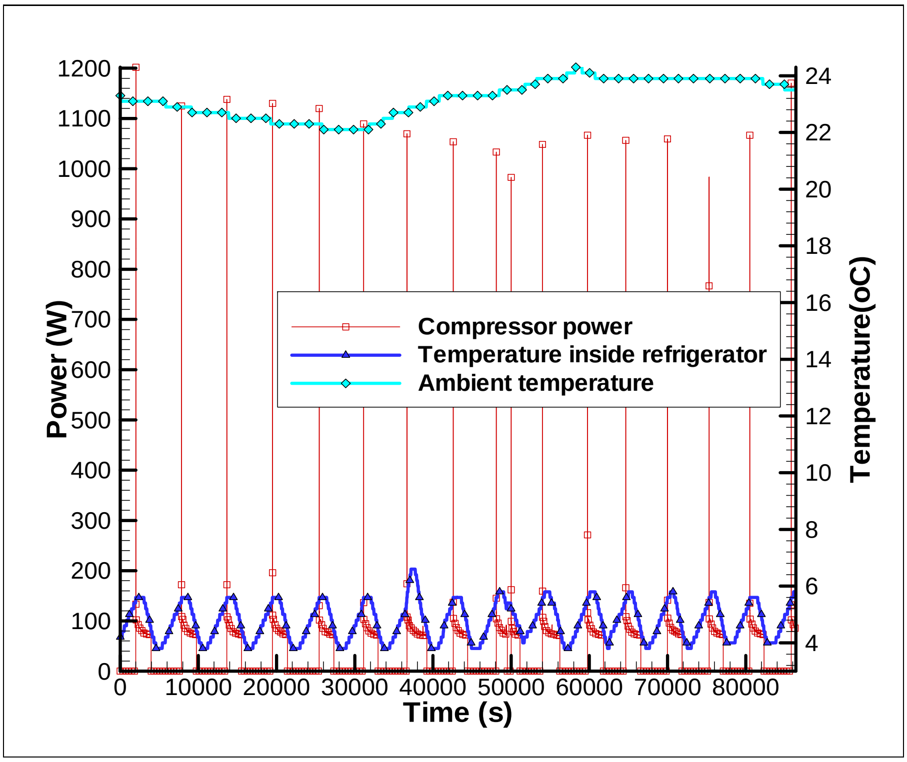


Figure 7-4: Daily Monitoring Results for Scenario B

Figure 7-4 shows the results of the refrigerator performance within a day for *Scenario B*. The control type – basic temperature-based control with cut-in (5.5 °C) and cut-out (4.5 °C) points – is applied to operate the refrigerator via the SMART plug. The patterns of compressor power and inside temperature are shown in the graph. The average temperature swing based on this type of control is about 1.8 °C per cycle. The energy consumption within a cycle is 0.0433kWh, resulting in 0.692kWh per day. However, the total on/off cycles of the compressor are significantly reduced, by around 50%, compared with that in *Scenario A*. The ratio of energy delivered to temperature reduced is 0.024kWh/ °C, which shows a slight improvement on *Scenario A*.

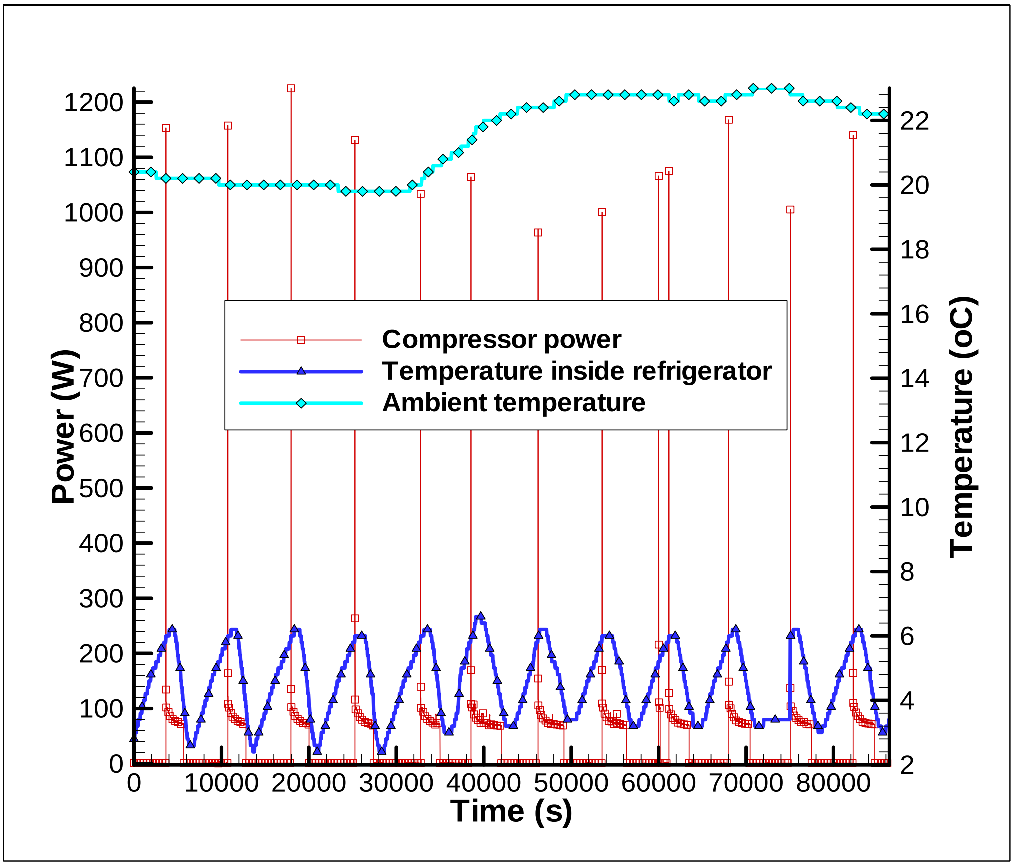


Figure 7-5: Daily Monitoring Results for Scenario C

Similar to *Scenario B*, the same type of control is adopted for *Scenario C*. The difference is the setting points, with the cut-out point at 4 °C and the cut-in point at 6 °C. This allows a wider range of temperature fluctuation within the cabinet. The results are shown in **Figure 7-5**. Comparing these to *Scenario B*, it can be seen that the average temperature swing within each cycle is higher, 3.3 °C, while the compressor starting time decreases by 25%, 12 times per day. The average energy consumption within one cycle is 0.0535kWh, indicating that the compressor runs longer than that in *Scenario B*. The total daily energy consumption for *Scenario C* is 0.642kWh, a reduction of 7.2% on *Scenario B*. In addition, the ratio of energy delivered to temperature reduced is 0.0133kWh/ °C, which shows a significant improvement of 44.6% over *Scenario B*.

As far as food preservation is concerned, no violation of food quality was found during the monitoring period. According to Morose (2003), a temperature fluctuation of 4 °C inside the refrigerator is acceptable. Furthermore, most food within a refrigerator is updated each week, so the impact of temperature fluctuations upon food quality can likely be ignored. However, this must be further strictly monitored, as it would cause potential health problems for users. Manufacturers should provide consumers with the information about foods suitable for refrigeration and their permissible temperature fluctuation ranges. A certain degree of temperature change for a short period is viable as long as it is within the tolerable range for the users, the refrigerator itself, and the food in it. This degree of flexibility makes it practical to integrate the DSM+c algorithm into a refrigerator control system.

7.1.4 Conclusion

This case study uses the DSM+c algorithm to exercise control over a domestic refrigerator by changing the thermostat setting-points. The impact of the DSM+c algorithm on the refrigerator's internal environment and energy performance was investigated. From the results of this case study, a certain degree of flexibility in respect of the thermostat settings is tolerable for a short period by the refrigerator contents, and at the same time it is beneficial to the refrigerator operation in terms of energy efficiency. This outcome lays the foundation for the next case, which investigates the potential for utilising the intermittent energy from green and low carbon sources.

7.2 Case Study 2 - Facilitating Intermittent Renewable Energy

The focus of this case study is on the application of the DSM+c algorithm to an individual appliance to facilitate usage of the power generated from intermittent renewable energy resources. Building upon the previous case, the DSM+c algorithm not only considers flexibility within the thermal demand system but also takes into account the availability of power supply from renewable energy sources. Depending on the value of the supply power and the environmental parameters at a certain time, the DSM+c algorithm initiates the control command upon the demand device to reshape the demand profile and better match it with the available supply.

7.2.1 Experimental System

An experimental configuration was established to investigate the performance of the demand system when demand is supplied with power generated from intermittent energy resources. The system was based on the one described in ***Case Study 1***, but a new module has been added, monitoring the conditions of the renewable energy generation plant. The architecture of the new experimental configuration is shown in **Figure 7-6.**

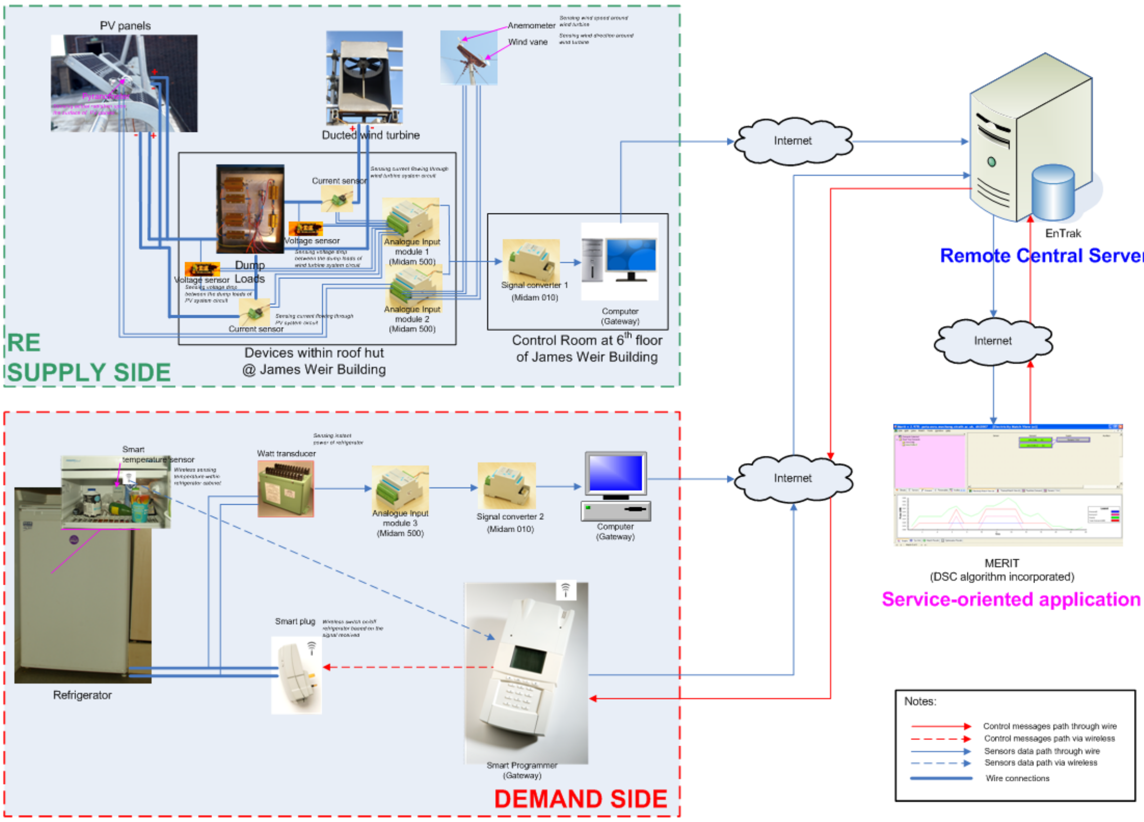


Figure 7-6: Architecture of the Whole Experimental System for Case 2

- ***Hardware (supply side only)***

Building upon the configurations of the experimental system in the previous case, this case integrated the renewable energy systems consisting of two PV panels and one ducted wind turbine. Sensors for monitoring the performance of PV and ducted wind turbine systems were connected to a gateway (i.e., a computer in this case) using wire and ethernet cable through which weather conditions and energy data associated with these two systems were monitored and transferred to the central database server (EnTrak). In this particular case, two PV panels, shown in **Figure 7-**

7, were selected as an example of an energy source to supply the energy demand of the above-described domestic refrigerator. These two PV panels are manufactured by BP Solar (2004) and rated at 80W each. The parameters for this type of PV panel are illustrated in **Table 7-2**. A highly-sensitive pyranometer with the generation of a voltage output (4.73μV/W/m^2), shown in **Figure 7-7**, was also installed to measure the incidental radiation on the tilted PV panels. The AC/DC current sensor (±20A) and precision voltage sensor (±30V) from Phidgets (2008), shown in **Figure 7-8**, were used to monitor current flow and voltage drop continuously within the circuit of the PV system. These two sensors were both calibrated before being installed within the circuit. The signals from each sensor were sent to the central database server (EnTrak) every minute via the Internet simultaneously. The power generated by the PV panels was emulated based on the monitored current and voltage data through which the pattern of energy output from the PV system could be obtained. In addition, the aluminum-housed wire-wound resistors, shown in **Figure 7-9**, were used to dump the energy generated by the PV panels.

Figure 7-7: PV panels and Pyranometer Installed on the Roof of James Weir Building, Glasgow

Table 7-2: Specifications of the PV System

Parameter	Value
Manufacturer	BP Solar
Cell type	Mono-crystalline
Nominal power (W)	80
Maximum power point current (A)	4.72
Maximum power point voltage (V)	18.0
Short circuit current @ STC(A)	5.0
Open circuit voltage @ STC (V)	22.03
Standard test condition (STC) temperature (ºC)	25
Standard test condition (STC) isolation (W/m^2)	1000
Panel height (m)	1.197
Panel width (m)	0.530

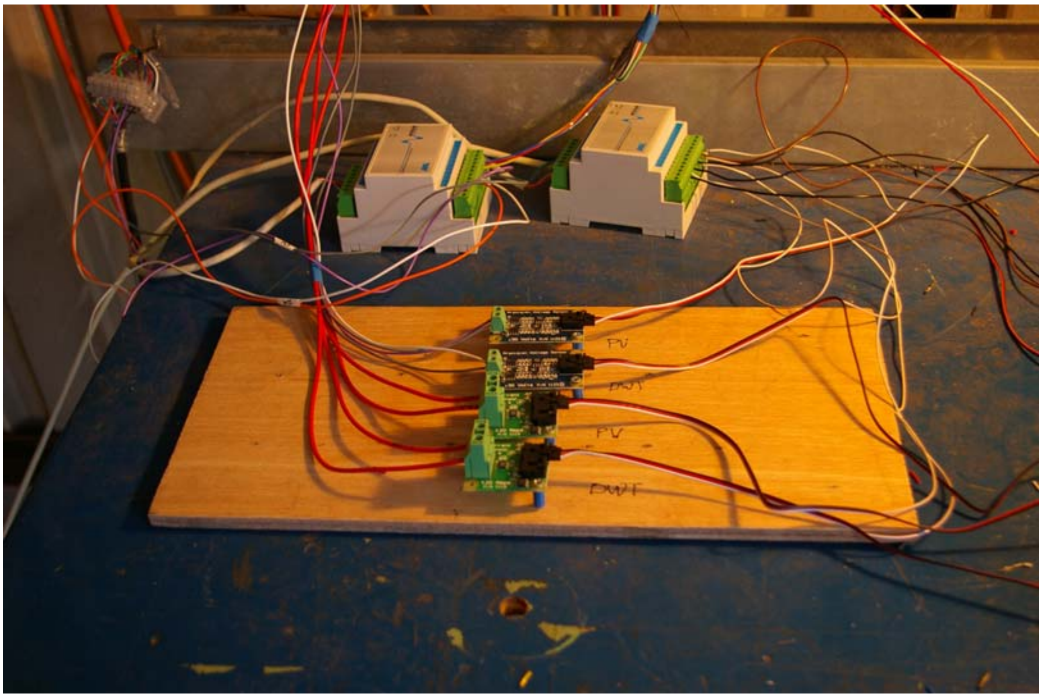


Figure 7-8: Sensors for Measuring Energy Output from the PV and Wind Turbine System

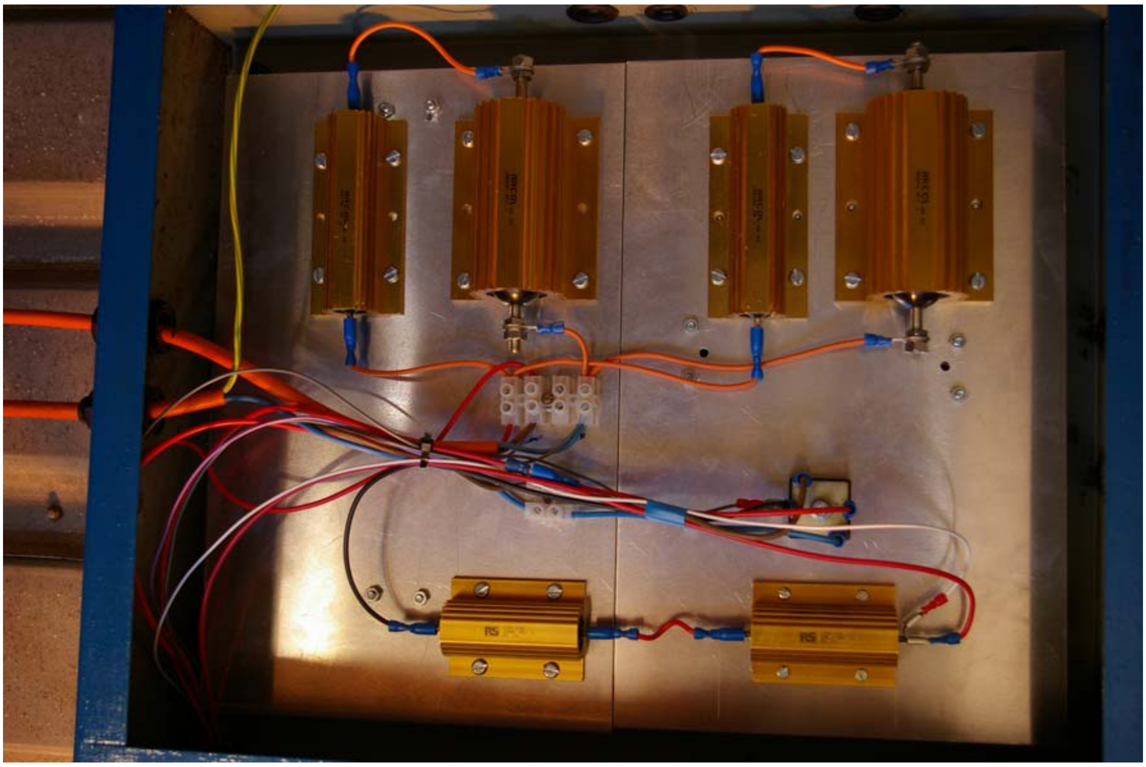


Figure 7-9: Load Dumping Devices

- ***Software***

Apart from the environmental variables (inside temperature in this case), another factor – instantaneous power supply from RE resources – was also taken into account within the DSM+c algorithm. After having processed the data within the DSM+c algorithm, the control commands, containing the information of which demand device was to be controlled and when, were generated and transmitted via the Internet to the remote database server. In this case, these commands were executed to control the operation of the refrigerator through the use of a SMART plug.

7.2.2 Description of the Scenario and its Procedure

In *Case Study 1*, all the scenarios were designed considering only the environmental variable (the temperature inside the refrigerator). However, while the reference scenario in *Case Study 1* was adopted as a reference point in this case, a new scenario (***Scenario D***) was also developed, focusing on the investigation of environmental data relating to the demand system together with supply data from intermittent renewable energy resources. The main objective of *Scenario D* is to examine the operational performance of the demand system and test the robustness of the DSM+c algorithm under intermittent energy supply conditions on a real-time basis.

Scenario D used the same approach as the scenarios in Case Study 1 to specifying the cut-in and cut-out temperature set-points for the compressor operation. These set points can be adjusted to the users' requirements inside the DSM+c algorithm. The difference, however, was that the energy demand (i.e., of the refrigerator in this scenario) was supplied with the power produced by PV panels. Furthermore, a two-minute delay period for the refrigerator's compressor in switching was considered within the DSM+c algorithm, in order to avoid the negative impact of high starting torque on the compressor (Bjork and Palm, 2006). The value of the delay time can also be re-specified within the DSM+c algorithm. In order to obtain more accurate and detailed data, the sampling time interval for the temperature and power were set as 30 seconds and 1 second respectively. The detailed parameters for this scenario are illustrated as follows:

Scenario D

Demand side:

Cut-in temperature --- 6.0 ºC

Cut-out temperature --- 2.0 ºC

Delay-time for compressor restart-up --- 2mins

Supply side:

Two PV panels from BP, rated at 80W each

7.2.3 Results and Discussions

Currently the system is used to monitor the power consumption of the refrigerator, the inside temperature of the refrigerator compartment, the outside ambient temperature, and the power produced by the PV panels on the supply side simultaneously. The data captured is then stored in the central database server. The service-oriented application, MERIT with the DSM+c algorithm incorporated, is able to carry out demand-side control analysis on the appliance, based on the availability of supply from the PV system. These components communicate with each other through the Internet connection. The energy and environmental data on both the demand and supply sides before and after having the DSM+c algorithm applied are illustrated as follows.

Within this case study, the current and voltage components are monitored using a current sensor and voltage sensor at one-second timesteps. The results for the refrigerator's operation during a typical summer's day in Glasgow (30 July 2008) are shown in **Figure 7-10**. The power is calculated according to the monitored current and voltage results, as shown in **Figure 7-11**. It can be seen from the supply pattern generated by the PV panels, that no power is generated during the early morning and late evening, and that the majority of power generation occurs during the afternoon. This finding represents a typical power supply pattern from a PV-based renewable system in this type of case. The demand from a domestic appliance is also monitored and shown in **Figure 7-12**, which is used as a reference scenario for this case study.

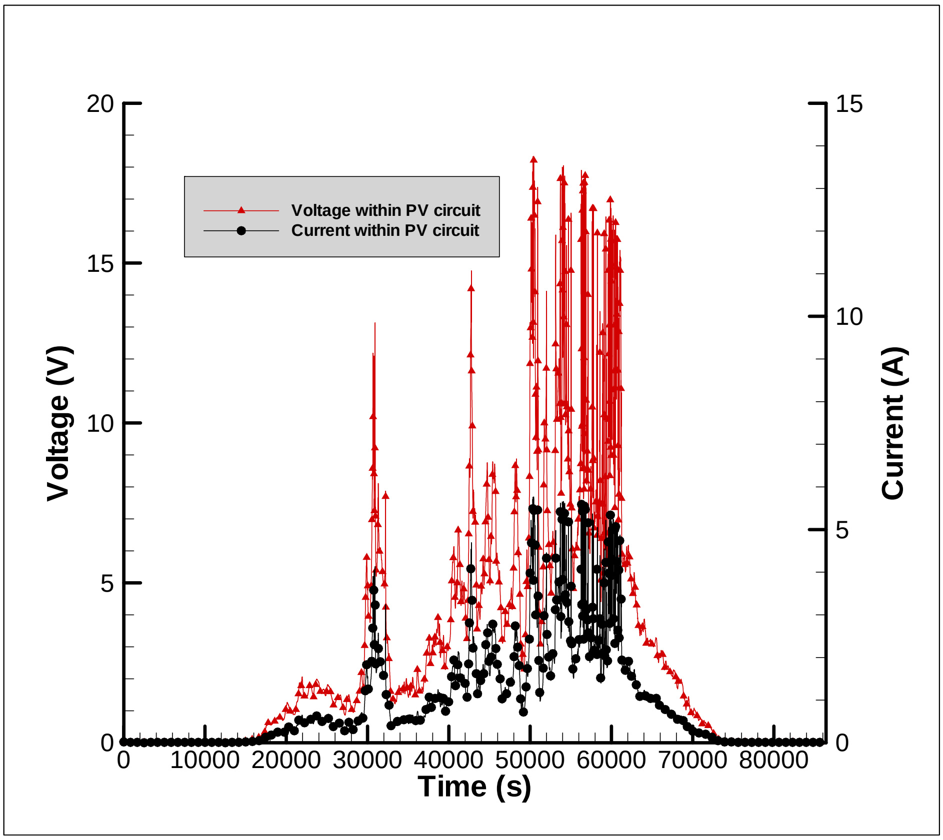


Figure 7-10: Daily Monitored Results for Voltage and Current within the PV Circuit (On 30-07-2008)

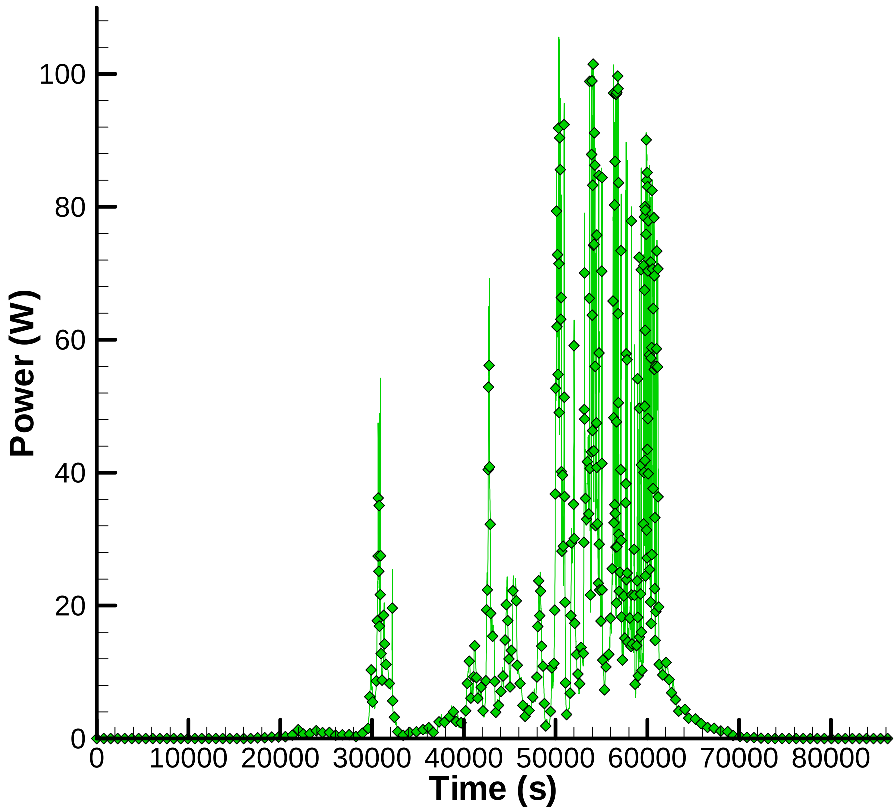


Figure 7-11: Power Produced by the PV Panels on the Roof of James Weir Building in Glasgow

In order to show the match between the original refrigerator demand and the PV supply clearly, some of the daily monitoring results (from 7:10 am to 7:30 pm) are used, as shown in **Figure 7-12**. As can be seen, the mismatch problem is obvious. During some periods (from 30 000 s to 40 000 s), the supply is insufficient to meet the required demand, yet for others (from 42 000s to 44 000s), the supply produced by the PV is wasted as there is no demand, and for other periods, the supply generated is greater than the demand. The actual PV systems doesn't generate sufficient supply to meet the energy demand of the refrigerator. In order to make the refrigerator work most of time and the effect of the DSM+c algorithm obvious, the magnitude of supply is scaled up to a certain extent (assumed as seven for this case). This could be achieved by adding more PV panels to the system. The new match graph between the increased capacity of the PV system and the refrigerator demands appears in **Figure 7-13**. The analysis of the effect of the DSM+c algorithm is based on the scaled-up supply profile.

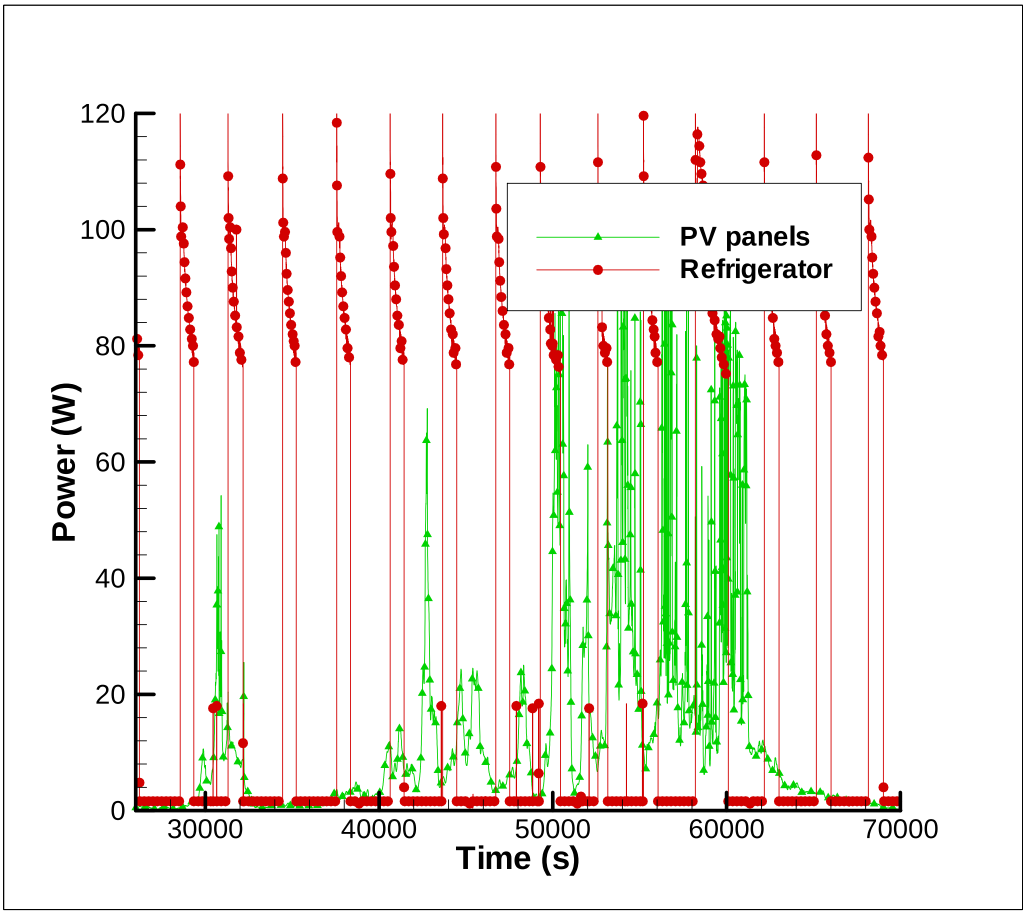


Figure 7-12: Match between PV and the Refrigerator based on Actual Monitored Data

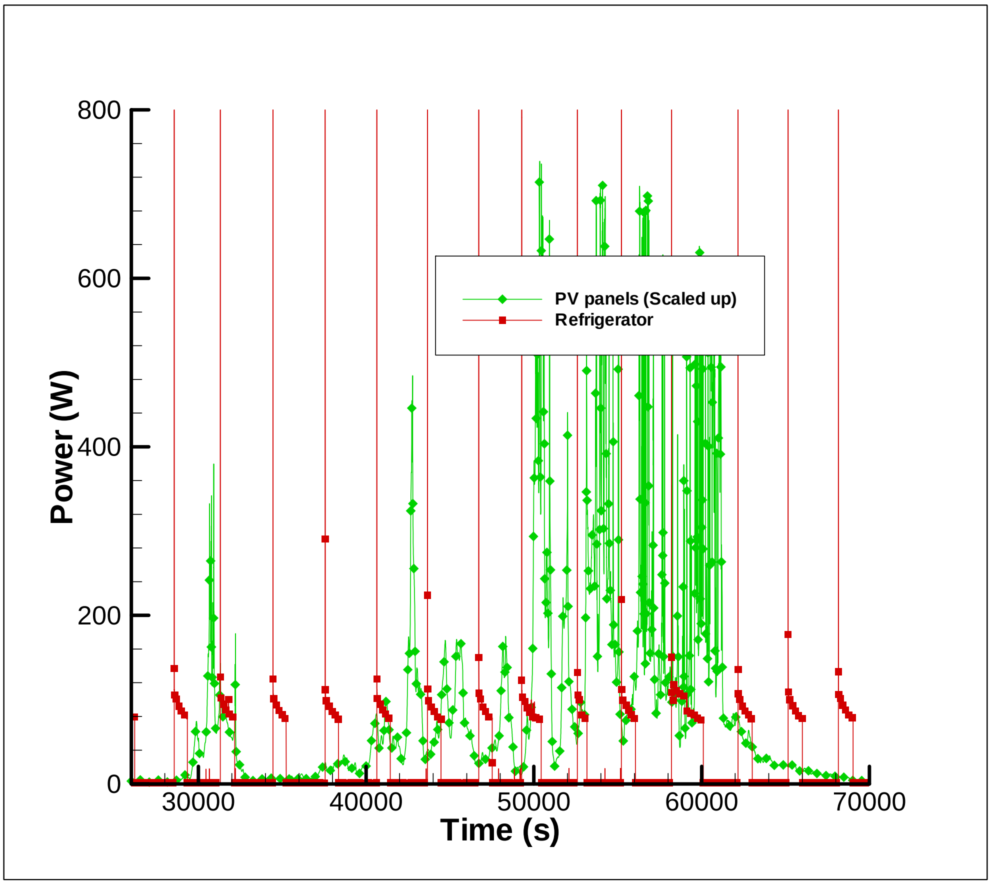


Figure 7-13: Match between PV with Scaling Factor and the Refrigerator based on Actual Monitored Data

After having applied the DSM+c algorithm to the refrigerator, the refrigerator was able to respond to the supply profile produced by PV. **Figure 7-14** shows the results when the refrigerator is driven by real-time supply data from the PV panels, and the specified safety range of the inside temperature. As can be seen from the graph, the compressor is switched off when there is not enough PV power available. Because of its high insulation, the inside temperature increases gradually. When there is sufficient PV power the compressor is turned on and the inside temperature drops correspondingly. The average temperature within the cabinet is around 4.5 ºC. No data point falls out with the predefined temperature cut-in and cut-out set points ranges. For the cases when the temperature monitored is beyond the range of the cut-in and cut-out set points, the supply from another source will be introduced or the compressor will be switched off, as both situations would likely harm the contents of the refrigerator. The pressure difference between the inlet and outlet of the compressor remains high after the refrigerator is switched off due to the existence of the expansion valve. A certain time is needed to balance the pressure on both sides of expansion valve. As mentioned above in *Section 7.2.2 Experimental System*, a two-minute delay period is introduced to avoid high starting torque of the compressor associated with the protection of refrigerator. That means that even when there is enough supply to power the compressor, the refrigerator will remain off for two minutes. After having applied the DSM+c algorithm, the demand follows the intermittent supply sources. A certain specified level of environmental satisfaction can be maintained. Through adjusting the environmental parameter settings and utilising the conventional supply as an auxiliary, the specified requirement can be achieved and at the same time supply better matched to demand can be realised.

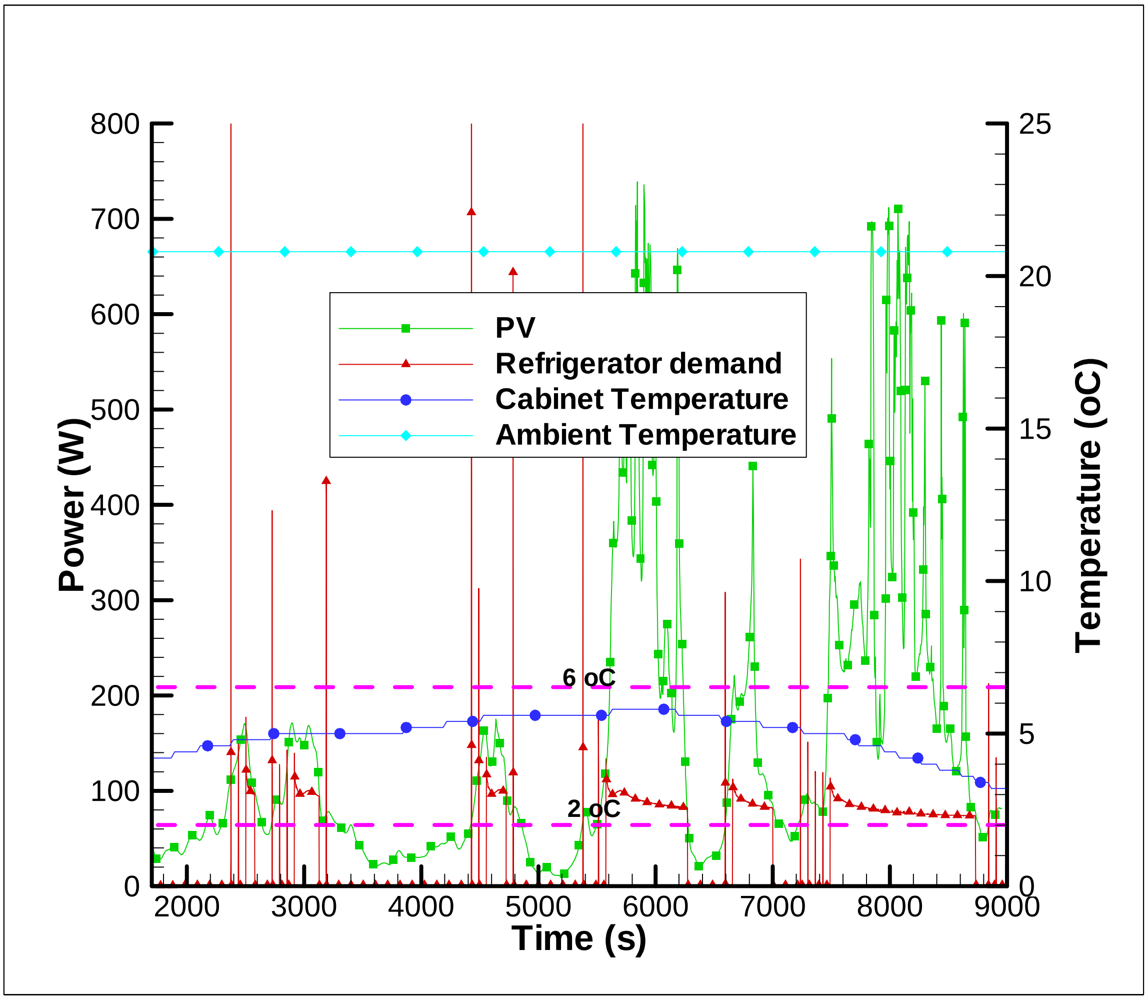


Figure 7-14: Monitoring Results for Case D after Applying the DSM+c Algorithm

7.2.4 Conclusion

This case study uses the DSM+c algorithm to realise control over a domestic refrigerator based on the supply pattern generated by PV panels, and also investigates the impact on the refrigerator's internal environment and its energy performance. From this study, it was shown that the energy demand of the refrigerator has been manipulated to match the available supply from PVs better, and also the temperature inside the refrigerator was maintained within the acceptable range. If users are more concerned about the temperature, they can be satisfied by adjusting the on/off temperature, and backing with the conventional energy supply. According to different user demands, the algorithm can be adjusted by changing the parameters.

7.3 Summary

.This chapter has discussed the use of the DSM+c algorithm under operational level in two cases. The first case investigated the feasibility of the algorithm at the operational level. It demonstrated that, through advanced IT technology, the DSM+c algorithm can maximise the use of renewable energy and low-carbon-emission energy systems based on pre-set environmental parameters. The DSM algorithm is generic and can be applied to any heterogeneous mix of devices at various scales. For large-scale DSM applications in respect of heating, cooling, and lighting systems, the algorithm can be deployed via the Internet. With the assistance of the DSM algorithm, the feasibility of better matching demand with certain RE and LCE (Low Carbon Emission) supply systems can be realised through introducing flexibility into demand.

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CHAPTER EIGHT CASE STUDY ON STRATEGIC APPLICATION OF DSM+c ALGORITHM

This chapter shows the whole decision-making process in the context of designing a next-generation multi-family building in Korea, in order to determine the best strategy for both demand and supply options. Particularly the role of the DSM+c algorithm within the procedure at the initial design stage is illustrated.

8.1 Background

The feasibility of applying DSM+c algorithm at operational level was demonstrated in last chapter. This chapter will look at the viability of using DSM+c algorithm for a strategic solution to design zero/low carbon energy systems in the context of a multi-family building. The selected multi-family building is used to analyse the potential for applying the DSM+c algorithm, as part of the outcomes of the PLUS50 project for the KICT (Korean Institute of Construction Technology).

The reason to use this as a case within this thesis is that the appliance-specific demand data with one hour frequency was available from KICT where as UK data was not device specific but house level. On the other hand, it’s believed that the role of DSM+c algorithm would become vital if it is applied to a larger scale, as the flexibility of demand at large scale is high and the demand varies in a great deal of diversity. The total demand curve can be shaped into more favorable for the integration of energy from intermittent and low carbon sources. The impact of DSM+c algorithm upon consumers can also be reduced.

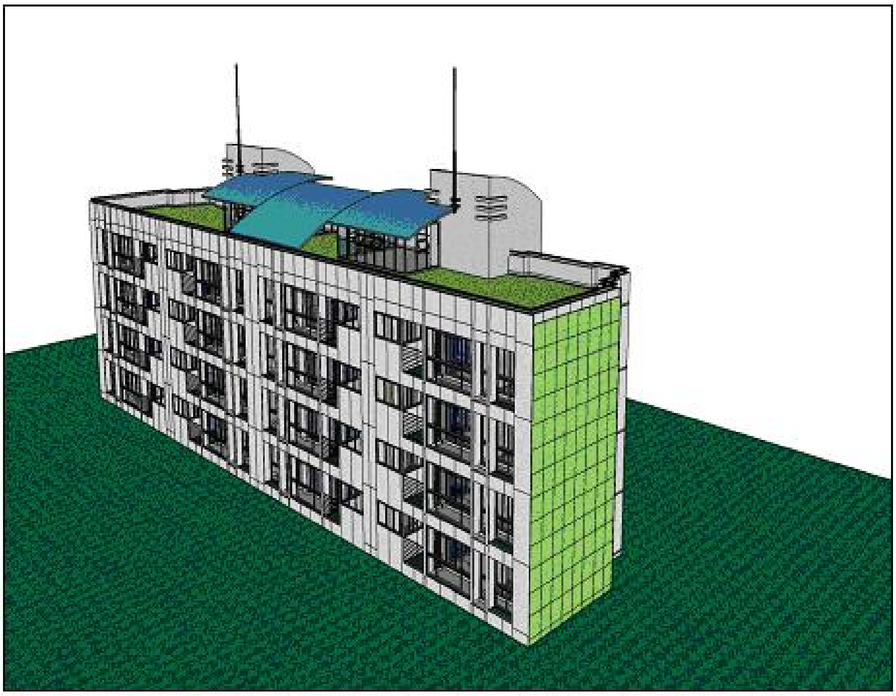

Figure 8-1: The PLUS50 building

The purpose of the PLUS50 project is to develop design technologies, construction structures, materials and energy systems for residential buildings which prolong building life by 50% and reduce environmental impact by 50% (KICT, 2004). A demonstration building will be constructed in an urban area of Seoul in Korea during the course of the research. One PLUS50 building design, as illustrated in **Figure 8-1**, comprises 16 households with four apartments on each floor. The study focused on the feasibility of building design options (e.g. roof shape, orientation etc) and RE systems including PV, solar collectors and heat pumps. In addition to RE systems, an LC system such as μCHP is a useful auxiliary device to compensate for the gap between renewable energy supply and residential energy demand. Because it can generate electricity and heat simultaneously, it is important to operate the system effectively to match the year-round heating and electricity loads. Due to the ever-changing demands, it is necessary to investigate strategies for simultaneously meeting heating and electricity loads within the PLUS50 building at the same time. The project concentrates on matching the outputs from LC and RE systems, called Hybrid Energy (HE) systems, with the demands.

Within the project, several distributed generation technologies, such as PV, CHP and Heat Pump etc., are proposed as supply options for the building. With the high percentage of renewable and low carbon energy supply technologies, the supply profile will become much more volatile than with a conventional supply method. The weather-dependent renewable energy systems have intermittent features and are difficult to predict, thereby demonstrating their limited capability to satisfy the required demand. Low carbon energy systems, such as CHP etc., are sensitive to the shape of demand profiles, as their overall efficiency and the environmental impact vary dramatically under different operating conditions. On the other hand, the building is intended for various types of families with different lifestyles. Its characteristic diversity offers better opportunities for designing DSM strategies without the loss of user satisfaction. Therefore, it is believed that the proposed DSM+c algorithm can play a vital role in managing the loads on the demand side, and thus better facilitate the energy generated by renewable or low carbon energy systems throughout the whole decision-making process.

8.2 Match Analysis

It is necessary to evaluate key technology elements in an integrated manner and establish appropriate strategies for demand/supply matching. The aim of this study is, therefore, to identify the effect of energy-efficient demand measures (e.g. roof-top gardens, innovative under-floor heating systems), maximise the utilisation from RE systems, and optimise the performance of LC systems.

8.2.1 Climate Analysis

ESP-r weather data for Seoul (37.34°N, 8.42°E) in 1983 (ESRU, 2006) was employed for the case study. According to the degree days (DD) analysis, the cooling DD (204.6 at 23ºC) is less than 10% of the heating DD (2637.4 at 17ºC), i.e. the heating load comprises the majority of the total load. While solar energy resources are readily available throughout the year (**Figure 8-2**), the annual wind speed distribution is mostly lower than necessary for effective wind energy generation

(**Figure 8-3**). Considering the wind speed reduction due to the urban location of the building, the feasibility of wind turbines is questionable.

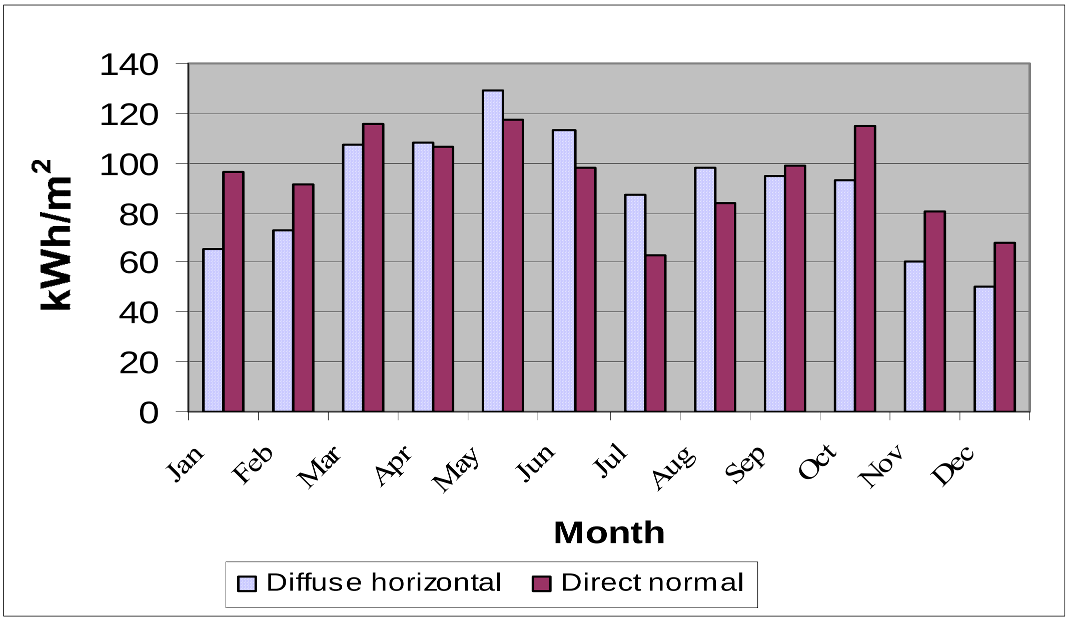

Figure 8-2: Monthly Solar Radiation

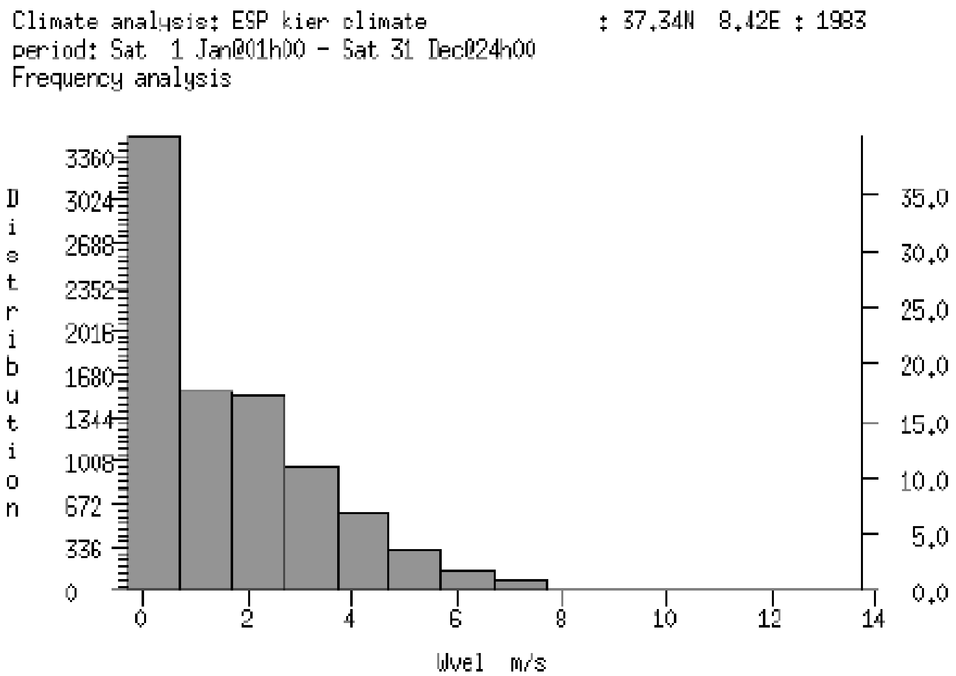

Figure 8-3: Frequency Histogram of Annual Wind Speed

8.2.2 Demand Profiles

Three types of demand profiles are examined in this case: electricity load, domestic hot water demand, and demand for space heating/cooling purposes.

Domestic hot water (DHW) and electricity demand are generally associated with occupant life-styles rather than climatic factors, so monitored and statistical data of 200 existing households within the same region were used. Typical DHW and electricity demand profiles were obtained from on-site measurement (KICT, 2004). To increase or decrease the magnitude of the profile, whilst maintaining its shape, a daily demand module was applied to the profile for different time periods throughout the year and for different days of the week.

In the same way, an annual DHW profile was generated on the basis of typical DHW demand data. **Figure 8-4** illustrates typical DHW profiles by season (winter, transition, and summer) assuming that the profiles of weekday and weekend are identical. A generated weekly DHW demand profile for 16 households is shown in **Figure 8-5**. The generated data were then imported into EnTrak database (Kim, 2004) to be used in the matching analysis.

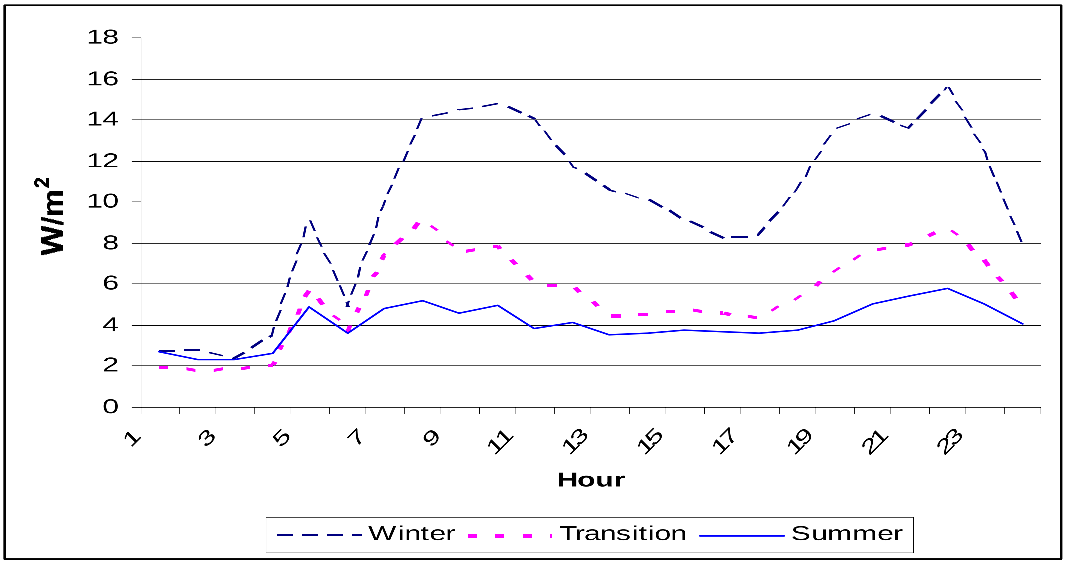

Figure 8-4: Typical Hot Water Profiles by Season

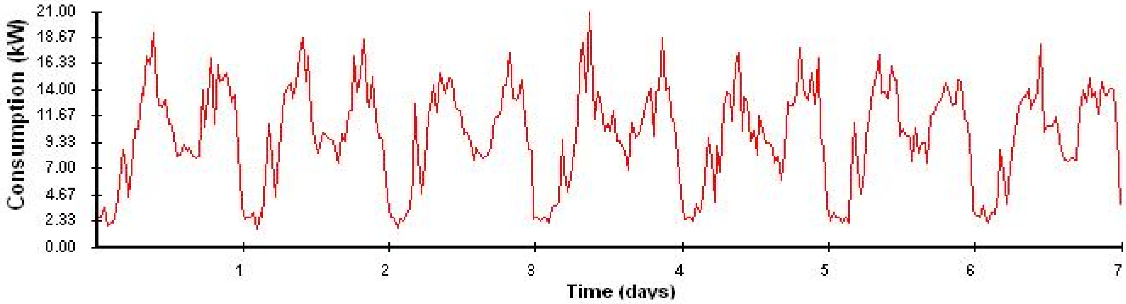

Figure 8-5: A Generated Weekly DHW Demand Profile (15/01/1983~21/01/1983)

Electricity demand profiles were based on a survey conducted by the Korea Power Exchange (2004), in which typical daily use patterns of home appliances were identified through the seasons by monitoring the electricity usage of 500 households. The typical electricity usage pattern was adjusted for the PLUS50 building (i.e. 16 households) and extended to cover annual profiles using MERIT's profile designer. **Figure 8-6** shows the demand profiles of home appliances during a week while **Figure 8-7** shows the total electrical demand profile of the PLUS 50 building on the basis of the individual electrical profiles.

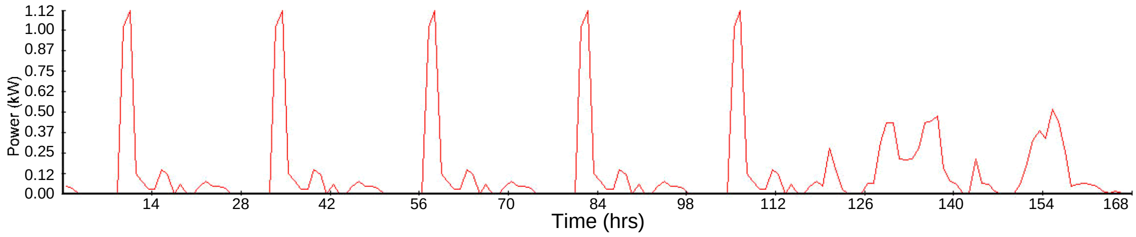

Figure 8-6 (a): Audio

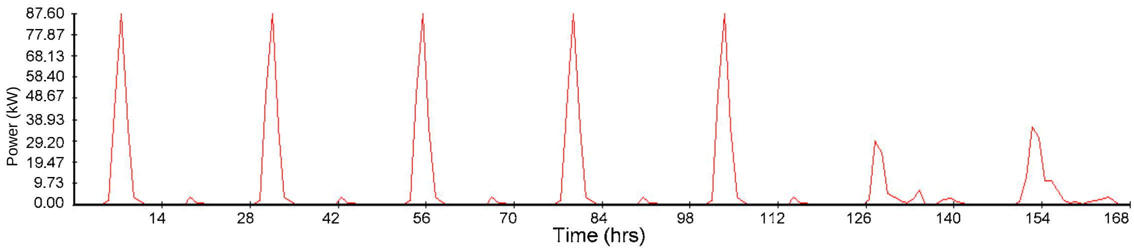

Figure 8-6 (b): Hair dryer

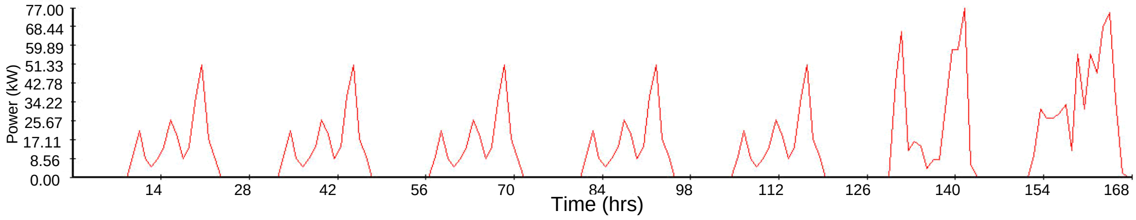

Figure 8-6 (c): Ironing

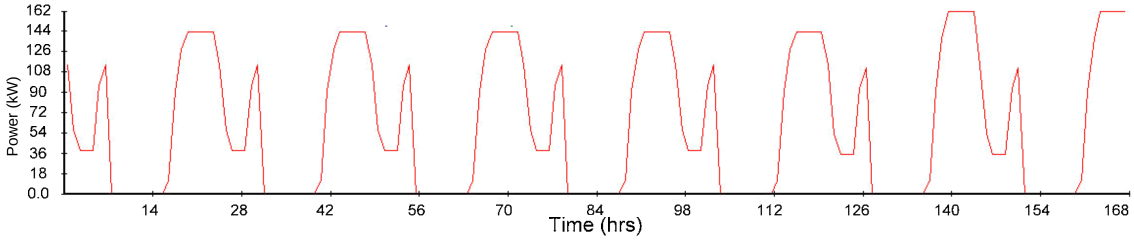

Figure 8-6 (d): Light

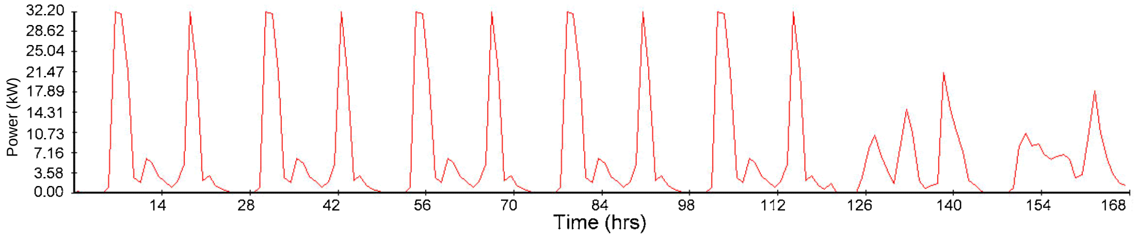

Figure 8-6 (e): Micro wave

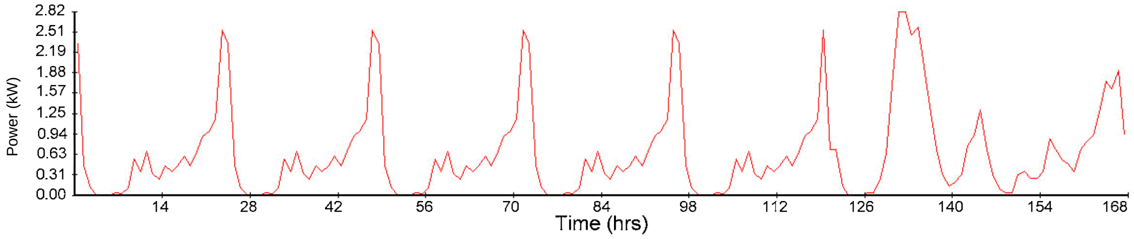

Figure 8-6 (f): PC

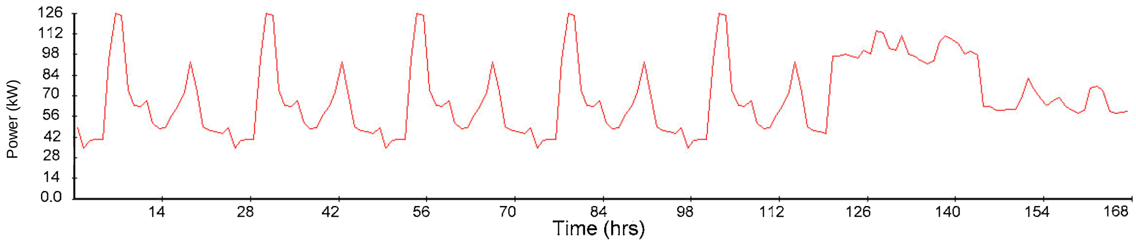

Figure 8-6 (g): Slow cooker

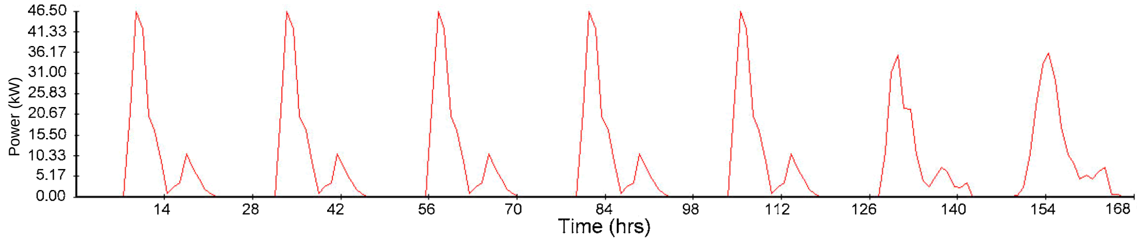

Figure 8-6 (h): Vacuum cleaner

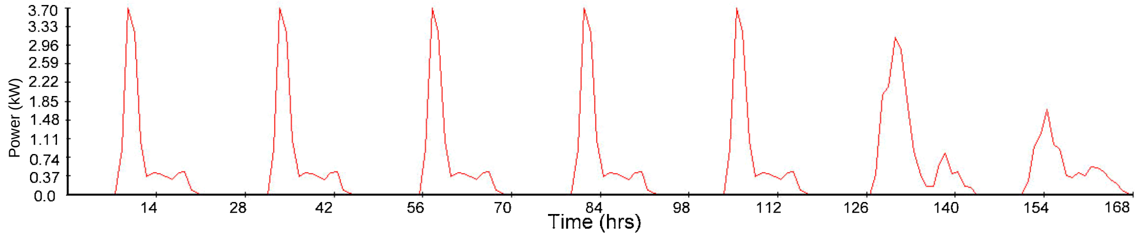

Figure 8-6 (i): Washing machine

Figure 8-6: Typical Demand Profiles of Home Appliances in Korea

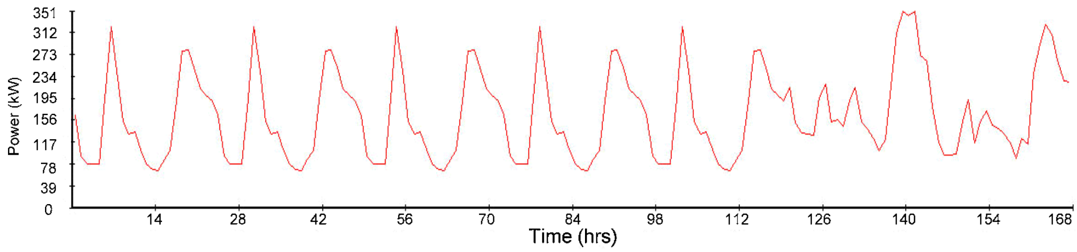

Figure 8-7: Total Electricity Demand Profile of the PLUS50 Building

The heating/cooling load profile is dependent on the building design and is directly related to climatic factors. A detailed simulation technique was adopted to create the load profiles. To this end, a reference building model was created based on an initial design for the PLUS50 project through using detailed dynamic building simulation software ESP-r, shown in **Figure 8-8**. The construction represents a typical Korean multi-family dwelling equipped with an under-floor electricity-based heating system. The model focuses on a column of apartments in the building in order to identify the thermal characteristics of apartments located vertically, which are decided by factors like solar gain and the heat exchange rate between floors associated with the under-floor heating system. Apartments consist of three zones: room, front balcony and back balcony. To model the under-floor heating system, an energy supply zone is introduced beneath each apartment. This zone is controlled by a multi-sensor controller that supplies energy in response to apartment temperatures.

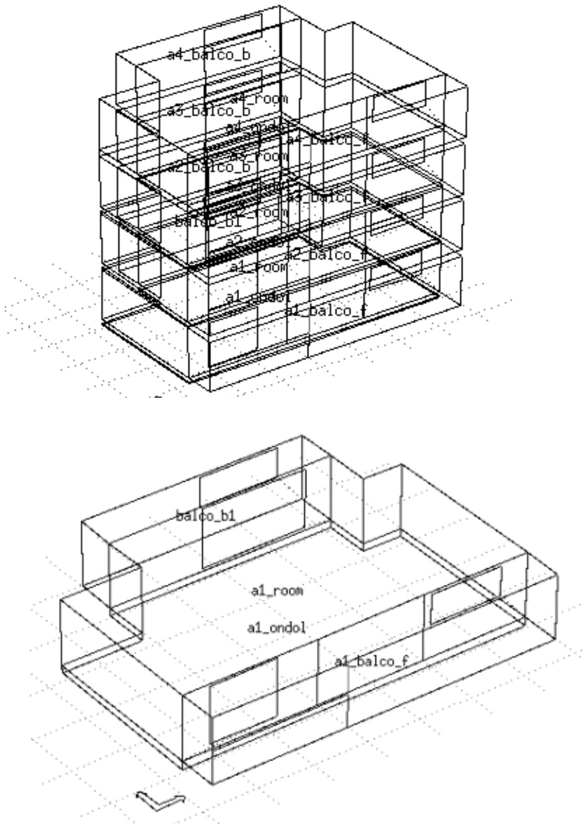

Figure 8-8: ESP-r Model of the PLUS50 Building

The simulation results indicate that this model reasonably represents the thermal characteristics of an apartment with an under-floor heating system. Based on this reference model, various design scenarios were explored (e.g. a conventional under-floor heating versus a low energy under-floor heating system). The simulation results were then imported into EnTrak for subsequent matching using MERIT.

8.2.3 RE and LCE Supply Options

Ideally one should consider as many RE and LCE supply options as possible in order to meet the demand. From the climatic analysis, it was shown that the wind resource in Korea is insufficient for wind turbine operation. Therefore, other options such as solar collectors, PV panels, ground source heat pumps, and micro-CHP systems are chosen as possible sources, with the expectation that the best combination among these types of energy supply will be identified as the outcome of the analysis.

The manufacturer's information regarding each supply technology is illustrated as follows. The specification of the solar collector system used within the matching analysis is illustrated in **Table 8-1**. The PV system is dedicated to the domestic electricity demand and incorporates a battery to improve the match. The specification of the PV system (BP Solar, 2004) is shown in **Table 8-2**. The capacity and COP of the heat pump system are 10 kW and 3.8 respectively for heating. Assuming that the heat pump is operated in an on/off mode, the supply from the system is essentially constant as ground temperature at a depth of 70-100m is steady at around 13ºC in winter and 15ºC in summer according to year-round field measurement taken by the Korea Institute of Construction Technology. A 30 kWe µCHP was selected for the PLUS50 building in favour of a 50 kWe supply to meet demand (Clarke et al. 2006). The specification of the µCHP is shown in **Table 8-3** (Energy Nexus Group, 2002). All the systems were defined according to the structural conditions of the PLUS50 building type.

Table 8-1 Specification of Solar Collector

Parameter	Value
Collector length (m)	2.49
Collector width (m)	1.323
Collector depth (m)	0.095
Plate thickness (m)	0.0005
Plate length (m)	1.17
Plate longwave emissivity	0.95
Plate solar absorbance	0.95
Plate conductivity (W/mK)	380
Number of tubes	11
Spacing between tubes	0.0114

Table 8-2: Specification of PV System

Parameter	Value
Manufacturer	Siemens
Cell type	Mono-crystalline
Nominal power (W)	110
Maximum power point current (A)	6.3
Maximum power point voltage (V)	17.5
Short circuit current @ STC(A)	6.9
Open circuit voltage @ STC (V)	21.7
Standard test condition (STC) temperature (ºC)	25
Standard test condition (STC) isolation (W/m^2)	1000
Panel height (m)	1.32
Panel width (m)	0.66
Number of cells in parallel	1
Number of cells in series	72

Table 8-3: Specification of Micro-CHP System

Parameter		Value
Fuel Type		Natural Gas
LHV (MJ/m^3)		34.6
Nominal Power (kW)		30
Engine Type		Micro-turbine
Fuel Consumption (m^3/min)	25%	0.13
	50%	0.22
	75%	0.29
	100%	0.37
Turbine Efficiency (%)		92
Electrical Efficiency (%)		98
Generator Efficiency (%)		92
Electricity Frequency (Hz)		50/60
Heat-to-Power Ratio	25%	4.44
	50%	2.83
	75%	2.33
	100%	1.99

8.2.4 Match Results

Several scenarios are created to compare the match results of different combinations of demand and supply options. The detail of each scenario, listed in **Table 8-4**, is used to evaluate energy performance, the environmental impact of demand measures and incorporated technologies.

Table 8-4: Scenarios for Match Analysis in Detail

Case	Demand	Supply
Reference	Conventional Ondol*/roof	Gas Boiler
PLUS50	Panel-type Ondol, roof-top garden, reinforced insulation	Gas Boiler
RE 1	PLUS50 building	Solar collectors, gas boiler
RE 2	PLUS50 building	PV, gas boiler
HE 1	PLUS50 building	Solar collectors, heat pump
HE 2	PLUS50 building	PV, heat pump
HE 3	PLUS50 building	CHP
HE 4	PLUS50 building	CHP, solar collectors
HE 5	PLUS50 building	CHP, PV
HE 6	PLUS50 building	CHP, heat pump

*: under-floor heating system

The '*Reference*' case represents a conventional domestic building, while the '*PLUS50*' case represents a PLUS50 building model with demand measures adopted for thermal performance. Supply systems for both the '*Reference*' and '*PLUS50*' cases are conventional options (i.e. gas boilers for thermal requirements [heating and DHW] and the grid for electricity demand).

The demand of '*PLUS50*' case was used for all of the other scenarios with RE and LC supply systems.

'*RE 1*' and '*RE 2*' cases are examples of RE systems with gas boilers based on the '*PLUS50*' case. The solar collectors (84 panels) for the '*RE 1*' case or photovoltaic panels (229 panels) for the '*RE 2*' case are installed on the roof (256m^2 coverage).

‘*HE1*’ to ‘*HE6*’ cases are possible combinations of REs and LCs with the ‘*PLUS50*’ case.

The assumptions of this case study are as follows: The CHP follows thermal demands for all cases. No thermal storage was considered in this study. DHW, electricity demand profiles apply to all cases. It is assumed that electricity from the grid is imported when the RE and LC systems cannot meet electricity demand.

Using MERIT, the match analysis was carried out based on the scenarios given in **Table 8-4**. **Figure 8-9** shows one example of the match view of demand/supply for the case of ‘*HE5*’ using MERIT. **Table 8-5** displays the results of the performance assessment for the heating season (January to March) for each scenario. Energy usage and CO_2 reduction rates against the reference case are presented in **Table 8-6**.

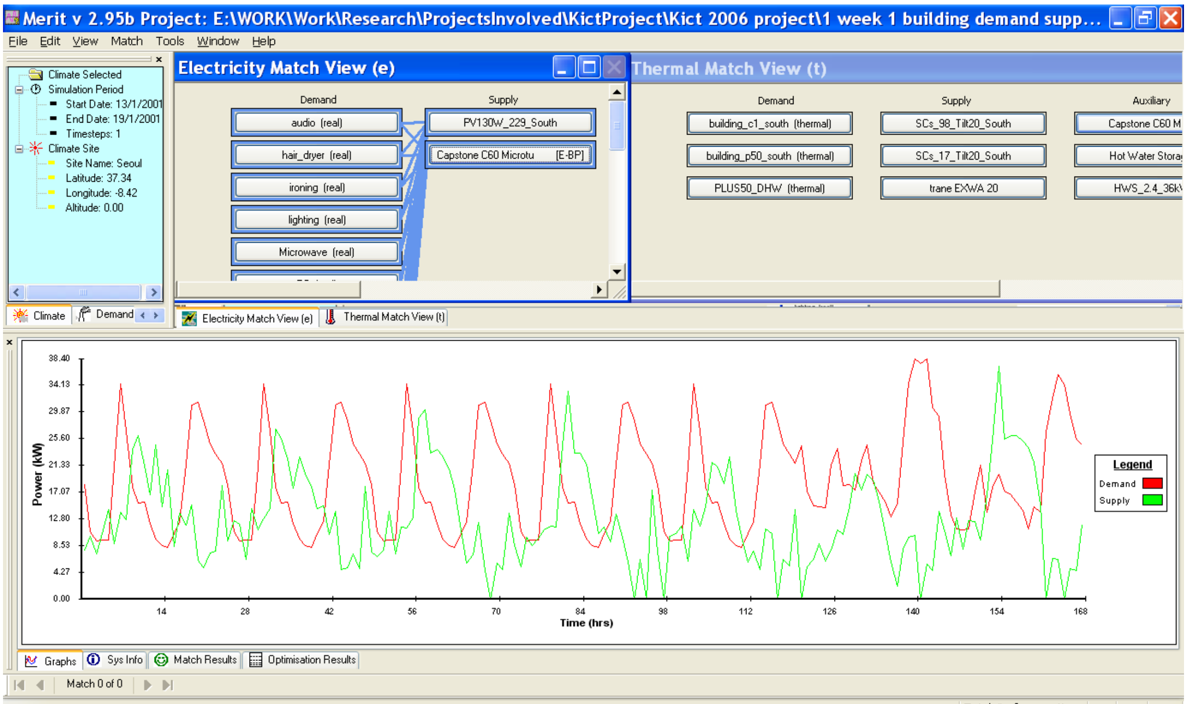

Figure 8-9: Match view of demand/supply for HE5 case

Table 8-5: Comparison of the Performance Indices of Cases

Scenario	Demand [MWh] (Electrical /Thermal)	RE Supply [MWh] (Electrical /Thermal)	Aux Supply [MWh] (Electrical /Thermal)	Surplus [MWh] Electrical /Thermal	Deficit [MWh] Electrical /Thermal	Match Rate [%] Electrical /Thermal	CHP Efficiency [%]	Energy usage (MWh)	CO_2 Emission (ton) 1) (Electrical /Thermal)
Reference	41.0/59.8	-/-	-/68.8 2)	-	-	-	-	109.8	19.8 / 13.3
Plus50	41.0 / 54.0	-/-	-/62.1 2)	-	-	-	-	103.1	19.8 / 12.0
RE 1	41.0 / 54.0	-/ 13.97	-/46.0 2)	-/7.1	-/47.0	29.8	-	87.0	19.8 / 8.9
RE2	41.0 / 54.0	9.33 /-	-/62.1 2)	1.73/-	33.35/-	32.7	-	93.77	15.3/ 12.0
HE 1	47.0 / 54.0	- / 36.9	-/19.7	-/12.1	- /28.9	50.2	-	66.7	22.7 / 3.8
HE 2	47.0 / 54.0	9.3 / 22.9	-/35.8	1.0 /0.7	38.6 /31.5	31.2 / 46.1	-	73.4	18.2 / 6.9
HE 3	41.0 / 54.0	-	11.9 3) / 53.0	0.4/-	29.3/-	42.1 /95.7	55.7	82.1	14.1 / 11.6
HE 4	41.0 / 54. 0	- /14.0	10.5 3) / 46.5	0.3/7.3	30.6 /1.0	39.9 / 82.5	58.2	77.0	14.7 / 7.9
HE 5	41.0 / 54.0	21.2/-	11.9 3) /53.0	3.5/-	23.07/-	52.8 /95.7	55.7	60.9	3.8 / 11.6
HE 6	47.0 / 54.0	-/ 22.9	6.5 3) / 30.6	0.06 / 0.8	40.5 /1.3	22.6 /96.1	38.7	71.1	19.6 / 4.8

1) CO_2 emission factor: 223 kg CO_2/MWh for natural gas boilers (based on gross calorific value) and 483.6 kg CO_2/MWh for electricity from the grid (national average in Korea) .
2) Gas Boiler efficiency 85 %.
3) Electricity generated by the CHP when running on thermal-follow mode.

Table 8-6: Energy Usage and CO2 Reduction Rates against the 'Reference' Case

case	Energy Usage Reduction rates (%)*	CO_2 reduction rates (%)
Reference	0	0
Plus50	5.49	3.90
RE 1	9.06	6.40
RE 2	11.69	15.44
HE 1	24.13	12.87
HE 2	28.95	23.46
HE 3	27.76	35.81
HE 4	30.52	38.32
HE 5	32.01	42.36
HE 6	38.08	39.14

- Energy usage from GHG emission energy systems (i.e. Grid, CHP, boiler)

The electricity generated by '*RE 2*' case (PV-installed roof) contributes to the reduction of electricity imported from the grid while '*RE 1*' case (solar collector-installed roof) contributes to the reduction of energy from the gas boiler. However, in terms of CO_2 reduction, '*RE 2*'case makes more of a contribution. This is because the natural gas boiler has a better CO2 emission factor than that of the national grid. In terms of the demand-supply energy matching rate and residual, '*RE 1*' case generates a surplus thermal supply. Especially during the warmer season, this surplus increases and the matching rate decreases. Although the overall CO_2 reduction contribution could change if another type of boiler were adopted (e.g. an oil boiler), PV is preferable to solar collectors in terms of the way it can fully utilise the energy generated and the environmental impact.

A fuel consumption reduction of 18-39% can be achieved when adopting an Hybrid Energy System (HES). In terms of energy use reduction, '*HE5*' is the best. By using the electricity produced by the CHP and PV systems, '*HE5*' makes the greatest contribution to CO_2 reduction. If a heat pump is adopted, the extra consumption of electricity for the heat pump system is taken into account. While a heat pump can be used for the base load, a CHP follows residual demand. '*HE6*' is also a reasonable energy system choice. However, the efficiency of a CHP is expected to be improved, as the durability of CHPs need to be considered as well.

8.3 Role of DSM+c Strategy

The demand side measures (such as green roof, insulation, etc.) have a limited demand reduction potential for multi-family high-rise dwellings. HES is the recommended option for this type of building and plays a significant role in satisfying both the thermal and electricity demands. As can be seen, CO_2 emission reduction by more than 40% can be achieved by adopting CHP and PV systems (as shown by '*HE5*'). However, the calculated figures are achieved under ideal conditions. There is still some effort needed to achieve the expected target. In order to achieve the PLUS50 project's target (50% reductions in both energy use and CO_2 emissions), it is necessary to adopt the new demand side management and control algorithm. Advanced demand-side measures, such as active demand-side management and control (DSM+c) systems, were considered in order to reduce overall energy consumption by over 50%. By considering the features of each appliance load, the DSM+c algorithm was used to control devices to match the individual demand/supply profile without sacrificing user comfort. The algorithm coordinates with available supply resources to create more favourable demand profiles for intermittent and unpredictable energy supply resources.

Table 8-7: DSM+c Parameter Settings for Various Loads

Load Type	Control Priority	Control Method
Audio	No control	
Hair Dryer	No control	
Ironing	No control	
Lighting	High	Energy efficiency (25% upgrade)
Microwaves	No control	
PC	No control	
Refrigerator	High	Load control (20% proportional)
Slow cooker	High	Load control (40 % proportional)
TV	No control	
Vacuum Cleaner	Medium	Load shift
Washing machine	Medium	Load shift

Several electricity loads are selected for DSM+c analysis, as described in **Table 8-7**. For the lighting load (**Figure 8-6 (d)**), high efficiency light bulbs will be used, which results in around 25% energy saving. For the vacuum cleaner (**Figure 8-6 (h)**) and washing machine (**Figure 8-6 (i)**), the operation period is fixed. The load shifting measure is suitable for this type of load. In this case, the loads are set as shiftable at the whole defined period (no boundary limitations for shifting) and shifting increments are set as one hour. The other two electricity loads, refrigerator (its status assumes to be on all the time) and slow cooker (**Figure 8-6 (g)**), can be regarded as TCAs (thermostat-controlled appliances). This TCA type of demand is suitable for load control due to the high thermal capacity of the device. They can be controlled when the demand is greater than the supply and can be switched on when the supply is greater than demand. They also have a long enough duration available for control. In this particular case, due to the group appliance control, the controllable loads for refrigerator is set as 20% of total load and for slow cooker is 40%, both available for control during the specified period.

The simulation period is the same as before, i.e. three months from January to March. The results for the case with DSM+c are shown in **Tables 8-8** and **8-9**.

Table 8-8: Performance Indices for the case of HE5+DSM

Scenario	Demand [MWh] (Electrical /Thermal)	RE Supply [MWh] (Electrical /Thermal)	Aux Supply [MWh] (Electrical /Thermal)	Surplus [MWh] Electrical /Thermal	Deficit [MWh] Electrical /Thermal	Match Rate [%] Electrical /Thermal	CHP Effici-ency [%]	Energy usage (MWh)	CO_2 Emission (ton) [1] (Electrical /Thermal)
HE5+DSM	33.94 / 60.87	8.80 / -	4.62 / -	13.15 / -	20.26 / 59.24	64.15 / 96.06	59.75 (374 /0/26)	72.93	6.62 / 11.29

Table 8-9: Energy Usage and CO2 Reduction Rates against the 'Reference' Case

case	Energy Usage Reduction rates (%)	CO_2 reduction rates (%)
Reference	0	0
HE5	32.01	42.36
HE5+DSM	37.91	50.79

From the results, the CO_2 reduction rate for the new case meets the target, whereas the energy savings rate still shows room for improvement. In this analysis, the air conditioning load is not included, as the data is not available. According to the Korea Power Exchange survey in 2004, that load accounts for almost 30% of the total demand. Therefore, it is expected that another 10% electricity saving can be achieved after the AC demand load is considered. Furthermore, if more loads are adopted within the DSM+c concept, it is possible to reduce the energy use beyond 50%, and the CO_2 emissions would also be further reduced.

8.4 Conclusion

This case study shows the application of the DSM+c algorithm at a strategic level. Various DSM options (such as energy efficiency, load shifting, and demand side control) are tested on different demands within the preferred case after match analysis without DSM. Around 10%~20% further reductions upon both energy consumption and GHG emissions are found after DSM+c algorithm is applied upon the suitable loads. This percentage varies according to the number of appliances that are subjected to the DSM+c algorithm. A broad view of the approximate results after applying DSM+c algorithm is given, which can then be used for decision-making purposes. The impact of the DSM+c algorithm is analysed by considering the control duration for different kinds of demands specified by users. Through this project, it has been seen how this algorithm is embedded into the project effectively, and how it plays an important part within in terms of adopting certain RE and LCE (Low Carbon Emission) supply systems.

8.5 References

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CHAPTER NINE CONCLUSION AND FUTURE WORK

The main findings of this thesis are summarised in this chapter, and recommendations are given regarding ways in which the DSM+c algorithm and its relevant aspects can be improved, in order to increase its scope and applicability.

9.1 Conclusions

Thanks to increasing environmental concerns, new energy policy encourages the integration of renewable energy technologies within the built environment to tackle the conflicts between limited primary energy sources and excessive energy consumption due to ineffective control systems and low level energy awareness among users. Several demand measures (such as insulation, double glazing etc.) exist to reduce the building heat loss and have been adopted to increase the performance of buildings. However, these measures reach saturation point, beyond which further energy reduction is limited. At the same time new kinds of appliances are now available that whilst attractive to users, nonetheless increase the burden on the supply side and make this situation worse. Hence, an advanced control algorithm enacted on the demand side is needed to handle all sorts of appliances effectively without affecting people's quality of life to test the feasibility of utilising energy from RE and LC sources. Precisely how a flexible demand profile can be controlled has been a major question answered within this study.

The principal objectives of this research were to:

i) develop a Demand-Side Management and control (DSM+c) algorithm for improving the efficiency of energy utilisation and better facilitating energy from renewable and low carbon emission technologies within the built environment without significantly compromising user satisfaction;
ii) embed this algorithm within a decision support platform (MERIT);
iii) and demonstrate the feasibility of applying such an algorithm to both strategic and operational level.

The key of which is to find the minimum difference between supplies and aggregated demands for each time step when different control actions are applied. Two types of demand measures, load shifting and demand side control, have been developed and considered in detail.

Load shifting (LS) is one of the most popular energy management measures, suitable for those demands with a fixed-period operation pattern. The developed methodology involves the identification of the optimum shifting position during a specified period by seeking the maximum shared area with the given supply profile, whether this be from an intermittent or reliable source. Variables, such as load flexibility, shifting increments, and shifting boundary and directions, have been incorporated to factor in all the constraints upon performance, and to optimise the value of the load shifting analysis. The values of these constraints can be adjusted through the developed interface, which enables users to undertake an analysis of all possible load-shifting strategies for a certain load. The logic for the load shift algorithm and the part load shift algorithm is illustrated and demonstrated.

Demand side control (DSC), another load management measure, can be used for all demands. The DSC algorithm is comprised of two main modules: the load control module and the load recover module. Before performing a DSC analysis, three parameters need to be specified: load priority, control method, and duration. Four priorities from high, medium, low and no control can be specified about the demand, depending on its characteristics (mainly the impact level on users). Two main control methods, on/off and proportional, can be chosen. The control duration can be identified in several ways depending on the sources of demand. Historical demand, based on the demand feature, can be specified through the interface provided, simulated demand can be quantified through demand models, and real-time monitored demand can be identified through comparisons of the monitored data from environmental sensors with the setting points. At each time step, the total demand and supply are compared, and depending on the result, either the load control module or the load recover module is selected to perform further actions. The aim of the load control component is to impose as little control as possible, while that of the load recover component is to recover the demands as much as possible. The optimum

DSC actions for this time step are achieved when the minimum positive difference between supply and demand is found.

In order to perform DSM+c analysis, both demand and supply profiles are required. Reproduction of sympathetic demands have been the focus within this study, as the DSM+c algorithm is concerned with the measures taken on the demand side to best satisfy the changeable supply. Demand data can be statistical, simulated and real-time monitored. The DSM+c algorithm is sufficiently generic to accommodate demands from all sources, but the more accurate and detailed the demand, the better the control strategy that can be generated by the algorithm. Moreover, the more the parameters relevant to the DSM+c algorithm are specified, the more accurate the control strategy that can be realised. The DSM+c algorithm can be used to simulate the DSM strategy which is applied at various stages, from initial feasibility analysis using statistical demand, to detailed design stage using simulated demand models, and to operation in practice via real-time monitoring encompassing demands, supplies and environmental variables.

Supply and demand models have been developed to enable the analysis of the DSM+c algorithm. Low carbon emission supply technologies have been the focus within this study. Consequently, generic μCHP and heat pump modelling procedures have been described. Simplified electricity-based thermal demand models, especially the refrigerator, hot water storage etc., are also illustrated, in order to quantify the impacts of the DSM+c algorithm upon these demands.

Electricity-based thermal demands, such as a refrigerator, hot water storage, and air conditioning systems etc., account for a large percentage of total energy consumption within the residential sector. Therefore, a study of their DSM potential is valuable since it offers great potential for curtailing usage. Also these appliances are ideal candidates for the application of the DSM+c algorithm because of their high inertial features. In order to quantify the control impact after having applied the DSM+c algorithm to these demands systems, mathematical demand models are required, and physically-based models for a refrigeration system and hot water storage have been developed. The energy balance analysis method, incorporating a certain number of assumptions, has been used to establish the models. Based on the specified thermal and physical parameters of the demand systems and the given thermal profile, the temperature within the refrigerated space or the tank and the consumed power, can be simulated.

Different supply technologies generate different DSM strategies. Given the increasing concerns about the environment and energy security, distributed generation such as small-scale renewables and low carbon emission technologies offer huge potential in the near future. To facilitate the power from these new technologies, favourable demand profiles are normally required for the operation of RE and LCs. CHP and HP have been chosen as the focus for this study, as they are the best options to assure the energy supply reliability and to meet environmental requirements. Hybrid systems are the way forward in energy supply for the built environment, and CHP and HP are the two most attractive options.

The CHP model proposed within this study has been developed from performance curves supplied by manufacturers. Detailed modelling procedures have been described in order to assess the performance of CHPs under three different operation modes, these being: running at constant load, following electricity load, and following thermal load. Various types of CHP prime movers, part load performance in terms of fuel consumption and heat to power ratio, minimum starting load, de-rating factors for altitude and ambient temperature, different types of fuel and their GHG emission, have been considered.

The heat pump model used in this thesis was based on a multi-dimension interpolation algorithm using available data from the manufacturer. This is a generic algorithm which can be used for various types of heat pumps such as air source, water source or ground source, so long as the relevant data is available from the manufacturers. Depending upon the level of detailed performance data provided by them, the appropriate dimension interpolation algorithm is applied to analyse the heat pump performance. A two-dimension interpolation algorithm is demonstrated within this study. For the heating mode, using the data set of the outdoor dry bulb temperature and indoor dry bulb temperature under nominal air flow rate condition, total heating capacity and total power required have been calculated. For the cooling mode, given the input data set of the outdoor dry bulb temperature and indoor wet bulb temperature under nominal air flow rate, the total cooling capacity and the total consumed power of heat pump was quantified. Furthermore, the dimensionless correction factors for total capacity and compressor power under various air flow rates are available from manufacturers to adjust the heat pump performance under non-nominal condition.

Two levels of implementation have been accomplished. The first is the implementation within a demand-supply matching tool, MERIT. The DSM+c algorithm, refrigeration system module, hot water storage module, CHP module, and heat pump module have been successfully integrated within the existing structure of MERIT. Additionally, the verification process was described. The second level is the implementation of functionality incorporated into MERIT platform within an Internet-enabled energy system (IE-ES), in order to apply the DSM+c algorithm in practice on a real-time basis. Additional modules, such as the data acquisition module from the remote database server, real-time control and communication module with the remotely located control server for applying control messages to the remote real devices, were developed within MERIT.

In addition, other modules were developed to extend the functionality of MERIT. The development of a Two-Match-View (TMV) interface allowed MERIT to handle energy systems which involve both electrical and thermal energy forms, such as CHP and heat pump etc. Another component is the multi-index assessment module. The index includes total demand, total supply, match rate, energy delivered, energy import/export, fuel consumption, system efficiency and GHG effect. An optimisation table with multiple columns of various criteria can be generated after all possible combinations between demand and supply have been specified by users. Through this table, the best combination in terms of certain criteria can be identified. This module is not only suitable for assessing the renewable system performance but also capable of evaluating the performance of low carbon emission energy systems. More importantly, it can be used to compare match results and quantify the changes in some criteria according to demand, with or without the DSM+c algorithm.

The applicability and usefulness of the DSM+c algorithm were demonstrated via two case studies. The first illustrated its use at a strategic level. When the DSM+c algorithm was applied to a multi-family building, 5%~20% of improvements in energy savings and GHG reductions were found. The second case focused on its applicability at operational level, the key aim being to prove the viability and robustness of the DSM+c algorithm when applied to real appliances on a real-time basis. A domestic refrigerator was selected as the study object to incorporate the DSM+c algorithm. The performance of the refrigerator was measured through sensors when the refrigerator ran under various conditions, different temperature setting points and different types of supply (reliable or intermittent). It is feasible to use intermittent RE supply for a refrigerator using the DSM+c algorithm within a range of acceptable temperature tolerance inside the refrigerator. Significant energy savings were achieved after switching to such a renewable supply. The same method can be applied to other demands. Using the internet as the common communication platform it is easy to increase the scope of DSM+c application.

To sum up, the DSM+c algorithm developed in this thesis analyses demands together with supplies and relevant environmental parameters, and generates strategies or commands which relate to when, which device and what action can be applied. It plays an important role in re-generating favourable demand profiles that in turn better facilitate the utilisation of energy from RE and LC sources with a certain degree of acceptable compromise on the demand side. With the use of the DSM+c algorithm, the degree of demand flexibility can be assessed and the permeation level of RE and LC supplies can be enhanced.

9.2 Suggestions for Future Work

This thesis has presented the methodology associated with the DSM+c concept, which is designed particularly for a distributed generation system with a high penetration of renewable and low carbon energy sources. In the thesis, the implementations of the DSM+c algorithm in a software platform MERIT, and the viability of its applications at the initial design stage, or even at the real-time operational level, have been considered. The research project has been a preliminary and broad investigation into a bottom-up DSM concept, covering various aspects from design, implementation, evaluation, to application in practice. However, a few limitations of the study can be identified, and consequently there are some suggestions regarding future work that might address these.

9.2.1 Further Improvements to the DSM Algorithm at the Simulation Level

It is believed that demand and supply systems' modelling is the way to enhance the functionality of the DSM algorithm. Not only can the impact upon the users' convenience be quantified, but also the performances of demand and supply systems before and after the application of the DSM algorithm can be assessed and compared. Some representative demand and supply models have been described in this thesis but there remains much room for improvement within these two fields. A feasibility study of the integration of these models within the framework of the DSM algorithm was carried out, but since the focus of this study is the development of the DSM algorithm and the development of an implementation platform, only the simplified demand and supply models were employed, and this introduces some limitations, such as result accuracy. Hence, more research is necessary on supply and demand models.

The physically-based demand models for the refrigeration system and the water heating system were illustrated respectively, being modelled at the individual level and based on energy balance within the studied system. Some simplifications were made to the current models. For instance, the vertical temperature gradient within the refrigerated space was neglected in the current refrigeration system model; and a lumped parameter method was applied to the air and products inside the zone. In the model of the hot water storage system, an assumption was made that the water inside the tank was fully-mixed. To improve the level of accuracy, detailed demand models for the heating/cooling system are needed. Not only should the thermal interactions within the refrigerated space in the refrigeration system model and stratification in the water tank model be taken into account. Uncertainty factors such as the occupant behaviour and outside weather conditions are equally important and should be addressed. Furthermore, experiments should be conducted to validate the models. As the above-mentioned demand model is for each individual appliance, the total demand may be achieved through aggregation in a bottom-up approach described by Capasso et al. (1994). Nevertheless, the recommended way is to model various demands in an integrated manner, through which the random nature of the factors influencing load use and the interactions among all the demand devices and their impact upon the micro-environment can be taken into consideration. This can be realised via a detailed building energy simulation tool, such as TRNSYS (Solar Energy Lab, 2004), ESP-r, etc. Thus, after having integrated the detailed demand model within the DSM algorithm framework, the multi-objective approach, which has as one of its objectives the maximisation of the quality of service to consumers, can result in the design of an optimal DSM strategy.

On the supply side, current energy policy encourages the use of distributed generations (DGs) with no or low carbon emissions for energy generation. Some DG technologies, such as wind turbine and PV, are inherently stochastic in nature, thereby resulting in random variations in the quantity of power delivered. Other load-following DGs, such as CHP and heat pumps, are highly sensitive to the load variations. Therefore, the ability to predict the performance of these DG systems in a reasonably accurate way is important. As mentioned in Chapter Four, the current CHP and heat pump models are based on the performance curve and catalogue data provided by their manufacturers. One limitation of this performance-curve-based model is that it is highly dependent on the data availability, and not all types of CHP or heat pump systems have the data at the required resolution. Another limitation is that it is hard to predict performance when variables fall beyond the range of available data points. Empirical verification should be undertaken via experiments carried out to verify the performance data provided by manufacturers, and some adjusting factors might then be implemented to correct the existing models under various working conditions. In addition, detailed simulation models, such as the control volume-based CHP model (Kelly 1998) and the parameter estimation-based heat pump model proposed by Jin (2002), could be used to improve the accuracy level of predicted results. It is common for more than one DG to be installed within a consumer's dwelling, and hence, the supply-side management algorithm also needs to be able to generate the optimal strategy for managing heterogeneous supply devices effectively and efficiently under certain specified criteria. The ultimate goal is to achieve maximum operating efficiency and to minimise the impact upon the environment of the whole DG system.

As far as the DSM algorithm itself is concerned, some further improvements could be made. Firstly, research efforts should be directed to the prioritisation of various loads depending on the relationship between the nature of the load and the awareness level of users after having applied controls upon the load. Secondly, the advanced search algorithm could be employed to determine the best strategy in terms of certain criteria, quickly and effectively. Currently the maximum number of demands with the same priority that the DSM algorithm can handle is ten. For each demand, depending on the control method specified, the control step is 2 for on/off or 10 for proportional control. Thus, as the number of demands increases, it would take an excessively long time to search for the best one among all possible control actions. Therefore, it would be worth devoting time to finding better search procedures such as heuristic search method in respect of the process of finding a range of optimal solutions based on user-selectable criteria. Optimisation methods could also be incorporated, such as a genetic algorithm, a simulated annealing algorithm, taboo search etc., to improve the speed and effectiveness of the search procedure among the possible result set. Last but not least, other optimal objectives based on economics, environmental concern, or user satisfaction acceptance, could also be integrated into the DSM algorithm. This would increase the conflicting aspects both in amount and intensity. The problem to be solved becomes multi-objective in nature, with economic, technical, and quality of service aspects all needing to be taken into account in the mathematical model. Using such a multi-objective model, a decision-maker should understand the conflicting nature of the various goals and decide on the trade-offs to be made in order to obtain a satisfactory solution.

9.2.2 Further Improvements to the DSM+c Algorithm at Operational Level

This thesis proposed an internet-enabled energy system infrastructure upon which the DSM algorithm at operational level was implemented. The example presented demonstrated the real-time application of the DSM+c algorithm in the context of a domestic refrigerator. It is confined to a single demand, single environmental variable and a simulated supply. Applications which involve multiple demands and supplies together with multiple environmental variables (e.g. temperature, occupancy, humidity and light intensity), are needed in order to test the robustness and effectiveness of the DSM algorithm at a higher order and on a larger scale. More efforts are required to modify the current control logics in order to incorporate all these elements into practice.

One of the key components of an internet-enabled energy system is the gateway device. In this respect, a multi-protocol gateway device needs to be developed which encompasses various communications protocols, such as wireless/wire standard protocol and proprietary protocol, for the purpose of greater flexibility, expandability and interoperability. A new, open wireless communication protocol, such as Zigbee (ZigBee Alliance, 2005) and Z-wave (Z-Wave Alliance, 2007), is recommended to monitor and control the devices within the built environment because of their features of low power consumption and reliability in receiving the information. Additionally, more devices could then be tested within this system. In respect of the processing performance of the DSM algorithm at the operational level, the two factors of system response time and the reliability of transmitting and receiving the control signals, need further improvement, in order to improve user acceptance level. Furthermore, the capability of real-time diagnosis and fault detection for both supply equipment and demand devices is also important, with error detection not only being based on redundancy, but also on the physics of the process being monitored (e.g.

relationships between variables, rates of change, values outside the plausible range). Other services based on this system can also be offered, such as health care, entertainment, safety and security etc.

9.3 Perspective

With the addition of the DSM algorithm as a decision-making tool in the demand-supply match analysis (MERIT), decision-makers now have the ability to analyse any proposed DSM strategy-set and identify the optimal strategy for any scenario with certain pre-defined criteria. The scale of flexibility introduced to the demands can be assessed through the utilisation of the DSM algorithm when the loads are linked with a renewable or low carbon emission supply system. As the popularity of on-site distributed generations grows, energy supply becomes more unpredictable and fluctuating. Matching the changeable local demands with this type of supply becomes more challenging than ever before. A new component such as an SSM (Supply Side Management) algorithm will make the tool comprehensive and integrative, thereby allowing both demand and supply sides to be analysed simultaneously. The ultimate goals of this decision-making tool are to improve the efficiency of the energy utilisation from distributed generation sources, to decrease unnecessary energy waste, and to increase consumers' awareness level of energy usage. Furthermore, with the flexible internet-enabled energy system proposed in this thesis, an optimal control strategy can be performed in the real environment. It is hoped that the research on the demand side undertaken in this thesis is a sound stepping stone for the continuous exploration of such opportunities.

9.4 References

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APPENDIX A: MANUFACTURER CATALOGUE DATA (TRANE)

The followings show the catalogue data for heat pump model WCZ036F –A AT 1100CFM manufactured by Trane. The unit of data used for developing the algorithm for heat pump in Chapter Four has been converted into SI unit.

A.1 Performance Data For Cooling

Table A1- 1 Trane WCZ060F100 Cooling Performance Data

WCZ060F100—A AT 1100 CFM

(CAPACITIES ARE NET IN BTUH/1000-INDOOR FAN HEAT DEDUCTED)

O.D. D.B.	I.D. W.B.	TOTAL CAP.	SENS. CAP. AT ENTERING D.B. TEMP. 72	74	76	78	80	COMPR. KW	APP.DEW PT.
85	59	28.4	23.6	25.5	27.4	28.7*	29.4*	1.56	46.7
	63	30.4	19.7	21.7	23.6	25.5	27.5	1.58	50.7
	67	32.6	15.5	17.4	19.4	21.3	23.3	1.61	54.9
	71	34.8	11.2	13.1	15.1	17.0	18.9	1.63	59.2
90	59	27.2	23.0	25.0	26.9	27.7*	28.4*	1.66	47.3
	63	29.2	19.2	21.2	23.1	25.0	27.0	1.69	51.2
	67	31.3	15.0	17.0	18.9	20.8	22.8	1.72	55.4
	71	33.5	10.7	12.6	14.6	16.5	18.5	1.75	59.7
95	59	25.9	22.5	24.5	26.1*	26.8*	27.4*	1.77	47.9
	63	27.9	18.7	20.7	22.6	24.5	26.5	1.80	51.8
	67	30.0	14.5	16.5	18.4	20.3	22.3	1.83	56.0
	71	32.1	10.2	12.2	14.1	16.1	18.0	1.86	60.3
100	59	24.7	22.0	23.9	25.1*	25.8*	26.4*	1.87	48.5
	63	26.6	18.2	20.1	22.1	24.0	26.0	1.90	52.4
	67	28.7	14.0	16.0	17.9	19.9	21.8	1.94	56.6
	71	30.7	9.8	11.7	13.6	15.6	17.5	1.98	60.8
105	59	23.5	21.5	23.5*	4.1*	24.8*	25.4*	1.97	49.1
	63	25.4	17.7	19.6	21.6	23.5	25.4*	2.01	53.0
	67	27.4	13.5	15.5	17.4	19.4	21.3	2.05	57.1
	71	29.4	9.3	11.2	13.2	15.1	17.1	2.09	61.4
115	59	21.1	20.4	21.6*	22.2*	22.8*	23.5*	2.18	50.3
	63	22.9	16.7	18.6	20.6	22.5	23.5*	2.23	54.1
	67	24.8	12.6	14.5	16.5	18.4	20.3	2.28	58.3
	71	26.7	8.4	10.3	12.2	14.2	16.1	2.33	62.5

CORRECTION FACTORS - OTHER AIRFLOWS
(multiply or add as indicated)

AIRFLOW	975	1250
TOTAL CAP.	X0.99	X1.01
SENS. CAP.	X0.95	X1.06
COMPR. KW	X1.00	X1.00
A.D.P.	-1.2	+1.1

VALUES AT ARI RATING CONDITIONS

TOTAL NET CAPACITY = 30000 BTUH
AIRFLOW = 1100 CFM
APP. DEW PT. = 56.0 DEG. F
COMPRESSOR POWER = 1830 WATTS
I.D. FAN POWER = 140 WATTS
O.D. FAN POWER = 340 WATTS
E.E.R. = 13.00 BTUH/WATT

*** DRY COIL CONDITION (TOTAL CAPACITY = SENSIBLE CAPACITY)**
TOTAL CAPACITY, COMP. KW AND APP. DEW PT. ARE VALID ONLY FOR WET COIL
ALL TEMPERATURES IN DEGREES F.

A.2 Performance Data For Heating

Table A1- 2 Trane WCZ060F100 Heating Performance Data

WCZ060F100—A AT 1100 CFM

O.D. TEMP. F.	HEATING CAPACITY (BTUH/1000) AT INDICATED INDOOR DRY BULB TEMP. 60	70	75	80	TOTAL POWER IN KILOWATTS AT INDICATED INDOOR DRY BULB TEMP. 60	70	75	80
-18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-3	3.83	3.70	3.63	3.57	1.51	1.59	1.64	1.68
2	6.18	5.95	5.84	5.72	1.57	1.66	1.70	1.75
7	8.52	8.20	8.04	7.88	1.63	1.73	1.77	1.82
12	10.9	10.5	10.2	10.0	1.70	1.79	1.84	1.89
17	13.2	12.7	12.4	12.2	1.76	1.86	1.91	1.96
22	15.1	14.5	14.2	13.9	1.84	1.94	1.99	2.05
27	16.9	16.3	16.0	15.6	1.91	2.02	2.08	2.13
32	18.8	18.1	17.7	17.4	1.99	2.10	2.16	2.22
37	20.7	19.9	19.5	19.1	2.06	2.18	2.24	2.30
42	22.5	21.7	21.2	20.8	2.14	2.26	2.32	2.39
47	27.3	26.2	25.7	25.1	2.14	2.26	2.32	2.38
52	29.6	28.5	27.9	27.3	2.20	2.33	2.39	2.45
57	31.9	30.7	30.1	29.5	2.26	2.39	2.46	2.52
62	34.3	33.0	32.3	31.6	2.32	2.46	2.53	2.60
67	36.6	35.2	34.5	33.8	2.39	2.53	2.60	2.67
72	39.0	37.5	36.7	35.9	2.45	2.59	2.66	2.74

CORRECTION FACTORS - OTHER AIRFLOWS
(Value at 1100 CFM times corr. factor = Value at New Airflow)

AIRFLOW	975	1250
HEATING CAP.	X0.99	X1.01
COMPR. KW	X1.01	X0.99

VALUES AT ARI RATING CONDITIONS OF:
70&47/43 (HIGH TEMP. POINT)
70&17/15 (LOW TEMP. POINT)
AIRFLOW = 1100 CFM
HEATING CAP. (HIGH TEMP.) = 26200 BTUH
HEATING CAP. (LOW TEMP.) = 12700 BTUH
COMPR. POWER (HIGH TEMP.) = 1780 WATTS
COMPR. POWER (LOW TEMP.) = 1380 WATTS
HSPF (MIN DHR) = 8.10
COEFF. OF PERF. (HIGH TEMP.) = 3.40
COEFF. OF PERF. (LOW TEMP.) = 2.00
OUTDOOR FAN POWER = 340 WATTS
INDOOR FAN POWER = 140 WATTS

APPENDIX B: DETAILED INTERFACES FOR DEMAND AND SUPPLY MODELS IN MERIT

The demand and supply models, including hot water storage system, refrigeration system, CHP and heat pump, have been implemented and integrated within MERIT in Chapter Five. They are component-oriented. Each module has a system component, which contains the general information for the system and communicates with the subcomponents through their reference IDs. The detailed interfaces for these modules are attached as follows.

B.1 Hot Water Storage System (HWS) Module

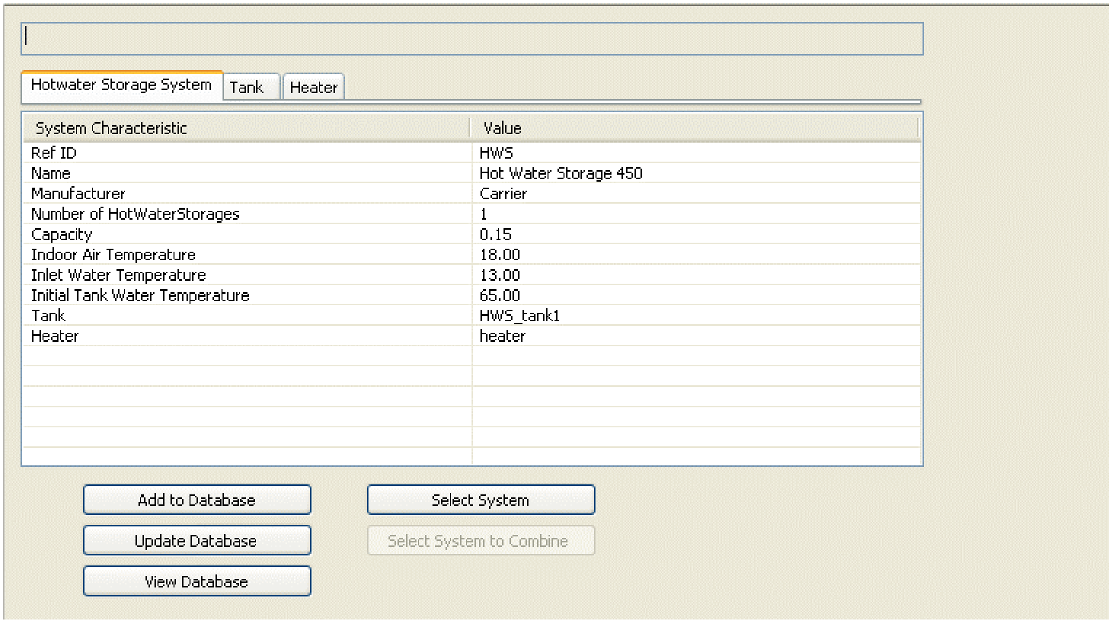


Figure B1- 1 Interface for Hot Water Storage System Component

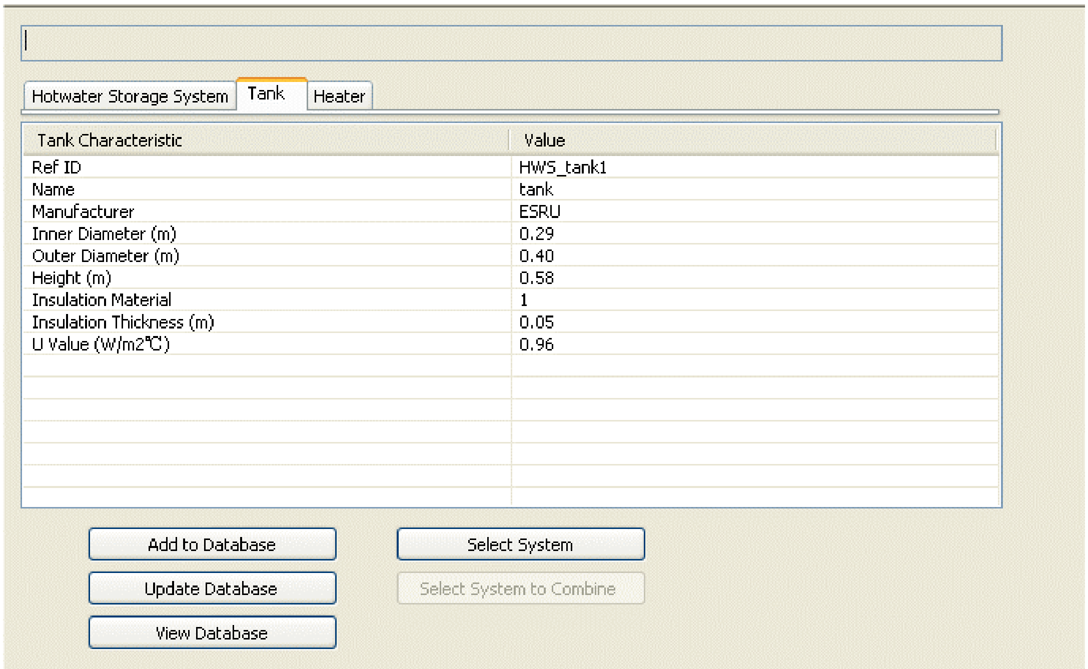


Figure B1- 2 Interface for Tank Component of HWS

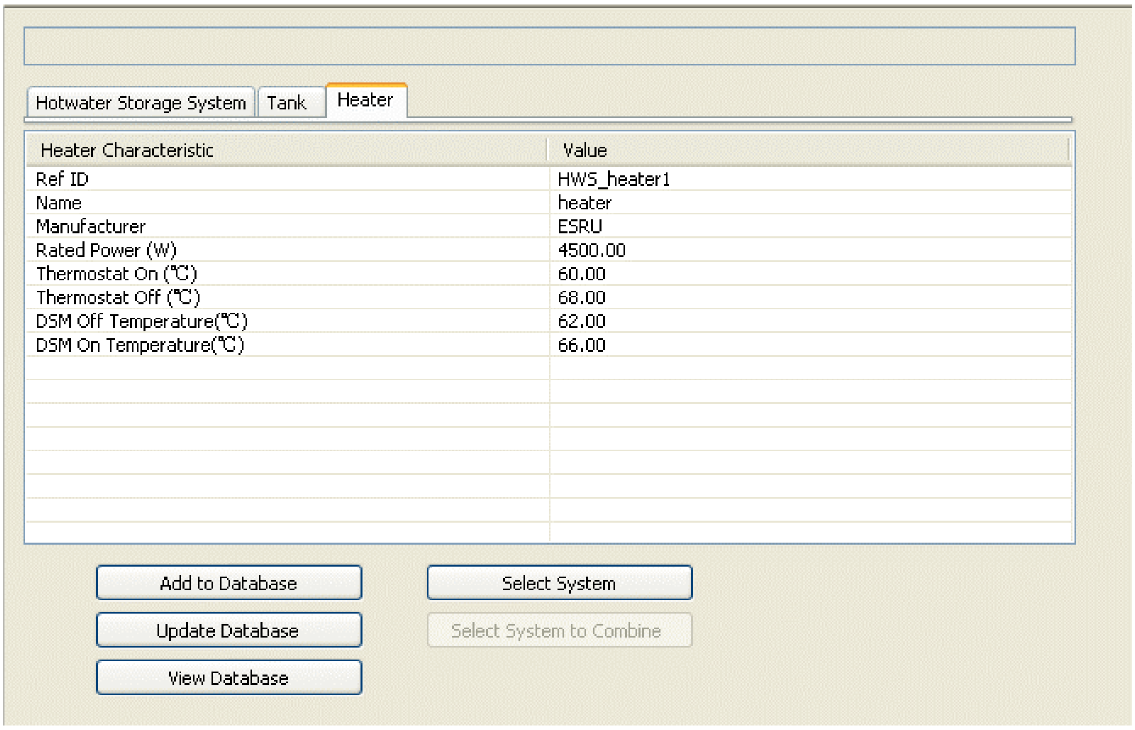
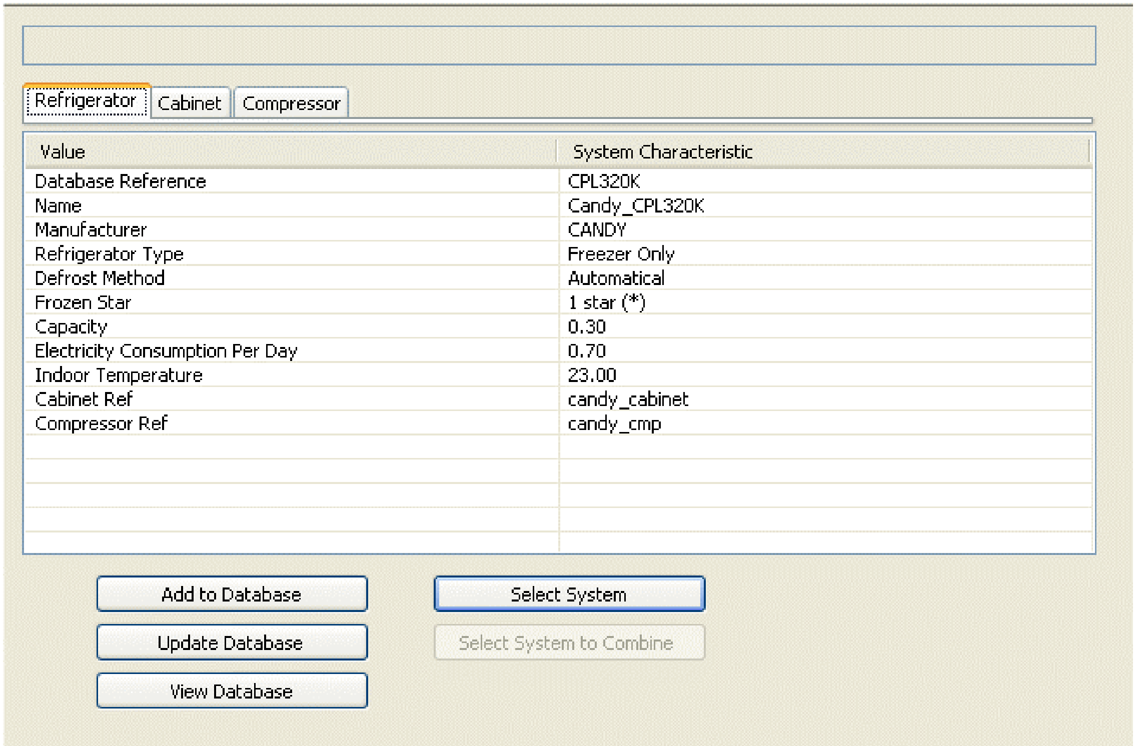


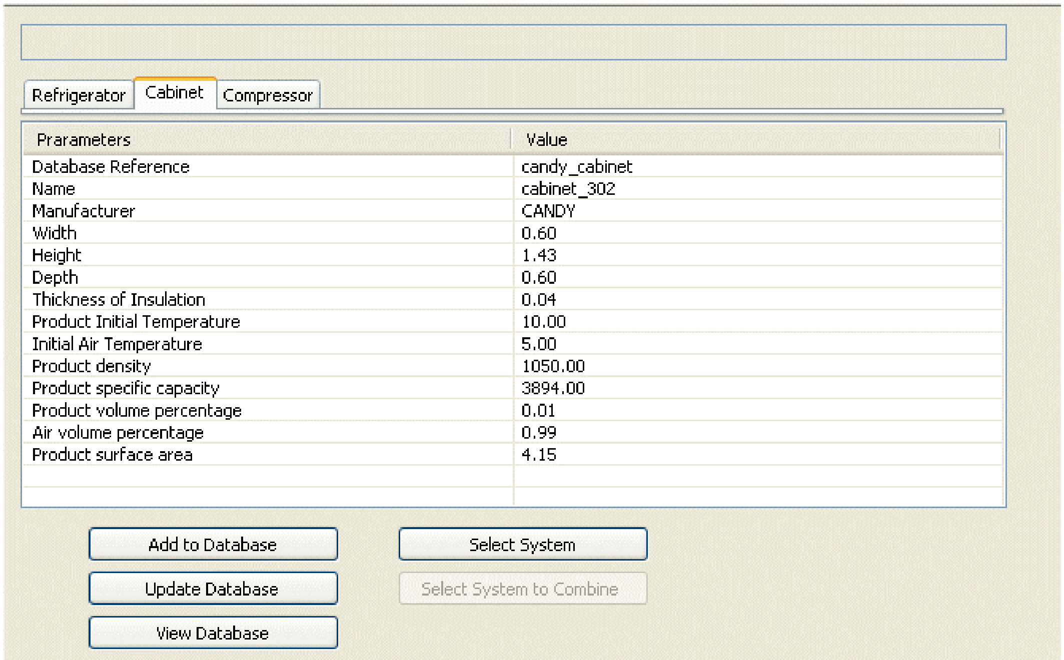
Figure B1- 3 Interface for Heater Component of HWS

B.2 Refrigeration System Module



Value	System Characteristic
Database Reference	CPL320K
Name	Candy_CPL320K
Manufacturer	CANDY
Refrigerator Type	Freezer Only
Defrost Method	Automatical
Frozen Star	1 star (*)
Capacity	0.30
Electricity Consumption Per Day	0.70
Indoor Temperature	23.00
Cabinet Ref	candy_cabinet
Compressor Ref	candy_cmp

Figure B2- 1 Interface for Refrigeration System Component



Parameters	Value
Database Reference	candy_cabinet
Name	cabinet_302
Manufacturer	CANDY
Width	0.60
Height	1.43
Depth	0.60
Thickness of Insulation	0.04
Product Initial Temperature	10.00
Initial Air Temperature	5.00
Product density	1050.00
Product specific capacity	3894.00
Product volume percentage	0.01
Air volume percentage	0.99
Product surface area	4.15

Figure B2- 2 Interface for Cabinet Component of Refrigeration System

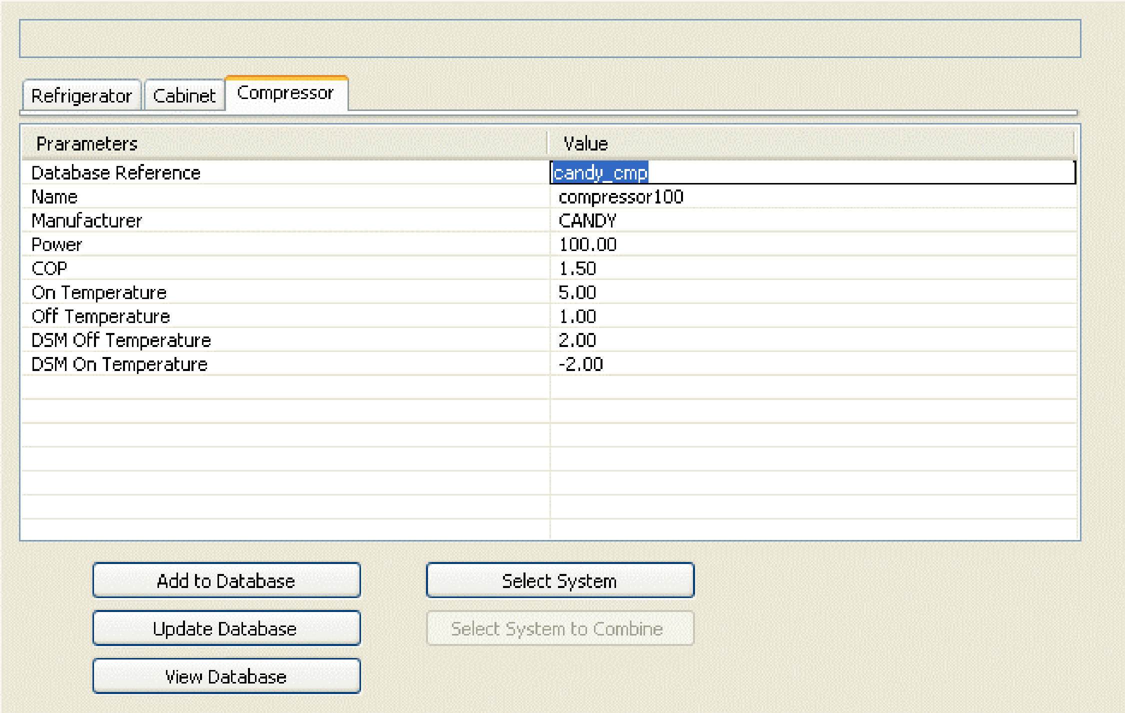


Figure B2- 3 Interface for Compressor Component of Refrigeration System

B.3 CHP Module

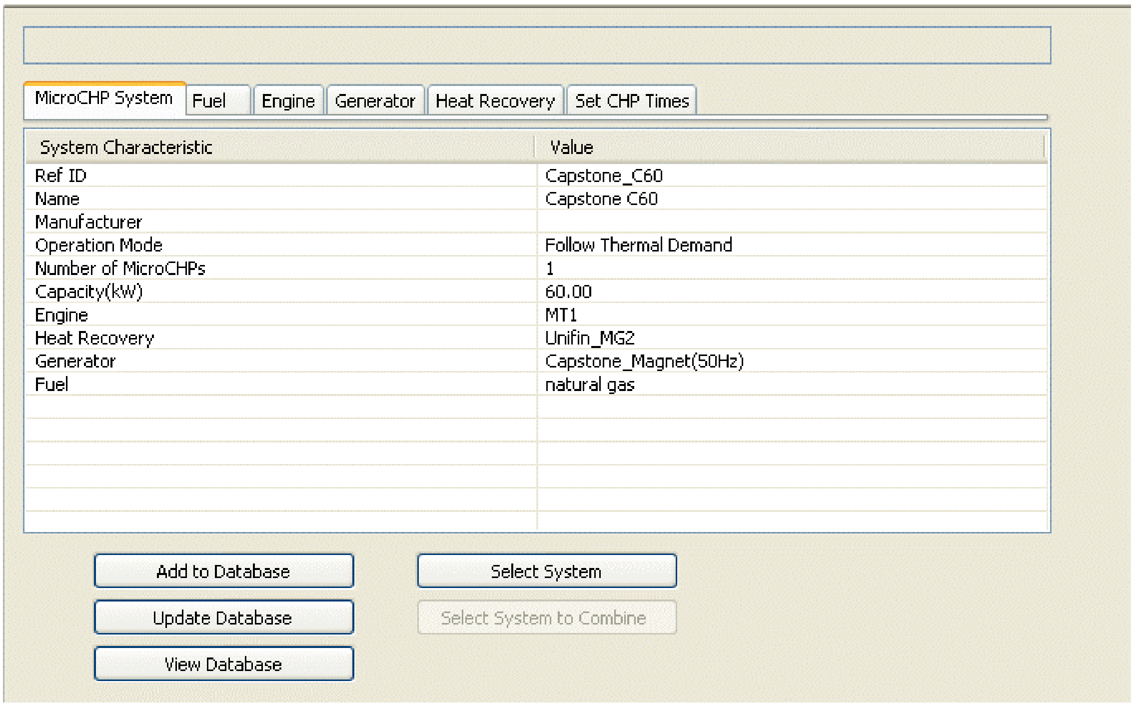


Figure B3- 1 Interface for CHP System Component

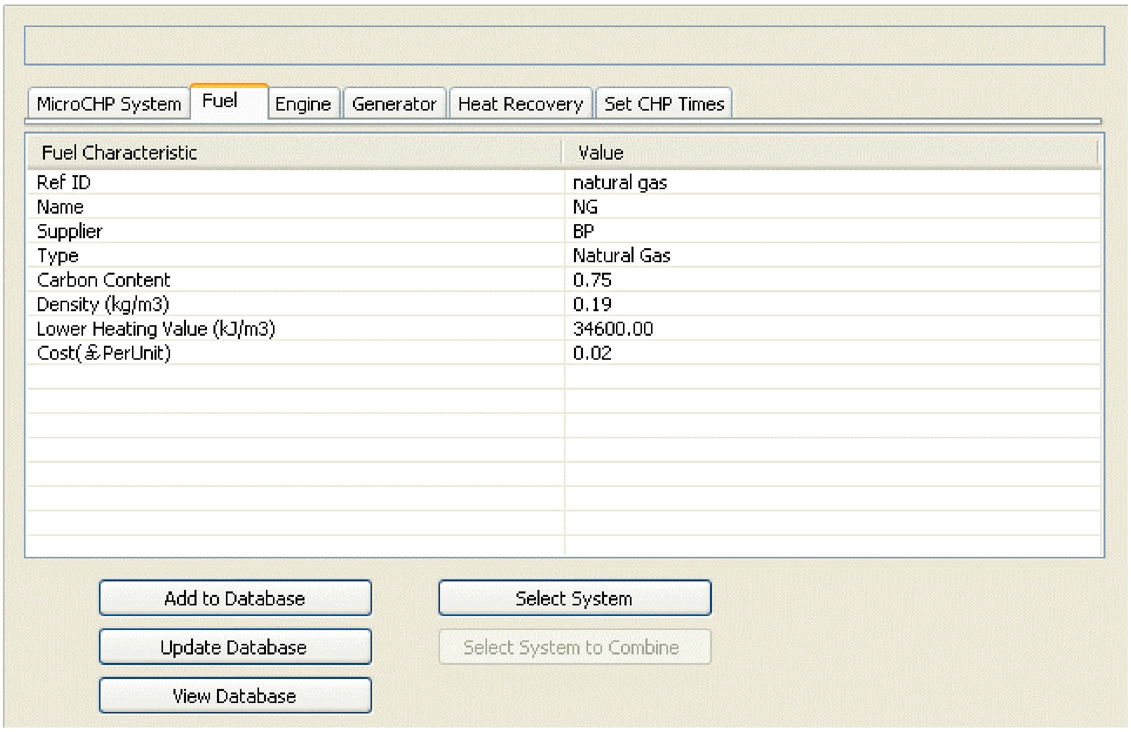


Figure B3- 2 Interface for Fuel Component of CHP

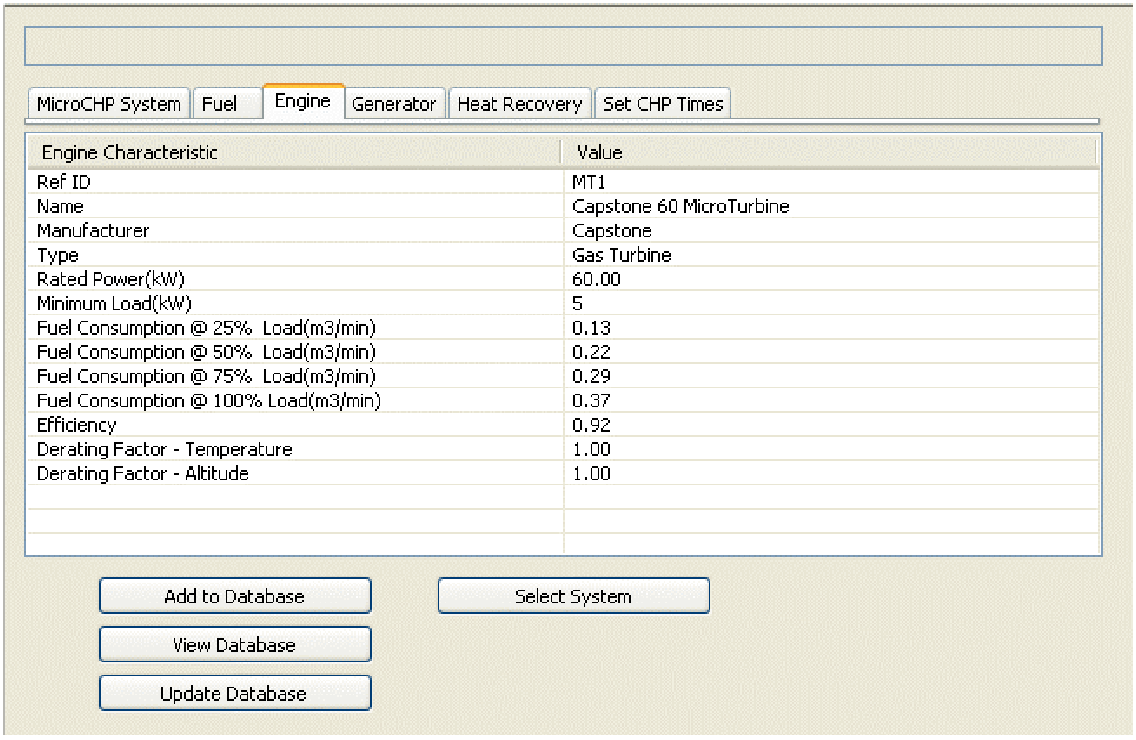


Figure B3- 3 Interface for Engine Component of CHP

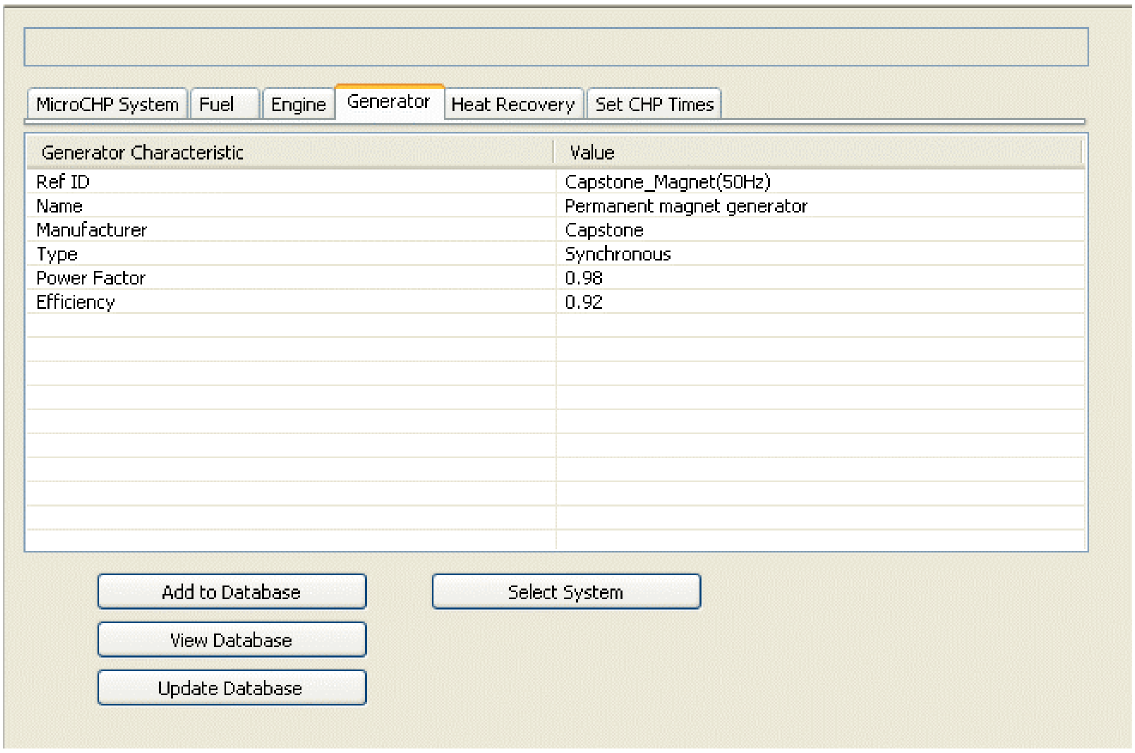


Figure B3- 4 Interface for Generator Component of CHP

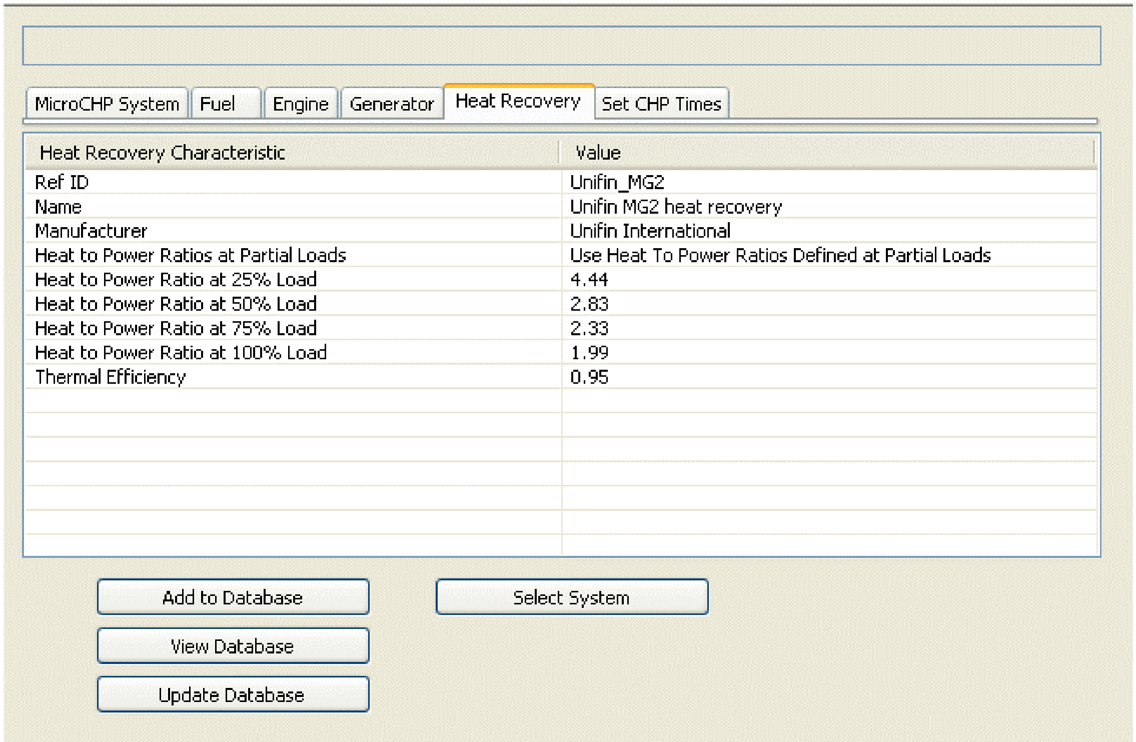


Figure B3- 5 Interface for Heat Recovery Component of CHP