A SMART APPLIANCE CONTROL METHOD FOR SMART HOME MANAGEMENT SYSTEMS

Master's Thesis

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MASTER'S THESIS

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This thesis titled “A Smart Appliance Control Method For Smart Home Management Systems” has been prepared and submitted by Ahmet ÇALIŞKAN in partial fulfillment of the requirements in “Eskişehir Technical University Directive on Graduate Education and Examination” for the Degree of Master of Science in Electrical Electronics Engineering Department has been examined and approved on 01/08/2019.

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ABSTRACT

A SMART APPLIANCE CONTROL METHOD FOR SMART HOME MANAGEMENT SYSTEMS

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Eskişehir Technical University, Institute of Graduate Programs, August 2019

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In this thesis, a study which is related to a home energy management system has been investigated in order that power consumption is more efficiency against increasing energy demand. Appliances in smart home are classified as controllable and uncontrollable appliances. In smart home, usage habits of appliances have been determined by using sensors and power measurement units. Operating times of appliances have been recorded in database with certain time intervals. By scheduling operating times of controllable appliances, it is aimed that user comfort increases. It is also aimed that cost of consumed energy is low level. Furthermore, by determining a maximum power, it is investigated whether power limit exceed when appliances operate.

In the proposed home energy management system, operating time scheduling problem of controllable appliances has been solved while user comfort increases, electricity cost reduces, and power limit does not exceed. In order to be able to solve this problem, three different purposes are minimized. These purposes which have different parameter are brought same level by using normalization technique. LMS (Least Mean Square) method has obtained optimal solution by using Euclidean distance approach. Operating time scheduling of controllable appliances has demonstrated with examples.

Keywords: Home energy management system, Smart home, Appliance scheduling, Normalization technique, LMS

ÖZET

AKILLI EV YÖNETİM SİSTEMLERİ İÇİN AKILLI BİR CİHAZ KONTROL YÖNTEMİ

Ahmet ÇALIŞKAN

Elektrik-Elektronik Mühendisliği Anabilim Dalı
Kontrol ve Kumanda Sistemleri Bilim Dalı

Eskişehir Teknik Üniversitesi, Lisansüstü Eğitim Enstitüsü, Ağustos 2019

Danışman: Doç. Dr. HANİFE APAYDIN ÖZKAN

Bu tezde, artan enerji talebine karşı enerji tüketiminin daha verimli olması için ev enerji yönetim sistemi ile ilgili bir çalışma gerçekleştirilmiştir. Akıllı evdeki cihazlar kontrol edilebilen ve kontrol edilemeyen olarak iki şekilde sınıflandırılmıştır. Akıllı evde sensörler ve güç ölçüm üniteleri kullanılarak evdeki cihazların kullanım alışkanlıkları belirlenmiştir ve cihazların çalışma zamanları belirli zaman aralıklarıyla veri tabanında kayıt altına alınmıştır. Kontrol edilebilen cihazların çalışma zamanları planlanarak kullanıcı konforunun artırılması amaçlanmıştır. Kullanıcı konforu artarken tüketilen enerjinin maliyetinin de düşük seviyede olması amaçlanmıştır. Bir maksimum güç belirlenerek, cihazlar çalıştığında güç sınırının aşılıp aşılmadığı da incelenmiştir.

Önerilen ev enerji yönetim sisteminde kullanıcının konforunun arttığı, elektrik maliyetinin azaldığı ve güç limitinin aşılmadığı kontrol edilebilen cihazların çalışma zamanlarını planlama problemi çözülmüştür. Bu problemi çözebilmek için bu üç farklı amaç minimize edilmiştir. Farklı parametrelere sahip olan bu amaçlar normalizasyon tekniği kullanılarak aynı seviyeye getirilmiştir. LMS metodu öklid mesafesi yaklaşımını kullanarak en uygun çözümü elde etmiştir. Kontrol edilebilen cihazların çalışma zamanı planlaması örneklerle gösterilmiştir.

Anahtar Kelimeler: Ev enerji yönetim sistemi, Smart home, Cihaz planlaması, Normalizasyon tekniği, LMS

01/08/2019

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principle and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with “scientific plagiarism detection program” used by Eskişehir Technical University, and that “it does not have any plagiarism” whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

……………..

AHMET ÇALIŞKAN

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Finally, the author wishes to express her thanks to her family for their help, encouragement and support during her study.

CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

NOMENCLATURE

Symbol	Description
T	Number of uniform time slots in a day
t	time slot
$\mathcal{T}$	The set of time slots $\{1,2,3,\ldots,T\}$
Δ_t	length of each time slot t
$\mathcal{L}$	set of appliances
$\mathcal{L}_{uncont}$	set of uncontrollable appliances
$\mathcal{L}_{cont}$	set of controllable appliances
X	The set of a measured day
K_X^a	appliance usage matrix
m	the number of measurement of appliance
t_{int}	local time of appliance during operating time
$P^a(\mathrm{t})$	power that appliance a spends at t time slot
$\mathcal{L}_{uncont-fix}$	the set of uncontrollable fix-power appliances
$\mathcal{L}_{uncont-var}$	the set of uncontrollable variable-power appliances
$P_{xexpected}^a$	the expected power consumption of appliance a
ts_a	operating time of appliance a
ts_{WM}	operating time of WM
ts_{DW}	operating time of DW
$P_{xexpected}^{\mathcal{L}_{\mathrm{uncont}}}(t)$	the expected power consumption of $\mathcal{L}_{uncont}$
$P_x^a(t)$	Power consumption of $a \in \mathcal{L}$ at time t for $x \in X$
TS_X^a	a set of operating start times for $\mathcal{L}_{cont}$ at $x \in X$
$PR_X^a(ts_a)$	probability of $a \in \mathcal{L}$ at the time slot ts_a
$PRlevel_X^a(ts_a)$	Priority level of $a \in \mathcal{L}_{cont}$ at ts_a for $x \in X$

$PRlevel_X^{WM}(ts_{WM})$	Priority level of WM at ts_{WM} for $x \in X$
$PRlevel_X^{DW}(ts_{DW})$	Priority level of DW at ts_{DW} for $x \in X$
$M_X^a(ts_a)$	cost that $a \in \mathcal{L}_{cont}$ operates at ts_a for $x \in X$
M_X^a	cost vector of $a \in \mathcal{L}_{cont}$ for the set of x days
T_a	operating duration of appliance a
$Tariff(j)$	the unit price of electricity per kWh
$P_x^{\mathcal{L}_{cont}}(t, ts_{a1}, ts_{a2}, \dots)$	Power consumption of controllable appliances
P_{limit}	Power limit
$P_x^{\mathrm{Total}}(t, ts_{a1}, ts_{a2}, \dots)$	Power consumption of all appliances
$PL_x^{Total}(ts_{a1}, ts_{a2}, \dots)$	Power limit indicator

ABBREVIATIONS

AC	: Air Conditioner
CPP	: Critical Peak Pricing
DR	: Demand Response
DSM	: Demand Side Management
DW	: Dishwasher
EMS	: Energy Management System
HEMS	: Home Energy Management System
MC	: Main Control
PMU	: Power Measurement Units
RTP	: Real Time Pricing
TOU	: Time of Use
WM	: Washing Machine

1. INTRODUCTION

Since world population and industries depending on energy increase day by day, energy production has been a priority for all countries. Just as energy production, energy consumption has also been important. There are efforts to consume energy more efficiently. Almost half of the produced energy is consumed in buildings. It is expected that the energy consumed in buildings increases. However, existing energy consumption is not sustainable. Therefore, studies on energy saving in building have increased in recent years [1]. The efficient usage of energy and the reduction of energy demand have been two main concerns of international community, both economically and environmentally. It is made a great effort in order to be able to find feasible solutions for energy consumption problem which changes from discovering new energy sources to raising people's awareness [2].

There are a limited number of solutions to be able to meet growing raise of energy demand. One of the limited solutions is raise of electric generation. For this solution, it is necessary to establish more suitable facilities. However, this solution is not continuous. When too many plants are established, carbon dioxide absorption which causes climate changes increases. Moreover, establishment of plant is costly.

Another solution is Demand Side Management (DSM) which is an effective tool to reduce power demand. Demand Response (DR) program, which is one of DSM solutions, provides appropriate energy by reducing energy consumption during peak hours and by increasing facility usage. The targets of this program are which energy consumption is reduced at peak hours and energy demand is shifted to non-peak hours. Residential DR programs are classified as incentive programs and price-based programs. In price-based programs, users follow real time electricity cost by using time of use (TOU) pricing tariff. TOU offers different prices at different times of day. TOU pricing is most common residential electricity tariff. It is also considered to be implemented in many organizations around the world [3]. Most of studies on DR programs are focused on DSM strategies to manage energy demands during peak load hours. In these programs, users can stop or turn off unnecessary loads in order to be able to reduce electricity costs. However, they may disturb user's comfort. A demand response program under a dynamic pricing environment is proposed both to reduce electricity cost and to increase user comfort [4]. The proposed DR program provides a balance between user comfort and reduction in electricity cost. Similarly, in order to reduce electricity cost for end users, energy consumption limits is introduced for each time period [5], [6].

Habits of users and occupancy play an important role in energy demand of home. User’s activities and behaviors have a significant impact on the amount of energy consumed in any building. In a home, which has same physical and environmental conditions, energy consumption can be different according to behavior of occupant. In respect to this, homes have been monitored according to behavior of residents at single person households in South Korea, energy consumption of each home and characteristics of homes have been analyzed [1]. In a home in which four person live, usage characteristics of household appliances have been observed by using data mining techniques and data which obtained from user habits have been analyzed in order to be able to demonstrate high energy awareness [7]. How effectively can be learned usage pattern of household appliances and preferences of occupant in order to provide energy saving in smart homes has been discussed [8]. It has been believed that smart homes need to be able to predict future needs of individuals before they go into action to reduce energy consumption without disturbing occupants’ comfort. Furthermore, a recommender system which advises users to reduce energy consumption has been proposed.

By using load shifting techniques, it has been focused on the fact that peak loads reduce [9]. These techniques emphasize importance of device programming on a single resident which uses a home energy management system (HEMS) that has two type communication advantages between home and grid. Scheduling problem of household appliances has been discussed [10] and it has been show that this load planning problem has been solved by considering user’s preferences. A real time device planning system has been developed to reduce electricity cost while maintaining user comfort [11]. Moreover, a new device control algorithm has been developed that interacts with devices based on user comfort. Operating times of household appliances which take into account characteristics of user as well as user comfort has been programmed for energy consumption optimization [12]. By using proposed approach, user comfort has been guaranteed, electricity cost has been reduced and total loads have been flattened in the main grid. Thus, global energy efficiency has increased. A multi-agent system has been developed to achieve effective building energy and comfort management b taking into account user activities [13]. It has been demonstrated effects of seasonal changes on electrical load profiles of home [14]. Load profiles of electrical devices which is used at home have been observed by taking into account user's behavior.

Electricity distribution companies that use tariffs (such as real-time pricing (RTP), time-of-use (TOU) and critical peak pricing (CPP)) which are different according to time and consumption instead of fixed tariff for more regular and balanced consumption encourage users in order to use more efficiently electricity energy. Manufacturers of electrical appliances have focused their research and development on the design and production of products that consume less energy. The unions as European Union in which various states are involved make sale and usage of energy efficient devices mandatory by changing the energy regulation of devices which use in the households. In recent years, scientific studies on home energy management systems and methods have increased. In these studies, user comfort is usually taken into consideration while energy management is provided. Real time optimal schedule controller for HEMS has been used to manage energy consumption [3]. The proposed algorithm has provided the most appropriate program to limit total load demand and to plan operation of household appliances at certain times of day. It has been developed a model to minimize electricity bills while technical operation restrictions and user references are fulfilled [15]. A smart resident DSM system that reduces power losses in the grid and user's energy usage costs and a scheduling algorithm have been introduced [16]. It has been avoided user's disturbances by considering historical data of user habits. A HEMS has been developed for a smart home which consists of renewable energy source, energy storage system, many programmable home appliances and dynamic electricity tariffs [17]. Without, compromising user comfort, it has been aimed to minimize energy cost which requires to meet planned load demand. A HEMS has been proposed in order to minimize electricity cost and reduce peak power demand while user comfort continues [18].

Smart homes are one of the effective ways in order that energy in buildings uses efficiency. As a result of increasing of energy cost and demand, necessary of monitoring, control and saving energy has emerged. By using low pricing smart meters, a smart home can obtain information about electricity price and electricity consumption, also electricity consumption planning and create a family's energy saving awareness. Furthermore, it can improve comfort and safety of home life and optimize people's lifestyle. A smart home is a house which is equipped with intelligent technologies that aim to provide services for user demand. These smart technologies can increase quality life and save money by using energy efficiently. Smart home literature has been systematically reviewed [19]. The nature of smart homes on basis of technological developments has been discussed [20], [21]. Main service offered by a smart home has been stated as management of energy consumption [22], [23]. Smart home has been defined as a system equipped with many devices that cooperate with each other to monitor electronic devices, promote efficient energy management and sustainability [22]. Real time planning of home appliances in a smart home has been presented to control energy consumption optimally by using an energy optimization technique [24]. Therefore, it has been aimed to reduce electricity bills of end users without compromising user comfort. Residents in home have many purposes and limits. Smart homes aim to fulfill these purposes and limits. In other words, they aim to meet human needs. A human-centred system has been developed to optimize goals or constraints of individuals in home [25]. A home energy system which collects load profiles of devices has been introduced [26]. A profile matching time shift approach has been proposed in order to minimize total energy cost. The proposed approach has determined starting times of more than one household appliance. Characteristics of smart homes have been analyzed [27]. A detailed study has been carried out on architecture, technologies and systems of smart homes. An approach based on exploring daily activities created by inhabitants and creating predictive model for them has been proposed in [2]. This approach has defined a new perspective to model user habits with more efficient coding. Smart home energy management has been examined by taking into account changes between resident privacy and energy costs [28]. A multi objective approach has been proposed to minimize energy costs and maximize privacy protection. An energy management system for smart homes has been presented [29].

In the context of this study, the number of inhabitants in the home at any time of day has been determined via the monitoring system which is placed to homes of families belonging to different socioeconomic and sociocultural classes. Furthermore, usage habits of household appliances in the home have been observed. In addition to, it has been observed that occupancy status and the number of users are similar for each day of the week in each house.

In this study, for controllable appliances, a home energy management system (HEMS) which does not cause overloading in the grid, is suitable for user preferences and makes planning economic operating time is proposed. With the proposed HEMS, it will be possible both to increase user comfort and to reduce the cost without exceeding the power limit in the grid. In the next part of thesis, it will be given information about general features of the monitoring smart home. Classification, features and power consumption of appliances are given in this part. In third part, general info will be given about home energy management system. For proposed HEMS, solution methods are expressed by formulas and notations. With information obtained from second and third part, operating scheduling for controllable appliances will be demonstrated by case studies in part 4. Finally, results which emerged from case studies are discussed and concluded.

2. SMART HOME

Smart grids are gradually replacing traditional power networks with a real time monitoring system, information transmission system, DSM system and internet of thing technologies. The most important feature of smart grids is that they can control effectively power usage to achieve goal of energy saving. Smart home service is an important part of smart grid consumption. It has real time interaction between users and power network.

Smart home is a residential based platform which uses internet of things, computer technologies, control technology and communication technology [27]. Its main objective is to provide an efficient, comfortable, safe, convenient and environmentally friendly living environment that integrates systems, services and management into people. The core of smart home is technology consisting of hardware and software components which include sensors and household appliances.

The foreseen smart home system consists of main control (MC) unit, communication units, household electrical appliances, occupancy sensors, power measurement units (PMU), smart meter and smart switches. Main control units communicates with sensors and power measurement units in house, monitors activities of residents and use of appliances, and stores this information in database. Furthermore, it interferes to operation of appliances. In addition to, main control unit takes tariff information via smart meter and calculates cost of the consumed energy based on power consumption of appliances. Figure 2.1 shows smart home system.

2.1. Smart Home Monitoring

The home is monitored for a certain period of time. During the monitoring, at the beginning of each time slots, main controller communicates with the power measurements units and sensors to gather home occupancy and appliance usage information. Home occupancy and appliance usage information are stored in database as historical data.

In this monitoring, one execution period (e.g., one day, 24 hours) is discretized into a prescribed number T of uniform time slots, i.e., $t \in \mathcal{T} = \{1, 2, \dots, T\}$, so that the total number of time slots in a day is $T = {}^{24}/_{\Delta_t}$ where Δ_t represents the length of each time slots.

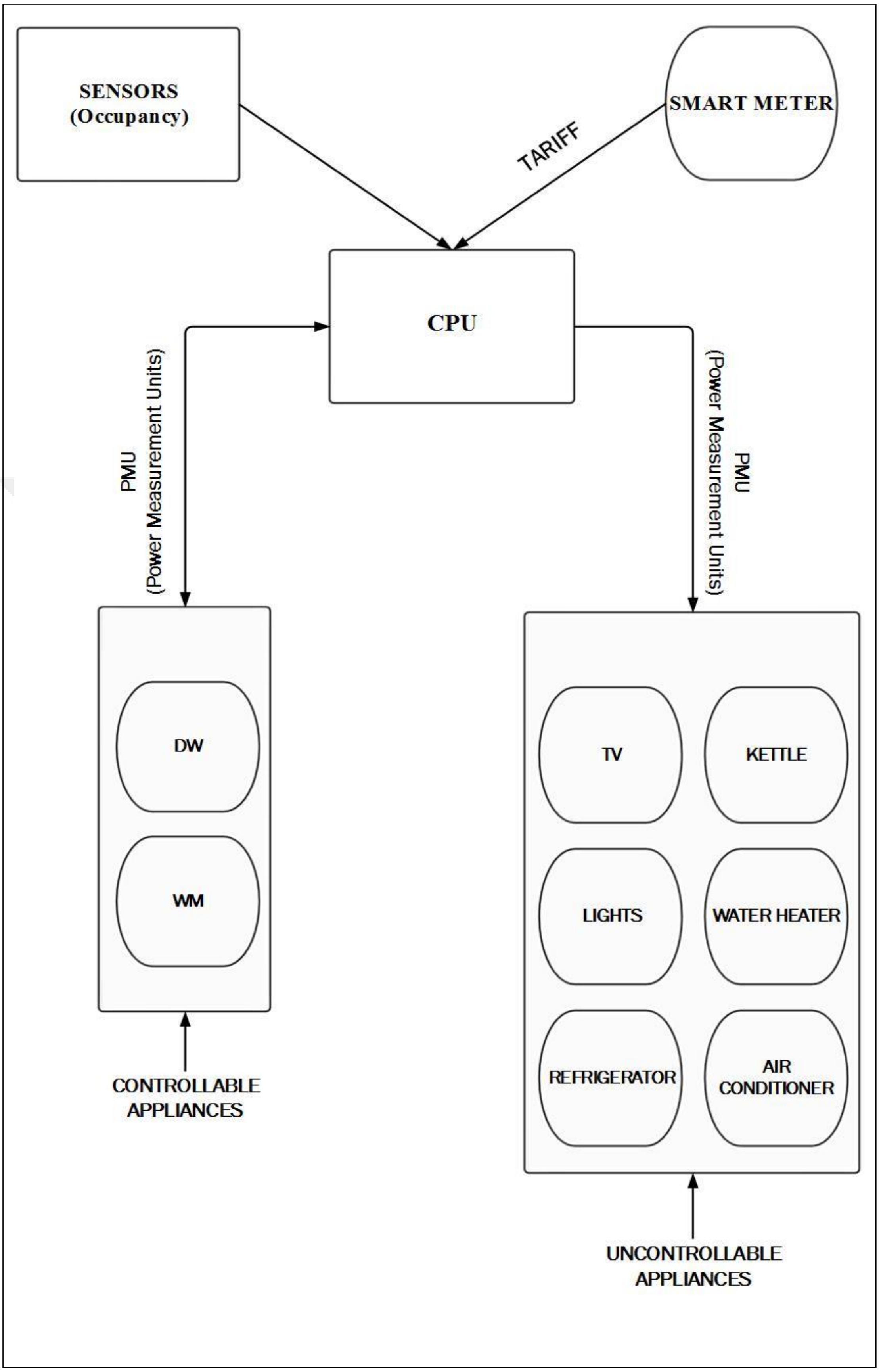

Figure 2.1. *Smart Home System*

2.2. Appliances

Electrical appliances which is used in the smart home can be divided into two classes according to their usage places and habits; uncontrollable and controllable appliances. The concept of the controllability in this classification refers to the ability interfering with the operation of appliance from outside. With appliances such as lamps, kettle, TV and water heater that can be used or operated at any time by users, appliances such as refrigerator and air conditioner (AC) which are used continuously in the house will be evaluated in the class of uncontrollable appliances. Uncontrollable appliances will be shown as $\mathcal{L}_{uncont}$ in part 3. On the other hand, appliances such as washing machine (WM) and dishwasher (DW), which can be intercepted in their working conditions and which can be shifted working time according to requests and expectations of users, will be evaluated in the class of controllable appliances. Controllable appliances will be shown as $\mathcal{L}_{cont}$ in part 3.

2.2.1. Uncontrollable appliances

The operating time and duration of appliances which affects directly user comfort are classified as uncontrollable appliances. MC cannot interfere with the operation of these appliances. The operating time and duration of appliances such as lambs, kettle, TV, water heater and AC which operate at any time and duration or such as refrigerator which operates continuously according to working principle cannot be affected by MC interferences. The usage features of these appliances are given below.

a. TV

If users decide TV watch, they turn on TV. TV stays on during its watching duration. The power consumption of TVs can be assumed to be constant, although power consumption can be slightly different according to displayed image, brightness and sound level. Figure 2.2 shows power consumption of LED-TVs in different sizes.

Usage of TV is directly related to user habits. TV usage time of each observed house is similar in itself. It has been observed that working durations of TVs in all observed houses are directly proportional with occupancy of home.

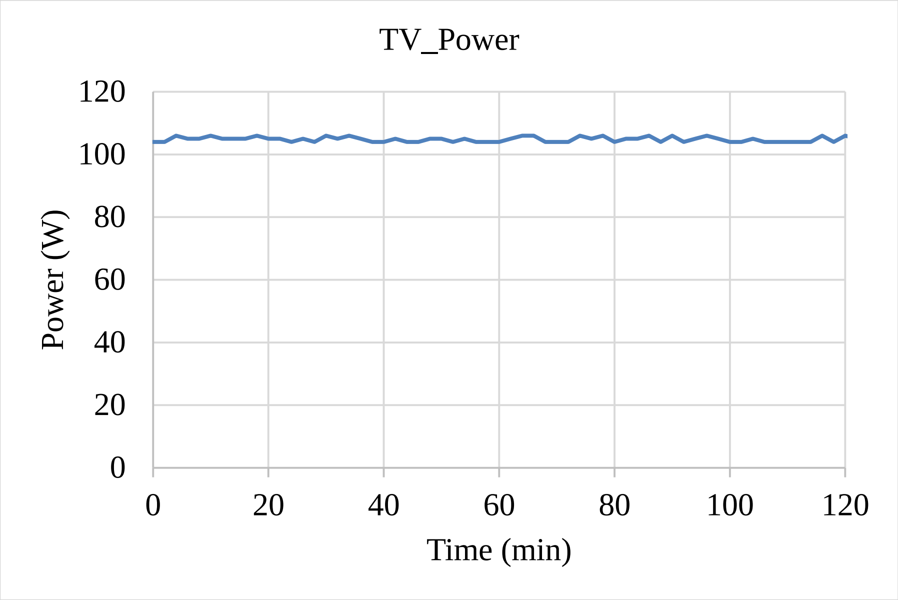

Figure 2.2. *Power Consumption of LED-TVs*

b. Lights

When users enter any room of house, if there is not sufficient lightning, they turn on lamp inside of room. As long as activity in the room continues, lamp remains on. Lamps are usually electrical appliances that consume constant power. Power consumption of lamp in any room is independent from time and other factors (e.g. temperature, occupancy number, etc.). Power consumption graphs of lamps are given Figure 2.3 with different nominal wattage.

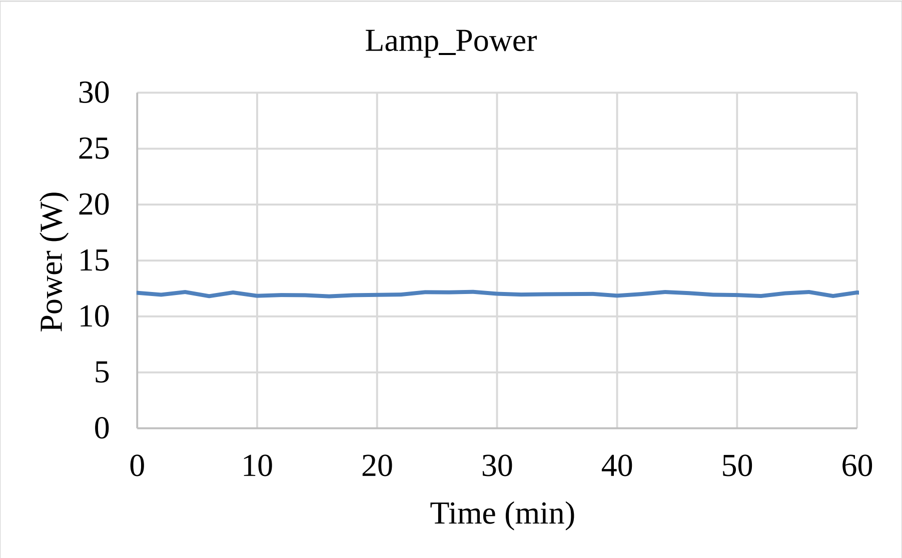

Figure 2.3. *Power Consumption of Lamps*

In seasons when sunlight is less taken, it is necessary a longer lightning. It has been observed that the usages of illuminations in all observed houses are inversely proportional with using time length of energy from solar radiation, and directly proportional with the number of users in home.

c. Kettle

If users need hot water, kettle runs for an average of 3-4 minutes. After hot water is provided, kettle is closed. Kettle is an electrical appliance that consumes constant power depending on used heater power. The following power consumption curve (Figure 2.4) shows power consumption while kettle is running.

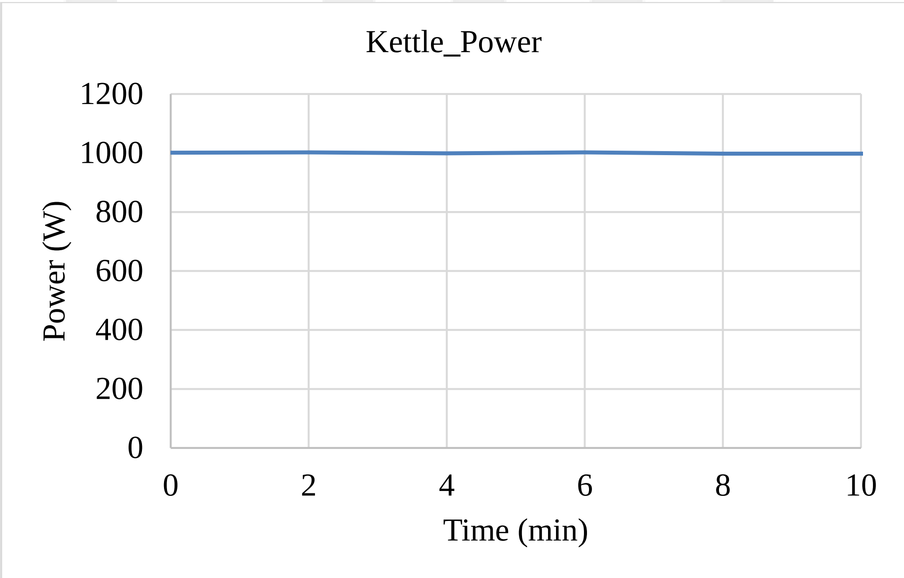

Figure 2.4. *Power Consumption Curve of Kettle*

Usage of kettle is directly related to user habits. Using time of kettle in each observed house is similar in itself. It has been observed that the average number of kettle usage during day is directly proportional with the number of users at home and duration of occupancy.

d. Water Heater

Like kettle, water heater is usually used when residents want to take a shower. Water heater, which is operated during the shower, is switched off after the operation. Like other uncontrollable appliances, frequency of water heater usage is proportional with the number of household residents. Water heater is also an electrical appliance which consumes a constant power as depending on the used heater power. Water heater power consumption curve (Figure 2.5) is given as follows.

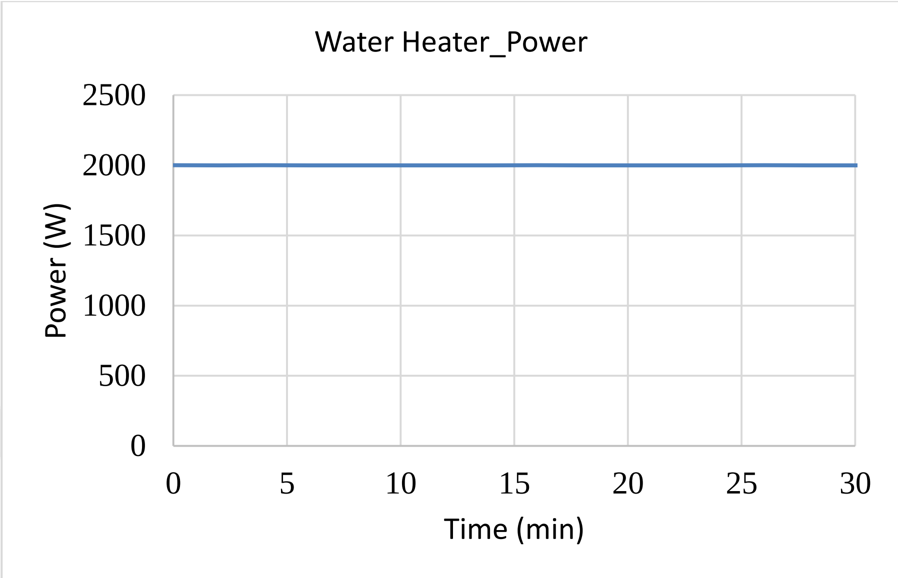

Figure 2.5. *Water Heater Power Consumption Curve*

e. Air Conditioner

Air condition maintains the room temperature in the range of a specific value set by the user. Conventional AC works by cycling the compressor on or off completely to meet room temperature preferences. Air conditioners have usually cooling and heating functions. While AC is used in order to heat room in winter, AC is also used to cool room in summer. When outdoor temperature is too high or too low, consumed energy of air conditioner which tries to keep the domestic temperature within a certain range increases. In all observed houses, it has been observed that AC is working less in the spring months while working longer in summer and winter months according to climatic conditions. It has also been observed that AC working time is directly proportional with the duration of occupancy in the home.

f. Refrigerator

Refrigerator keeps food fresh by cooling them. The refrigerator operates continuously 24 hours in a day. New generation refrigerators are inverter type refrigerators. In these refrigerators, the local controller of inverter type refrigerator adjusts the compressor speed to provide precise cooling performance by using several temperature sensors. When the cabinet temperature of the refrigerator rises, cooling is automatically increased by increasing the compressor speed. When cooling is sufficient, compressor speed is reduced and the minimum cooling capacity is maintained. Thus, unnecessary power consumption is avoided since the consumed power is reduced as the compressor speed of the refrigerator decreases.

That the refrigerator door is opened or closed and a new product at room temperature is placed to the refrigerator increase indoor temperature of the refrigerator. It needs more cooling to keep the cabinet temperature within a certain range. Therefore, compressor speed and energy consumption of the refrigerator increase. In the observed houses, it has been observed that more energy is consumed in the evening when occupancy increases at home.

2.2.2. Controllable appliances

Electrical appliances whose operating time can be intervened without disturbing user comfort are classified as controllable devices. MC can interfere with only operation time of these appliances. Other all options are related to the user's preferences. For example, each program mode of a washing machine is suitable for certain laundry types and an appropriate program is selected by user. Therefore, in accordance with the definition of controllable appliances, the selected program mode for washing machine cannot be allowed to interfere with by MC. The usage features of these devices are given below.

a. Washing Machine

There are different program modes for washing machines (WMs) according to the type, amount and dirtiness of the laundry, for example, prewash, main wash, rinse, softener, intermediate spin and final spin.

Kinds of program modes of washing machine are classified as 'regular', 'long' and 'express'. Figure 2.6, Figure 2.7 and Figure 2.8 show the power profiles of different program modes a 7 kg front-load WM.

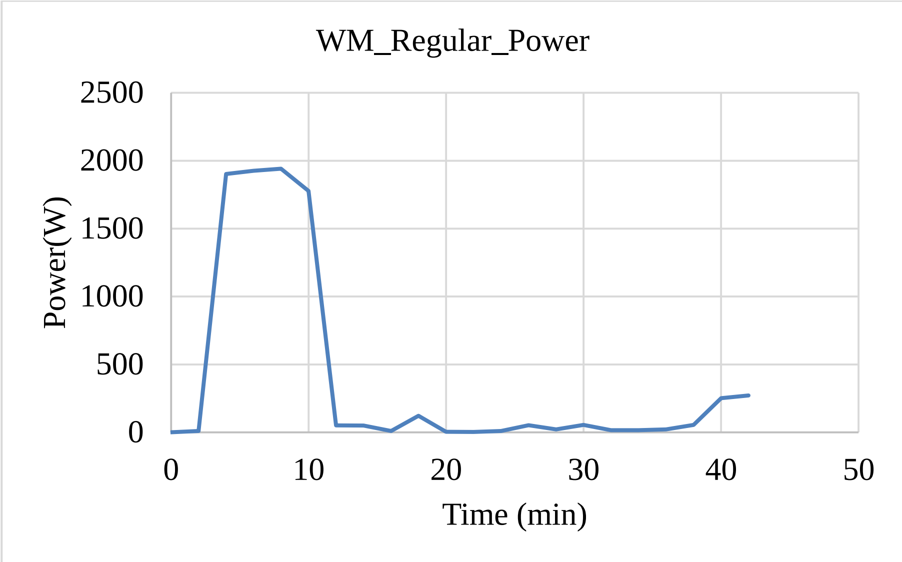

Figure 2.6. *The Power Profile of Regular Program Mode of WM*

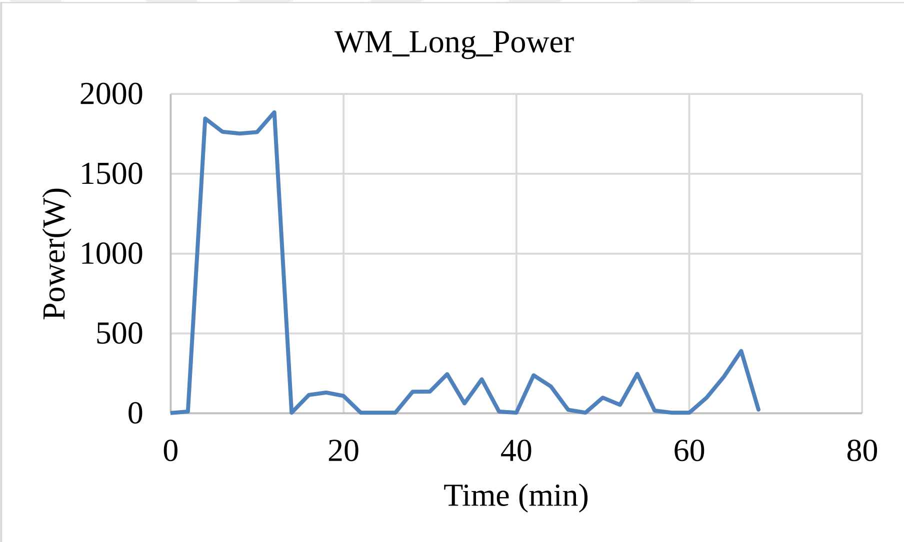

Figure 2.7. *The Power Profile of Long Program Mode of WM*

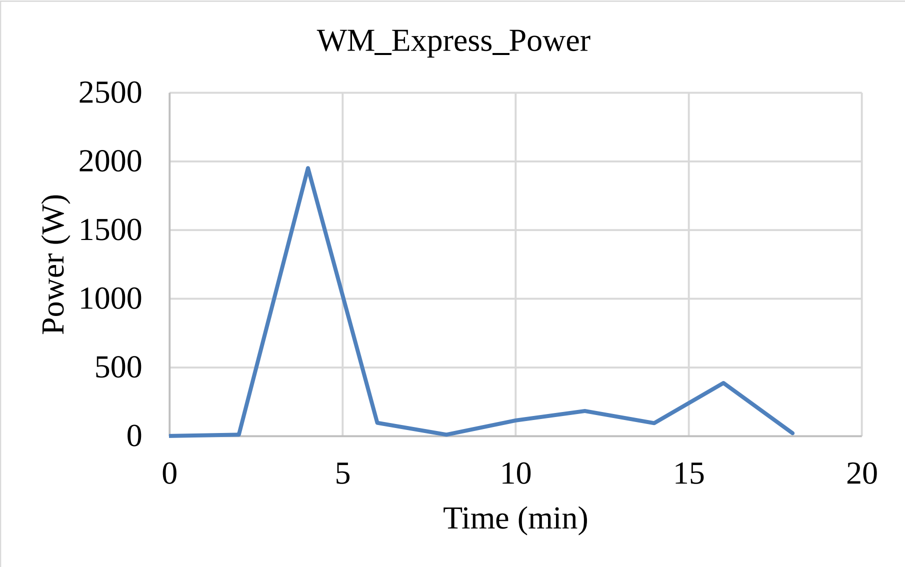

Figure 2.8. *The Power Profile of Express Program Mode of WM*

b. Dishwasher

Just as washing machines, there are different program modes for dishwashers (DWs) according to the type, amount and dirtiness of dishes, for example, prefill, heat, wash, drain, rinse and sanitize. Kinds of program modes of dishwasher are classified as ‘normal’, ‘intensive’ and ‘express’. Figure 2.9, Figure 2.10 and Figure 2.11 show the power profiles of different program modes for a 60 cm freestanding DW. Program modes of a DW are selected by the user.

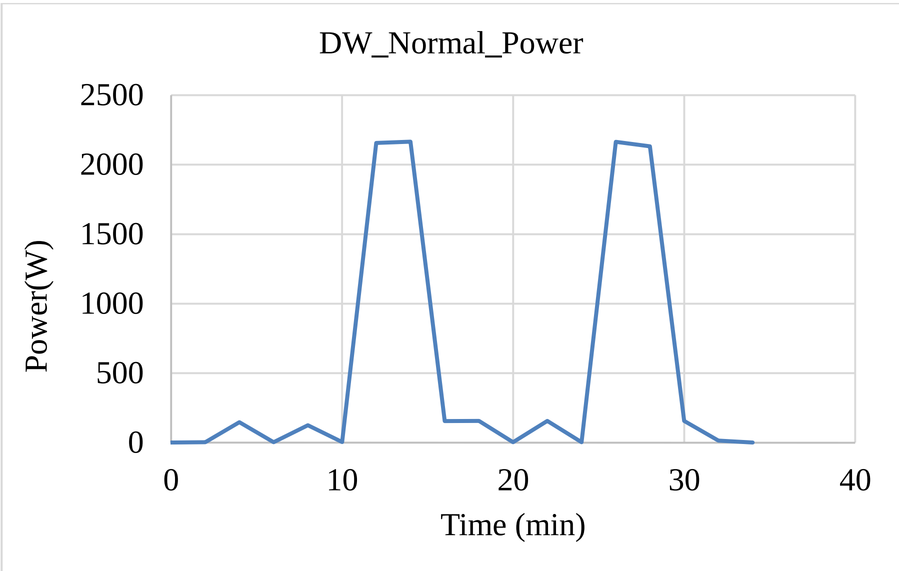

Figure 2.9. *The Power Profile of Normal Program Mode of DW*

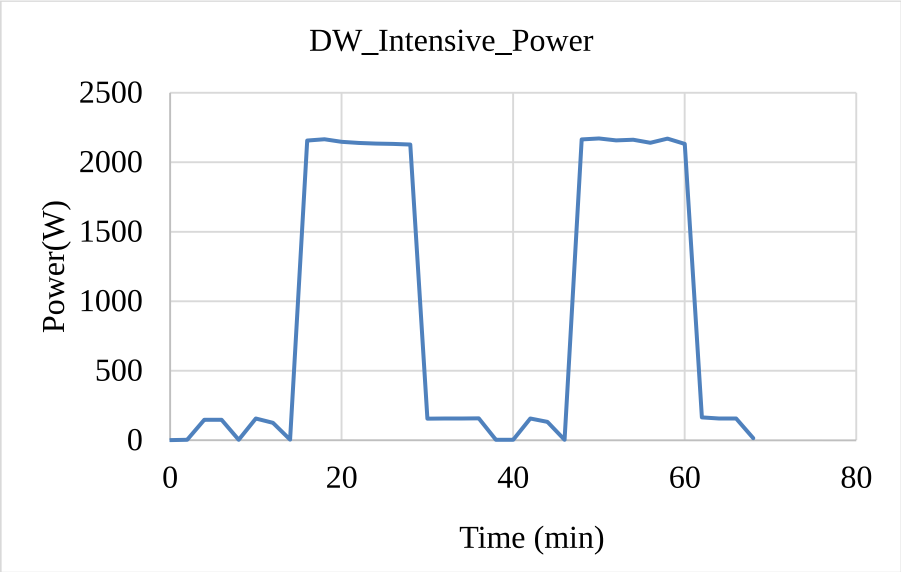

Figure 2.10. *The Power Profile of Intensive Program Mode of DW*

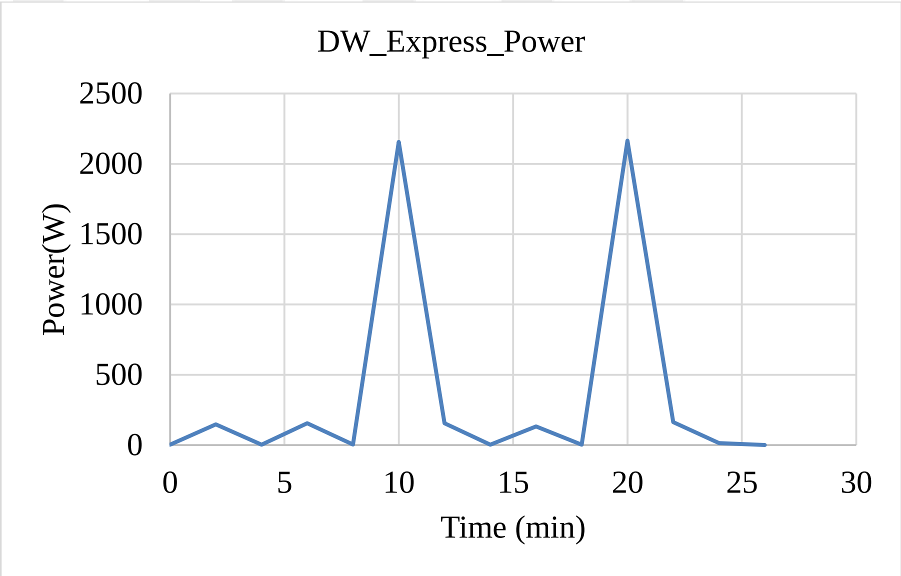

Figure 2.11. *The Power Profile of Express Program Mode of DW*

3. HOME ENERGY MANAGEMENT SYSTEM

Energy management system (EMS) is an intelligent automatic control tool that dynamically foresees consumer behaviors, predicts future behaviors and appliance can be programmed and controlled according to behavior and grid signal. Center of the system is energy consumption of occupants. Their habits and daily life activities form consumption profiles. The purpose of EMS is to perform an appliance scheduling based on existing consumer activities, appliance energy demands, grid signals and user compliance parameters.

Electricity distribution companies apply a different strategy to prevent high power demand which can be occurred in grid. This strategy is to determine maximum power level that is allowed to usage of home for houses which is connected to grid. The power level may be time dependent, or can be kept constant for whole day. In this study, it has been aimed that electrical appliances in the house has operated without causing any sudden power demand and a constant power limit has been determined for whole day.

In the context of this study, the number of inhabitants in the home at any time of day has been determined via the monitoring system which is placed to homes of families belonging to different socioeconomic and sociocultural classes. Furthermore, usage habits of household appliances in the home have been observed. In addition to, it has been observed that occupancy status and the number of users are similar for each day of the week in each house.

For example, in a family which consists of working parents and a child that goes to school, while leaving from home start at 7:00 in the morning, there is no one in home at 9:00. Similarly, when returning home from work and school start at 16:00, all residents return to home at 18:30. This activity is a routine activity in the home. The situation of being at home on one day of the week is similar to the situation of being at home on the same days of the month.

This causes that uncontrollable appliances which cannot be intervened by MC and is used entirely with user control operate at similar working hours and similar duration during day. It is seen that increase of the number of residents in the house and usage durations of home causes which usage frequency and duration of these devices increases.

For example, kettle is used frequently when residents are at home. Similarly, residents can take a shower when they wake up in the morning or before they go to sleep at night. Lamps are opened by users according to usage status of rooms in the house. As the number of residents in house increases, the number of used lamps and rooms increases also.

Unlike uncontrollable appliances, operating times of controllable appliances such as WM and DW are independent from occupancy status and the number of users at home. These appliances can be adjusted according to demands and user usage habits without changing user comfort.

In this study, for controllable appliances, a home energy management system (HEMS) which does not cause overloading in the grid, is suitable for user preferences and makes planning economic operating time is proposed. With the proposed HEMS, it will be possible both to increase user comfort and to reduce the cost without exceeding the power limit in the grid.

In order that controllable appliances does not cause overloading in the grid, expected power consumption of uncontrollable appliances in the home is determined by using historical data obtained from measurements made for each day of week. Taking into account the expected power consumption, it is aimed that controllable appliances is operated at time intervals which intensive power consumption does not occur. The calculation of the expected power expenditure in houses will be explained in detail in Section 3.1.

In order to be able to improve user comfort, it is determined times when users want to operate controllable appliances for each day of week in the observed houses. By using data which is stored in a database, possibility that user operates appliance has been determined for each day and each time interval. In these possibilities, priority level has been determined for operation times by ranking from the highest to the lowest. In terms of high user comfort, it has been aimed that appliance operates within time interval which priority level has as low as possible. The creation of priority matrices of appliances will be described in detail in Section 3.2.

Electricity demand which is used in homes during a day varies at different times of day. When a large number of people use electricity, power demand expected from grid increases and overloading may occur in grid. Electricity distribution companies apply different pricing tariffs in order to prevent overloading in grid. They apply different tariffs at different time intervals, such as real-time pricing (RTP), time of use (TOU) pricing and critical peak pricing (CPP). With TOU which is considered as pricing tariff in this study, electricity prices are low when demand is low, otherwise they are high when demand is high. Generally, electricity usage increases due to rising of the number of people at home in some time periods. In these time periods, price of electricity is kept high and it tries that demand is reduced.

In this study, it is aimed to reduce electricity cost as well as user comfort. For this reason, when operating starting time of WM is determined, it is aimed that the appliance is operated at possible lower tariff time by taking into account the tariff information.

In monitoring system which is a part of HEMS, MC unit communicates in 2 minute time intervals with occupancy sensors installed in home and PMU in feeds of electrical appliances. Thus, numbers of residents and using appliances in the house are determined. According to this information, daily occupancy matrix and appliance usage matrices have been formed.

Power measurement units which exist at entrance of appliances provide instantaneous power consumption measurement. Moreover, depending on communication period with central controller, PMU send average power consumption information to central controller from previous communication moment to new communication moment.

3.1. Expected Power Consumption

When operating time of controllable appliances is scheduling, power consumption which is expected from operating of uncontrollable appliances in home is taken into account in order to prevent instantaneous excessive power demand.

For this purpose, first of all, usage matrix of an appliance $a \in \mathcal{L}$ is created for each day of the week. Thus, 7 appliance usage matrices are created for each appliance.

For an appliance, the set of x days measured at different weeks are expressed by the set X. For example, the set of measured Sunday days is expressed by SUNDAY. In addition to, the number of measurements made during day is expressed by m. For each $a \in \mathcal{L}$, appliance usage matrix belonging to x days is expressed by $K_X^a\colon |X| \times m \rightarrow \{0,1\}$.

Matrix components belonging to day and time which appliance operates are expressed with 1, others matrix components are expressed with 0.

$$K_X^a(x,t) = \begin{cases} 1, & a \in \mathcal{L} \; is \; operating \; at \; t \\ 0, & a \in \mathcal{L} \; is \; not \; operating \; at \; t \end{cases} \quad (3.1)$$

In this study, measurements for each $a \in \mathcal{L}$ appliance were made during 52 week ($|X| = 52$) with 2 minute intervals each day (m=720). Thus, obtained appliance usage matrices are expressed by $K_X^a: 52 \times 720 \to \{0,1\}$.

In this study, local times of appliances during their operation time are indicated t_{int}. In other words, $t_{int} = 0$ when appliance is turned on, and t_{int} increases as long as appliance is operating, t_{int} value is reset when appliance is switched off. $P^a(t_{int})$ is power that appliance $a \in \mathcal{L}$ spends at t_{int} local time.

As the power consumption of appliance varies very little for uncontrollable appliances (for example; TV, kettle, etc.) as long as they operate, they are called uncontrollable fix-power appliances ($\mathcal{L}_{uncont-fix}$). For these appliances, instantaneous power consumption during operation time of appliance is constant. That is, if any $K_X^a(x,t) = 1$,

$$P^a(t_{int}) = P_x^a(\mathrm{t}) = P^a * K_X^a(x,t) \tag{3.2}$$

for all t_{int} .

The expected power consumption for any $a \in \mathcal{L}_{uncont-fix}$ for the set of x days, i.e. X, is calculated by taking into account all x days measured.

$$P_{xexpected}^a(t) = \frac{\sum_{j \in X} P^a * K_X^a(j,t)}{|X|} \tag{3.3}$$

Uncontrollable appliances which power consumption varies as long as appliance operates are called uncontrollable variable-power appliances ($\mathcal{L}_{uncont-var}$) (Refrigerator and Air Conditioner).

Power consumption at any time t ($K_X^a(x,t) = 1$) during operating of an appliance $a \in \mathcal{L}_{uncont-var}$ at the set of x days is calculated.

$$P_x^a(t) = P^a(\mathrm{t} - ts_a) * K_X^a(x,t) \tag{3.4}$$

ts_a is operating time of the appliance a.

The expected power consumption for any $a \in \mathcal{L}_{uncont-var}$ for the set of x days is calculated by taking into account all x days measured.

$$P_{xexpected}^a(\mathrm{t}) = \frac{\sum_{j \in X} P^a(\mathrm{t} - ts_a) * K_X^a(\mathrm{j,t})}{|X|} = \frac{\sum_{j \in X} P_X^a(t) * K_X^a(\mathrm{j,t})}{|X|} \tag{3.5}$$

For the set of x days of a house, the expected power consumption which is occurred by uncontrollable appliances is stored in $P_{xexpected}$ vector by using equation (3.3) and (3.5).

$$P_{xexpected}^{\mathcal{L}_{\text{uncont}}}(t) = \sum_{a\in\mathcal{L}_{\text{uncont}}} P_{xexpected}^{a}(t) \tag{3.6}$$

On the other hand, for controllable appliances, power consumption of appliance during its operating varies according to current activity of appliance. It also depends on the local time of appliance, t_{int}. Power consumption at any time t ($K_X^a(x,t) = 1$) during operating time of an appliance $a \in \mathcal{L}_{cont}$ at the set of x days is calculated similar to uncontrollable variable power appliances ($\mathcal{L}_{uncont-var}$).

$$P_x^a(t) = P^a(\mathrm{t} - ts_a) \ * K_X^a(x,t) \tag{3.7}$$

3.2. Priority Vector

The usage of controllable appliances can be scheduled during day in such a way as not to disturb user comfort. While doing this scheduling, the appliance usage habits of users are taken into account in order not to disturb the user comfort. In this context, priority level at the moment appliance starts operating has been determined for each measured time slot by using the appliance usage matrices created for appliances.

First of all, a set of operating start times TS_X^a for each set of x days is created for each appliance $a \in \mathcal{L}_{cont}$.

$$TS_X^a = \{ts_a |\ K_X^a(x,ts_a) - K_X^a(x,ts_a - 1) = 1 \ \ x \in X\} \tag{3.8}$$

Then, priority level is determined for each $ts_a \in TS_X^a$. While the priority level of each time slot is determined for a day of the week, operating time when appliance starts operating is obtained for similar days. For this day of the week, probability which appliance starts operating at this time slot is calculated by dividing the number of the time slot which is selected by the total number of similar days which are measured.

$$PR_X^a(ts_a) = \frac{\sum_{i=1}^{|X|} K_X^a(i,ts_a) - K_X^a(i,ts_a - 1)}{|X|} \tag{3.9}$$

By using probability value, priority level ($PRlevel_X^a(ts_a)$) is calculated for starting time (ts_a) on x days of $a \in \mathcal{L}_{cont}$.

The priority level of the highest possibility time slot will be 1, and all time intervals are numbered, respectively. That is, the user's most preferred start-up time when user comfort is highest has the smallest priority value in priority matrix. Table 3.1 shows priority level for WM while Table 3.2 shows priority level for DW. These tables validate for scenario 1 which will be mentioned in case studies.

Table 3.3 shows priority level for WM while Table 3.4 shows priority level for DW. These tables validate for scenario 2 which will be mentioned in case studies.

Table 3.5 shows priority level for WM while Table 3.6 shows priority level for DW. These tables validate for scenario 3 which will be mentioned in case studies.

Table 3.1. *Priority level of WM for a Friday in January.*

$PRlevel_{friday}^{WM}(ts_{WM})$	**Starting Time(ts_{WM})**	**Start No**	$PR_{FRIDAY}^{WM}(ts_{WM})$
1	05:10	18	34,6154
2	00:00	9	17,3077
3	05:40	9	17,3077
4	23:30	6	11,5385
5	06:00	4	7,69231
6	05:30	2	3,84615
7	23:40	2	3,84615
8	05:00	2	3,84615

Table 3.2. *Priority level of DW for a Friday in January.*

$PRlevel_{friday}^{DW}(ts_{DW})$	**Starting Time (ts_{DW})**	**Start No**	$PR_{FRIDAY}^{DW}(ts_{DW})$
1	16:40	16	30,7692
2	22:00	9	17,3077
3	17:00	8	15,3846
4	22:10	8	15,3846
5	16:30	5	9,61538
6	16:10	4	7,69231
7	22:30	2	3,84615

Table 3.3. *Priority level of WM for a Tuesday in April*

$PRlevel_{tuesday}^{WM}(ts_{wm})$	**Starting Time (ts_{WM})**	**Start No**	$PR_{TUESDAY}^{WM}(ts_{WM})$
1	05:30	13	25
2	23:10	9	17,3077
3	05:00	9	17,3077
4	04:40	9	17,3077
5	23:00	6	11,5385
6	05:10	4	7,69231
7	23:30	2	3,84615

Table 3.4. *Priority level of DW for a Tuesday in April*

$PRlevel_{tuesday}^{DW}(ts_{DW})$	**Starting Time (ts_{DW})**	**Start No**	$PR_{TUESDAY}^{DW}(ts_{DW})$
1	16:40	16	30,7692
2	16:30	11	21,1538
3	22:30	7	13,4615
4	22:00	6	11,5385
5	22:10	6	11,5385
6	16:10	4	7,69231
7	17:00	2	3,84615

Table 3.5. *Priority level of WM for a Wednesday in June*

$PRlevel_{wednesday}^{WM}(ts_{wm})$	**Starting Time (ts_{WM})**	**Start No**	$PR_{WEDNESDAY}^{WM}(ts_{WM})$
1	05:30	13	25
2	05:10	11	21,1538
3	23:00	9	17,3077
4	04:40	9	17,3077
5	23:30	6	11,5385
6	05:40	2	3,84615
7	00:00	2	3,84615

Table 3.6. *Priority level of DW for a Wednesday in June*

$\boldsymbol{PRlevel_{wednesday}^{DW}(ts_{DW})}$	**Starting Time ($\boldsymbol{ts_{DW}}$)**	**Start No**	$\boldsymbol{PR_{WEDNESDAY}^{DW}(ts_{DW})}$
1	22:00	14	26,9231
2	16:40	13	25
3	17:00	9	17,3077
4	22:10	6	11,5385
5	16:30	6	11,5385
6	22:30	4	7,69231

In this study, priority values for all combinations of each appliance $a_i \in \mathcal{L}_{cont}$ are selected as ts_{ai} on $x \in X$ day are calculated as follows:

$$PRlevel_x^{Total}(ts_{a1}, ts_{a2}, \dots) = \sqrt{\sum_{a_i \in \mathcal{L}_{cont}} (PRlevel_x^{a_i}(ts_{ai}))^2} \quad (3.10)$$

3.3. Cost Vector

The fact that appliances whose starting time can be controlled is operated at different starting times causes different electricity cost according to TOU tariff system. In this study, cost is calculated for all possible start-up times of each controllable appliance $a \in \mathcal{L}_{cont}$. It is calculated as follows

$$M_x^a(ts_a) = \sum_{j=ts_a}^{ts_a+T_a} P^a(j - ts_a) * Tariff(j) \quad (3.11)$$

In here, T_a is operating duration of appliance a. $Tariff(j)$ is the unit price of electricity per kWh at a ts t. Also, cost vector (M_x^a) is formed.

$$M_x^a : 1 \times |TS_X^a| \rightarrow R \quad (3.12)$$

The cost formed in case that starting time of each appliance $a_i \in \mathcal{L}_{cont}$ is selected as ts_{ai} on $x \in X$ day is expressed by

$$M_x^{\mathcal{L}_{cont}}(ts_{a1}, ts_{a2}, \dots) = \sum_{a_i \in \mathcal{L}_{cont}} M_x^{a_i}(ts_{ai}) \quad (3.13)$$

3.4. Power Limit Excess Matrix

When operating start time of any controllable device is selected as "ts_a", power consumption of any appliance $a_i \in \mathcal{L}_{cont}$ at any time of $t \in T$ is calculated:

$$P_x^a(t) = P^a(\mathrm{t} - ts_a) * (K_X^a(t - ts_a) - K_X^a(t - (ts_a + T_a)) \qquad (3.14)$$

Here, T_a is operating duration of appliance a. For all controllable devices ($a_i \in \mathcal{L}_{cont}$), power consumption is expressed by:

$$P_x^{\mathcal{L}_{cont}}(t, ts_{a1}, ts_{a2}, \dots) = \sum_{a_i \epsilon \mathcal{L}_{cont}} P^a(\mathrm{t} - ts_{ai}) * \{(K_X^a(t - ts_{ai}) - K_X^a(t - (ts_{ai} + T_{ai}))\} \qquad (3.15)$$

Total power consumption of house is expressed by:

$$P_x^{\mathrm{Total}}(t, ts_{a1}, ts_{a2}, \dots) = P_{x_{expected}}^{L\mathrm{uncont}}(t) + P_x^{\mathcal{L}_{cont}}(t, ts_{a1}, ts_{a2}, \dots) \qquad (3.16)$$

Resulting of this power consumption equation, $PL_x^{Total}(ts_{a1}, ts_{a2}, \dots)$ is expressed by power limit indicator which demonstrates whether the power limit is exceeded at any time of day $x \in X$

$$PL_x^{Total}(ts_{a1}, ts_{a2}, \dots) = \begin{cases} 0, & P_{limit} - P_x^{\mathrm{Total}}(t, ts_{a1}, ts_{a2}, \dots) > 0 \ \ \forall t \\ 1, & otherwise \end{cases} \qquad (3.17)$$

If the power limit does not exceed, it gives "0" value. Otherwise, it gives "1" value.

3.5. Determination of Start-up Time

In order to determine the start-up time of WM and DW:

1. Power limit must not exceed,
2. Maximum comfort (minimum priority value) must be provided,
3. Minimum electricity cost must be obtained.

Therefore, while the start-up time for WM and DW is determined, minimization of the objective functions is shown in Figure 3.1.

For minimization objective functions, optimization problem should be solved by minimizing equation (3.18).

$$a * PL_x^{Total}(ts_{a1}, ts_{a2}, \dots) + b * \ M_x^{\mathcal{L}_{cont}}(ts_{a1}, ts_{a2}, \dots) + c * \ PRlevel_x^{Total}(ts_{a1}, ts_{a2}, \dots)$$

$$ts_{ai} \in TS_X^{ai} \qquad (3.18)$$

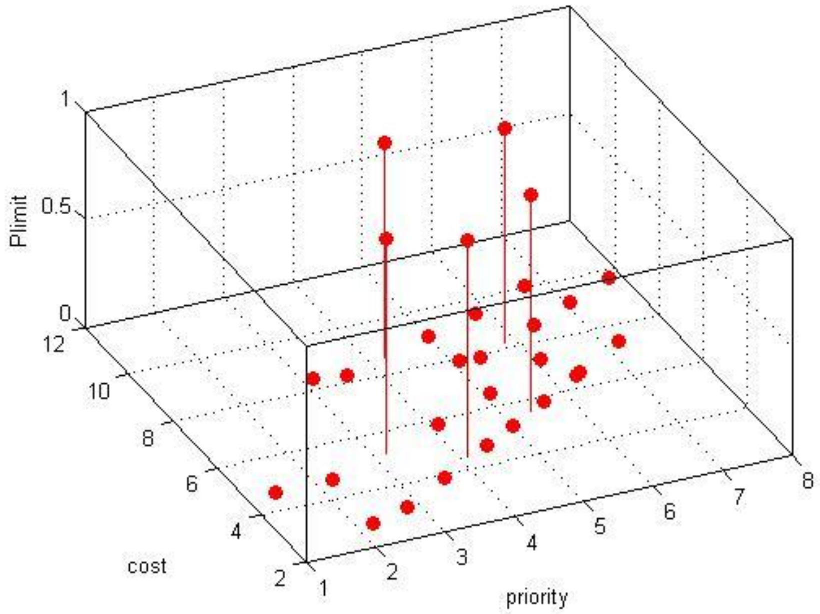

Figure 3.1: *Minimization of objective functions (Cost, Priority and Plimit)*

3.6. Normalization and Optimization

Since the minimum electricity cost and maximum user comfort without exceeding power limit are foreseen in the proposed home energy management system, there is a need to make the price, comfort and power information comparable. The price and power exceed information are brought to the same level by min-max according to the user comfort.

First, by using priority matrices for DW and WM, the common priority value is calculated according to equation (3.10). The priority tables are shown in Section 3.2. The points in these tables that have the lowest common priority value are the lowest priority points in WM and DW. The lowest priority times are the time when the user has the highest preference for WM and DW to operate.

Min-max normalization is a normalization strategy, where x is the minimum and maximum values. It can be easily seen when x=min, then y=0.

The total cost values for each run probability are converted to new cost values by min-max normalization using the minimum and maximum values of the common priority matrix.

$$Cost_{new} = \frac{(Cost - Cost_{min}) x (PRlevel_{max} - PRlevel_{min})}{Cost_{max} - Cost_{min}} + PRlevel_{min} \qquad (3.19)$$

$PRlevel_{max}$: Maximum priority level value,

$PRlevel_{min}$: Minimum priority level value,

$Cost_{max}$: Maximum cost value,

$Cost_{min}$: Minimum cost value.

The power limit indicator values for each run probability are converted to new power limit indicator values by min-max normalization using the minimum and maximum values of the common priority matrix.

$$PL_{new} = \frac{(PL - PL_{min})x(PRlevel_{max} - PRlevel_{min})}{PL_{max} - PL_{min}} + PRlevel_{min} \tag{3.20}$$

$PRlevel_{max}$: Maximum priority level value,

$PRlevel_{min}$: Minimum priority level value,

PL_{max}: Maximum power limit indicator value,

PL_{min}: Minimum power limit indicator value.

The decision value is calculated according to 3.18 by using the transformed cost matrix and power limit indicator matrix generated by the number of runs depending on the probability that WM and DW are executed, and the common priority value in each probability.

4. CASE STUDIES

In this section, contributions of the proposed home energy management system will be shown with scenarios and examples on different months and different days. Let us inspect one of these scenarios, Scenario 1, in detail. In this scenario, runtime scheduling which WM is going to operate long program and DW is going to operate intensive program will be made for a Friday in January. Home occupancy matrix and appliance usage matrices on Friday in January are extracted by using the historical data bank.

According to the historical database, the possible runtime matrices for WM and DW are shown in Table 3.1 and Table 3.2. A common priority matrix is generated from the possible runtime matrices for WM and DW by using the equation (3.10).

$$PRlevel_x^{Total}(ts_{WM}, ts_{DW}) = \sqrt{(PRlevel_x^{WM}(ts_{WM}))^2 + (PRlevel_x^{DW}(ts_{DW}))^2} \quad (4.1)$$

According to running probabilities of WM and DW, power possibility matrix, cost probability matrix and power exceed indicator matrix (PL_x^a) are generated for the Friday in January by using the common priority matrix.

Table 4.1. *Minimization of the priority level, cost and power limit for Friday in January*

WM Priority Level	DW Priority Level	Sqr (Priority Level)	Cost	New Cost	Power exceed	New Power	Result
1	1	1,41421	0,766443	8,88121	1	10,6301	13,9239
2	1	2,23607	0,760359	8,76236	1	10,6301	13,9563
3	1	3,16228	0,773704	9,02305	1	10,6301	14,2974
4	1	4,12311	0,739529	8,35545	1	10,6301	14,1355
5	1	5,09902	0,823185	9,98966	1	10,6301	15,4529
6	1	6,08276	0,772334	8,99629	1	10,6301	15,1965
7	1	7,07107	0,737146	8,30891	1	10,6301	15,2328
8	1	8,06226	0,764209	8,83759	1	10,6301	16,0032
1	2	2,23607	0,413499	1,98652	1	10,6301	11,0429
2	2	2,82843	0,407415	1,86766	1	10,6301	11,1574
3	2	3,60555	0,42076	2,12835	1	10,6301	11,425

Table 4.1. (Continue) *Minimization of the priority level, cost and power limit for Friday in January*

4	2	4,47214	0,386585	1,46076	1	10,6301	11,6247
5	2	5,38516	0,470241	3,09496	1	10,6301	12,3117
6	2	6,32456	0,41939	2,10159	1	10,6301	12,5466
7	2	7,28011	0,384203	1,41421	1	10,6301	12,9615
8	2	8,24621	0,411266	1,94289	1	10,6301	13,5932
1	3	3,16228	0,79923	9,5217	1	10,6301	14,6172
2	3	3,60555	0,793145	9,40284	1	10,6301	14,6429
3	3	4,24264	0,80649	9,66354	1	10,6301	14,9794
4	3	5	0,772316	8,99594	1	10,6301	14,7962
5	3	5,83095	0,855972	10,6301	1	10,6301	16,1245
6	3	6,7082	0,805121	9,63678	1	10,6301	15,8388
7	3	7,61577	0,769933	8,9494	1	10,6301	15,8459
8	3	8,544	0,796996	9,47807	1	10,6301	16,6082
1	4	4,12311	0,413499	1,98652	1	10,6301	11,5735
2	4	4,47214	0,407415	1,86766	1	10,6301	11,6828
3	4	5	0,42076	2,12835	1	10,6301	11,9386
4	4	5,65685	0,386585	1,46076	1	10,6301	12,1299
5	4	6,40312	0,470241	3,09496	1	10,6301	12,7898
6	4	7,2111	0,41939	2,10159	1	10,6301	13,016
7	4	8,06226	0,384203	1,41421	1	10,6301	13,4164
8	4	8,94427	0,411266	1,94289	1	10,6301	14,0276
1	5	5,09902	0,695142	7,48837	0	1,41421	9,16928
2	5	5,38516	0,689058	7,36951	0	1,41421	9,23633
3	5	5,83095	0,702403	7,6302	0	1,41421	9,7067
4	5	6,40312	0,668228	6,96261	0	1,41421	9,56441
5	5	7,07107	0,751884	8,59681	1	10,6301	15,3917
6	5	7,81025	0,701033	7,60345	0	1,41421	10,9915
7	5	8,60233	0,665846	6,91607	0	1,41421	11,128
8	5	9,43398	0,692909	7,44474	0	1,41421	12,1006
1	6	6,08276	0,674517	7,08545	1	10,6301	14,1493
2	6	6,32456	0,668432	6,96659	1	10,6301	14,1962

Table 4.1. (Continue) *Minimization of the priority level, cost and power limit for Friday in January*

3	6	6,7082	0,681777	7,22729	1	10,6301	14,4994
4	6	7,2111	0,647603	6,55969	1	10,6301	14,4232
5	6	7,81025	0,731259	8,1939	1	10,6301	15,5287
6	6	8,48528	0,680408	7,20053	1	10,6301	15,3899
7	6	9,21954	0,64522	6,51315	1	10,6301	15,5055
8	6	10	0,672283	7,04182	1	10,6301	16,2045
1	7	7,07107	0,413499	1,98652	1	10,6301	12,9208
2	7	7,28011	0,407415	1,86766	1	10,6301	13,0188
3	7	7,61577	0,42076	2,12835	1	10,6301	13,2488
4	7	8,06226	0,386585	1,46076	1	10,6301	13,4214
5	7	8,60233	0,470241	3,09496	1	10,6301	14,0207
6	7	9,21954	0,41939	2,10159	1	10,6301	14,2273
7	7	9,89949	0,384203	1,41421	1	10,6301	14,5945
8	7	10,6301	0,411266	1,94289	1	10,6301	15,1583

Total cost values and power exceed indicator matrix calculated for each running probability are converted to new cost and power exceed values with min-max normalization by using minimum and maximum values of the common priority matrix.

$$Cost_{new} = \frac{(Cost - Cost_{min})x(PRlevel_{max} - PRlevel_{min})}{Cost_{max} - Cost_{min}} + PRlevel_{min} \quad (4.2)$$

$$PL_{new} = \frac{(PL - PL_{min})x(PRlevel_{max} - PRlevel_{min})}{PL_{max} - PL_{min}} + PRlevel_{min} \quad (4.3)$$

Decision values are calculated by using common priority matrix, the new cost values matrix and power exceed indicator matrix.

$$a * PL_x^{Total}(ts_{WM}, ts_{DW}) + b * M_x^{\pounds_{cont}}(ts_{WM}, ts_{DW}) + c * \ PRlevel_x^{Total}(ts_{WM}, ts_{DW})$$

$$ts_{WM} \in TS_X^{WM}$$

$$ts_{DW} \in TS_X^{DW} \quad (4.4)$$

According to Table 4.1., When the cheapest electricity consumption on Friday in January is 0.3843 TL, WM needs to run at 23:40, and DW needs to run at 22:00 or WM needs to run at 23:40, and DW needs to run at 22:10 or WM needs to run at 23:40, and DW needs to run at 22:30. In these three study cases, user comfort is reduced.

At the same time, power exceed is seen when WM and DW have operate at these times. Power exceed is seen in Figure 4.1.

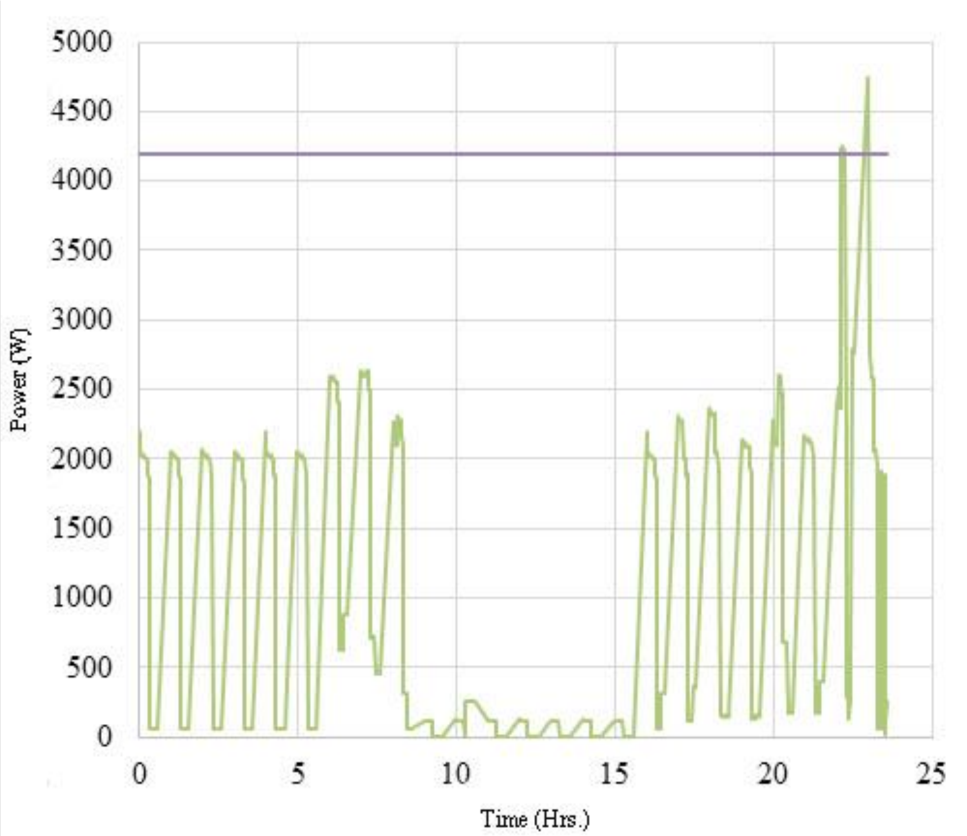

Figure 4.1. *When WM and DW operate at the cheapest electricity consumption for Friday in January, power excess graph*

When both the cost is minimized and the user comfort is maximized without taking into account power exceed, decision values are shown in Figure 4.2.

If the power exceed is not taken into account, the point which is shown as the decision value is the lowest is the point where the cost and common priority are the closest to minimum. If WM is executed 1 priority level and DW is executed 2 priority level, both the cost is reduced and the user comfort is maximized.

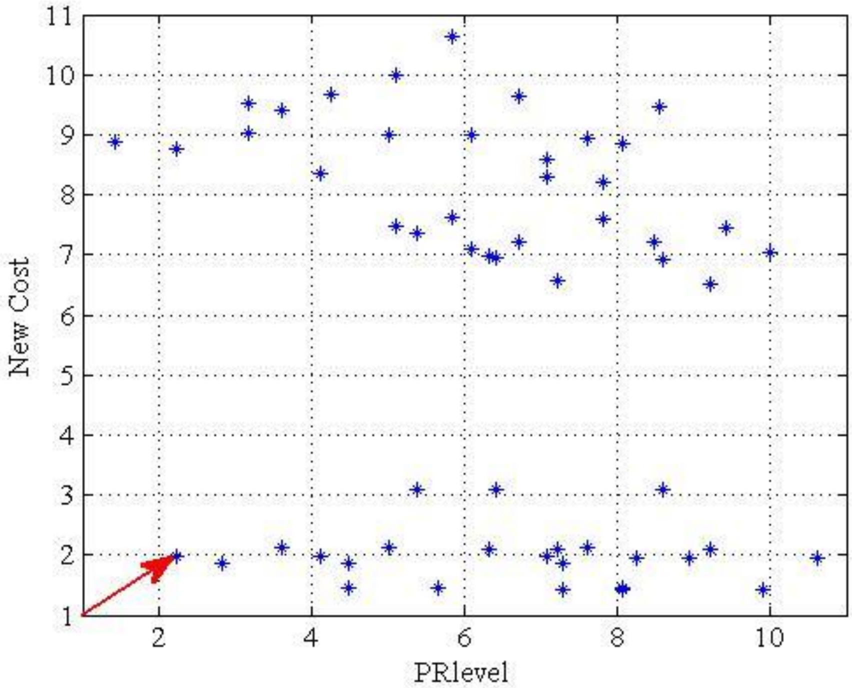

Figure 4.2. *Minimization of objective functions (PRlevel and Cost) for Friday in January*

When both the cost is minimized and the power isn't exceeded without taking into account the user comfort, decision values are shown in Figure 4.3.

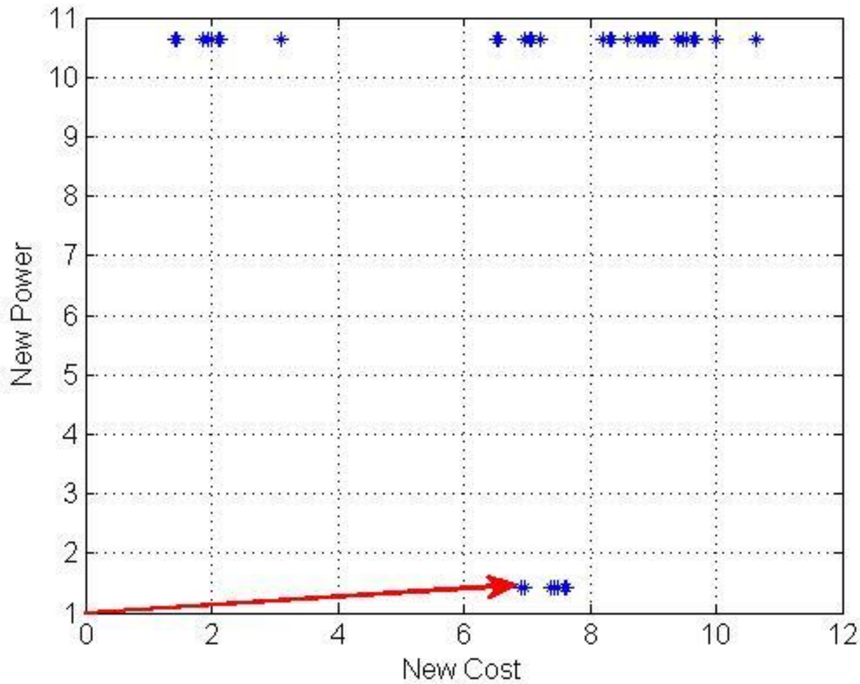

Figure 4.3. *Minimization of objective functions (Cost and Power) for Friday in January*

If the user comfort is not taken into account, the point which is shown as the decision value is the lowest is the point where the cost is the closest to minimum and power is not exceeded. If WM is executed 4 priority level and DW is executed 5 priority level, both the cost is reduced and power exceed is not observed.

When both the user comfort is maximized and power isn't exceeded without taking into account cost, decision values are shown in Figure 4.4.

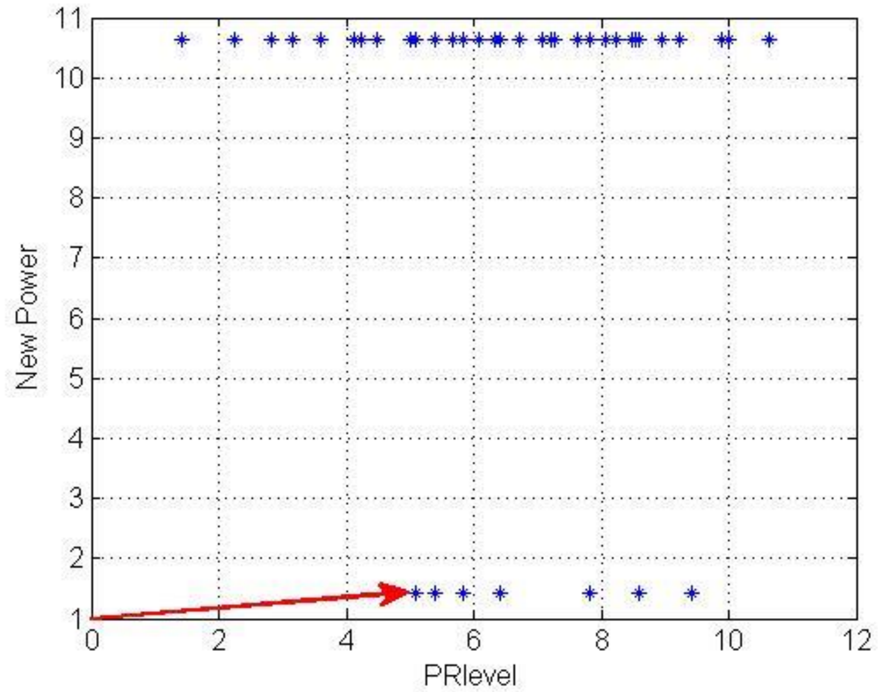

Figure 4.4. *Minimization of objective functions (PRlevel and Power) for Friday in January*

If the cost is not taken into account, the point which is shown as the decision value is the lowest is the point where the common priority is the closest to minimum and power is not exceeded. If WM is executed 1 priority level and DW is executed 5 priority level, both the power exceed is not observed and the user comfort is maximized.

The smallest of the decision objective functions is obtained from Table 4.1 and shown in Figure 4.5 when WM priority is executed 1 priority level (hour 05:10) and DW priority is executed 5 priority level (hour 16:30). In this combination, the cost of electricity consumption is 0.6952 TL,

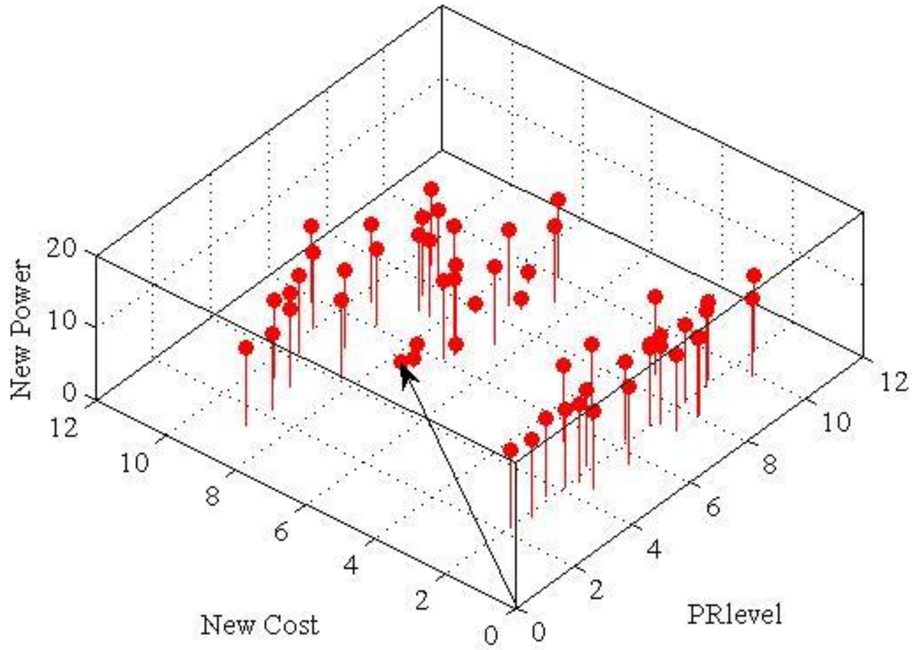

Figure 4.5. *Minimization of objective functions (Cost, PRlevel and Power) for Friday in January*

This combination is also the highest in comfort. Figure 4.6 shows that power limit is not exceeded.

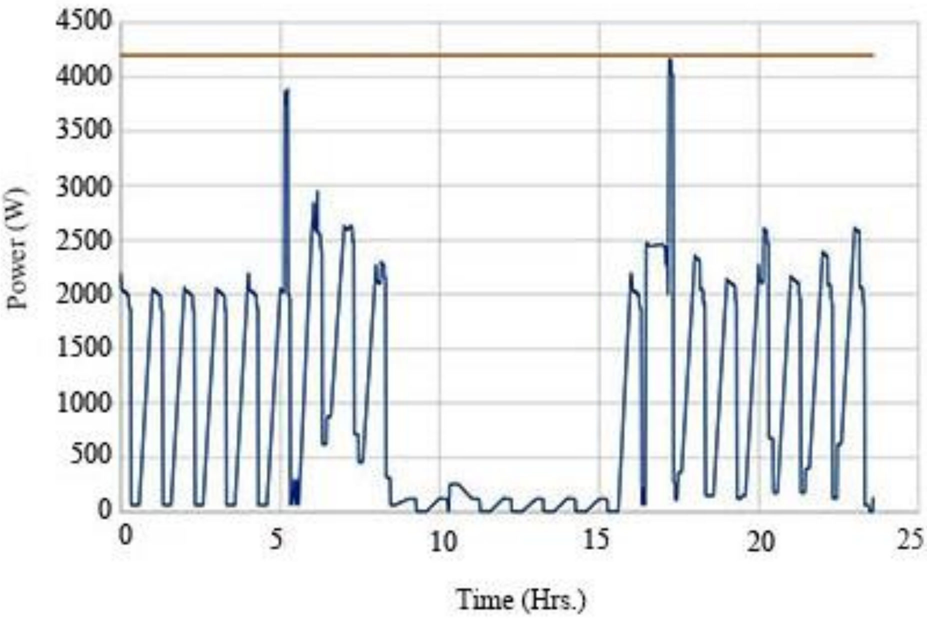

Figure 4.6. *When WM operates at 5:10 and DW operates at 16:30 for Friday in January, power excess graph*

In Scenario 2, runtime scheduling which WM is going to operate normal program and DW is going to operate short program will be made for a Tuesday in April. Home occupancy matrix and device usage matrices on Tuesday in April are extracted by using the historical data bank.

According to the historical database, the possible runtime matrices for WM and DW are Table 3.3 and Table 3.4, respectively. A common priority matrix is generated from equation (4.1).

According to running probabilities of WM and DW, power possibility matrix , cost probability matrix and power exceed indicator matrix (PL_x^a) are generated for the Tuesday in April by using the common priority matrix.

Total cost values and power exceed indicator matrix calculated for each running probability are converted to new cost and power exceed values with equation (4.2) and (4.3).

Decision values are calculated by using common priority matrix, the new cost values matrix and power exceed indicator matrix with equation (4.4).

Table 4.2. *Minimization of the priority level, cost and power limit for Tuesday in April*

WM Priority Level	DW Priority Level	Sqr (Priority Level)	Cost	New Cost	Power exceed	New Power	Result
1	1	1,41421	0,772334	9,23478	1	9,89949	13,6118
2	1	2,23607	0,749776	8,77745	1	9,89949	13,418
3	1	3,16228	0,764209	9,07007	1	9,89949	13,7937
4	1	4,12311	0,760359	8,992	1	9,89949	13,9949
5	1	5,09902	0,753661	8,85621	1	9,89949	14,2279
6	1	6,08276	0,766443	9,11535	1	9,89949	14,7679
7	1	7,07107	0,739529	8,56971	1	9,89949	14,8809
1	2	2,23607	0,701033	7,78925	0	1,41421	8,22633
2	2	2,82843	0,678475	7,33192	0	1,41421	7,9848
3	2	3,60555	0,692909	7,62454	0	1,41421	8,55182
4	2	4,47214	0,689058	7,54647	0	1,41421	8,88534
5	2	5,38516	0,68236	7,41067	0	1,41421	9,2692

Table 4.2.(Continue) *Minimization of the priority level, cost and power limit for Tuesday in April*

6	2	6,32456	0,695142	7,66982	0	1,41421	10,0412
7	2	7,28011	0,668228	7,12417	0	1,41421	10,2837
1	3	3,16228	0,41939	2,07929	1	9,89949	10,5983
2	3	3,60555	0,396832	1,62195	1	9,89949	10,6598
3	3	4,24264	0,411266	1,91458	1	9,89949	10,9392
4	3	5	0,407415	1,83651	1	9,89949	11,2416
5	3	5,83095	0,400717	1,70071	1	9,89949	11,6143
6	3	6,7082	0,413499	1,95986	1	9,89949	12,1178
7	3	7,61577	0,386585	1,41421	1	9,89949	12,5698
1	4	4,12311	0,41939	2,07929	1	9,89949	10,9235
2	4	4,47214	0,396832	1,62195	1	9,89949	10,9832
3	4	5	0,411266	1,91458	1	9,89949	11,2546
4	4	5,65685	0,407415	1,83651	1	9,89949	11,5487
5	4	6,40312	0,400717	1,70071	1	9,89949	11,9119
6	4	7,2111	0,413499	1,95986	1	9,89949	12,4033
7	4	8,06226	0,386585	1,41421	1	9,89949	12,8452
1	5	5,09902	0,41939	2,07929	1	9,89949	11,328
2	5	5,38516	0,396832	1,62195	1	9,89949	11,3855
3	5	5,83095	0,411266	1,91458	1	9,89949	11,6476
4	5	6,40312	0,407415	1,83651	1	9,89949	11,932
5	5	7,07107	0,400717	1,70071	1	9,89949	12,2838
6	5	7,81025	0,413499	1,95986	1	9,89949	12,7609
7	5	8,60233	0,386585	1,41421	1	9,89949	13,1909
1	6	6,08276	0,680408	7,37109	1	9,89949	13,7598
2	6	6,32456	0,657849	6,91376	1	9,89949	13,6308
3	6	6,7082	0,672283	7,20638	1	9,89949	13,9618
4	6	7,2111	0,668432	7,12831	1	9,89949	14,1708
5	6	7,81025	0,661734	6,99252	1	9,89949	14,4186
6	6	8,48528	0,674517	7,25166	1	9,89949	14,9193
7	6	9,21954	0,647603	6,70601	1	9,89949	15,0987
1	7	7,07107	0,805121	9,89949	1	9,89949	15,6844

Table 4.2.(Continue) *Minimization of the priority level, cost and power limit for Tuesday in April*

2	7	7,28011	0,782562	9,44216	1	9,89949	15,4969
3	7	7,61577	0,796996	9,73478	1	9,89949	15,8356
4	7	8,06226	0,793145	9,65671	1	9,89949	16,0079
5	7	8,60233	0,786447	9,52092	1	9,89949	16,2064
6	7	9,21954	0,79923	9,78006	1	9,89949	16,6928
7	7	9,89949	0,772316	9,23442	1	9,89949	16,7712

According to Table 4.2., When the cheapest electricity consumption on Tuesday in April is 0.3866 TL, WM needs to run at 23:30, and DW needs to run at 22:30 or WM needs to run at 23:30, and DW needs to run at 22:10 or WM needs to run at 23:30, and DW needs to run at 22:00. In these three study cases, user comfort is reduced.

At the same time, power exceed is seen when WM and DW have operate at these times. Power exceed is seen in Figure 4.7.

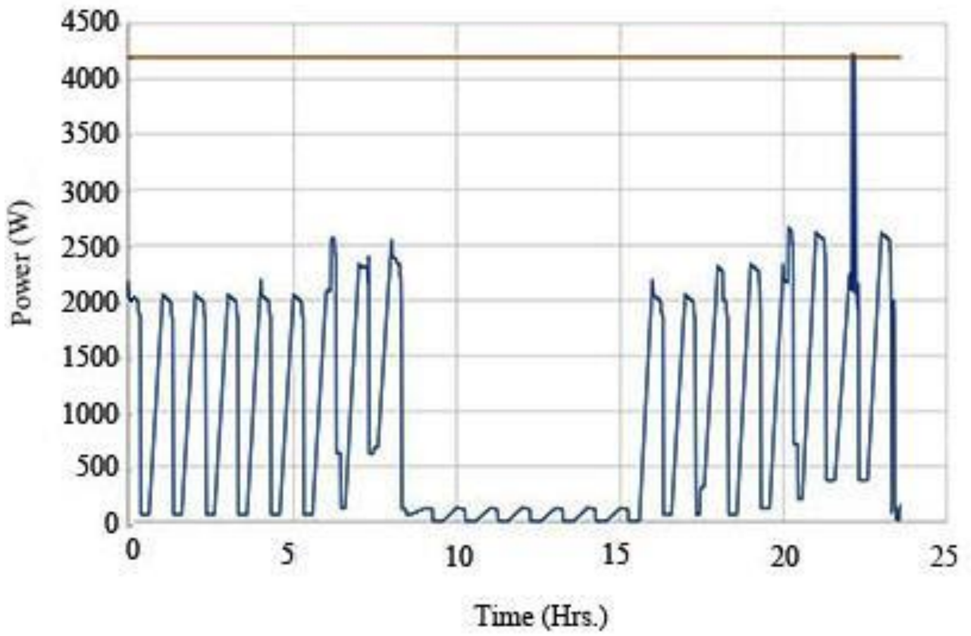

Figure 4.7. *When WM and DW operate at the cheapest electricity consumption for Tuesday in April, power excess graph*

When both the cost is minimized and the user comfort is maximized without taking into account power exceed, decision values are shown in Figure 4.8.

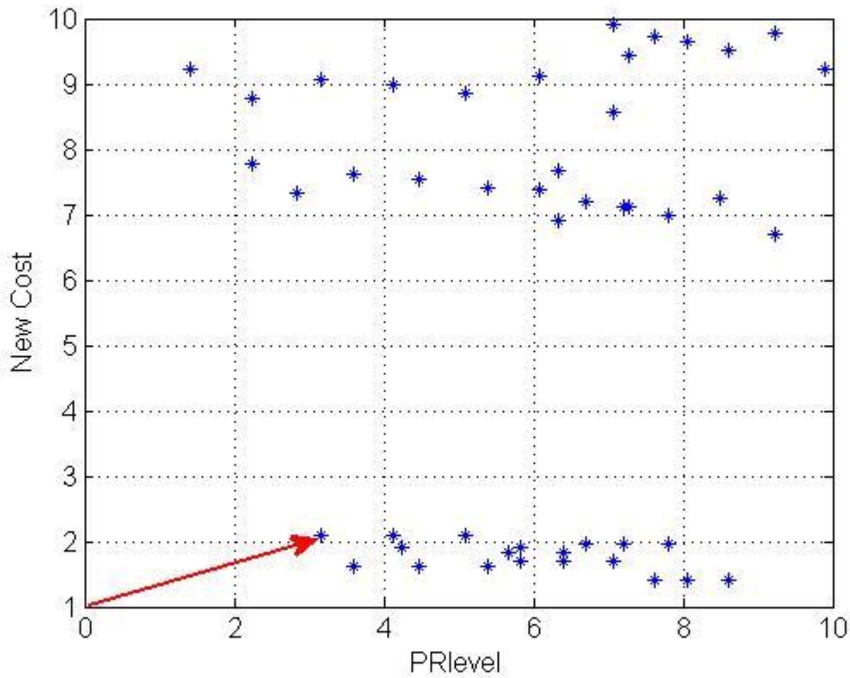

Figure 4.8. *Minimization of objective functions (PRlevel and Cost) for Tuesday in April*

If the power exceed is not taken into account, the point which is shown as the decision value is the lowest is the point where the cost and common priority are the closest to minimum. If WM is executed 1 priority level and DW is executed 3 priority level, both the cost is reduced and the user comfort is maximized.

When both the cost is minimized and the power isn't exceeded without taking into account the user comfort, decision values are shown in Figure 4.9.

If the user comfort is not taken into account, the point which is shown as the decision value is the lowest is the point where the cost is the closest to minimum and power is not exceeded. If WM is executed 7 priority level and DW is executed 2 priority level, both the cost is reduced and power exceed is not observed.

When both the user comfort is maximized and power isn't exceeded without taking into account cost, decision values are shown in Figure 4.10.

If the cost is not taken into account, the point which is shown as the decision value is the lowest is the point where the common priority is the closest to minimum and power is not exceeded. If WM is executed 1 priority level and DW is executed 2 priority level, both the power exceed is not observed and the user comfort is maximized.

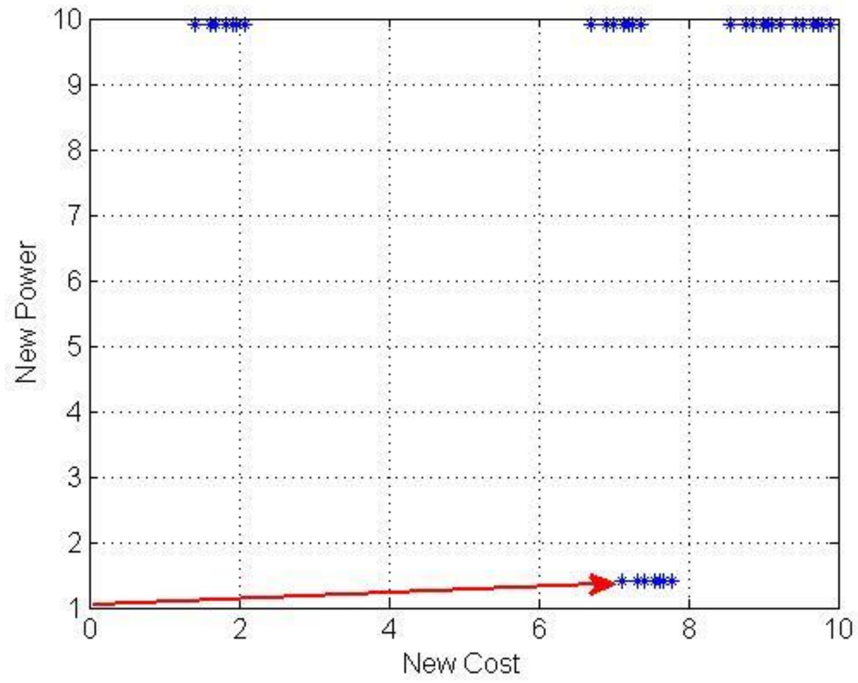

Figure 4.9. *Minimization of objective functions (Cost and Power) for Tuesday in April*

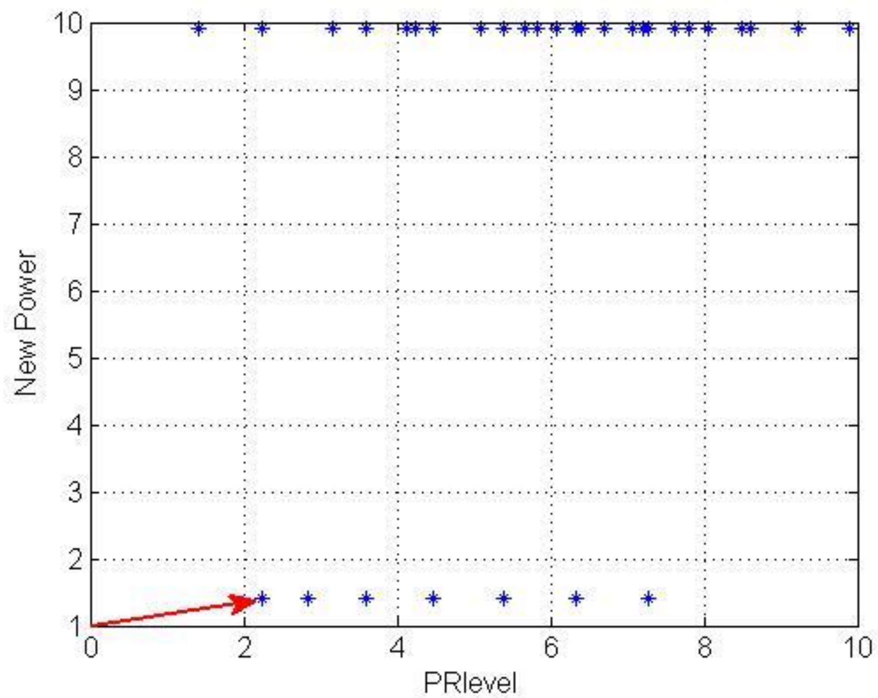

Figure 4.10. *Minimization of objective functions (PRlevel and Power) for Tuesday in April*

The smallest of the decision objective functions is obtained from Table 4.2 and is shown in Figure 4.11, when WM priority is executed 2 (hour 23:10) and DW priority is executed 2 (hour 16:30). In this combination, the daily cost of electricity consumption is 0.6784 TL.

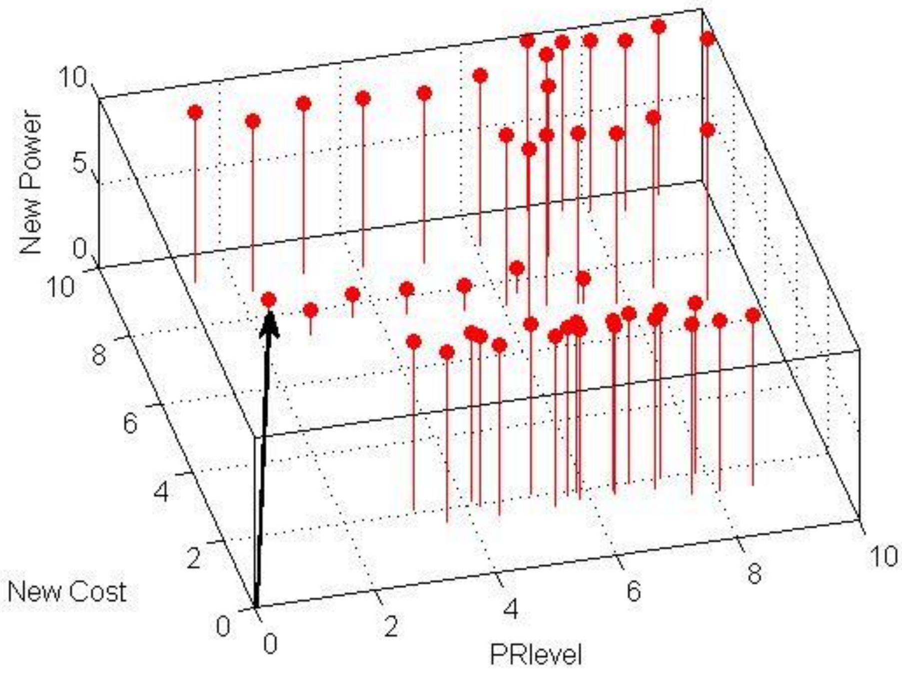

Figure 4.11. *Minimization of objective functions (Cost, PRlevel and Power) for Tuesday in April*

This combination is also one of the highest in comfort. Figure 4.12 shows that power limit is not exceeded.

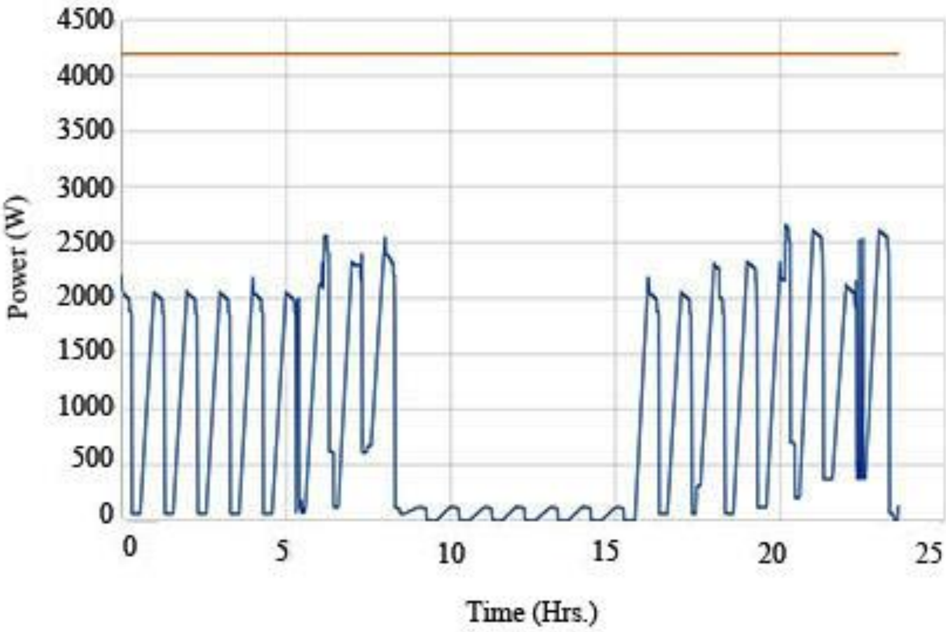

Figure 4.12. *When WM operates at 23:10 and DW operates at 16:30 for Friday in January, power excess graph*

In Scenario 3, runtime scheduling which WM is going to operate normal program and DW is going to operate short program will be made for a Wednesday in June. Home occupancy matrix and device usage matrices on Tuesday in April are extracted by using the historical data bank.

According to the historical database, the possible runtime matrices for WM and DW are Table 3.5 and Table 3.6, respectively. A common priority matrix is generated from equation (4.1).

According to running probabilities of WM and DW, power possibility matrix, cost probability matrix and power exceed indicator matrix (PL_x^a) are generated for the Wednesday in June by using the common priority matrix.

Total cost values and power exceed indicator matrix calculated for each running probability are converted to new cost and power exceed values with min-max normalization by using minimum and maximum values of the common priority matrix with equations (4.2) and (4.3).

Decision values are calculated by using common priority matrix, the new cost values matrix and power exceed indicator matrix with equation (4.4).

Table 4.3. *Minimization of the priority level, cost and power limit for Wednesday in June*

WM Priority Level	DW Priority Level	Sqr (Priority Level)	Cost	New Cost	Power exceed	New Power	Result
1	1	1,41421	0,126809	2,11595	1	9,21954	9,56437
2	1	2,23607	0,124576	1,85978	1	9,21954	9,66741
3	1	3,16228	0,124576	1,85978	1	9,21954	9,92264
4	1	4,12311	0,124576	1,85978	1	9,21954	10,2693
5	1	5,09902	0,120693	1,41421	1	9,21954	10,6301
6	1	6,08276	0,127311	2,17352	1	9,21954	11,2572
7	1	7,07107	0,124576	1,85978	1	9,21954	11,7669
1	2	2,23607	0,169747	7,0431	1	9,21954	11,8155
2	2	2,82843	0,167514	6,78694	1	9,21954	11,7925
3	2	3,60555	0,167514	6,78694	1	9,21954	12,0026
4	2	4,47214	0,167514	6,78694	1	9,21954	12,2908

Table 4.3.(Continue) *Minimization of the priority level, cost and power limit for Wednesday in June*

5	2	5,38516	0,163631	6,34137	1	9,21954	12,4183
6	2	6,32456	0,170248	7,10068	1	9,21954	13,2446
7	2	7,28011	0,167514	6,78694	1	9,21954	13,567
1	3	3,16228	0,188212	9,16197	0	1,41421	9,79498
2	3	3,60555	0,185979	8,9058	0	1,41421	9,71151
3	3	4,24264	0,185979	8,9058	1	9,21954	13,5023
4	3	5	0,185979	8,9058	0	1,41421	10,3108
5	3	5,83095	0,182096	8,46023	0	1,41421	10,3719
6	3	6,7082	0,188713	9,21954	0	1,41421	11,4891
7	3	7,61577	0,185979	8,9058	0	1,41421	11,8031
1	4	4,12311	0,126809	2,11595	1	9,21954	10,3188
2	4	4,47214	0,124576	1,85978	1	9,21954	10,4144
3	4	5	0,124576	1,85978	1	9,21954	10,6517
4	4	5,65685	0,124576	1,85978	1	9,21954	10,9754
5	4	6,40312	0,120693	1,41421	1	9,21954	11,3137
6	4	7,2111	0,127311	2,17352	1	9,21954	11,9048
7	4	8,06226	0,124576	1,85978	1	9,21954	12,3878
1	5	5,09902	0,154093	5,24686	0	1,41421	7,45181
2	5	5,38516	0,151861	4,99069	0	1,41421	7,4771
3	5	5,83095	0,151861	4,99069	1	9,21954	11,9961
4	5	6,40312	0,151861	4,99069	0	1,41421	8,24057
5	5	7,07107	0,147978	4,54512	0	1,41421	8,52398
6	5	7,81025	0,154595	5,30443	0	1,41421	9,54657
7	5	8,60233	0,151861	4,99069	0	1,41421	10,0452
1	6	6,08276	0,126809	2,11595	0	1,41421	6,59373
2	6	6,32456	0,124576	1,85978	0	1,41421	6,74231
3	6	6,7082	0,124576	1,85978	1	9,21954	11,5524
4	6	7,2111	0,124576	1,85978	0	1,41421	7,58016
5	6	7,81025	0,120693	1,41421	0	1,41421	8,06226
6	6	8,48528	0,127311	2,17352	0	1,41421	8,87267
7	6	9,21954	0,124576	1,85978	0	1,41421	9,51098

According to Table 4.3., When the cheapest electricity consumption on Tuesday in April is 0.1207 TL, WM needs to run at 23:30, and DW needs to run at 22:00 or WM needs to run at 23:30, and DW needs to run at 22:10 or WM needs to run at 23:30, and DW needs to run at 22:30. In these three study cases, user comfort is reduced.

At the same time, power exceed is seen when WM and DW have operate at these times. Power exceed is seen in Figure 4.13.

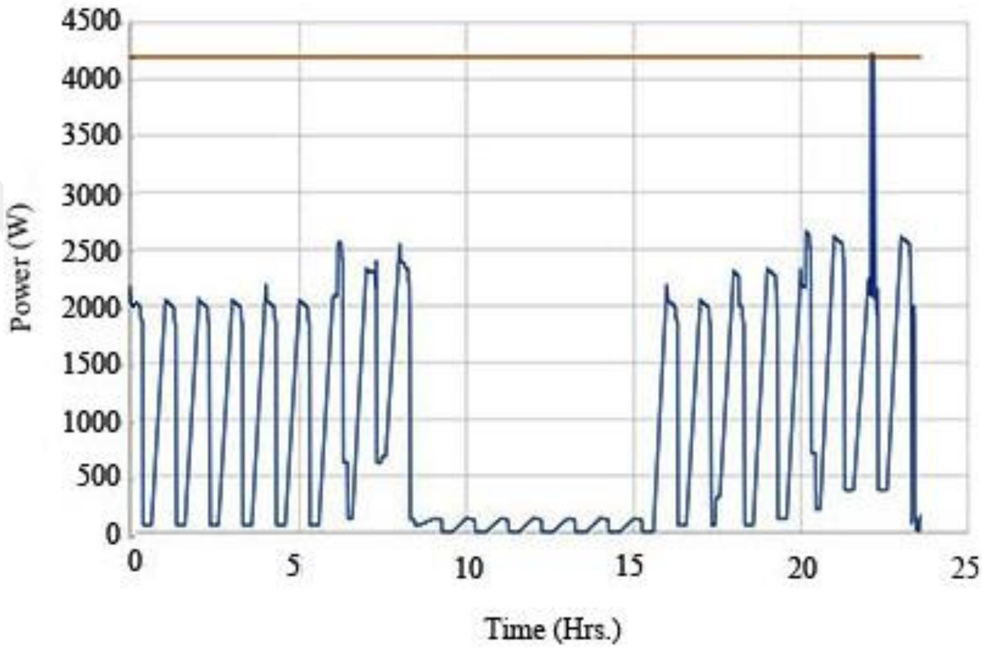

Figure 4.13. *When WM and DW operate at the cheapest electricity consumption for Wednesday in June, power excess graph*

When both the cost is minimized and the user comfort is maximized without taking into account power exceed, decision values are shown in Figure 4.14.

If the power exceed is not taken into account, the point which is shown as the decision value is the lowest is the point where the cost and common priority are the closest to minimum. If WM is executed 1 priority level and DW is executed 1 priority level, both the cost is reduced and the user comfort is maximized.

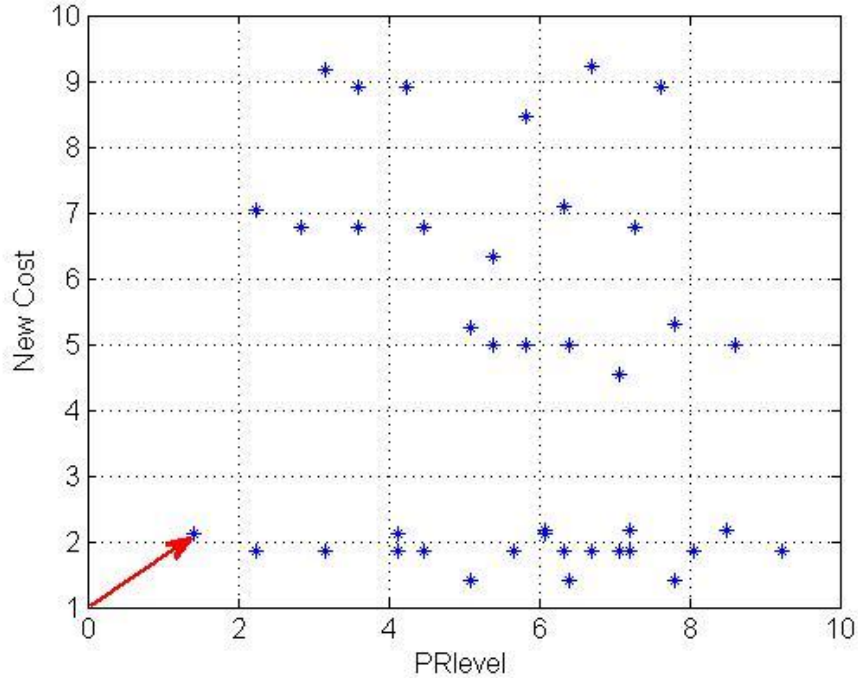

Figure 4.14. *Minimization of objective functions (PRlevel and Cost) for Wednesday in June*

When both the cost is minimized and the power isn't exceeded without taking into account the user comfort, decision values are shown in Figure 4.15.

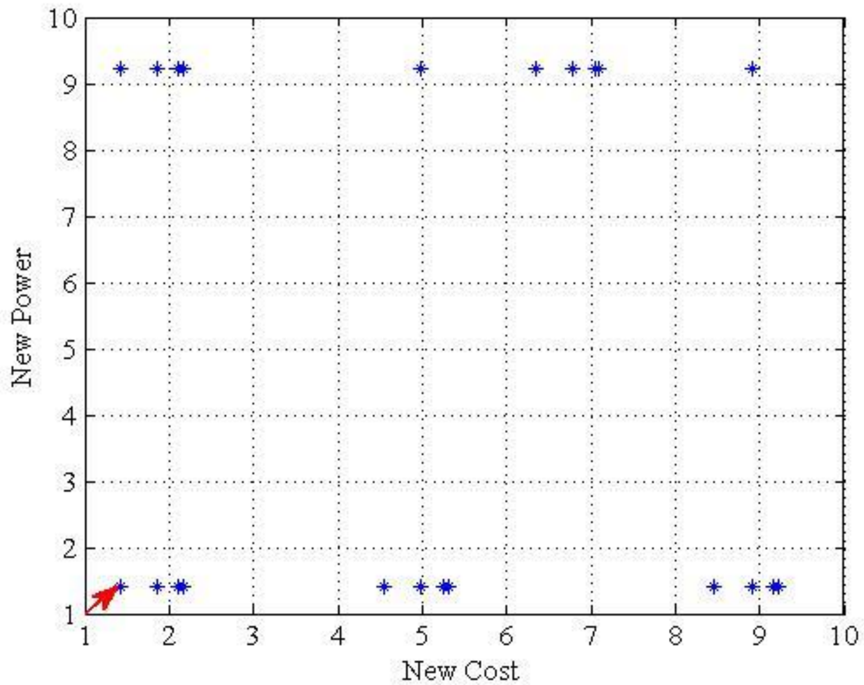

Figure 4.15. *Minimization of objective functions (Cost and Power) for Wednesday in June*

If the user comfort is not taken into account, the point which is shown as the decision value is the lowest is the point where the cost is the closest to minimum and power is not exceeded. If WM is executed 5 priority level and DW is executed 3 priority level, both the cost is reduced and power exceed is not observed.

When both the user comfort is maximized and power isn't exceeded without taking into account cost, decision values are shown in Figure 4.16.

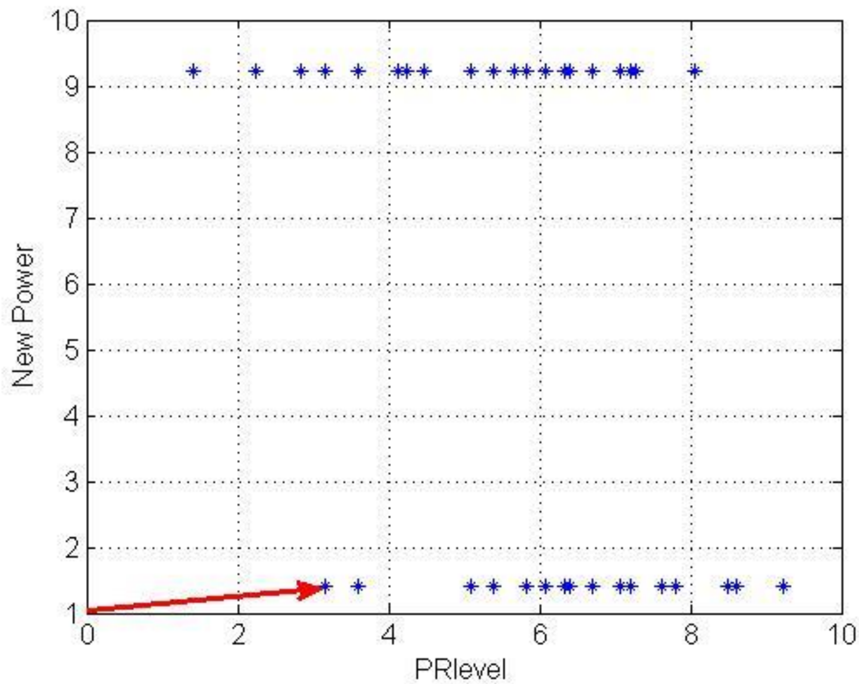

Figure 4.16. *Minimization of objective functions (PRlevel and Power) for Wednesday in June*

If the cost is not taken into account, the point which is shown as the decision value is the lowest is the point where the common priority is the closest to minimum and power is not exceeded. If WM is executed 1 priority level and DW is executed 3 priority level, both the power exceed is not observed and the user comfort is maximized.

The smallest of the decision objective functions is obtained from Table 4.3 and shown in Figure 4.17 when WM priority is executed 1 (hour 05:30) and DW priority is executed 6 (hour 22:30). In this combination, the daily cost of electricity consumption is 0.1268 TL.

This combination is also one of the highest in comfort. Figure 4.18 shows that power limit is not exceeded.

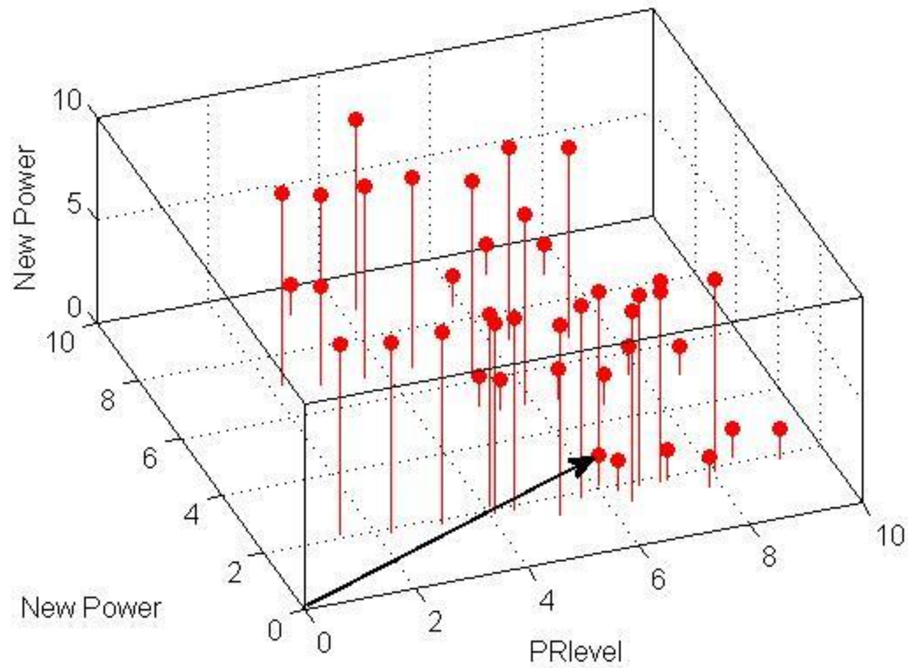

Figure 4.17: *Minimization of objective functions (Cost, PRlevel and Power) for Wednesday in June*

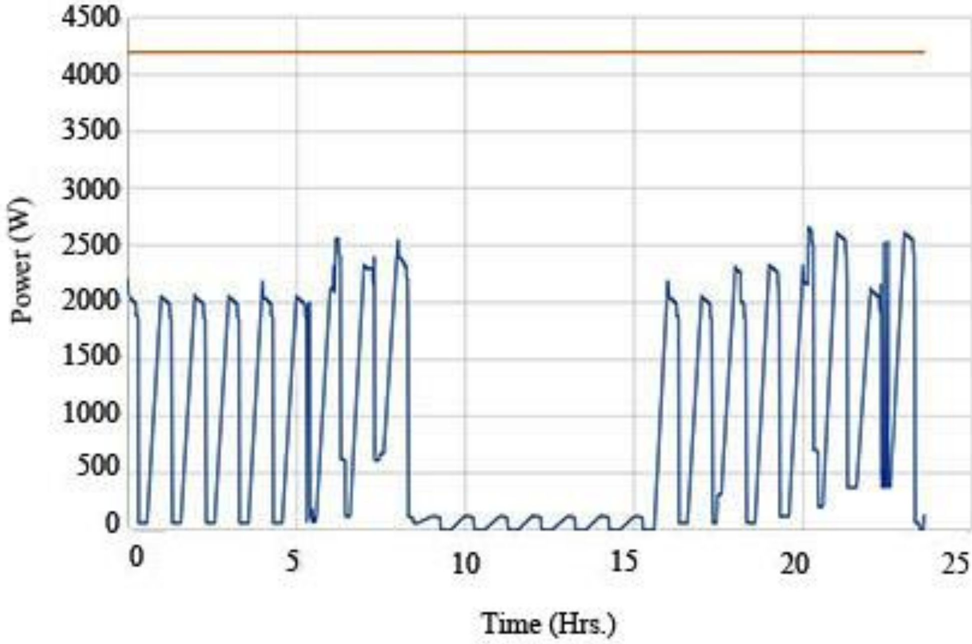

Figure 4.18. *When WM operates at 05:30 and DW operates at 22:30 for Wednesday in June, power excess graph*

5. CONCLUSION

Today, the fact that produced energy is not consumed efficiently is an important problem. For this problem, a home energy management system has been proposed for electrical appliances which are used at smart home. In this system, an appliance scheduling for controllable appliances like as washing machine and dishwasher has been made real.

By following all electrical appliances at home, usage habits of each appliance have been defined by user. Thus, user comfort context has been occurred according to priority level. Then, power consumption of home has been calculated by taking into account operating duration of appliances. It has been controlled whether power limit exceeds. Furthermore, electricity cost has been calculated by using TOU pricing tariff.

According to usage habits of controllable appliances, the fact that washing machine is operated at too early o’clock (like as 05:00 and around) in the morning or too late o’clock (between 23:00 and 00:00) in the evening has been observed. At the same way, it has been observed that dishwasher is operated at between 16:00 and 17:00 or too late o’clock (like as 22:00 and around) in the evening. The reason of the fact that they are operated at those time intervals is times when electrical power demand is lower. Therefore, according to TOU pricing tariff, electricity cost is lower.

The aim of making case studies for different days and months can show that appliance usage habits of appliances in the home are totally different day by day. For example, results shows that consumed electrical power and calculated electricity cost in the January (winter season) are higher than other months since air condition is operating continuously in order that temperature in the home keeps constant. Therefore, power demand increases and according to TOU pricing tariff, cost increases as well.

In order to find optimal solution, parameters of cost, priority level and power have been brought to the same level by using min-max normalization method. Then, LMS (Least Mean Square) method has been applied for optimal solution.

At the result of making appliance tracking and making real analysis, it has been observed that DW and WM are scheduled for operating time when electricity cost and user comfort are optimal and power limit does not exceed. When given case studies in the fourth part were examined in detail, the fact that these appliances has not been operated at operating time interval in which user comfort is only maximum or electricity cost is only minimum has been showed. At the same way, these appliances have been operated at operating time interval in which power limit does not exceed.

In the next decades, smart home energy management systems will become widespread much more in order to be able to use the produced electricity more efficiently and provide energy saving.

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