Universidad del Norte
Department of Electrical and Electronics Engineering

# Management Model for Energy Efficiency – Intelligent System Module

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MASTER THESIS

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Barranquilla, Atlántico, Colombia
December 2012

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A dissertation presented to the Universidad del Norte in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE

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# ABSTRACT

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The power consumption in buildings represents a 30-40% of the final energy usage, which is caused by: HVAC (Heating, Ventilation and Air Conditioning), lighting and appliances with any connection to the power grid. The major challenge is to minimize the power consumption by optimizing the operation of several loads without impacting in the customer's comfort. A manner to reach this objective is setting states suitable and replacing those inefficient devices. About this, it is necessary considering the exogenous variables that bring suitable information about environment, devices and customers characteristics to analyze and carry out inferences that can help to operate efficiently an environment. An intelligent approach framing in a management model is presented for the power consumption management of devices taking into account some variables as indoor temperature, outdoor temperature, illuminance and presence. Hence, in this research the integration of several Demand Side Management (DSM) criteria with one criterion based on neural networks and other inspired on differential tariff is carried out through dynamic and intelligent selections according to variables performance and customer´s preferences. In this case the customer´s preferences include also priority list of criteria, operation based on comfort or consumption, in addition to other preferences

as temperature. Furthermore, a previous diagnosis analysis through energy audit is carried out to evaluate devices performance and customer habits.

Experimental testing to the proposed approach has been performed in an environment object of study with the consumption data base and its performance tested in simulations runs. The testing results show that energy savings can be achieved through of improvement plans and/or recommendations provided by energy audit and proposed states by dynamic manager.

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*To my God, mother, family and friends*

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# PART I

# INTRODUCTION AND RELATED WORK

# Chapter 1

# Introduction

*This chapter provides an introduction to the work presented in this thesis. Specifically, the motivation in the research area, the pursued aims and the main contributions are briefly described. Finally, the chapter concludes with an overview of the structure and contents of the thesis.*

## 1.1. Motivation

Power consumption associated to higher rates of green-house gases emission generate great interest in studying this problem (Rockwool, 2011). The demand in electric energy consumption has triplicated because of an increment in the use of primary energy sources such as coal and natural gas. A 42.2% of electrical energy was produced from coal (Frank, 2007) showing a preference for this type of energy for current applications (heating, cooking, and lighting, among other.).

The 40% of total energy is consumed in buildings in industrialized countries, of which 68% is electricity (Frank, 2007; Huang, 2006). Recent research shows that 20%–30% of building energy consumption can be saved through optimized operation and management without changing the structure and hardware configuration of the building energy supply system (Guan, Xu, & Jia, 2010).

The management of electrical energy is an activity that involves the identification, implementation and verification of improvement plans in which the main goal is reducing the consumption of electricity without impacting customer´s comfort. Consistent with the above, for the development of management process of energy efficiency is crucial the systematic inclusion of two functional stages, these are: energy audit and efficient management of the operation of the devices.

The energy audit provides opportunities for electrical energy saving through identification of bad consumption habits and devices whose operation and technology cause an excessive level of power consumption. While, the electric energy management allows setting suitable operation states according to exogenous variables (e.g., Temperature, illuminance, presence, among others) and customer´s preferences adjustment to efficiency policies .

The use of energy audit integrated with a stage of demand management of electrical energy brings two advantages. First, the energy audit brings potential electrical energy saving to priori, providing the possibility of improvement plans that are related to the culture of saving and suitable acquisition of efficient technologies. Second, the implementation of a management stage provides the possibility to efficiently operating the equipment in consideration to the necessity of use by the customer and operating constraints from the environment. The management stage implies the integration knowledge base according to principles of efficiency; hence in some cases, soft computing techniques and other application criteria are integrated to bring guidelines for power energy savings.

Some authors have worked in achieving power consumption saving without impacting the customer's comfort (Frank, 2007)(Salehfar, 1999)(Ravibabu, Praveen, Ch, P, & M, 2009), e.g., HVAC Management presents an opportunity of electric energy saving. DSM techniques application as load priority provided suitable management according to customer´s factors (e.g., Priority List). In other cases, those devices with more consumption during demand peaks are identified (Ravibabu, Praveen, Ch, et al., 2009; Salehfar, 1999). Management criteria using computational intelligent techniques provide a reduction of power consumption around to 10-30%.

Integrating different management approaches provides the possibility of exploiting strengths and compensating weaknesses of each of them if used altogether. However, this approach requires a system able to select suitable criteria according to basics principles of efficiency, i.e., a dynamic manager.

A dynamic manager (DM) determines the management criteria (DSM or intelligent technique) in order to indicate the suitable devices operation (States) to reach their goals of electrical energy saving in consideration to customer preferences. In other words, a DM defines at what time, and what states should be selected each equipments to accomplish their goals.

In this research, these problems are solved by implementing an integration of energy audit and dynamic manager. In first case, a neural network-based criterion was developed taking into account policies of efficiency and exogenous variables as temperature, presence, illuminance, load profile of PC and type of activity. In second case, a fuzzy logic-based criterion was developed inspired on differential tariff. The design of a hybrid manager using several DSM and intelligent criteria is proposed, using selection preferences based on priority, comfort or consumption. The selection of each criterion depends on proposed curve by dynamic manager, which it is figured out according to knowledge base adjustment to efficiency policies of each equipment type.

## 1.2. Objectives

This work is focused on development intelligent management algorithms that include knowledge and integration of several demand side management criteria to reduce power consumption without impacting on the costumer´s comfort.

- **Problem**: Dynamic selection of several demand side management and intelligent criteria according to efficiency polices and customer preferences to minimize power consumption in an environment.
- **General Objective**: Developing and implementing a management model energy efficiency based on computational intelligence techniques with features that guide the user to the solution of problems related to energy resources in a power grid.
- **Goals:**
    - ✓ To identify the variables that affect to the energy efficiency.
    - ✓ To minimize the power consumption in an environment.
    - ✓ To incorporate several demand-side management and intelligent criteria, choosing those which best fit on efficiency polices and customer preferences.

### 1.2.1. Thesis Question

The principal question addressed in this dissertation is:

***¿Could a computational intelligence system integrated to the model for energy management bring support at the decisions of the system operator for energy efficiency management in an environment?***

### 1.2.2. Approach

In this research is proposed the design of a management model for energy efficiency based on the integration of several demand side management and intelligent criteria. This proposal looks for an intelligent and dynamic selection according to the efficiency policies and user preferences. This approach incorporates an energy audit process capable of identifying the loads with higher power consumption and inefficient operation.

Energy audit is a previous stage before applying some management criterion. It is a good opportunity to identify those bad consumption habits and devices with inefficient operation. This strategy seeks to establish improvement plans to help performing the progressive replacement of those equipments with technological limitations for energy efficiency, i.e., plans for rational use of energy. The results of this stage is focuses on presenting the user related indicators as payback time, total cost payback, power consumption before and after the energy audit.

The management approach based on computational intelligent is required to emit recommendations about equipments states according to specifies efficiency polices and relevant variables that affect energy efficiency. The efficiency polices can be change according to equipment type and environment characteristics. Hence requires a separate analysis for each type of equipment, i.e., a system for each type of equipment with different exogenous variables.

When one criterion is considered to evaluate and analyzing the power consumption in an environment, can limit the functionality of the management system due restrictions presented in some of DSM criteria, e.g., management in only type of equipment, consideration of user preferences, etc. In this sense, the dynamic manager as proposed algorithm is based on selecting the equipments states with minimum cost in terms of power consumption, comfort level or priority setting by user.

## 1.3. Contributions

This thesis makes the following contributions in power consumption management problems:

- *An intelligent approach for the dynamic selection of several demand management criteria of electric energy (load priority, direct load control, proposed criteria inspired on differential tariff and proposed approach using neural networks) for the power consumption management taking into account energy efficiency polices and customer preferences as priority-based, consumption-based and comfort-based selection.*
- *To improve the energy efficiency in an environment, it is developed a computational tool that integrates a stage of energy audit (diagnosis) and demand management of electric energy using fuzzy logic, neural networks and genetic algorithms.*

## 1.4. Reader's Guide to the Thesis

Following is a general description of the contents of this dissertation. This master thesis is organized in three main parts distributed by chapters.

**Part I: Introduction and Related Works**

Chapter 1 presents a motivational introduction on the main topics, objectives and contributions regarding this dissertation.

Chapter 2 gives a general overview of background information regarding energy efficiency strategies and demand side management criteria which are required to develop the propose approach described in chapter 4 and 5.

Chapter 3 provides a general survey of the most relevant work related to the research addressed in this thesis.

**Part II: Proposed Approach**

Chapter 4 describes the formal aspects of the energy efficiency management model presented in this thesis.

Chapter 5 presents the implementation of the approach proposed in chapter 4. The chapter also contributes to complete the description of such proposal.

**Part III: Results and Conclusions**

Chapter 6 provides experimental results of the implemented approach. An experiment design is presented to evaluate the performance of different criteria demand management of electrical energy and dynamic manager in simulation runs.

Chapter 7 discusses and analyzes the results, summarizes the conclusions and contributions of the thesis and outlines the most promising directions for future work.

# Chapter 2

# Background Information

*This chapter introduces and reviews general concepts of energy efficiency strategies, demand side management and computational intelligent system on management model for energy efficiency required for developing the proposed approach.*

## 2.1. Energy Efficiency

This concept is related to the activities necessary to achieve optimal energy service delivery, ensuring the supply, without impact of user´s comfort or quality of life. For the application of this concept is necessary to guarantee a reduction in the power consumption of the system (Erenovable, 2007).

To achieve this efficiency, is necessary that the management supports improvement processes, cogeneration, retraining and reorientation of production towards cleaner (Jackson, 2010).

### 2.1.1. Efficient Operation of Equipments

Power consumption of equipments generally is associated to the functional aspects and operation time as main characteristics. At First, it refers to the performance due to design and built specifications, e.g., luminaries type (e.g., incandescent, fluorescent, led, etc), screen type (LCD, LED, CRT, plasma, etc), among others. In this case the actions must applied previously to the acquisition process. Secondly, it is possible to reduce the power consumption with suitable management of the equipments according to efficiency policies established by the management. Here are some considerations relevant to the efficient use of some equipment used by this proposed management model approach.

- **Luminaries**

Luminaries are a main contributing agent in developing activities of a job environment. Its performance affects the health and comfort of the user. The contribution of luminaries in power consumption can vary according to type environment, e.g. in factories it can reach 10% of total power consumption bill, while in commercial and office type environments it reaches 40%-60% of the total electricity consumption. The level of visual requirement varies according to location and type of activity to be carried, which causes luminance levels change in function of the needs of user's comfort.

| Environment and Activity Type | UGR. | Illumination Levels | | |
|---|---|---|---|---|
| | | Min. | Med. | Max. |
| **General places in buildings** | | | | |
| Corridors | 28 | 50 | 100 | 150 |
| Stairs | 25 | 100 | 150 | 200 |
| Locker room, bathroom | 25 | 100 | 150 | 200 |
| Stores, wineries | 25 | 100 | 150 | 200 |
| **Electric Industry** | | | | |
| Cable manufacturing | 25 | 200 | 300 | 500 |
| Assembly handsets | 19 | 300 | 500 | 750 |
| Assembly windings | 19 | 500 | 750 | 1000 |
| Assembly of radio receivers and television | 19 | 750 | 1000 | 1500 |
| Assembly elements ultra precision electronic components | 16 | 1000 | 1500 | 2000 |
| **Offices** | | | | |
| General offices | 19 | 300 | 500 | 750 |
| Open offices | 19 | 500 | 750 | 1000 |
| Drawing offices | 16 | 500 | 750 | 1000 |
| Conference hall | 19 | 300 | 500 | 750 |

Table 2.1-1 Recommended illumination levels for energy efficiency

Recommended illumination levels at different locations are given by the illuminance, property indicating the luminous flux received by a surface (lm/m3), illuminance unit is lux (lx) (Gracia, et al., 2006). Table 2.1 shows a resume of ISO

8995 "Principles of visual ergonomics -- The lighting of indoor work systems" presented in (RETILAP, 2011).

The minimum requirements can help to guarantee suitable equilibrium between comfort and power consumption, hence during management is possible establishing strategies that allow operating in illumination range shown as in table 2.1-1 for each environment type. Furthermore, it is necessary implementing saving plans based on activities parallel with the intention of the management, i.e. coherent with availability of economic resources. Some recommendations are applied according to the investment preferences and payback period (Gracia et al., 2006).

a) Low cost
   - To clean luminaries and paint with light colored walls and ceilings.
   - To reduce illumination levels into a minimum level, consistent with type of activities in the environment.
   - To take advantage of maximum natural illumination, especially in buildings.
b) Low initial investment, but with payback period in a little months
   - If possible, incandescent bulb replace, low power consumption bulb and more lifetime.
   - Implement timer, movement sensors or illumination level control.
c) High investment, which can paid by itself in a few years
   - Installing the complete system to reach minimum operation cost.
   - Increasing the windows sizes or redistribute work areas to maximize the use of natural light.
   - Installing an illumination control system and incorporating capacitor bank to compensate reactive energy in street lighting.

- **Air Conditioning**

This equipments type represents a major load in power consumption in an environment due several factors associated to the price decline, technology and manufactures variety. Controlling its operation is key factor, however requires several considerations such as: comfort temperature stability, suitable definition of temperature levels and operation time of air conditioning, among others.

Some institutes have carried out research about comfort temperature range, the results allows guarantee user comfort when temperature range is from 22ºC to 26ºC during occupied periods (Department of building Science, 2011). While unoccupied period there are no requirements for humidity, $CO_2$ concentration or luminance, and the required indoor can be lager, e.g.,, from 20ºC to 28ºC (Luh, 2010). Compared with the occupied period, the lower bound during unoccupied period is lower to allow for pre-cooling and the upper bound of is higher, which is beneficial for energy saving.

Currently there are several ways to reach power consumption savings in air conditioner, actually, some of this it is not require major investments because depends on culture of customer consumption. Below are presented some of weatherization considerations associated with operation air conditioning (Gracia et al., 2006).

- Whenever the temperature is below 25 °C and the indices are not too high, it is possible using natural ventilation. In some cases ventilators produces the same performance that air conditioner between 3ºC to 5ºC lower than real temperature and its consumption is generally the 10% of air conditioning power consumption.
- It is advisable obstructing to block the entry of direct sunlight.
- Avoid accumulate several equipments that generates too hot, must be turn them off when not in use.
- The doors must be closed when the air conditioner start.
- Set thermostat in comfort level around of 25ºC, because per each grade below comfort threshold is wasted the 8% the energy.
- It must be limit the number of air conditioner starts due to high power consumption during this moment.
- Turn off the air conditioner 30 minutes before vacate the environment.

In this research is not studied the operation and types of air conditioning, hence only the opportunities to minimize the power consumption are analyzed.

- **Computer**

The power consumption of one computer is not very representative within the total electric demand, however when increasing the amount of computers this appreciation can vary. The computers have many tools that allow implementing several saving strategies, e.g., standby mode, screensavers, states operation as hibernate or suspend. Furthermore, the available technologies have modified their design and power consumption as the time; hence it is possible to say that the energy savings can be achieved if you implement a culture of energy savings to improve consumer habits. The table showed below presents values for power consumption of a computer.

| Name | States | Consumption |
|---|---|---|
| Computer/LCD | Off | 0.0016kWh |
| | Hibernate | 0.01kWh |
| | Suspend | 0.0018kWh |
| | Screen Off | 0.056kWh |
| | On | 0.078kWh |

Table 2.1-2 Power consumption of the computer (functional states)[1]

Table 2.1-2 shows several states for a computer (desktop). Some recommendations should be taking account to achieve power consumption saving in a PC (Gracia et al., 2006).

- Turning the computer off when not in use in over half hour periods.
- Energy saving mode allows electric savings up 60%.
- Use dark screensavers because it can save 7.5W.
- If choose it dark wallpapers it is possible saving around 25%.
- To compensate low power factor in computers (around 0.53), is necessary to use a capacitor bank.

[1] Data from computer consumption were obtained using a fluke 435 network analyzer, measuring the power each five seconds for a LCD computer.

- New computers use hardware with supply of 3.3V to different conventional computer that uses 5V, this allows savings between 40% and 50%.
- The laptops are more efficient than conventional computer because liquid crystal display use supposed less energy than any conventional computer.

- **Television**

In general, this equipment type represents a very low fraction of power consumption in an environment. Currently it is possible to find several technologies that allow considering a balance between prices and saving percentage, e. g. Cathode Ray Tubes (CRT), Light-Emitting Diode (LED), Light Crystal Display (LCD) and Plasma. In this case, the efficiency polices can limit them to choose LED televisions because requires 20% and 30% less energy than LCD television.

### 2.1.2.Energy Audit

Recommendations at first instance are subject to the study through the systematic procedure established within the energy audit. Following this stage is subject to guidelines established in the standard ISO 50001:2008 and UNE. 216.501. At this stage, it is to identify those points of the edification that operate inefficiently. No-cost or very low-cost operational changes can often saving a customer or an industry 10-20% on utility bills; capital cost programs with payback times of two years or less can often save an additional 20-30% (Turner, 2004).

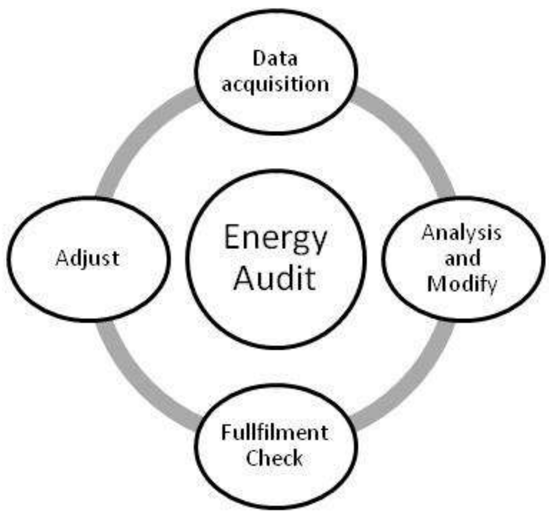

Fig. 2.1-1 Energy Audit Process

Fig. 2.1-1 shows the energy audit process which can analyzed as PDCA (Plan Do Check Act or Plan Do Check Adjust) for the control the power consumption activities, i.e., continuous improvement focused to reach savings every time higher. The energy audit cycle has four steps that allow acquire information associated to those places with higher power consumption, analyze and propose strategies that help to minimize the energy demand and monitoring the results obtained along of every process. Below it is presented a brief analysis of each stage of this process.

- *Data Acquisition*

To develop a good analysis is necessary to ensure the selection and acquisition of suitable data that allow for relating levels of specific electric energy consumption and consumption habits within the environment under study. In this stage is very important obtaining specific information about technology and consumption of equipments, physical structure characteristics, e.g., isolation, construction materials, location, etc. Furthermore, it is necessary to present a measuring method according to the guidelines presented in the rule governing the energy audit, i.e., instruments and appropriate measurement techniques.

- *Analysis of Information*

In *pro* of identifying the challenges of Energy Conservation Opportunities (ECOs) the analysis of information can help to verify no conformities in an environment. In this stage are verified some aspects as fulfillment of quality and levels of illuminance, air conditioning (temperature), isolation or thermal efficiency are evaluated. The results of the energy audit allows the user to specify which aspects to improve in the environment, in order, they can establish improvement plans in fulfillment of the recommendations presented by the auditor. It is important the user considers investment and time available to carry out these actions, because it should establish a plan consistent with the period provided for the execution of all necessary activities.

The power consumption savings depends on investment scopes that the user is willing to take, e.g., if detected excess consumption in the luminaries by bad habits of consumption and obsolescence of technology can generate plans based on rational use of energy both in adjusting the minimum required illuminance level and replacement by more efficient lighting.

- *Fulfillment Check*

After giving recommendations, it is necessary to check the fulfillment level of the improvement plans, that means, reviewing if consumption habits has improved or comfort levels has been adjusted, i.e., check if luminance and temperature levels in the work place are good. Furthermore, in design aspects of environment as isolation, construction materials, among others are reviewing too.

The targets should be measurable so that throughout the implementation process of improvement plan is to assess compliance with the objectives set.

- *Adjust*

In this last stage all the necessary adjustments in search of achieving compliance objectives are carried out. All nonconformities must be corrected to ensure electricity savings achieved. This process is cyclic therefore requires continuous monitoring to detect and correct anomalies associated with the power consumption within the environment.

## 2.2. Management of Electrical Energy Demand (DM)

DM consists in all activities focused on minimizing the power consumption without impact customer comfort. This type of activity is more important in those users with higher power consumption because it is possible reach power consumption savings that allows optimizing the company productivity. The implementation of electrical power consumption management of electrical energy demand entails restrictions of economic and technical, which can be classified into the following characteristics (Gracia et al., 2006).

- Necessity to produce of suitable manner to be more competitive.
- Minimizing energy bill.

- Protecting the environment in waste.
- Maximize the safety of production facilities.
- Necessity of optimizing the existing management system, to automate and make it more reliable.

In electric utilities the demand curve is analyzes on the customer side (Demand Side Management or DSM), this have allowed to develop different management strategies that aim to change the way customer consumption (consumption profile). DSM techniques are considered as strategies to minimize the power consumption during peak demand on power grid. Strategies are most useful in real time pricing environment (Goel, Wu, & Wang, 2010). It is possible to find several criteria according to the implemented strategy, e.g., differential tariff, peak clipping and valley filling, direct load control, load priority, among others. In this case only we analyze the below criteria (Bhattacharyya & Crow, 1996):

### 2.2.1. Load Priority

The computers in the environment object of study are classified as interruptible (low priority) or no interruptible (priority), i.e., manipulated by the agent without the risk to affect the production of industrial or commercial customers. The priority list is established with the user's full consent.

### 2.2.2. Peak Clipping and Valley Filling

This criterion seeks identifying those equipments that are directly responsible for peak demand, therefore, provides direct control over them. Moreover, power consumption is to increase the demand for valleys, this in order to achieve a flatter curve demand.

### 2.2.3. Differential Tariff

The concept of differential tariff is subject to variability in energy prices in some instants of time. The institutional policies of some companies engaged in the marketing and distribution of electricity end seek to encourage energy during those valley hours and penalize the same during peak hours. From a consumer perspective this is directly reflected in the value of the monthly bill, which it forces to change their consumption habits and shift a little towards the peak hours. With regard to the company, benefits by reducing excessive load during time where there is a greater consumption.

For application in the case study, we have proposed a variant of the proposed case (Ravibabu, Praveen, & Vikaschandra., 2009). This amendment seeks to provide management of electrical energy demand in order to avoid excessive penalties during those peak hours of electricity consumption.

### 2.2.4. Direct Load Control

This criterion is to identify, in general, the equipments that present a higher power consumption, to help reduce the level of electricity demand.

## 2.3. Heating and Cooling of Buildings

Modeling the temperature profile in building during 24 hours as function of external temperature ($M(t)$), heat generates within the building ($H(t)$), e.g., luminaries, people and machines and heater or air conditioner ($U(t)$), it is necessary to know what is the effect produces per the air conditioning within environment. Previous analysis can help to establish suitable cooling level $K_U$ that allows maintaining stable the indoor temperature within the comfort requirements (Section 2.1). The function that describes the relation of these three factors ($M(t)$, $U(t)$ and $H(t)$) is presented by (Nagle, Saff, & Snider, 2005) and it is described through of Fig. 2.3-1

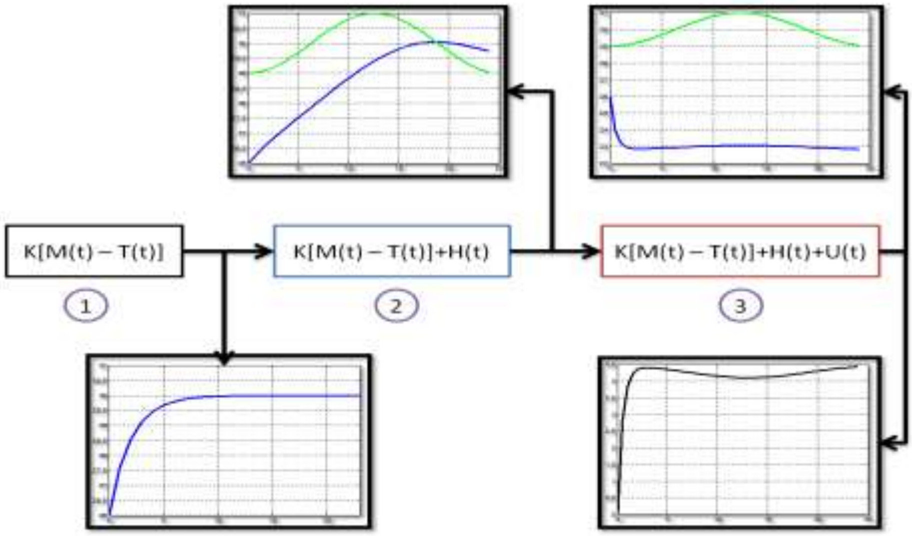


Fig. 2.3-1 Thermal model of heating and cooling in building

Fig. 2.3-1 shows several considerations of the thermal model used in the proposed approach. The stage (1), (2) and (3), represent rate of change in temperature over time. In this case only is analyzed the stage (3) because this approach is more precise than stage (1) and (2). Stage (3) incorporates a proportional controller with the objective of maintaining a stable temperature near the desired values.

Additional heating or cooling rate is described in terms of energy per unit of time. However, multiplying by the heat capacity of the building (in units of temperature change per unit of heat energy), the two quantities can express $H(t)$ and $U(t)$ in terms of temperature per unit of time. The equation (2.3.1) expresses the three factors that impact in indoor temperature of building. The first factor indicates the effect the outdoor temperature on indoor temperature of environment, this phenomenon is modeled by Newton´s law[2] such as in stage (1) in Fig. 2.3-1. The second factor modeled the additional heating produced by the people and appliances into the environment; this factor is always non negative such as in stage (2) in Fig. 2.3-1 Finally, the third factor shows in equation (2) corresponds to the quantity of heating and cooling, it positive for the heating and cooling such as in stage (3) in Fig. 2.3-1. Equation presented below is used to carry out this proposal.

[2] This law establishing the rate at which an object is cooled (or heated) is proportional to the difference of the temperature between the object and surrounding environment. (Joseph et al., 2007)

$$\frac{dT(t)}{dt} = K[M(t) - T(t)] + H(t) + K_U[T_D - T(t)] \quad (2.3\text{-}1)$$

$$\mathrm{U(t)} = K_U[T_D - T(t)] \quad (2.3\text{-}2)$$

$$T(t) = B_2 - B_1F_1(t) + Cexp(-K_1t) \quad (2.3\text{-}3)$$

$$F_1(t) = \frac{cos(wt)+\left(\frac{w}{K_1}\right)sen(wt)}{1+\left(\frac{w}{K_1}\right)^2} \quad (2.3\text{-}4)$$

$$w := \frac{2\pi}{24}{}_0 \quad (2.3\text{-}5)$$

$$K_1 := K + K_U \quad (2.3\text{-}6)$$

$$B_1 := \frac{BK}{K_1} \quad (2.3\text{-}7)$$

$$B_2 = \frac{K_UT_D+KM_0+H_0}{K_1} \quad (2.3\text{-}8)$$

$$C = T_0 - B_2 + B_1F_1(0) \quad (2.3\text{-}9)$$

Where,

$M(t)$: Outdoor temperature

$H(t)$: Cooling (heater) rate

$T(t)$: Indoor temperature

$K_U$: Cooling level

$w$: Angular frequency of variation.

$\frac{1}{K_1}$: Constant of time with heating and air conditioner.

$B_2$: Mean temperature in building (daily) without considering the exponential term.

$B_1F_1(t)$: Sinusoidal variation of temperature in building corresponding of outdoor temperature variation.

$K$: Positive constant, that depends of physical properties of building as amount of doors and windows and type of isolation. For a typical heating and air conditioning, $K_U$ is a little less than 2; for a common building, the constant K is between ½ and ¼ (Nagle et al., 2005).

The equation (2.3-3) is the solution of differential equation (2.3-1). This equation represent thermal model figured out based on considerations expressed in the Fig. 2.3-1.

Below it is presented some constraints of thermal applied model.

- Compartmental model analysis
- Only considered a single compartment
- Additional heating rate is constant
- Only is incorporated single type of controller (proportional)
- Constant of time is typical for a building (2 to 4 hours)
- Outdoor temperature is evaluated behave a sinusoidal function, i.e. typical summer day.

## 2.4. Computational Intelligent System

From a broader view, it can be defined as a system which proposes solutions to complex cases where conventional algorithms are unable to solve (Jabbar et al., 2010). This concept may be subject to ambiguities, and therefore, it is necessary to clarify that a computational intelligence system must meet the following criteria (Eberhart & Shi, 2007).

– Only deals with the numerical data (low level).

– It has a pattern recognition component.

– Number Sense –Activities of the human being as problem solving, decision making and learning–.

This type of system combines elements of learning, adaptation, evolution and fuzzy logic to design programs with some level of intelligence. It is based on experience and provides the right decisions despite limitations (Konar, 2005).

Computational intelligence applied in energy study has allowed developing several applications oriented to power consumption forecast, energy quality, management demand, etc.

### 2.4.1. Artificial Neural Networks (ANN)

This type soft-computing technique is based on biological neural networks performance of the human brain. Therefore are comprised of units called neurons and are also able to learn from experience, generalize from previous examples and to abstract the main characteristics of a data series. Thus, ANN, change their behavior depending on the environment, provide correct answers to inputs with small variations, among other advantages (Bilbao, 2008; Flórez & Fernández, 2008).

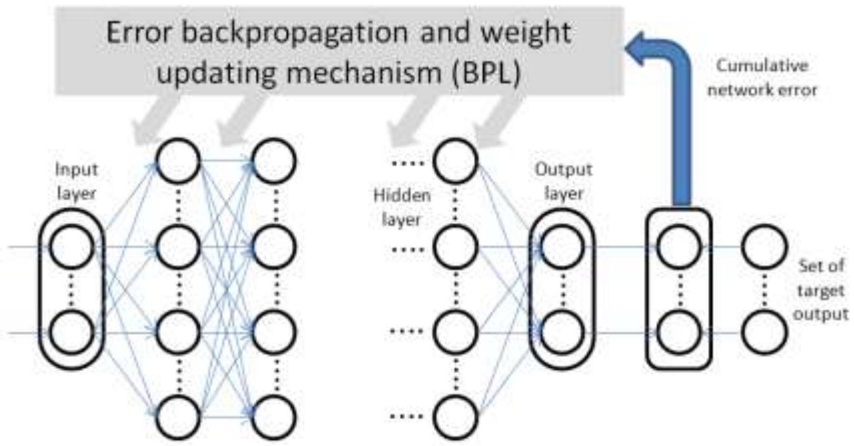


Fig. 2.4-1 Neural network topology (Fakhreddine O. Karray & Silva, 2004)

Fig. 2.4-1 shows the basic structure of a neural network trains with backpropagation algorithm. Back propagation is a method of training the neural network using three or more layers. Commonly used topology of three layers: a lower one and an upper hidden: The bottom layer or layer of input layer is the only processing units which receive inputs from the outside, therefore points serve as distributors and no perform a calculation operation. The layer (in the case of a topology that is more than three layers) between the lower and the upper layer is called hidden therein, the processor units are interconnected with adjacent layers and carry out the operations calculation. Finally, the output layer is the one that represents the response of the network. The practice of this topology is monitored, i.e., input patterns matched and target outputs must be entered (Bilbao, 2008; Flórez & Fernández, 2008).

The main idea in energy management system is to use neural network to model recommendations that indicates how operating the equipments in a environment, i.e., training ANN according efficiency polices to propose states for each equipment.

### 2.4.2. Fuzzy Logic

This concept is an extension of bivalent logic and it consists in assign a certain membership level to sets of values and associates them through of several compositional rules of inference (CRI). The membership level is defined by a function that indicates the shape and representation of fuzzy set. In modern control this concept has been applied in several control system, e.g., air conditioner, washers, photographic camera, among others. The performance logic and typical of fuzzy system begin with fuzzification of crisp variables to monitor with the purpose of decision making. Also, the control decisions generated in this manner are fuzzy quantities, and they have to be defuzzified prior to using them in a physical action of control (Fakhreddine O. Karray & Silva, 2004). Several membership functions have been developed in order to represent the associate grade with linguistic descriptor, such as: triangular, Gaussian, trapezoidal, sigmoid, among others. Replicate expert knowledge to carry out any activity monotone it is possible by the extended concept of conventional logic, this is called, fuzzy logic (FL). FL is based on common sense, i.e., FL Allows mapping input and output variable according to rules set (see Fig. 2.4-2).

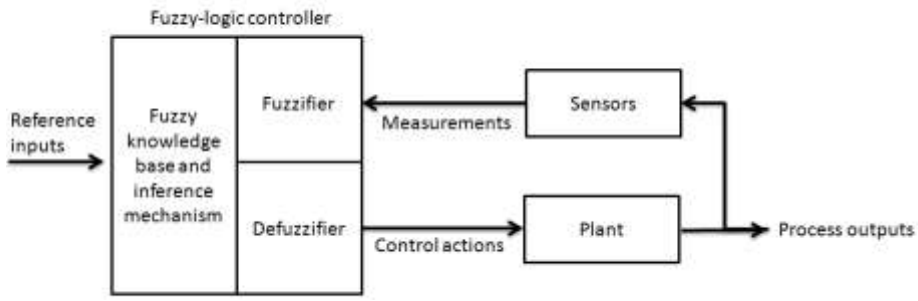


Fig. 2.4-2 Architecture of fuzzy control (Fakhreddine O. Karray & Silva, 2004)

To implement this approach it is choose a structured inference engine based on fuzzy logic for two main reasons (Marcos de Armas Teyra, 2009):

– Easy adaptation to different criteria for establishing levels of electricity consumption and peak demand delimited.
– Allows weighting and integrating the effect of each one variable of the system and determined the influence in the output.

### 2.4.3. Genetic Algorithm

The interesting factor in evolutionary process it is the possibility of modifying the population characteristics according to necessities presented a long time. Genetic algorithm (GA) is a type of evolutionary computing techniques used to determine among other things the global optima of a given function (or process) that may or may not be subject to constraints. Analog with natural process of evolution, GA has phases of evolution, in this case operators that allow carrying out modification in population, such as: selection, crossover, and mutation.

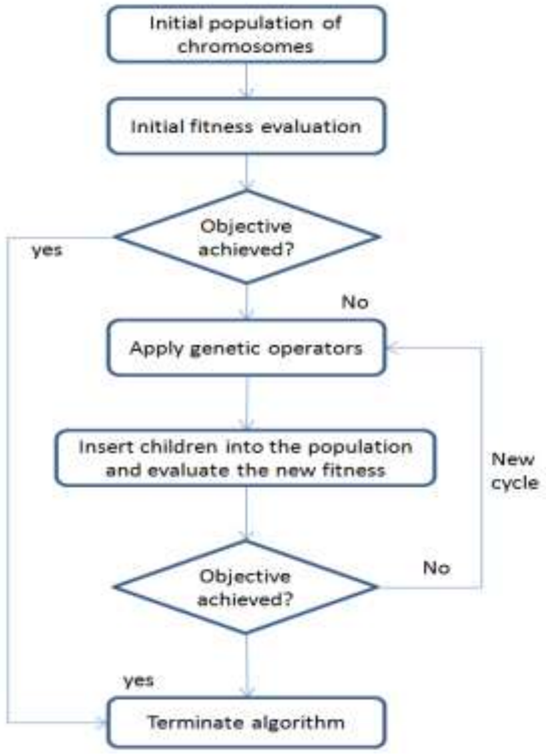


Fig. 2.4-3 Flowchart of evolutionary algorithm (Fakhreddine O. Karray & Silva, 2004)

Fig. 2.4-3 shows the process of selection and evaluation used by genetic algorithm to identify the optimal global within a population.

Below are presented a brief explanation of each stage showed in figure 2.4-3.

*Selection*

In this stage of process individuals of population are choosing according to evaluation of fitness function. Suitable selection seeks guarantee the reproduction of those individuals with greater characteristics. In general, selection operators are stochastic, probabilistically selection good solutions and removing bad ones based on the evaluation given to them by the objective function (Fakhreddine O. Karray & Silva, 2004). There are several selection models, first named elitist model, where the top 10 to 20 individuals of the population are chosen for further processing. The second selection model, named ranking model where similar in the above case each member is ranking by fitness function value; and the roulette where procedure where each individual have assigned a cumulative probability to be chosen for reproduction if this is greater than random number selecting previously (Fakhreddine O. Karray & Silva, 2004).

*Crossover*

Similar the natural case, the crossover consist in the mating of two chromosomes. In this case also it´s recurred to randomness selection of parents' genes to form child´s genotype. It exists several crossover operators which are analyzed in the literature (Fakhreddine O. Karray & Silva, 2004).

*Mutation*

In simple terms the mutation consists in the change of one o more bits of a string. In this case new solutions are explored while selection and crossover serve to explore variants of existing solutions while eliminating bad ones. The change can be randomness or through mechanism that change the alleles of fashion deterministic (Fakhreddine O. Karray & Silva, 2004).

# Chapter 3

# Related Work

*This chapter presents an overview of the main works focused on the topics addressed in this dissertation.*

## 3.1. Energy Audit

(Maricar & Jamal, 2005) development and integrated Web application and energy audit using data mining in an industrial site. The authors presented a methodology to carry out the energy audit to bring suitable information about energy level needs, hours of operation, task and general energy and consumption over time (annual, seasonal and monthly). The methodology is analyzed in four steps: 1) Worksheet is used to obtain information of existing building system (Database), 2) Energy cost calculations, 3) Comparison with standards value and 4) Retrofit suggestion and data assembled. An analysis of data collection is carried out for illumination case in a building. Variables as dimension of the room, light level reading in lux, number of luminaries, number of lamp per luminaries, lamps fixture and the lamp wattage are used to evaluate indoor efficiency of building. Evaluation and comparison are based on lumen method to indicate the optimum number of luminaries in each room. Results show a correct by application assessment using the existing calculated data and the installed load efficacy ratio (ILER) in a building.

(Prudenzi, Lillo, Silvestri, & Falvo, 2008) present a tool that consists in software installed in PDA in order to provide a portable tool that brings suitable suggestions about energy efficiency. Recommendations of application are based on energy audit methodology and it is focused on office and lighting equipment. The program has been implemented on a Windows Mobile 5.0 platform, by using the Microsoft .NET Framework; also, the program has been implemented in C# language. Software is named as EAST system, which it was structured in two main programs: EAST-I, focused on the on-site input of building´s data and EAST-CR, focused on the data screening and analysis, energy performance calculation, diagnosis report activities. The EAST I structure has four sections: 1) General: It is used to collect input data as location of building and its main constructive figures, 2) Energy: Input usage to collect energy consumption historical data as well as data concerning possible renewable resources as already, 3) Thermal load: it is implemented to support the input stage of data concerning heating, air conditioning, hot water production and use, 4) Electric load: Data base associated to the information required by the energy audit process. The analysis should be carry out by auditor posterior to load the data of building object of study. According to the input data, the application can be used to support some suggestions in order to minimize or optimize the power consumption in a location. Some typical suggestions were installing or improving the control system, vary the heating/cooling set points, change lighting fixtures, among others.

(X. Wang & Huang, 2009) present an analysis about energy audit applied a building case study. Historical data of power consumption of air conditioning system, electronically equipments, lighting system and elevators, furthermore, exogenous variables as indoor temperature, relative humidity and CO2 concentration were measured in winter. The load profile for building was performing considering energy utilization situation from 2005 to 2008. The energy audit investigation allowed identifying those sectors with most consumption in building. It achieved detecting to the air conditioning and elevator were the equipments with higher consumption during summer and winter. The results showed an importance of saving consumption after reconstruction and execution of recommendations performed. In the case study building envelop power consumption each month decreased by 869.41 kWh, for a rate 9.64% of the energy consumption before reconstruction.

(Gomes, Coelho, & Valdez, 2010) carried out an energy audit in school building in order to identify where are present the higher power consumption. Authors analyze the suitable strategies that allow an efficient operation of equipments and environment. It is carried out an analysis about relative importance of the different electric loads in the building, demonstrating computer relevancy, HVAC and bar equipments in total bill per electric energy. Power factor is considered due to its incidence in penalization per excessive in ratio between real power and reactive power. It is important noting the directly proportional relation between presence levels, season/weather and power consumption, which produces an increase in energy bill during winter. The results of implementation reach power savings up 28% in total power consumption of scholar building.

## 3.2. Management of Electrical Energy Demand

Accelerated development of technology and the easy access it has become one of the causal reasons for the current gap between the powers supply and electric demand by different types of users (industrial, commercial and residential). This aspect has been investigated and developments aimed at improving the load management of different types of users, based on the integration of some computational intelligence techniques, sequential or concurrent (Fuzzy logic, ANN, GA, PLC, FPGA, etc.). The paper presented in (Babu, Reddy, Ch, & M, 2008) shows the design of a fuzzy controller that responds to the presence of peak demand. The basic idea of this approach is to control only those equipments previously concluded with the user. These loads will be considered as interruptible or non-interruptible. The system consists of two inputs and four outputs. The two inputs are the comparator and time; the comparator is used to compare the power consumed by a reference, while the time is used to differentiate between peak and valley.

The purpose of the approach proposed in (Salehfar, 1999) is to determine the off time necessary to achieve power savings without affecting comfort levels. Different schemes have been developed to achieve peak clipping and saving operating costs. This system consists of four inputs: Ambient temperature, set temperature in air conditioning, temperature desired by the user (comfort) and size of the room. Two parameters chosen to model the customer preferences, two more are determined to accurately model the thermal losses of a building. The preferred temperature and actual temperature are the inputs to the first controller with the deviation as the output. The size and isolation of the building are the inputs to the second controller with the thermal losses of the building as the output. The knowledge base was determinate according to experience, intuition and consulting. The fuzzy method was compared with brute force methods; both methods reduce the peaks of the load curve. The improvement in the load factor is 0.5 of a percent higher for the fuzzy logic based method that the brute force method. As a result the system provides the number of minutes which remain off the air conditioner during a period of time. For the case study used by the authors is achieved savings of 9.5%.

The study proposed by (Z. Wang, Yang, & Wang, 2010) presents the design of two levels of a multi-agent controller. The main goal is guarantee the user comfort with the minimum power consumption. The comfort variable is measured through of illumination level, temperature and indoor air quality ($CO_2$ concentration) in the environment, to evaluate above; three agents are design to control each variable. This proposal involves the design of a central controller and local levels, the first is used to determine and monitor the flow of electricity between the power grid and smart building according to user preferences and other relevant information. The central coordinator-agent works with the intelligent optimizer to accomplish its control goal. The second group of agents is responsible for maintaining comfort levels as high as possible. The method PSO (Particle Swarm Optimization) is used to optimize the desired operating points, i.e., function is used to relation the comfort level with power consumption and PSO method is applied to reach maximum above function. The local controllers figure out the power consumption required in environment. The fuzzy controller evaluates the deviation between actual parameters and proposed states by central controller to derive the variation of the environmental parameters. In this case the system considers energy efficiency, user comfort and renewable energy sources. The results showed reduction in power consumption due tuning of set point for each variable that it was considered. The system is compatible with SCADA systems.

The implementation of neural networks to manage electricity demand provides an opportunity for savings when integrated with a management approach. (Babu, Divya, & Member, 2008) implement a feed-forward neural network, reaching a level of efficiency in terms of load factor, and further reduction is achieved in the bill due to the decrease of peak demand. Also supplemented its application with the addition of the differential tariff, allowing penalize to the user when this exceeds the allowable consumption during peak demand. It reaches a payback of 17.55 and electricity savings of 9%.

The paper presented in (Ravibabu, Praveen, & Vikaschandra., 2009) describes the design of a fuzzy system structured according to the methodology proposed by the criteria demand management of electrical energy and differential tariff clipping peak demand. This is carried out to control the power consumption and maintain the temperature of a liquid cooling system. The inputs used by this system are external to the tank temperature, water level and temperature in the tank, while the output is limited to two states (On/Off). The levels of power savings are for the case study between 34% and 91%.

Implementing techniques demand side management (DSM) have provided several alternatives to increase in energy efficiency in consumer-related terms, however, the time and computational effort required are high to achieve levels of precision adequate supply and demand. Papers as presented by (Jabbar et al., 2010) has provided an adequate results in which to the application of techniques of management of electrical energy demand are concerned. Multiple tests are performed with different techniques of management of electrical energy demand (LPT, End-Use Base, SD, etc.) on site of a regional control center of the distribution company of electricity. It uses a Feed Forward Neural Network to reduce fatigue and provide useful computational training other neural networks, referred to above calculation of the gap between supply and demand of electricity. Furthermore, combinations performed DSM techniques used allowing for a reduction in power consumption.

(Matallanas et al., 2012) describes how to optimize electrical energy usage based on DSM techniques to integrate local control systems with distributed generation in a residence object study, this also has an energy storage system and solar panels. It developed two modules, both performed with neural networks, the first to coordinate and other to program activities required by the user. With this application it optimized the energy used by the user-priority equipment and also provided the ability to maximize the use of renewable energies.

Some implementations of intelligent system have arrived to buildings design, specifically, in smart buildings. Advances in this thematic are shown in (Morvaj, Lugaric, Member, Krajcar, & Member, 2010), to balance the demand of this constructions type. In this case (Morvaj et al., 2010) proposes the design of smart buildings that have controllable loads, elements of electrical energy storage (batteries) and renewable energy (PV). For activation/deactivation of loads, is set by agreement with the owner a set of four loads manipulated by the system, these at the same time, are organized hierarchically and consistent with the level of need within the building. It is also necessary to adjust the demand curve according to some conditions as the price of energy at all times and the non-uniformity of the demand curve. It shows an automation system (AS) capable of disconnecting the equipment with less importance (top of the list) or otherwise activating the most important equipment (bottom of the list). Furthermore, the mode of operation of the control system is related to the cost of electrical energy at that instant, so that in case the electric power value is too high, it starts the power supply of renewable source. If the value continues to increase, the controller disconnects those charges (4) according to pre-established list of priorities. Otherwise, if the price of energy decreases, then, three cases occur: 1) Connect equipment according to the priority list, 2) Storage of energy from renewable sources and 3) Disconnect loads controller. For the case study performed two tests, one with the implementation of a control based on the price of energy and the other with price based control and loads. The results were satisfactory only in the second case despite the variations carried out in the scenarios.

## 3.3. Towards to a Smart Grid

In the thematic review presented by (Renewable Energy, 2011) is indicated that a smart grid can provide the user options and tools for consuming electricity more efficiently. Furthermore, it is clear that the fact of having a sophisticated communication infrastructure does not make the power grid is a 'really smart' if there is not a dynamic and bidirectional communication channel between the user and power grid. In this case it is necessary to integrate renewable energy sources within of the process of generating electricity. (Renewable Energy, 2011) describes a smart grid (SD), as a structure of three layers: 1) physical layer power (transmission and distribution), 2) and Transport Layer Control (Communications and Control) 3) application layer (applications and services). In the same paper, *Greentech* proposed the following features in the concept of an intelligent network (SD):

- Advanced Metering Infrastructure (AMI) smart meters.
- Incentives by the utilities to allow users to achieve a reduction of peak demand and consumption in general.
- Optimization of the power grid - reliable and efficient systems.
- Distributed generation - power stations, solar panels, micro wind turbines, etc.
- Energy storage.
- Availability of connection of electric vehicles.

(Hamidi, Smith, & Wilson, 2010) presents the benefits associated to the development of a smart grid:

a. Reliability and decrease the probability of failure of the power grid due to the possibility of communication and information transfer between the user and the service supplier of electricity (generation, transmission and distribution). Furthermore, it achieves a reduction in the need for human intervention in the operation of the mains.

b. Flexibility and integration of renewable energy sources.

c. Efficiency.

d. Operating environment friendly.

(Moshari, Yousefi, Ebrahimi, & Haghbin, 2010) explains the scope of the concept of Smart Grid, which is not only characterized by a structure of advanced metering

(AMI), a plan for demand management, a high level of energy efficiency or possibility of self-review, but also must consider environmental approach and a greater number of utilities and/or services to the user.

Fig. 3.3-1 Factors associated to the concept of Smart Grid (Moshari et al., 2010).

In Fig. 3.3-1 is shown smart grid concept as an emerging technology that converges in the application and integration of control systems and communication the power grids (Farhangi, 2010; Kirschen, 2003). This proposal is framed within the operational excellence shown in Fig. 3.3-1.

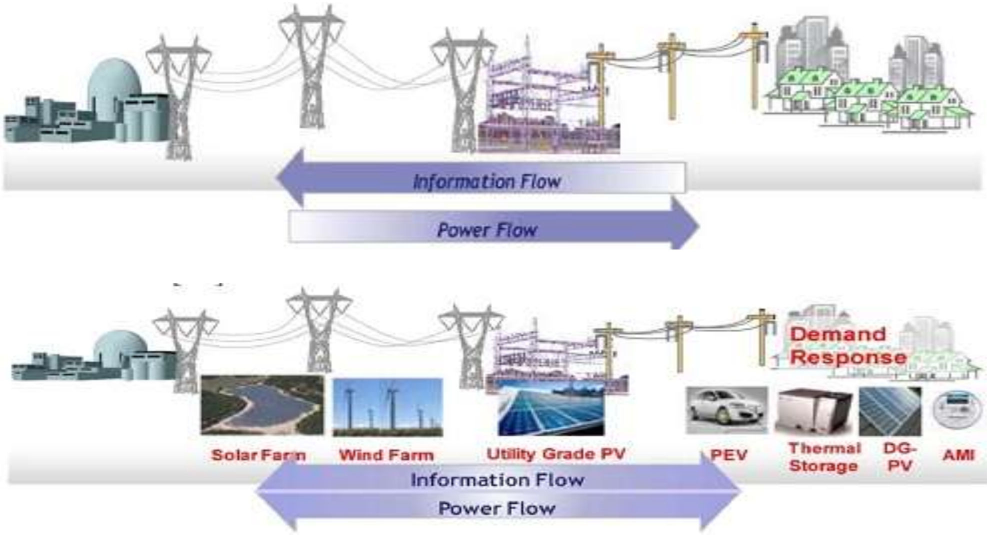

Fig. 3.3-2 Factors associated to the concept of Smart Grid (Moshari et al., 2010)

Fig. 3.3-2 shows the flow of electrical energy and the information flow associated to a conventional power grid. The flow is unidirectional in both cases, starting from the power generation centers at the point of demand, while in the case of the information flow occurs from the lower voltage levels at the centers of the power grid operation.

Electric Power Research Institute (EPRI) has focused its efforts since 2001 in a proposal known as the *IntelliGrid*. The main purpose of this project is to develop the technical basis necessary to achieve a smart grid with communication capabilities and computer control. The functionalities proposed by (EPRI, 2006)are visualization of the power system in real time, increasing system capacity, power grid able to 'heal' itself and allow connectivity to consumers, among others.

Within the proposed architecture is highlighted by the (EPRI, 2006) including greater integration of consumers through a portal called *EnergyPort*, which aims to ease restrictions that they have through a two-way portal where information flows. *EnergyPort* has specific main capabilities in order to achieve an electricity market in which users respond to price changes, which are real-time pricing, value-added services such as billing inquiries and quality monitoring energy, demand management of electric energy, easy connection of distributed energy resources and efficient long-term planning. In general, this consists of a device or set of devices that allow intelligent devices on the installation of a consumer to communicate with remote systems (Clark, 2009).

Several companies and organizations have also made efforts to establish a vision of smart grids. As such the proposals are developed by IBM (Michael, Allan, John, & Ekow, 2007), and the Department of Energy of the United States named 'The Modern Grid Strategy', which performed a description in terms of the features and functionality that should have power grids. Thus, this view states that the power grids should have the following characteristics: allowing active participation of consumers, provide all generation and storage options; allow additional incoming services, products and markets, providing power quality for the digital economy; optimizing asset utilization and operate efficiently, anticipate and respond to system disturbances (self-healing) and operate resiliently against attack and natural disasters (Deparment of Energy, 2009).

In Colombia the motivation of a restructuring of the electricity sector has led to the proposal of a national plan named "Colombia Inteligente". The proposed design of the route to the Smart Grid in Colombia was raised in five stages of development. In the paper presented by (Aldana, 2011). They are systematically presented: Starting situation, vision, objectives, and areas of interest and development phases. In this last stage are three phases that define the current development plan for the Smart Grid in Colombia. The first phase, conceptualization, theoretical and comparative study is performed. The estimated runtime is defined from 2011 to 2012. The second phase called development (2012-2025), intelligent and efficient technologies are adopted by the Colombian system. Consolidation (2026 - ...) as a final step, new technologies and renewable energy sources are integrated to the Colombian power grid.

## 3.4. Final Remarks

The management of electrical energy demand requires analysis of environmental variables in order to emit suitable recommendations according to user necessities. Exogenous variables are important to the moment of evaluating the relation between inference engine and behavior of environment (indoor and outdoor); hence, the success of the intelligent system depends on the variables selection and the correlation with the power consumption and comfort level of user. Usually in related work are used variables as indoor and outdoor temperature, relative humidity, illuminance and presence. Furthermore, in some reviews were incorporated physical variables associated to building architecture, e.g., size and isolation to adjust thermal requirements.

Energy audit is a systematic process widely used in the literature to analyze, verifying and correcting the mode of power consumption in an environment, e.g., inefficient characteristics of equipments and mode of power consumption. Methodology consists in set sequential steps that seek: 1) Acquiring variables associated to the power consumption and fulfillment of standard requirements (comfort), 2) Analysis of information obtained previously to identify those aspects related to inefficient operation of equipments and bad habits of energy consumption, 3) Check the execution grade of improvement plans and 4) Carry out adjustments to reach goal of savings and culture of power consumption established.

Several types of equipment that contribute in total power consumption. The inefficient operation of such loads by the users is a major cause of the increasing gap between demand and supply of electricity. Suitable management of demand brings greatest opportunities for power savings due to the possibility of adjusting the operation of the equipment to efficient rules. Generally in related work some demand side management criteria have been applied in order to establish management protocol that allow minimizing the power consumption without impact customers comfort.

The review of the related work presented above has allowed the identification of the contribution this project. This work proposes the development of a management model for energy efficiency based on computational intelligence. In this case the proposed model approach incorporates the computer performance profile and activity type as new variables that allow to the intelligent system evaluating suitable state according to the computer usage level, level of presence and policies of efficiency. The proposed model incorporates an energy audit process capable analyzing the equipments characteristics and emit recommendations associated to the replace of technology when is required. Furthermore, the system carries out a payback analysis in order to show to the user the requirements that allow reach efficiency characteristics, e.g., replace luminaries or screens. A strategy of electrical demand management based on neural networks was developed; in this case some of equipments as television, computer, air conditioner and luminaries are managed independently according to the evaluation to proposed variables. Finally the management model proposed integrates multiple criteria demand management of electrical energy. The selection of suitable criterion during each time will depend on environmental characteristics and customers preferences (comfort or consumption).

# PART II

# PROPOSED APPROACH

# Chapter 4

# Management Model for Energy Efficiency Approach

*This chapter presents the approach management model for energy efficiency proposed in this dissertation applied to buildings. The main definitions, general considerations and the algorithms for energy audit, management criteria and dynamic selection in this work are introduces in this chapter.*

## 4.1. Problem Statement

The increase in power consumption has motivated the research in energy efficiency field. The problem of reliability and optimization in the process of consumption of electrical energy in buildings requires the acquisition and analysis of data associated with power grid object of study. But these tasks cannot be performed by users or network operators without proper measurement equipment and criteria suitable for decision making that do not affect user comfort. The above problem has been analyzed in some proposals presented in the state of the art, but in most cases is required the implementation of non-conventional model techniques in a power grid; however this brings the following difficulties store and analyze data associated to the consumption of the power grid (SeriousEnergy, 2011).

1) Store and analyze data associated to the consumption of the power grid.
2) Identify opportunities for managers, administrators and engineers to implement those measures on the information, or perform actions

automatically by the system (e.g., Energy resource management, impact of new technologies for electricity infrastructure, etc.).

3) Provide powerful tools of communication on the objectives and progress through dashboards in real time.
4) Provide tools for optimization and an interface with different systems of management to increase productivity of staff and assets.

In this work, issues 1), 2) and 4) were analyzed. The result is the management of power consumption according to exogenous variables and efficiency polices. In first instance the inference motor interprets and analyzes the information obtained through of the sensors to emit recommendations about the characteristics of equipments and environmental. This is the problem of energy audit. This diagnosis problem itself has several aspects that have been studied intensively in the past. Among the most important aspects are the identification and evaluation of the recommendations during every time of operation of the environment. The power savings and improvement of habits of energy usage depends on these factors. Finally, the second important aspect of energy efficiency in environments is that the intelligent system has to manage the operation of equipments according to environments and customers characteristics. This is the problem of management of electrical energy demand. It involves establishing those functional states in such achieved balance between power consumption and comfort level of customer.

This thesis considers the problem of identifying and establishing the suitable states that allow the efficient operation of a number of equipments in an environment. Through characteristics of environment, equipments and customer the goal is to minimize power consumption considering preferences of customer and policies of efficiency. Using demand side management criteria and the proposal based on neural network the key problem can be solved with choosing the suitable criteria at each time according to priority-based, consumption-based or comfort-based. In order to address the problems related to the low efficiency of the equipments in the environment, the incorporation of a process of energy audit capable to identify and establish improvement plans associated to the technology replacement was proposed. In addition, we present a detailed report to provide information related to some economic variables such as payback and total cost savings by concept of consumption of electricity.

## 4.2. Proposed Management Model for Energy Efficiency

Below is presented the design of management model for energy efficiency which incorporates a dynamic manager in order to evaluate the suitable criteria according to environmental variables and customer preferences. The proposed approach is based principally on the achievement of power savings without great modifications on the building infrastructure. Fig. 4.1 shows the proposed management model. Each one of the stages involved will be analyzed; also these stages will be distributed in subsections: Subsection 4.2.1 User/Costumer, Subsection 4.2.2 Inference Engine/Dynamic Manager, Subsection 4.2.3 Recommendations.

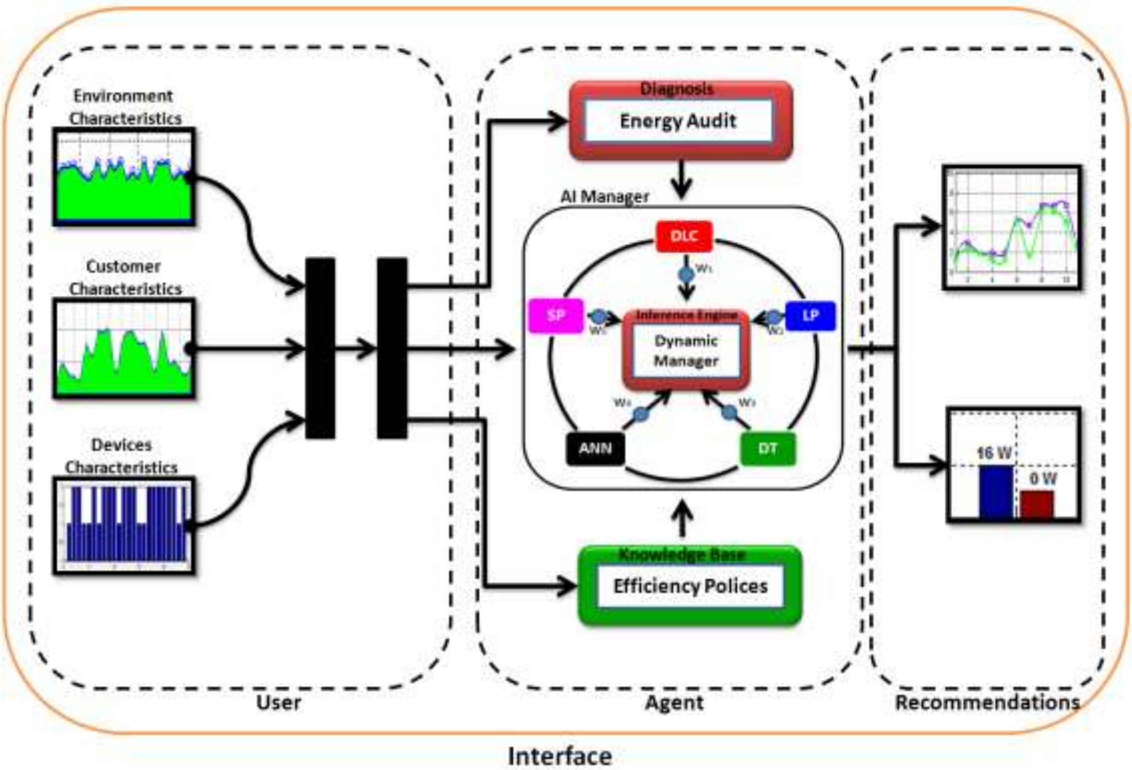


Fig. 4.2-1 Management Model for Energy Efficiency

### 4.2.1. User

The general parameters to characterize a user type are determined on this stage, as presented below.

1) *Customer Characteristic:* This stage is raised in order to define the profile of each user, that means, the way electrical energy is used by every customer, the number of devices to manage (e.g., Air conditioning, lighting, computers, appliances in general), and power levels of each device established operating levels to assess possible states of the device. The activity of the user has been reduced only to buildings. The user's comfort-level related variables were previously defined on section 2.1.

2) *Environment Characteristics:* It is relevant to the intelligent system has knowledge about environment behavior in order to adjust the recommendations according to customer necessities. The accuracy in this case it is very important, hence, the acquisition variables allows establishing operating parameters (all of equipments) suitable to efficiency policies, i.e., comfortable to the user.

3) *Equipments Characteristics:* Refers to the functional and structural characteristics of the equipments. Above it is necessary for two reasons: 1) To identifying how operates the equipments in environment and 2) To describe structural and manufacturing characteristics of equipments. This information allows establishing improvement plans related to replace of equipments and/or modification of functional states according to exogenous variables.

### 4.2.2. Agent

On the following analysis, the agent is consider as the formal definition[3] of its meaning, this means that it adjust to the following characteristics. The analysis of this block defines the proposal. The variable analysis has a direct incident on the response generated by the AI Manager[4]. It is important to mention that the

[3] It is an autonomous entity that perceives the environment through sensors and acts in half using actuators (i.e. an agent) and directs its activities towards the achievement of objectives (i.e., rational).

[4] In this thesis the term *agent* is refer to the set of blocks conformed by the energy audit process, knowledge base and AI manager. While AI manager corresponds to the integration between the several demand management of electric energy criteria and inference engine (Dynamic manager).

management criteria and energy audit allow us to determinate the emitted response by this element. The agent presents the recommendations according to the management criteria selected.

The agent has the possibility of establishing recommendations according to management criteria that better fit to the environment conditions. Energy audit is the basis to estimate power consumption savings. The systematic execution of the audit with the user`s role provide an opportunity to identify those points that present inefficient operation.

In this stage are presented three functional blocks, hence it is necessary analyze each one separately:

1. *Energy Audit:* this stage allows establishing initial recommendations before managing the operation of equipments. Diagnosis in environment is performed to evaluate improvement opportunities that help it to minimize the power consumption.

2. *Efficiency policies:* this information is considered to develop of the intelligent system, because brings it the guidelines associated to efficient management and suitable equipments to environment operation (section 2.1). The information above brings support to training and creating the knowledge base used to design the intelligent system.

3. *Dynamic Manager:* this block is important for the development of the agent because it concentrates the criteria used to manage the equipment operation considering efficiency policies and/or customer's preferences. The design of this inference engine was considered for several reasons:

1) To minimize the power consumption, taking advantage of some of the characteristics of the demand side management criteria (Direct Load Control, Load Priority and Differential Tariff).
2) To analyze and evaluate the degree of relevance of each one of above criteria.
3) To consider the advantage and strengthen the weakness of each criteria, through of theirs integration.

4) To allow more customer participation in the selection criteria according to its priorities (comfort or consumption).

The dynamic manager is integrated with five management criteria, these are: Direct Load Control (DLC), Load Priority (LP), Scheduled Programming (SP), Differential Tariff (DT) and artificial neural networks approach (ANN). The main objective of dynamic manager is to propose functional states or a power consumption curve that provide proper operation of the equipments according to the needs of comfort and consumption of electricity (power savings). To reach the above, it was implemented fuzzy inference engine (dynamic manager) for the case of computers, luminaries and televisions, while air conditioner case was used genetic algorithm to minimize the proportionality constant ($K_U$) that indicates the cooling or heating quantity. In the computers, luminaries and televisions the membership functions were design according to efficiency guidelines presented in section 2.1; while the air conditioner was required genetic algorithm because it is important minimizing the cooling level without impact the comfort of the customer. Above, it allows establishing the power consumption adjustments to efficiency policies. However, due the constraints of equipments operation (e.g., available functional states) it is necessary to select those states that have greater similarity with the proposed by the dynamic manager. The states proposed by the AI manager depend on priority and preferences customer selection (individual, priority, comfort or consumption).

An efficient management of air conditioner must to guarantee comfortable temperature with less power consumption. The opportunities of savings are related to isolation of environment and efficiency of equipment in operation and technology. In section 2.1 was presented some considerations associated to efficient operation of an air conditioner. In this case only considerations related to operation are used to the design of dynamic manager. The proposal seeks modeling the temperature profile in building during 24 hours in function of external temperature ($M(t)$), heat generated within the building ($H(t)$), e.g., luminaries, people and machines and heater or air conditioner ($U(t)$). The above in order to establish suitable cooling level ($K_U$) that allows maintaining stable the indoor temperature within the comfort requirements (Section 2.1). The function (4.2-1) describes the relation between $T(t)$ and $K_U$. The main idea is optimizing the function (4.2-2) according to constraints presented in (4.2-3 – 4.2-6). The function (4.2-2) allows evaluates the cooling point required to maintain the indoor temperature within the comfort zone, while function (10) is useful to measure the level of comfort.

$$T(t) = f(K_U) \quad (4.2\text{-}1)$$

$$P_{AC} = f(K_U) \quad (4.2\text{-}2)$$

$$22\ ℃ \leq\ T(t) \leq 26\ ℃ \quad (4.2\text{-}3)$$

$$K_U < 2 \quad (4.2\text{-}4)$$

$$1.4 \leq K_U \leq 1.48 \quad (4.2\text{-}5)$$

$$0 \leq P_{AC} \leq P_{ACmax} \quad (4.2\text{-}6)$$

Furthermore the proposal seeks to avoid an excessive number of on/off operations on the air conditioning equipment; hence optimization technique is implemented in order to established optimal points of cooling level ($K_U$ ) according to temperature deviation of comfort zone. A proportional control is integrated to the thermal model presented in section 2.3 to perform progressive adjustment the level cooling and thus prevent the equipment is always operating at peak cooling.

The integration of fuzzy inference engine (for the case of PC, TV and luminaries) and algorithm genetic (for the case of air conditioner) provide operation curves adjusted to the energy efficiency policies. However, the selection of each management criterion can vary according to the customer preferences, e.g., priority list, consumption-based or comfort-based. Hence, the idea is that AI manager selects the suitable management criterion at each instant time according to these preferences.

### 4.2.3. Recommendations

Analysis of user characteristics provides the opportunity to perform recommendations by the intelligent manager. Recommendations at first instance will be subjected to the study through the systematic procedure established within the energy audit.

Finally, several management criteria will serve as support for the proper selection of those states of the device that best adjustment to user preferences (comfort). A balance between power consumption and user comfort is reached. This is possible thanks to the consideration of variables that allow user participation e.g., the temperature range defined as comfortable.

## 4.3. General Considerations

Let us suppose that a management criterion (*MC*) is selected each instant time for a scenario *S* that fulfillment with requirements proposed by AI manager (*RDM*). In order to fulfill the recommendations given by AI manager (*RDM*) must generally involve more than one criterion to reach the goal of minimizing the power consumption without impacting the customer comfort. That is:

$$\forall MC_i \in RDM \ \ where \ RDM = \{MC_1, MC_2, \dots, MC_{24}\} \quad (4.3\text{-}1)$$

$$i = 1,2,3, \dots, 24$$

Where *RDM* is the total group of criteria selected by AI manager into the scenario (*S*) for a day (24 hours). In this case a scenario is a possible configuration for the equipments, environmental characteristics and customer preferences.

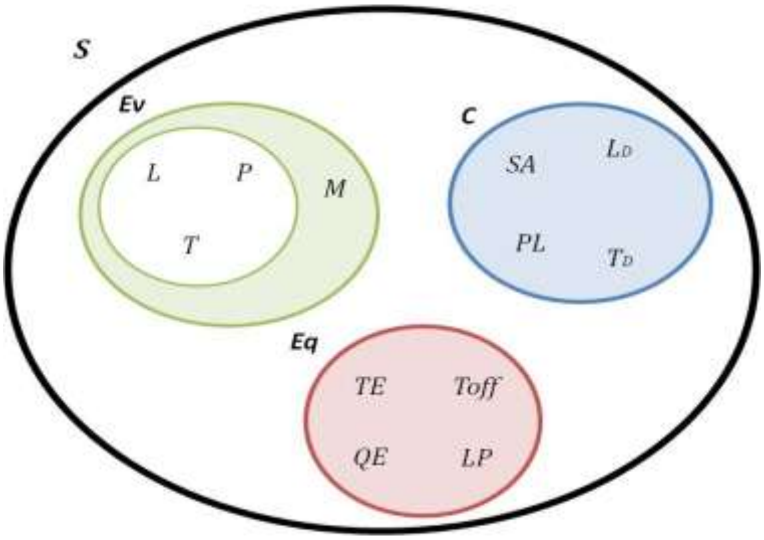


Fig. 4.3-1 General scheme of a scenario *S*.

The variables considered in this proposal for each scenario are presented in Fig. 4.3-1. In each case (*S*), it is must to specify all characteristics independently for the environment, equipments and customer. In environment characteristics are considered some exogenous variables such as temperature (outdoor ($M$) and indoor ($T$)), presence level ($P$) and illuminance level ($L$). Some customer preferences as illuminance ($L_D$), temperature ($T_D$) and scheduled activity ($SA$). Finally, the equipments characteristics as the type ($TE$), model and amount ($PW$) contribute in the power consumption. In addition, it is necessary specifying the scheduled on/off ($Toff$) and priority list (equipment) ($PL$) for each scenario.

In a scenario ($S$) is required the evaluation of the criteria behavior in order to know the recommendations proposed by each available criterion.

### 4.3.1. Dynamic manager

In this case, several management criteria of electric energy ($MC$) are evaluated in order to selecting those that it adjusted to the recommendations given by AI manager ($RDM$). The selection principle is based on a proposal of suitable curve of power consumption according to a scenario configuration. The design methodology is constituted by one main component (Dynamic manager) that allows establishing the suitable power consumption; at the same time, this component is constituted with four decision-making sections defined for each type of equipment. This proposal requires a system capable of adjusting the recommendations according to efficient polices as shows in section 2.1.

In this sense, the main goal is minimize the *time on* of the air conditioner maintaining the temperature ($T_D$), illumination ($L_D$) and other requirements or work conditions within of the parameters defined by user, e.g., scheduled activity ($SA$). For each case, the knowledge base brings separately information about suitable states according to the above considerations taking into account for each one of equipments; hence it is necessary to combine them in order to evaluate the power consumption proposed by dynamic manager.

Recommendations given by dynamic manager can be adjustment according to certain preference indicates by the user, these are: based on consumption, based on comfort or based on priority list. Below we will discuss each of them:

1. Based on consumption: Let us suppose that in a scenario ($S$) we have some requirements proposed by AI manager ($RDM$). To fulfill with the recommendations given by AI manager based on consumption must generally to select those criteria with similar power consumption in each instant of time, e.g., $GDM = \{MC_1, MC_2, MC_3 \ldots MC_{24}\}$.
2. Based on comfort: Similar to the based on consumption case let us suppose that in a scenario ($S$) we have some requirements proposed by AI manager ($RDM$). To fulfill with the recommendations given by AI manager in this case, it must selecting to a different criterion ($MC$) according to similarity degree between the functional states of each one with respect to the AI manager.
3. Based on priority: Let us suppose that in a scenario ($S$) we have some requirements ($DM$) proposed by AI manager. In this case is not relevant the recommendations given by AI manager ($RDM$), only it is considered the priority ($PL$) previously established by user before to start the management. However, the user must to indicate a threshold ($T_h$) of power consumption in order to switch of a criterion to other when latter has higher power consumption saving upper to this threshold.

# Chapter 5

# Implementation of a Management Model for Energy Efficiency

*This chapter presents the application of the proposed approach in an environment with similar characteristics to a building that includes some equipment as air conditioner, luminaries, televisions and computers. It describes some considerations about the environment and simulation software used to develop the experiments, a new proposal in a dynamic selection of management criteria algorithm to find the suitable state according to preferences of customer as priority, consumption or comfort. Likewise DSM algorithms proposed in the literature and in this proposal and the audit energy algorithm for emission of recommendations are analyzed.*

## 5.1. Developed Computational Tool

To the development of computational tool was taken into account some characteristics presented in a common building. In this case it was assumed that the building consists of $i$ = 1, 2, to $I$ individual rooms. Each room is equipped with a set of air conditioner, televisions, computers and luminaries. These loads are commonly used in the literature in order to validate the performance of management system. The scheduling horizon is discretized in time periods of 24 hours. The consumption profile is obtained from typical data of a residential customer. A day is divided into $k$ discrete time intervals of equal duration $\Delta t$ (e.g., 1 hour).

### 5.1.1.Environment

The equipments which are considered for the thesis were the air conditioning, computers, televisions and luminaries). The variables used for validation of the mentioned criteria are the described in equation (5.1-1), (5.1-2), (5.1-3) and (5.1-4).

$$\boldsymbol{T} = \left[T_1{}^I, T_2{}^I, \dots, T_k{}^I\right],\ k = 1, 2, \dots 24 \tag{5.1-1}$$

$$\boldsymbol{L} = \left[L_1{}^I, L_2{}^I, \dots, L_k{}^I\right],\ k = 1, 2, \dots 24 \tag{5.1-2}$$

$$\boldsymbol{P} = \left[P_1{}^I, P_2{}^I, \dots, P_k{}^I\right],\ k = 1, 2, \dots 24 \tag{5.1-3}$$

$$\boldsymbol{M} = \left[M_1{}^I, M_2{}^I, \dots, M_k{}^I\right],\ k = 1, 2, \dots 24 \tag{5.1-4}$$

Where,

$T_i{}^I$: Environment indoor temperature *I* at time *i*.

$L_i{}^I$: Environment luminance *I* at time *i*.

$P_i{}^I$: Environment presence *I* at time *i*.

$M_i{}^I$: Environment outdoor temperature *I* at time *i*.

Fig. 5.1-1 Environment object of study

Fig. 5.1-1 shows the environment used to perform the experiments.

### 5.1.2. Equipments characteristics

| Equipment | Model | States |
|---|---|---|
| Air Conditioner | Window | Off, sleep and on |
| | Mini Split | |
| Computer | LED | Off, hibernate, suspend, screen off and on |
| | LCD | |
| | CRT | |
| Television | LED | Off and on |
| | LCD | |
| | PLASMA | |
| | CRT | |
| Luminaries | FT5/54W | Off and on |
| | FT8/32W | |
| | H/100W | |
| | LT83/16W | |
| | LT53/12W | |

Table 5.1-1 Equipments characteristics to manage within of computational tool

Data from computer consumption were obtained using a fluke 435 network analyzer, measuring the power each five seconds for a LCD computer. The TV screen used operates with LED technology. The luminaries are fluorescent. Power consumption data is shown in the table 5.1-1. The remaining information was taken from data base of the author (EcoEnergy, 2011).

### 5.1.3. Comfort Requirements

The comfort ranges during occupied periods are given by (Department of building Science, 2011). The standard recommends conditions that have been found experimentally to be acceptable to at least 80 percent of the occupants within a space. The operative temperature range for building –North America– occupants in typical winter clothing (0.8 to 1.2 clo) is specified as 68° to 74°F (20° to 23.5°C). The preferred temperature range for occupants dressed in summer clothes (0.35 to 0.6 clo) is 73° to 79°F (22.5° to 26°C). These values are based on 60 percent RH, an activity level of approximately 1.2 met, and an air speed low enough to avoid drafts (ASHRAE, 2010).

$$T_C \in [22ºC, 26ºC] \qquad (5.1\text{-}5)$$

$$L \geq 400lx \qquad (5.1\text{-}6)$$

Where,

$T_C$: Comfortable temperature range for an average user.

$L$: Comfortable luminance for an average user.

During unoccupied period there are no requirements for humidity, $CO_2$ concentration or luminance, and the required indoor temperature range can be lager, for example,

$$T_C \in [20^{\circ}C, 28^{\circ}C] \tag{5.1-7}$$

Compared with the occupied period, the lower bound of $T_C$ during unoccupied period is lower to allow for pre-cooling and the upper bound of $T_C$ is higher, which is beneficial for energy saving (Luh, 2010).

### 5.1.4. Cost Calculations

The total consumption is adjusted for a day operation in the environment shown in Fig 5.1-1. The electrical consumption and cost are presented as follows:

$$\boldsymbol{St_i}^{\boldsymbol{e}} = [St_1{}^e, St_2{}^e, \dots, St_k{}^e] \tag{5.1-8}$$

$$\boldsymbol{Tf_i}^{\boldsymbol{s}} = [Tf_1{}^s, Tf_2{}^s, \dots, Tf_k{}^s] \tag{5.1-9}$$

Where,

$\boldsymbol{St_i}^{\mathrm{e}}$: State of the device *e* at time *i*.

$\boldsymbol{Tf_i}^{\mathrm{s}}$: Electrical energy tariff for any season *s* at time *i*.

The power consumption per device is calculated using the expression (5.1-10).

$$C_{ij}{}^I = \begin{bmatrix} St_1{}^1.Tf_1{}^1 & \cdots & St_k{}^e.Tf_1{}^1 \\ \vdots & \ddots & \vdots \\ St_k{}^1.Tf_m{}^1 & \cdots & St_k{}^e.Tf_m{}^1 \end{bmatrix} \tag{5.1-10}$$

Where,

$\boldsymbol{C_{ij}}^{\mathrm{I}}$: Electrical consumption cost at time *i* for device *j* at environment *I*.

The power consumption total cost for the environment *I*, are presented below:

$$C^I = \sum_{i=1}^{k} \sum_{j=1}^{e} St_i{}^j . Tf_i^1 \tag{5.1-11}$$

The previously showed considerations were included during the developing of the computational tool, which is shown in the Fig. 5.1.2. The information about environment, customer and equipments characteristics is presented in this interface.

### 5.1.5. *Interface:*


Fig. 5.1-2 Interface of computational tool for energy efficiency (Main window)

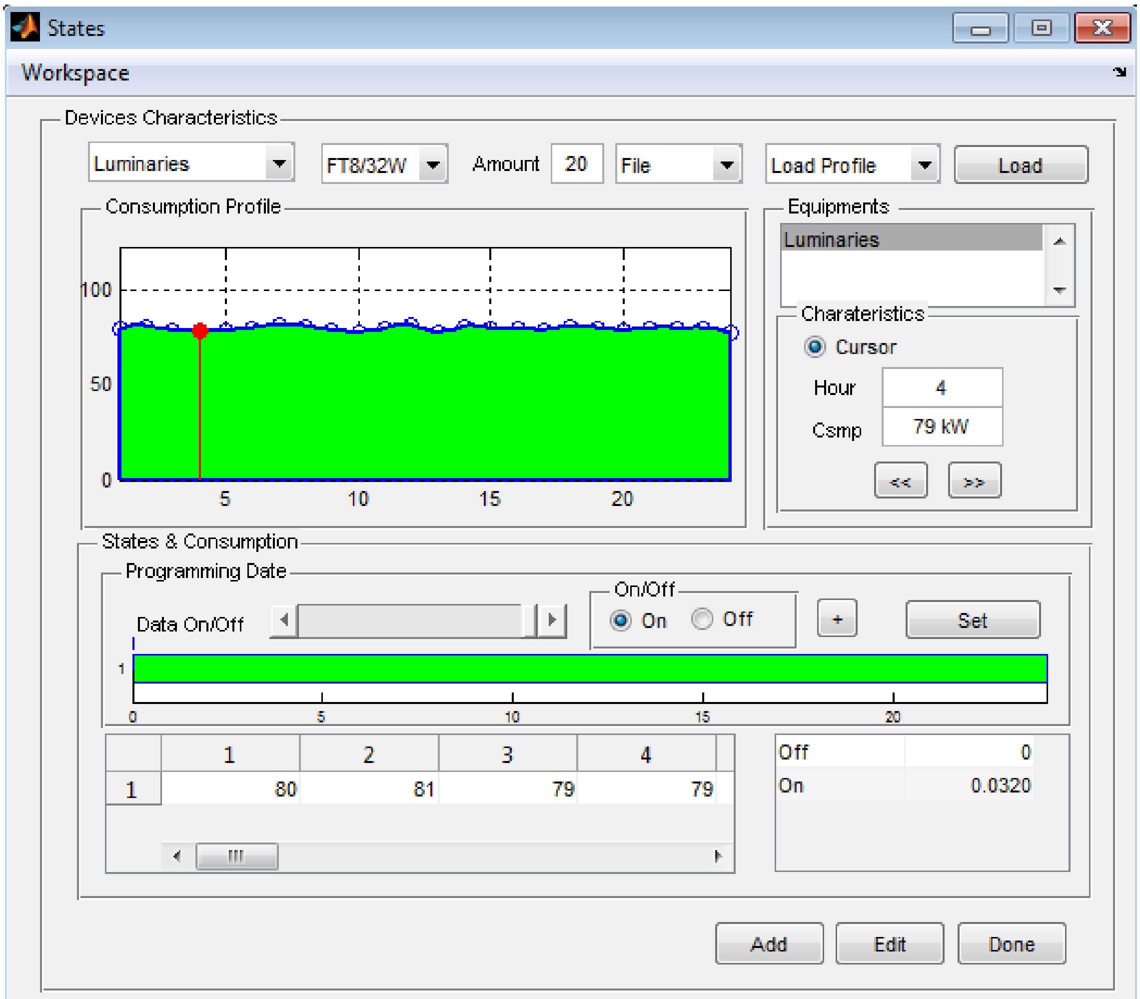


Fig. 5.1-3 Interface of computational tool for energy efficiency (Equipments configuration)

The interface of computational tool show has six (6) functional parts:

1. Environment characteristics: In this section the user should indicating the type and amount environments to manage. The exogenous variables as temperature, presence and illuminance are load manually in table format (.*csv) through of the *import* button that open a window that it allows choosing a file previously saved in data base for each type of variable. Likewise for the case of equipments opens a window that allow configuring some characteristics as: equipment type *TE*, amount *QE*, model, power consumption profile and on/off programming *Toff*. The characteristics of the equipments to manage can be modifies in window shows in Fig. 5.1-3. In this window the use should specifying for each one of equipment the type, model, amount and load mode. Thereupon the application visualizing the power consumption curve or profile load curve *LP* of the selected

equipment. Likewise appear two tables that show the power consumption data and nominal power (kWh) for each one of the equipments. Furthermore in *programming date* section, the user should to set the on/off configuration for a day; to carry out the above it is necessary selecting the number of hours of on and off through of *data on/off (slider)* and radio button on or off. Finally it is necessary to push the *set* button for each configuration case. When the configuration of equipments has finished the user should the *done* button to return the main window.

After to the selection of the equipments, these are grouped in a table showed in section 1 of main window (see Fig. 5.1-2). This table allows identifying those equipments vital or non vital and furthermore showing the curve of consumption, states and load profile (e.g., computer).

2. Power consumption cursor: In this section is possible activating the cursor and shifting it through the left (<<) and right (>>) button. This available for the curves presented in sections of environments variables and total consumption.
3. General information: The results and variables information are presented in this section, e.g., charts of total consumption, states for each equipments before and after of management and exogenous variables. Furthermore, an animation during the application of each management criteria is presented.
4. Management process: The selection of audit energy and management criteria is carried out in this section. First appear it the subsection *Audit* to *generate* and presenting the recommendations obtained through of diagnosis reached by energy audit; before the accept recommendations, the user must reviewing the *pdf report* generated by the computational tool. The savings in terms of power consumption and energy cost are shown in this section too. Second appear the *management criteria* section that brings the possibility to the user the selecting the criterion type (e.g., one criterion, DM based on consumption, DM based on comfort or DM based on priority). Furthermore, some *buttons* allows choosing the criterion or criteria to consider. The usage percentage and priority list are presented, and in case of priority list only is enable when DM based on priority is selected. Finally

when the recommendations have been proposed, the user can select the gmanagement criteria that he wants visualized in *total consumption* chart.

5. Statistics chart: In this section is presented the proportion of power consumption for each one of equipment within of total consumption.
6. Consumption Report: The results before and after of applying proposed approach are presented in this section. Likewise the results are shown per hour as the cursor is shifting.

## 5.2. Energy Audit Algorithm

The proposed algorithm to the development of energy audit process aims to compare, diagnose and verify the efficiency of all of equipments within the environment. The structure applied to the above algorithm seeks to assess systematically each one of available equipments in order to present improvement plans according to efficient policies and/or usage rationale of energy. The user has the possibility of accepting or rejecting the recommendations provided by this stage, however before this, it must reading the report generated previously for continuing with the process.

Fig. 5.2-1 shows the curve of power consumption after the implementation of the recommendations provided by the energy audit process. Furthermore, it generates a report that provides a detailed analysis of the improvement plan proposed by the computational intelligence system.

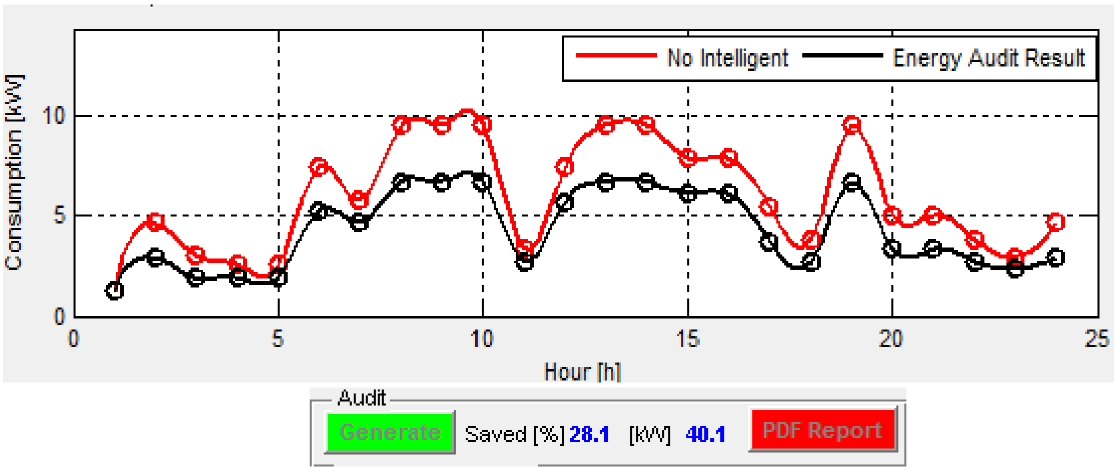


Fig. 5.2-1 Curve of power consumption after of the implementation of recommendations provided by the energy audit process

In addition a consumption result shown in Fig. 5.2-1, the computational intelligence system provides a detailed report on some plans for the rational use of energy for the case of the luminaries, televisions and computers. Fig. 5.2-2 shows an example obtained for a case of luminaries.

| Model | Power [W] | Characteristics | Unit Cost | Total Cost |
|---|---|---|---|---|
| FT8/32W | 0.0320 | Fluorescent Lamp | $5000 | $200000 |
| LT83/16W | 0.0160 | LED Lamp | $125635 | $5025400 |

| Technology | Daily Consumption | Daily Cos [$] | Mensual Cost [$] |
|---|---|---|---|
| LT83/16W | 8.6400 | 3110.4 | 93312 |
| FT8/32W | 23.0400 | 8294.4 | 248832 |
| Cost Difference | | | 155520 |
| Payback in Moths | 1.0771 | | |

Fig. 5.2-2 Example of a table provided by the energy audit process

## 5.3. Demand Management Algorithms

In this section, an agent system designed for an energy-efficiency model in a building will be discussed.

### 5.3.1. Load Priority Criteria

Management characteristics can vary according to the chosen criteria by the user. The priority-based approach seeks to mitigate load power consumption during those moments of high consumption in the demand curve (peak), according to a list of equipments (*PL*) selected by the user.

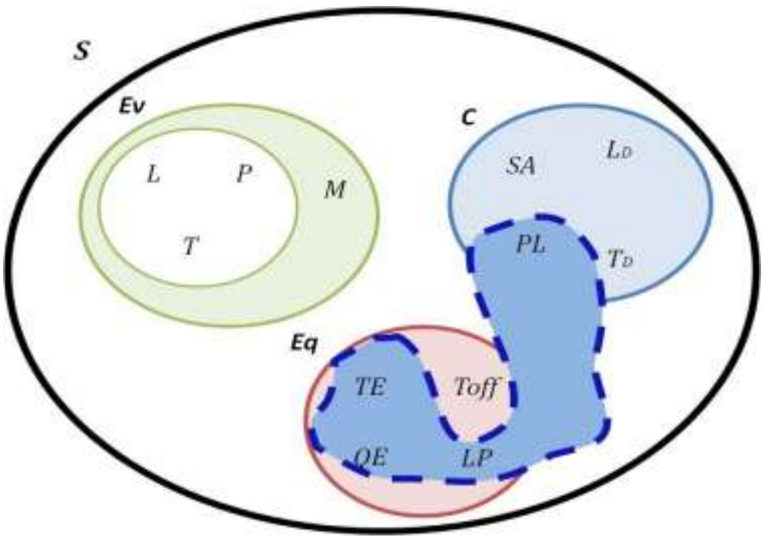


Fig. 5.3-1 General scheme of a scenario *S* for load priority criterion.

Fig. 5.3-1 shows a scenario with a variables universe that characterizes to a user.

Blue region indicates the variables used by this criterion to carry out the management. *Pl*: Air conditioner, *TE*: computer, television, air conditioner and luminaries, *QE:* computer (40), television (10), air conditioner (1) and luminaries (30). *LP:* air conditioner (*EV*) and computer, television and luminaries (*NEV*).

For the development of this approach, it was taken the design proposed by (Ravibabu, Praveen, Ch, et al., 2009). In this paper, a fuzzy controller that responds to the presence of peak demand is analyzed. Fig. 5.3-1 shows the architecture of this controller.

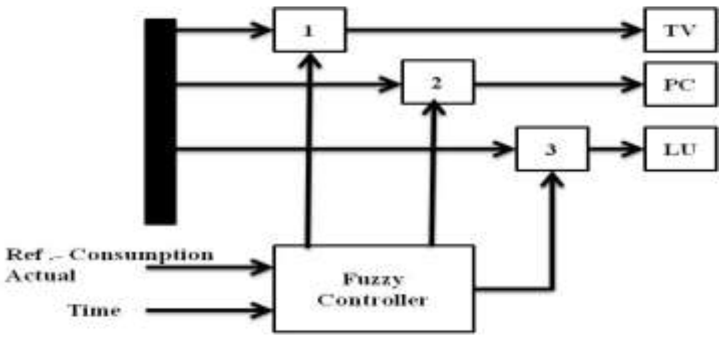


Fig. 5.3-2 Architecture of the fuzzy controller (LP Criteria)

The main idea of this approach is to control only those devices with the user arranger. These equipments will be considered as interruptible or otherwise non-interruptible. For the case study were considered as interruptible loads all except the air conditioning system (*EV*). The inputs of this system are summarized below:

*1) Feedback*: It selected from the comparison result between an electric energy consumption curve obtained according to the profiles of power consumption of the equipment stored on a server and the threshold that delimits the normal consumption of electric power for one day. In Fig. 5.3-3, the membership function in the 'feedback' input of the fuzzy controller is shown.

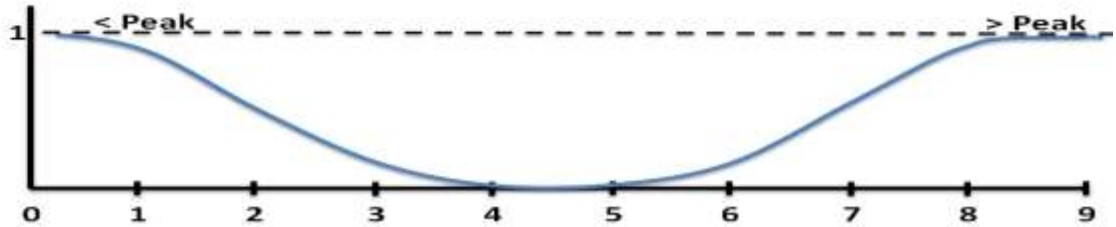


Fig. 5.3-3 Feedback membership function (LP criteria).

2) Time *t*: Data was sampled for a period of one day. Peak-on and peak-off are included in membership function trapezoidal type (Fig. 5.3-4).

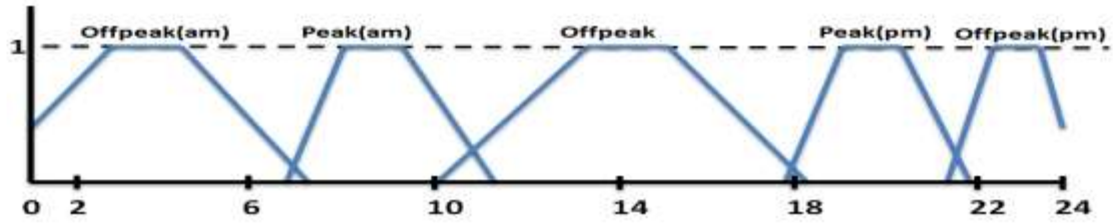

Fig. 5.3-4 Time membership function (LP Criteria)

Table 5.3-1 lists the types of membership functions selected for a *Sugeno* system.

| Input | | Output |
|---|---|---|
| Feedback | Time | [1-3] |
| Z-shaped and S-shaped | Trapezoidal | Constant |

Table 5.3-1 Membership functions for the fuzzy controller (LP criterion)

The controller outputs are presented with two states (on-off) which disconnect interruptible loads in the presence of peak demand.

Considering the needs and constraints, consumers' demand profile was obtained using 7 rules, few of which are listed in Table 5.3-21 (Ravibabu, Praveen, Ch, et al., 2009).

| Rules | Input | | Output |
|---|---|---|---|
| | Feedback | Time | [1-3] |
| 1 | >Peak | Peak(am) | Vital |
| 2 | | Peak(pm) | Vital |
| 3 | <Peak | Peak(am) | Non Vital |
| 4 | | Peak(pm) | Non Vital |
| 5 | None | Off peak | Non Vital |
| 6 | None | Off peak(am) | Non Vital |
| 7 | None | Off peak(pm) | Non Vital |

Table 5.3-2 Rule base for fuzzy controller (LP criterion)

Figure 5.3-5 shows an example of application of the load priority criterion for a case study. In this case have been selected computers, televisions, air conditioner (*EV*) and luminaries as equipments to manage. The purple line shows the power consumption of the environment before of implementing the recommendations, while the blue curve shows the power consumption after the implementation of the recommendations. The results show a reduction in consumption during peak demand.

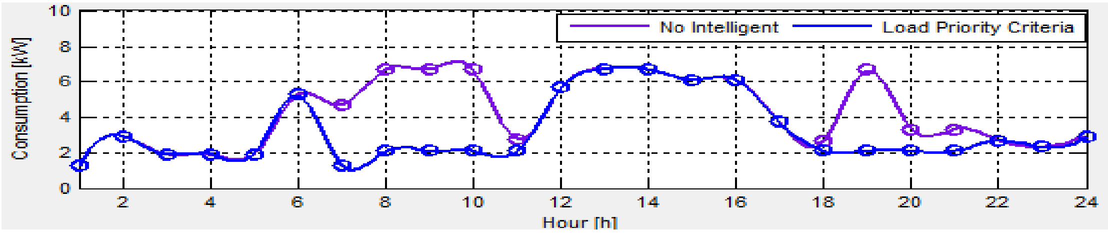


Fig. 5.3-5 Load priority criteria results

### 5.3.2. Direct Load Control

The purpose of DLC is to shape the load curve by cycling customer's large current drawing appliances. A number of DLC schemes have been developed to reach both peak load shaving and operating cost saving (Goel et al., 2010).

Next, the Block diagram proposed by (Salehfar, 1999) is shown in Fig. 5.3-5.

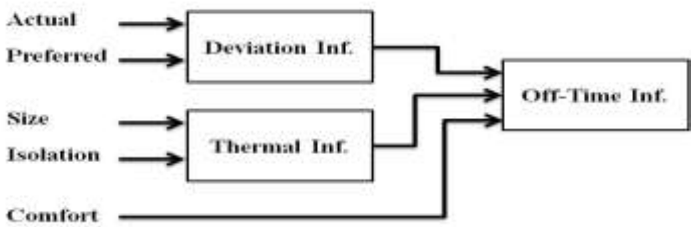


Fig. 5.3-6 DLC Fuzzy control block diagram

The main objective of this proposal is to determine the disconnection time required for saving energy without affecting comfort levels. A detailed analysis of each membership functions is carried out in (Salehfar, 1999).

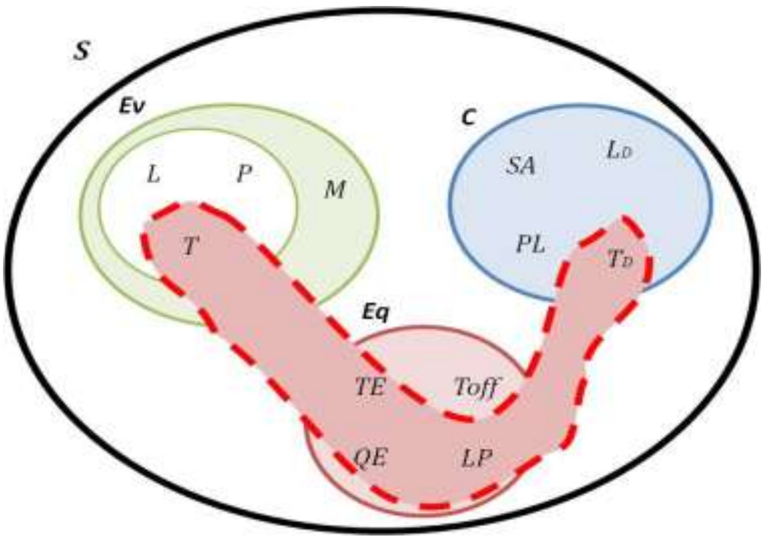


Fig. 5.3-7 General scheme of a scenario *S* for direct load control criterion.

Fig. 5.3-7 shows a scenario with a variables universe that characterizes to a user. Red region indicates the variables used for this criterion to carry out the management. *PL*: Air conditioner, *TE*: computer, television, air conditioner and luminaries, *QE:* computer (40), television (10), air conditioner (1) and luminaries (30). *LP:* computer and desired temperature ($T_D$).

*1) Inputs:*

- Functional states of the electric loads and the electric energy consumption associated to the state.
- Comfort Level: Temperature range specified by the customer.
- Thermal variation of the enclosure: Value obtained from the size and level of isolation from the environment.
- Time: The sampling data for a period of one day.

*2) Devices:* Computers, Televisions, luminaries y air Conditioning.

*3) Load list handled:* Air conditioning was selected as principal load to management due level and high degree of incidence within the peak demand of the user's consumption profile.

Fig. 5.3-6 shows the structure of the Off-Time fuzzy controller. The intention of this system is to determine a percentage of the Off-Time for air conditioner based mainly on user`s comfort level. This variable is assumed as the temperature range that a user can handle.

An example of membership functions and some of the rules used for the design of the system shown in Fig. 5.3-6 are brought below (Fig. 5.3-8 – 5.3-10).

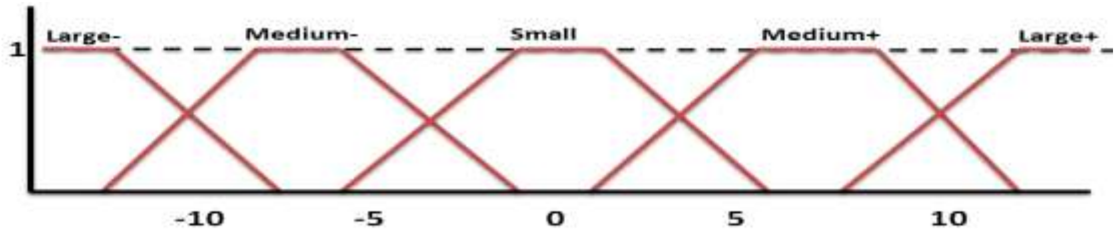


Fig. 5.3-8 Membership functions of temperature deviation (DLC criterion).

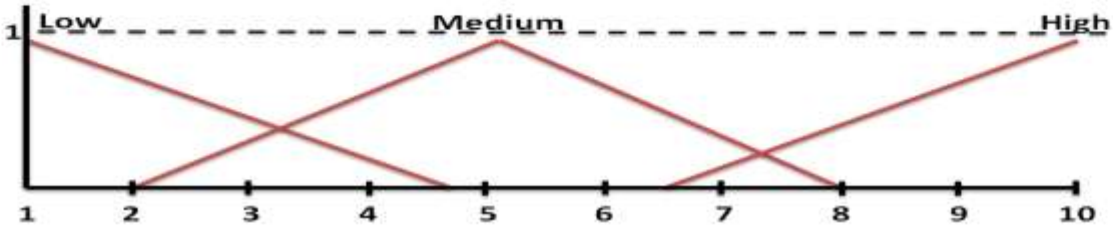

Fig. 5.3-9 Thermal variation membership function (DLC criterion)

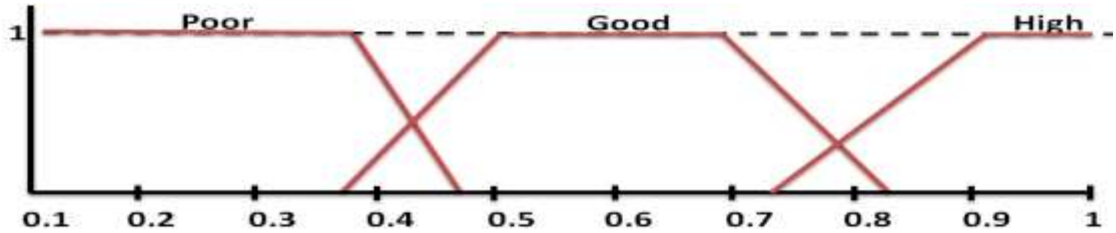

Fig. 5.3-10 Comfort membership function (DLC criterion)

Some of the rules of the system proposed by (Salehfar, 1999) are presented in Table 5.3-3.

| Rules | Input | | | Output |
|---|---|---|---|---|
| | Deviation | Thermal | Comfort | |
| 1 | LARGE+ | LOW | EXCELLENT | HIGH |
| 2 | LARGE- | LOW | GOOD | LOW |
| 3 | LARGE+ | MEDIUM | GOOD | HIGH |
| 4 | MEDIUM+ | MEDIUM | GOOD | MEDIUM |
| 5 | SMALL | MEDIUM | GOOD | MEDIUM |
| 6 | MEDIUM- | MEDIUM | GOOD | MEDIUM |
| 7 | LARGE- | MEDIUM | GOOD | LOW |

Table 5.3-3 Rule base for Off-Time fuzzy controller (DLC criterion)

The rule set showed above was adjusted to an environment such as was described in table 5.1-1.

Fig. 5.3-11 shows an example of application of direct load control criterion for a case study. In this case have been selected computers, televisions, air conditioner and luminaries as equipments to manage. The purple line shows the power consumption of the environment before of implementing the recommendations, while the red curve shows the power consumption after the implementation of the recommendations. The results show a reduction in consumption of electricity due to the direct management of the air conditioner.

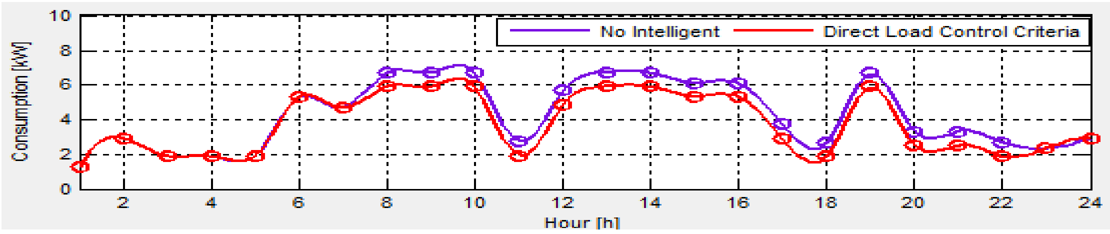

Fig. 5.3-11 Direct Load Control results

### 5.3.3. Differential tariff

The concept of differential tariff is related to variability in energy prices in some instants of time. The institutional policies of some companies engaged in the marketing and distribution of electricity aims to boost power consumption during those valley hours and penalize the same during peak hours. From a consumer perspective this is directly reflected in the value of monthly bill, it forces to change the consumption habits and move a little towards the valley hours.

For application in the case study, we have suggested a variant of the case suggested by (Ravibabu, Praveen, & Vikaschandra., 2009). This modification seeks to provide demand management in order to avoid excessive penalties during those peak hours of electricity consumption.

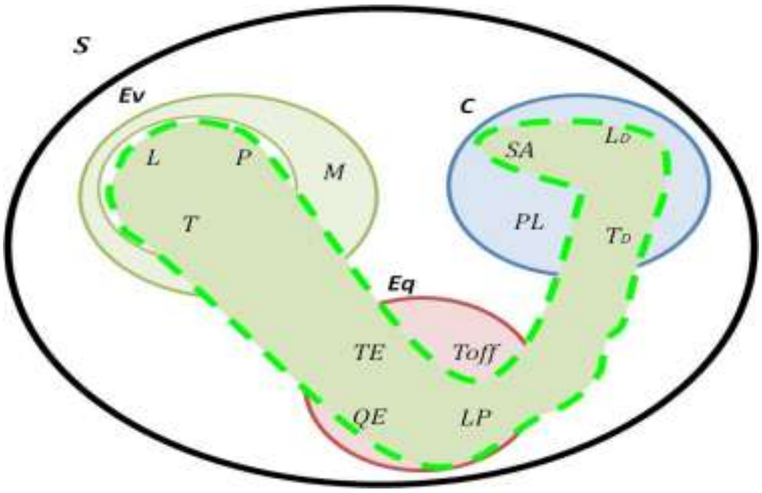

Fig. 5.3-12 General scheme of a scenario *S* for differential tariff criterion.

Fig. 5.3-12 shows a scenario with a variables universe that characterizes to a user. Green region indicates the variables used for this criterion to carry out the management. *PL*: Air conditioner, *TE*: computer, television, air conditioner and luminaries, *QE:* computer (40), television (10), air conditioner (1) and luminaries

(30). *LP:* computer, television and luminaries (non vitals), desired temperature $T_D$, *SA*: simulation at night and work session from 8:00 am to 6:00pm as scheduled activity for a day, $L_D$: 500 – 750 Lux (Illuminance level for a laboratory according to (RETILAP, 2011)).

For power management system based on the differential tariff criterion, was selected the computer and luminaries as equipments to manage. Below is presented a brief explanation of the proposed structure for each of the systems developed:

- *Computer*

The fuzzy system proposed for carrying out the management of electric power demand from the computer shown in Fig. 5.3-13.


Fig. 5.3-13 Fuzzy inference engine of computer (DT criterion)

1) Inputs

   - Load profile: The indicator implemented to measure the level of performance (CPU usage and memory). Fig. 5.3-14 shows the membership functions used to define the load profile as input to the fuzzy system.

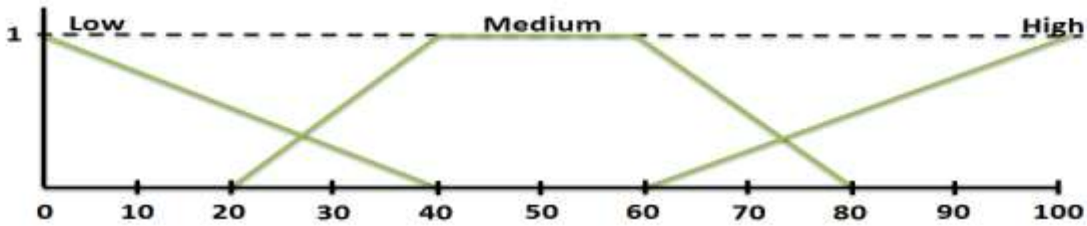


Fig. 5.3-14 Membership function of the load profile of computer (DT criterion)

   - *Presence*: Variable that establishes the occupancy level of the environment. Fig. 5.3-15 shows the membership functions used to define the level of presence as input to the fuzzy system.

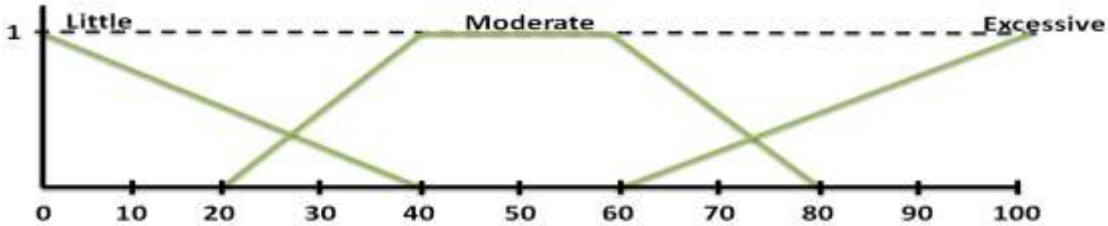


Fig. 5.3-15 Membership function of presence level (DT criterion)

2) *Output*

- *Recommended state*: New state proposed by the fuzzy inference engine according to the behavior described by the input variables. Fig. 5.3-16 shows the membership functions used to define the states recommended by the fuzzy inference engine.

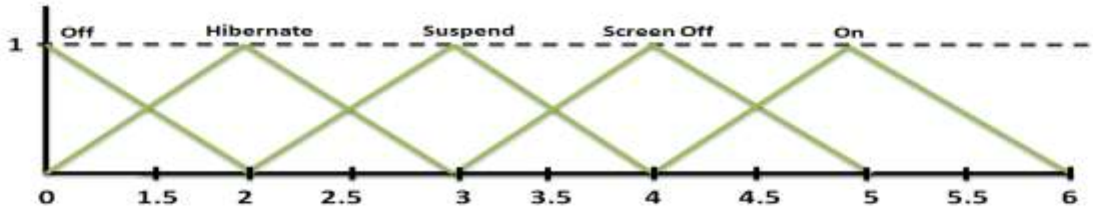


Fig. 5.3-16 Membership function of proposed states (DT criterion)

*Fuzzy Rules*

| Rules | Input | | Output |
|---|---|---|---|
| | PC Load Profile | Presence | |
| 1 | LOW | LITTLE | OFF |
| 2 | LOW | MODERATE | SCREEN OFF |
| 3 | MEDIUM | LITTLE | SCREEN OFF |
| 4 | HIGH | LITTLE | ON |
| 5 | LOW | EXCESSIVE | SCREEN OFF |

Table 5.3-1 Rule base for fuzzy controller of PC (differential tariff)

- *Luminaries*

  Fig. 5.3-17 shows the fuzzy system for management of electric energy demand from luminaries.


Fig. 5.3-17 Inference engine for luminaries

1) *Inputs*

- Illuminance: This refers to the level of illuminance (lux) current within the analyzed environment. Fig. 5.3-18 shows the membership functions used to define this variable as input the fuzzy inference engine.

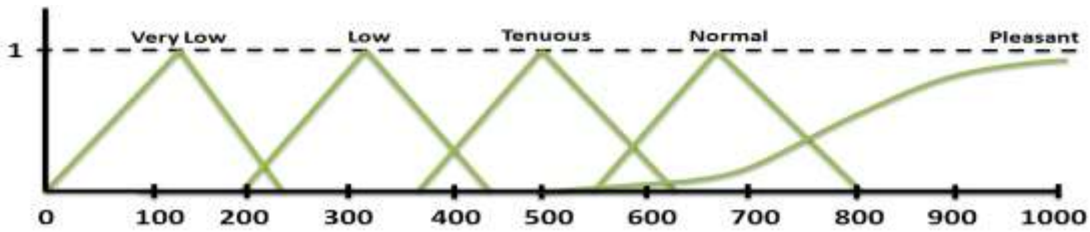


Fig. 5.3-18 Membership function of illuminance level (DT criterion)

- Presence: Variable that sets the level of occupation in the environment. Fig. 5.3-19 shows the membership functions used to define the level of presence as input to the fuzzy system.

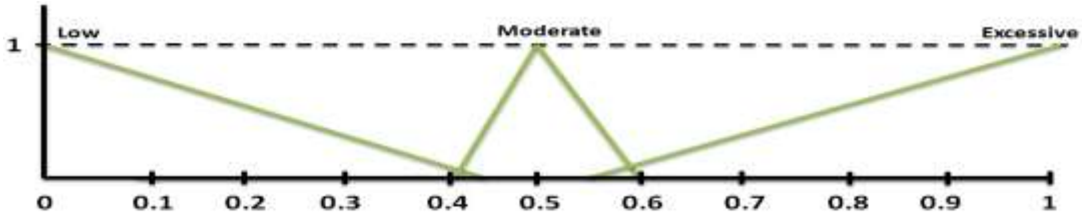


Fig. 5.3-19 Membership function of presence level (DT criterion)

- Visual requirement level: This variable sets the level of visual demand required by the user. The boundaries and shape of each of the membership functions used was set according to (RETILAP, 2011). Fig. 5.3-20 shows the membership functions used to define the level of presence as input to the fuzzy system.

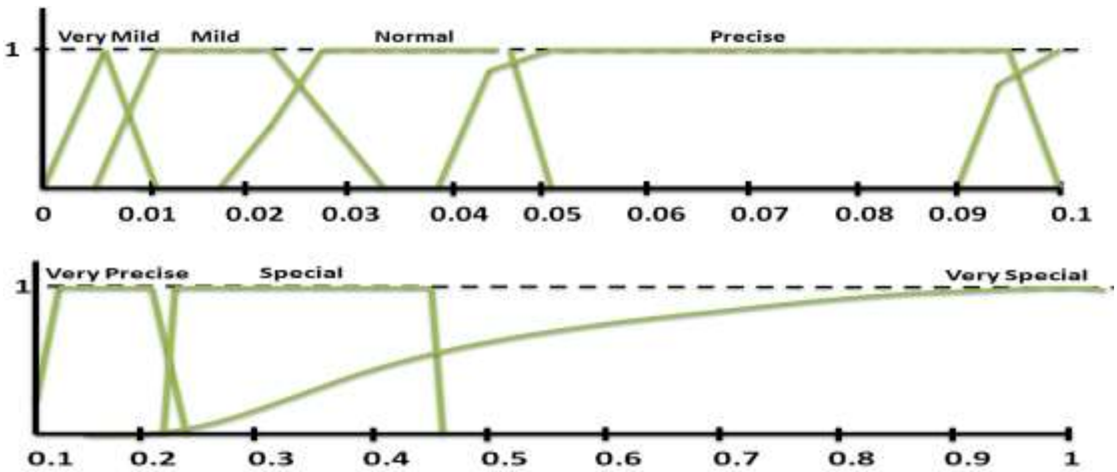


Fig. 5.3-20 Membership function of visual requirement level (DT criterion)

2) *Output*

- Proposed state: State recommended by the fuzzy inference engine consistent with the rules. Fig. 5.3-21 shows the membership functions used.

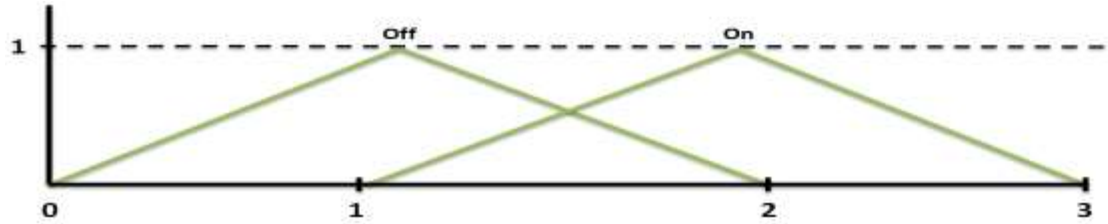

Fig. 5.3-21 Membership function of proposed state (DT criterion)

*Fuzzy rules*

| Rules | Input | | | Output |
|---|---|---|---|---|
| | Illuminance | Presence | Exigency | |
| 1 | NONE | LOW | NONE | OFF |
| 2 | NORMAL | HIGH | NORMAL | OFF |
| 3 | PLEASANT | HIGH | NORMAL | OFF |
| 4 | TENOUS | NOT HIGH | NORMAL | ON |
| 5 | VERY LOW | HIGH | NORMAL | ON |
| 6 | LOW | HIGH | NORMAL | ON |

Table 5.3-2 Rule base for fuzzy controller of luminaries (differential tariff)

In Fig. 5.3-22 is shown the power consumption before and after implementation of the fuzzy system based on the differential tariff criterion.

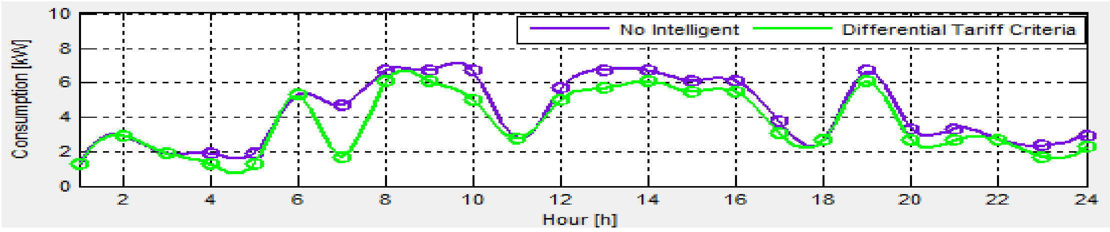

Fig. 5.3-22 Differential tariff results

### 5.3.4. Scheduled Programming Criteria

This criterion seeks to achieve energy savings based scheduling on and off device at certain instants of the day. To allow the system to create the scheduling, the user must provide a list with the appliances to be executed within the next 24 hours.

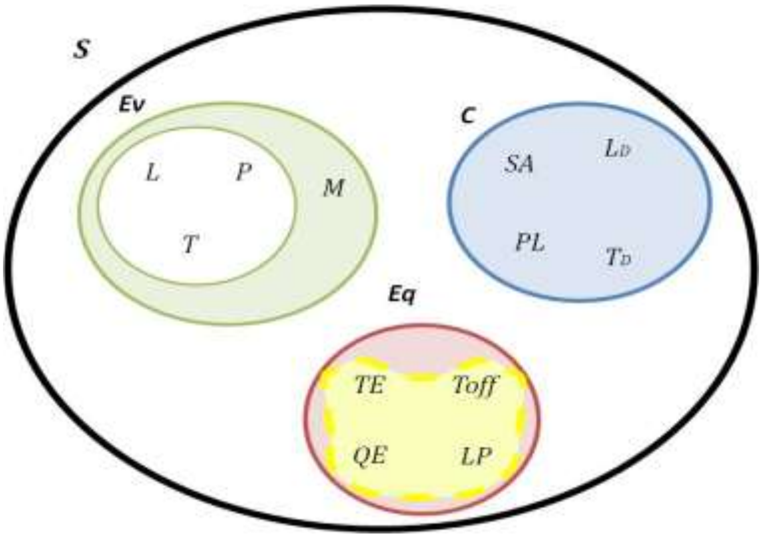

Fig. 5.3-23 General scheme of a scenario *S* for scheduled programming criterion.

Fig. 5.3-23 shows a scenario with a variables universe that characterizes to a user. Yellow region indicates the variables used for this criterion to carry out the management. *TE*: computer, television, air conditioner and luminaries, *QE:* computer (40), television (10), air conditioner (1) and luminaries (30), *LP:* computer and *Toff* = 10 hours.

The variables utilized for this criterion are presented below.

*1) Inputs:* Set Scheduled On/Off daily: It established scheduled On/Off those devices manipulated by the system, according to the selected scheduled.

*2) Devices:* Computers, televisions, luminaries and air Conditioning.

*3) Load List handled:* Televisions, Computers and Luminaries.

In this criterion, user`s comfort is not considered as a system variable.

In this case of user comfort is not considered as a variable in the system. Fig. 5.3-24 shows an example of application of scheduled programming in a case of study. In this case have been selected computers, televisions, air conditioner and luminaries as equipments to manage. The purple line shows the power consumption of the environment before of implementing the recommendations, while the magenta curve shows the power consumption after fulfillment of the program on and off.

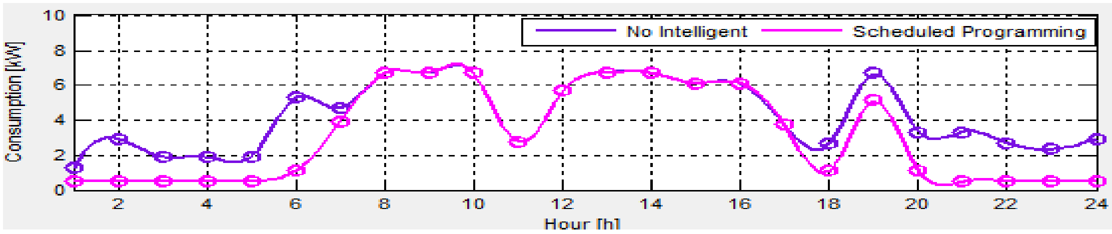


Fig. 5.3-24 Scheduled programming results

### 5.3.5. Neural networks

The main idea of this approach is to manage different loads independently within the same environment. The management of each of the devices depends mainly on the environmental variables (Presence, temperature and illumination level). For device such as computer, is considered such the profile due to the possibility of obtaining information regarding the current utility of this device.

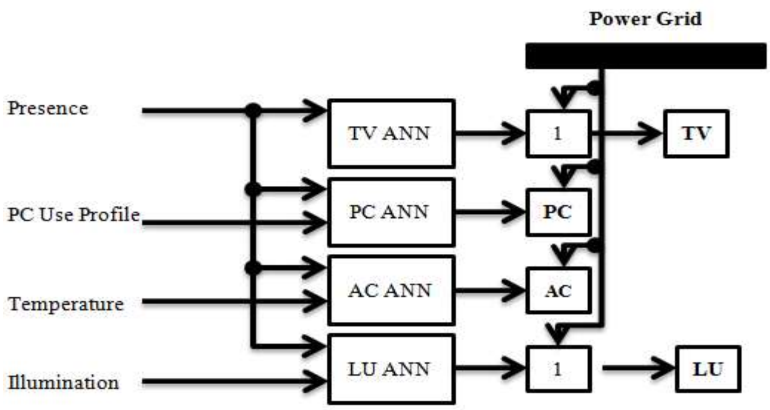


Fig. 5.3-25 Architecture of the neural networks approach

Fig. 5.3-25 shows the architecture of this criterion.

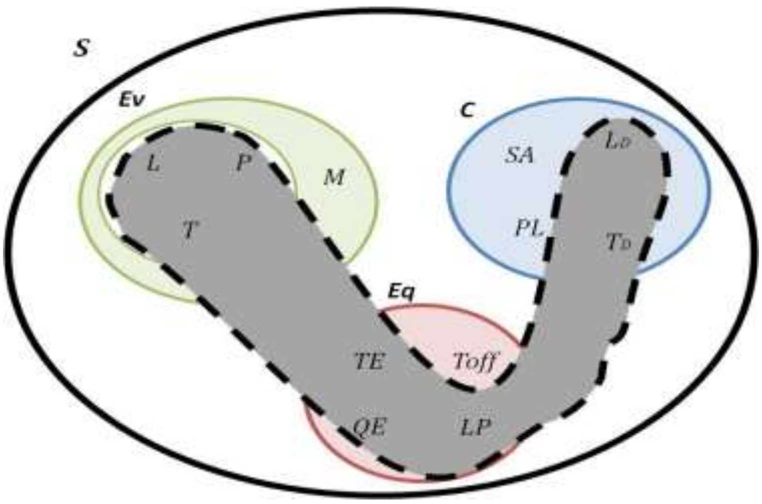


Fig. 5.3-26 General scheme of a scenario *S* for neural networks approach

Fig. 5.3-26 shows a scenario with a variables universe that characterizes to a user. Black region indicates the variables used for this criterion to carry out the management. *PL*: Air conditioner, *TE*: computer, television, air conditioner and luminaries, *QE:* computer (40), television (10), air conditioner (1) and luminaries (30). *LP:* computer, television and luminaries (non vitals), desired temperature $T_D$ [22ºC – 26ºC], *SA*: simulation at night and work session from 8:00 am to 6:00pm as scheduled activity for a day, $L_D$: 500 – 750 Lux (Illuminance level for a laboratory according to (RETILAP, 2011)).

*1) System Inputs*

- *Presence*: This data is used to establish the occupancy levels in an environment. This information will be useful for the TV, computer and light controllers as the basis for the indication of recommendations.

$$\boldsymbol{P^I} = [P_1{}^I,\ P_2{}^I, \ldots, P_k{}^I] \tag{5.3-1}$$

  Where,

  $P_i{}^I$: Presence levels at environment *I* at time *i*.

- *PC use profile*: Provides information related to the computational load of device, i.e. the percentage of resources used at time. This provides support for determining whether a device is running a scheduled application even though the system does not detect any presence.

$$\boldsymbol{LP^I} = [LP_1{}^I,\ LP_2{}^I, \ldots, LP_k{}^I] \tag{5.3-2}$$

  Where,

  $LP_i{}^I$: PC use profile at environment *I* at time *i*.

- *Temperature*: Temperature indoor level.

$$\boldsymbol{T^I} = [T_1{}^I,\ T_2{}^I, \ldots, T_k{}^I] \tag{5.3-3}$$

  Where,

  $T_i{}^I$: Temperature levels at environment *I* at time *i*.

- *Illumination:* Intensity level that rely on the work. The operating range in case study as shown in Fig. 5.1-1 requires a lux level near to 750 lx.

$$\boldsymbol{L^I} = [L_1{}^I,\ L_2{}^I, \ldots, L_k{}^I] \tag{5.3-4}$$

  Where,

  $L_i{}^I$: Illumination levels at environment *I* during time *i*.

*2) Controller System*

The controller design was realized with a *Multilayer Perceptron* (*MLPs*) as *ANNs*. The proposed architecture in Fig. 5.3-25 shows an *ANN* for each device, since it can handle independently the loads. The representation of possible situations for each type device to control was carried out, e. g. in the case a PC no use, the system will compare PC use profile with presence level to determinate if it is realizing any task or simply it is consuming energy aimless. The obtained data was used to train the neural networks, obtaining a good performance with feed-forward back-propagation network architecture, one hidden layer and sigmoid tangential transfer function for four *ANNs* performed.

In this thesis, the selection and determination of the number of layers and neurons was adjusted using an iterative algorithm.

Fig. 5.3-27 shows an example of application of proposed approach based on neural networks for a case study. In this case have been selected computers, televisions, air conditioner and luminaries as equipments to manage. The purple line shows the power consumption of the environment before of implementing the recommendations, while the black curve shows the power consumption after the implementation of the recommendations.

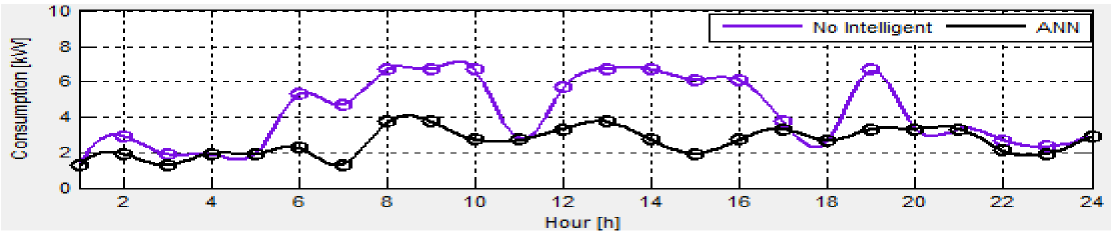


Fig. 5.3-27 Results of implementation using neural networks

## 5.4. Dynamic Manager Algorithm

The main idea of dynamic manager algorithm is evaluating several demand management of electric energy and selecting the suitable in each instant of time according to customer preferences as priority list, priority per consumption or priority per comfort. Hence it is necessary taking account all recommendations provided by the management criteria considered (load priority, direct load control, scheduled programming, differential tariff and neural networks) and selecting one that it adjust to the user preferences, such as priority, based on consumption or based on comfort. However, to selecting a suitable management criterion it is necessary establishing comparison factors that allow assessing the pertinence grade of the recommendation applied on each one the equipments, i.e. states or consumption efficient at instant time (only in comfort or consumption case). In this case, the comparison factors are obtained according to the efficient policies applied to the operation of each equipment type. Result of this, it is a curve of energy consumption and/or functional states (comfort) that have been evaluated as energy efficient and customer preferences. The preferences considered in this proposal are:

### 5.4.1. One criterion

In this case only is evaluated the criterion selected by the user. The design of each demand criterion of electric energy was presented in section 5.3.

### 5.4.2. DM based on priority

It is non intelligence approach that seeks selecting each criterion according to the priority established by the user. However, a threshold was applied in order to consider a possibility of switch to other criterion (immediately lower priority) when the criterion with higher priority does not exceed the threshold set by the user saving.

Below is presented an example of implementation of this criterion. In this case was used a threshold of power consumption saving *($T_h$)* equal to 30%.

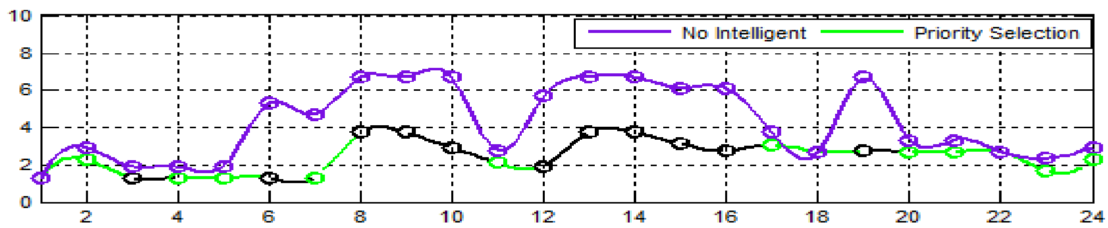


Fig. 5.4-1 Results of DM based on priority list

Fig. 5.4-1 shows a case of study where demand management criterion of electric energy using neural networks was selected as the first in priority list followed by differential tariff, load priority, direct load control and scheduled programming, respectively.

### 5.4.3. DM based on consumption

It is intelligence approach that allows selecting the criterion with greater similarity to the power consumption proposed by dynamic manager.

The design of inference engine of dynamic manager was performed using genetic algorithm (air conditioner) and fuzzy logic (luminaries, television and computer). Below is presented a case of implementation and some design considerations.

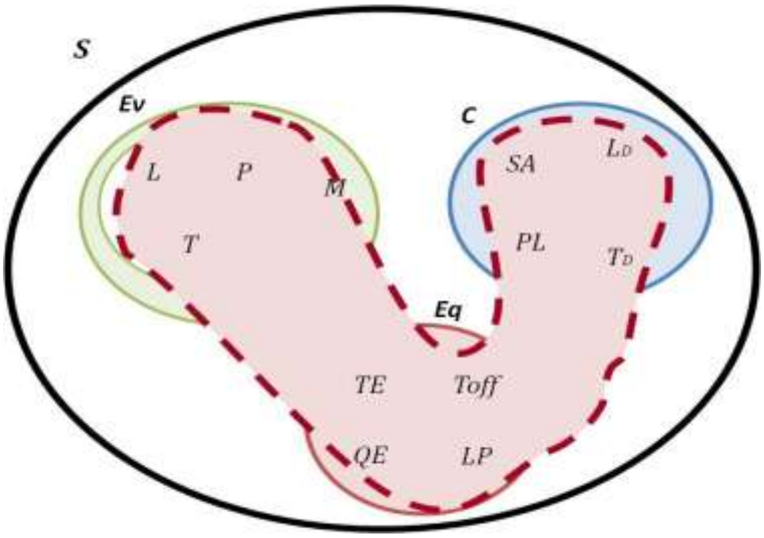


Fig. 5.4-2 General scheme of a scenario *S* for dynamic manager approach.

Fig. 5.4-2 shows a scenario with a variables universe that characterizes to a user. Burgundy region indicates the variables used for this criterion to carry out the management. *M:* Outdoor temperature, *PL*: Air conditioner, *TE*: computer, television, air conditioner and luminaries, *QE:* computer (40), television (10), air conditioner (1) and luminaries (30). *LP:* computer, television and luminaries (non vitals), desired temperature ($T_D$) [22ºC – 26ºC], *SA*: simulation at night and work session from 8:00 am to 6:00pm as scheduled activity for a day, $L_D$: 500 – 750 Lux (Illuminance level for a laboratory according to (RETILAP, 2011)).

- *Air conditioner*

The genetic algorithm implemented in air conditioner case seeks establishing the cooling factor required to maintain the temperature within the comfort zone. In this proposal the thermal model was used to evaluate the effect produced by the value set by the genetic algorithm in the environment temperature.

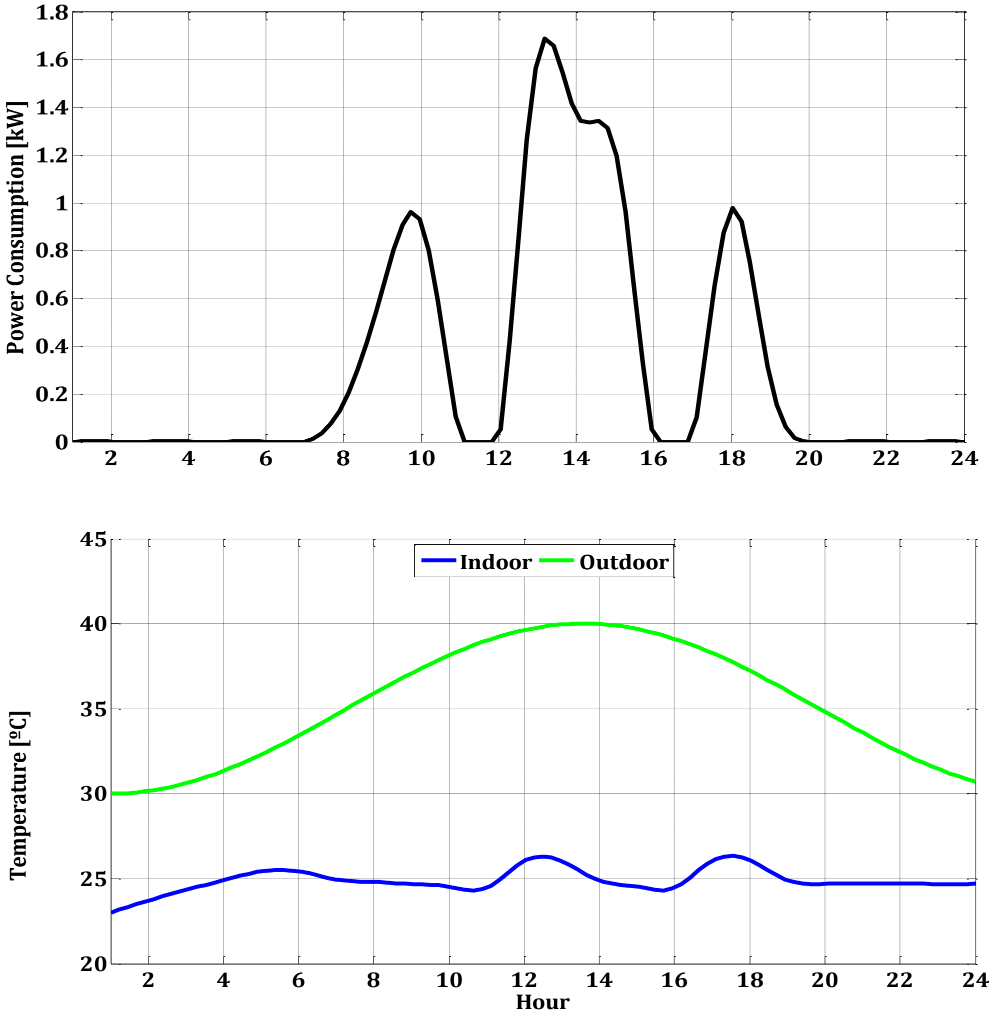


Fig. 5.4-3 Power consumption of air conditioner (upper) and indoor and outdoor temperature for a case of study (lower)

Fig. 5.4-3 shows two charts, first shows the cooling factor adjusted by genetic algorithm in each instant of time according to variables presented in section 2.3. It is notable as during the early hours (1 am – 6 am) the air conditioning is off due that indoor temperature is in comfort zone, the same occur to night hours (8pm – 12 pm). Likewise the second chart shows outdoor temperature (green) and indoor temperature (blue) for the case of study. In the indoor temperature case is notable as this it maintains within comfort zone for each cooling factor selected.

- *Computer*

In this case was used fuzzy inference engine to emit recommendations about efficient operation of computer. The proposed design has four inputs and one output, this considered scheduled activity as new variable. Below it is analyzed each one of parts of fuzzy system showed in Fig. 5.4-34.

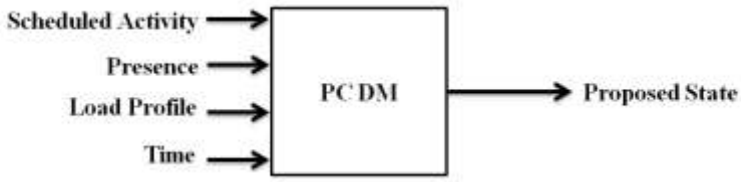


Fig. 5.4-4 Fuzzy inference engine for computer (DM)

Inputs

- Scheduled activity: allows considering every activities to carry out in the day in order to establish if modifying the computer state despite of there no presence, e.g., simulation. Membership function for this input is presented in Fig. 5.4-5.

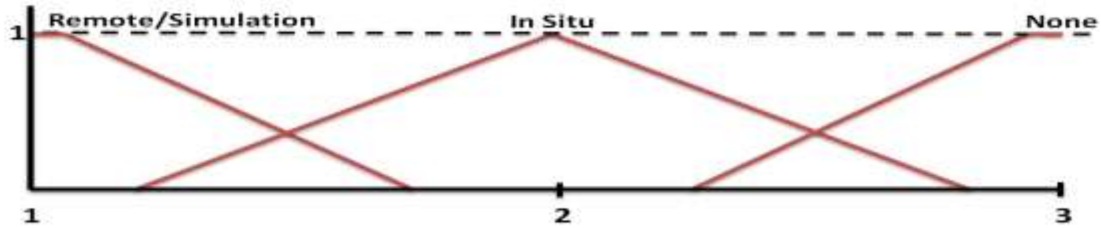


Fig. 5.4-5 Membership function for scheduled activity (DM)

- Presence: it is used to measure the absence or presence of people in the environment. Membership function for this input is presented in Fig. 5.4-6.

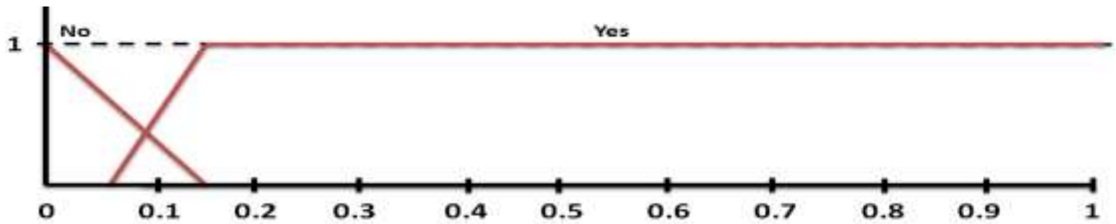


Fig. 5.4-6 Membership function for presence within of environment (DM)

- Load profile: it operates of similar manner that in the proposal presented in section 5.4.5. Membership function for this input is presented in Fig. 5.4-7.

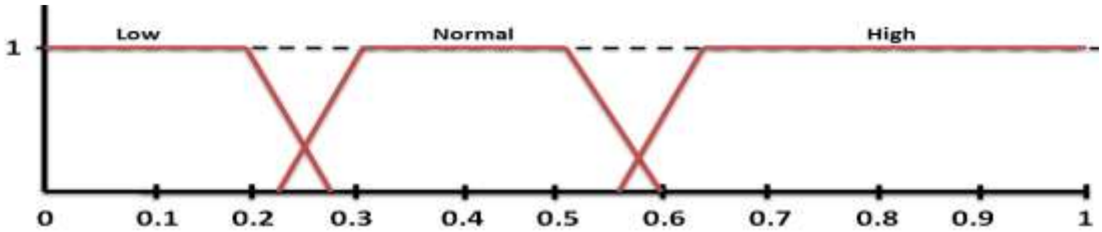

Fig. 5.4-7 Membership function for load profile (DM)

- Time: in this case it is necessary to evaluate the time due to in some cases is working only during certain instant of day, hence it is important to consider this variable to know if the operation is according to work plan. Membership function for this input is presented in Fig. 5.4-8.

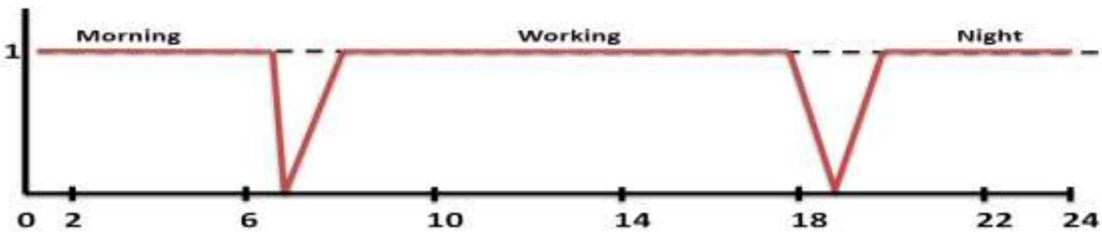

Fig. 5.4-8 Membership function for time of the day (DM)

<u>Output</u>

- Proposed states: this variable corresponds to the recommended states according to fuzzy rules. In this case was considered five functional states. Membership function for this output is presented in Fig. 5.4-9.

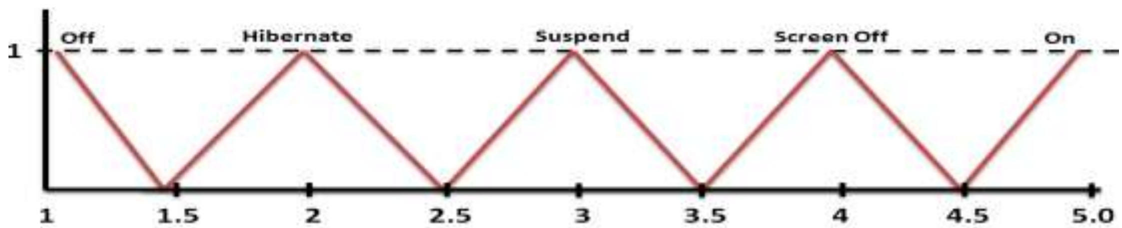

Fig. 5.4-9 Membership function for output of PC recommendations (DM)

- Luminaries

The efficient operation of luminaries is associated to some variables presented in section 2.1.1. The same that computer case to develop of this proposal was used a fuzzy inference engine. Fig. 5.4-10 presented the structure used to the design of this fuzzy system.

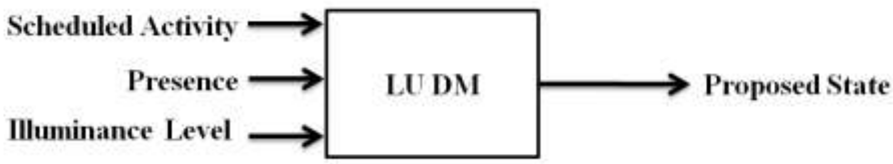


Fig. 5.4-10 Fuzzy inference engine for luminaries (DM)

Inputs

Type of activity: the exigency level of illuminance can vary according to the type of activity to perform; hence it is necessary adjusting the illuminance level without affect the labor of user. Fig. 5.4-11 presents the membership function used.

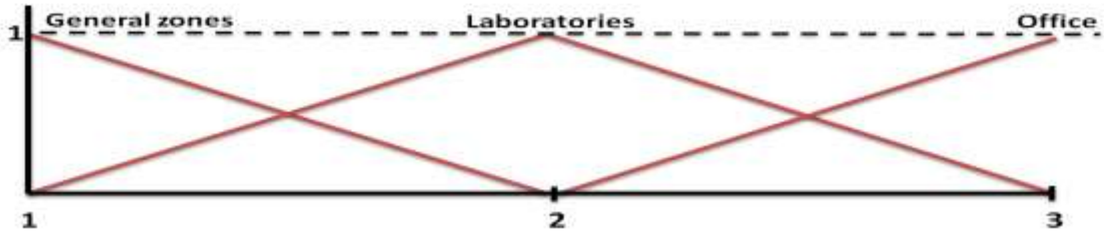


Fig. 5.4-11 Membership function for type of activity (DM)

- Presence: it is used of similar manner in computer case. Membership function for this input is presented in Fig. 5.4-12.

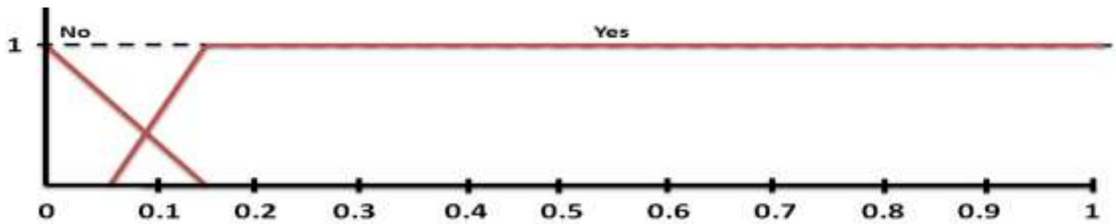


Fig. 5.4-12 Membership function for presence within of environment (DM)

- Illuminance level: this variable allows knowing the current illuminance level; the above in order to perform the necessary adjustment to vary the illuminance level within environment. Membership function for this input is presented in Fig. 5.4-13.

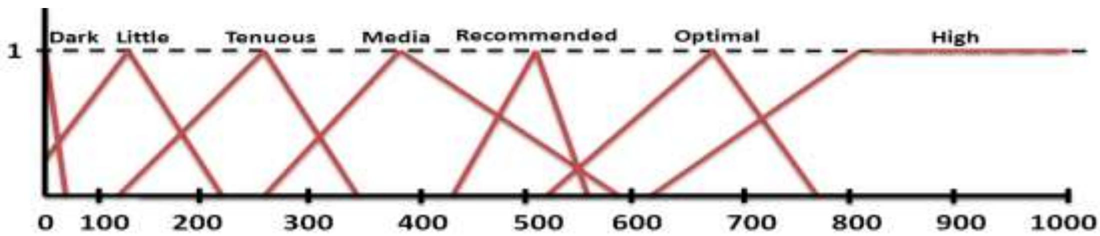


Fig. 5.4-13 Membership function for illuminance level within of environment (DM)

Output

- Illuminance level required: indicates the illuminance level to compensate or reduce in accordance with the fuzzy rule set. Membership function for this input is presented in Fig. 5.4-14.

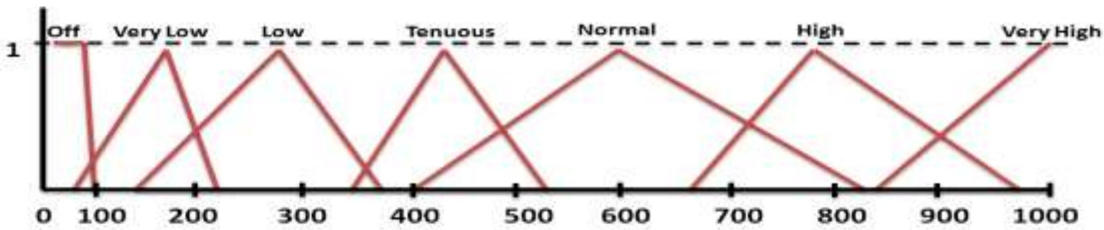


Fig. 5.4-14 Membership function for illuminance level required within of environment

The efficient operation of television is evaluated only considering the presence level within the environment.

The results of implementation of this criterion are shown in Fig. 5.4-15.

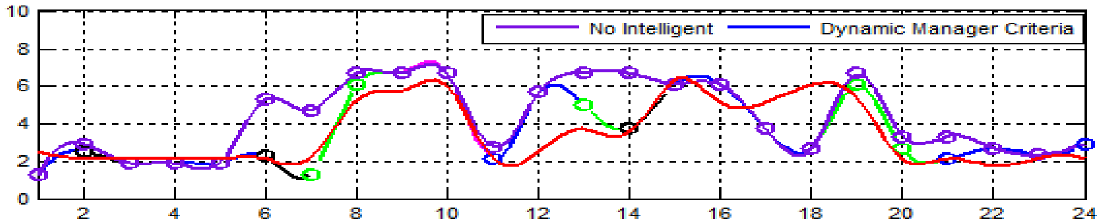


Fig. 5.4-15 Results of DM based on consumption

Fig. 5.4-15 shows three charts corresponding to power consumption before (purple) and after (color according to the selected criterion) of application of proposal and, power consumption curve proposed by dynamic manager (red).

### 5.4.4. DM based on comfort

It is intelligence approach that allows selecting the criterion with greater similarity to the functional states proposed by dynamic manager. Fig. 5.4-2 shows the scenario with a variables universe that characterizes to a user for this criterion. The other characteristics are similar to the presented in section 5.4.3.

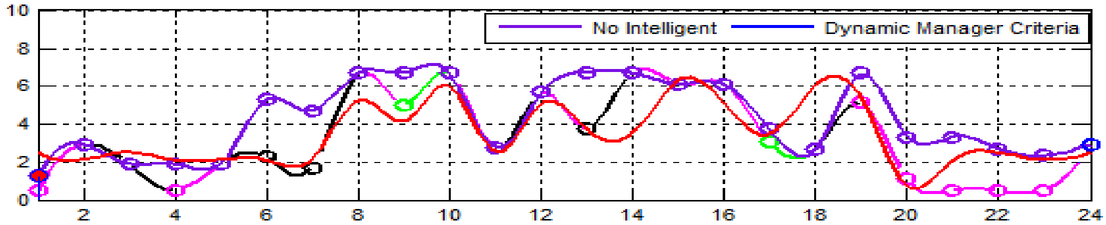


Fig. 5.4-16 Results of DM based on comfort

Fig. 5.4-16 shows three charts corresponding to power consumption before (purple) and after (color according to the selected criterion) of application of proposal and, power consumption curve proposed by dynamic manager (red).

# PART II

# EXPERIMENTS RESULTS AND CONCLUSIONS

# Chapter 6

# Analysis of the Experimental Results

*This chapter presents the discussion and analysis of the empirical experiments and testing that have been carried out for the proposed test beds. The results depicted in this chapter demonstrate the utility, feasibility and reliability of the overall proposed approach presented in the previous chapters.*

## 6.1. Experimental Design

The approach of the experiments was established to achieve independence between each one of the realizations required for generation of data of electric power consumption to be analyzed. For this, we have arranged power consumption obtained from the functional states of the equipment, the latter have been randomly generated for each realization (see Fig. 6.1-1). Furthermore, to assess the degree of uniformity in the performance of each of the criteria, an analysis was performed by varying the type of equipment to be managed. Finally we were performing a comparison of distribution of consumption for each one of management criteria of electric energy demand used in this work.

Fig. 6.1-1 Examples of two several configurations of power consumption for an environmental case of study

Taking in account the above, it defines the following characteristics to the experiment design:

Hypothesis or presentation of the problem:

*Could a computational intelligence system integrated to energy management model to provide reliable support decisions of the system operator for efficient management of electrical equipment connected to a power source?*

Response variable:

1. Power consumption savings *(PS)*: it is the difference between power consumption per analyzed equipments before and after of management of electric energy demand carried out by intelligent system proposed by us. Equation (6.1-1) was used to evaluate this metric.

$$PS_{MC} = \frac{PC_{NM} - PC_{MC}}{PC_{NM}} * 100 \ [\%] \qquad (6.1\text{-}1)$$

   Where,

   $PS_{MC}$ : Power consumption savings of management criteria ($MC$).

   $PC_{NM}$: Power consumption without management.

   $PC_{MC}$: Power consumption with management criterion ($MC$).

2. Time no off: it is the average time that the equipments remain off during a day of analysis (24 hours). Equation (6.1-2) expresses the metric to evaluate this variable.

$$P_{MC} = \frac{1}{n}\sum_{t=1}^{24} T_{off_t}{}^{e} \qquad (6.1\text{-}2)$$

Where,

$T_{off_{MC}}{}^{e}$ : Time off for equipment $e$ for the management criteria ($MC$).

3. Equipment states invariability: This variable indicates the number of states change proposed by each management criteria of electric energy demand used within of environment in comparison with the functional states without management.

$$RC_{MC} = \frac{1}{n}\sum_{t=1}^{24} St_{MC_t}{}^{e} - St_{NM_{t+1}}{}^{e} \begin{cases} RC_{MC} = 0 \to 1 \\ RC_{MC} \neq 0 \to 0 \end{cases} \qquad (6.1\text{-}3)$$

Where,

$St_{MC_t}{}^{e}$ : Functional states for equipment $e$ at time $t$ for the management criteria ($MC$).

$St_{NM_t}{}^{e}$ : Functional states for equipment $e$ at time $t$ within of environment before applying some management criteria.

4. Equipment management regularity: it indicates the availability of the management criteria to perform a demand management of electric energy on each one of equipment of the environment in an instant of time (hour).

$$RM_{MC} = \frac{1}{n}\sum_{t=1}^{24} St_{NM_t}{}^{e} - St_{MC_t}{}^{e} \begin{cases} RM_{MC} = 0 \to 1 \\ RM_{MC} \neq 0 \to 0 \end{cases} \qquad (6.1\text{-}4)$$

Where,

$St_{MC_t}{}^{e}$ : Functional states for equipment $e$ at time $t$ for the management criteria ($MC$).

$St_{MC_t}{}^{e}$ : Functional states for equipment $e$ at time $t$ without management.

5. Environment adaptability: it is the capability of each demand management criteria of electric energy to adjust the environmental conditions according

to change in exogenous variable. It is measured as repeatability of same functional states in succession.

6. User adjusted suitability: This variable indicates the degree of performance of each one DMC when it is used in particular equipment. In this case is weights the power consumption saving, productivity and regularity of each one DMC.

$$S_{MC} = a_1 \left( \frac{PS_{MC}}{\max(PS_{MC})} \right) + a_2 (RM_{MC}) + a_3 * Ad_{MC} \qquad (6.1\text{-}5)$$

   Where,
   $a_1$ : Coefficient to weigh the power saving.
   $a_2$ : Coefficient to weigh the equipment management regularity.
   $a_3$ : Coefficient to weigh the environment adaptability.

7. Uniformity: it is the response variation of the management criterion to the variation of type of equipments. In this case is used the slope figured out between management performed with one and four type of equipments.

<u>Independent variable</u>

- Management criteria of electric energy demand:
  1. Direct Load Control[5].
  2. Load Priority[6].
  3. Differential Tariff[7].
  4. Random.
  5. Scheduled Programming.
  6. Neural network approach.
  7. Dynamic manager based on priority.
  8. Dynamic manager based on consumption.

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[5] H, Salchfar, et al. "Fuzzy Logic-Based Direct Load Control Residential Electric Water Heaters and Air Conditioners Recognizing Customer Preferences In a Deregulated Environment," *Fuzzy Power Engineering Society Summer Meeting, 1999. IEEE,* vol. 2, 1999, p. 1055-1060.

[6] Ravibabu.P, et al., "An approach of DSM Techniques for Domestic Load Management using Fuzzy Logic," Fuzzy Systems, 2009. FUZZ-IEEE 2009. IEEE International Conference on, 2009, p. 1303-1307.

[7] Ravibabu, P.; Praveen, A.; Vikaschandra, C.; , "An intelligent water cooling techniques - A case study," Power Systems, 2009. ICPS '09. International Conference on , vol., no., pp.1-5, 27-29 Dec. 2009 doi: 10.1109/ICPWS.2009.5442691

9. Dynamic manager based on comfort.

- Appliances amount. 1 - 4 types of appliances (Computer, televisions, air conditioner and luminaries).

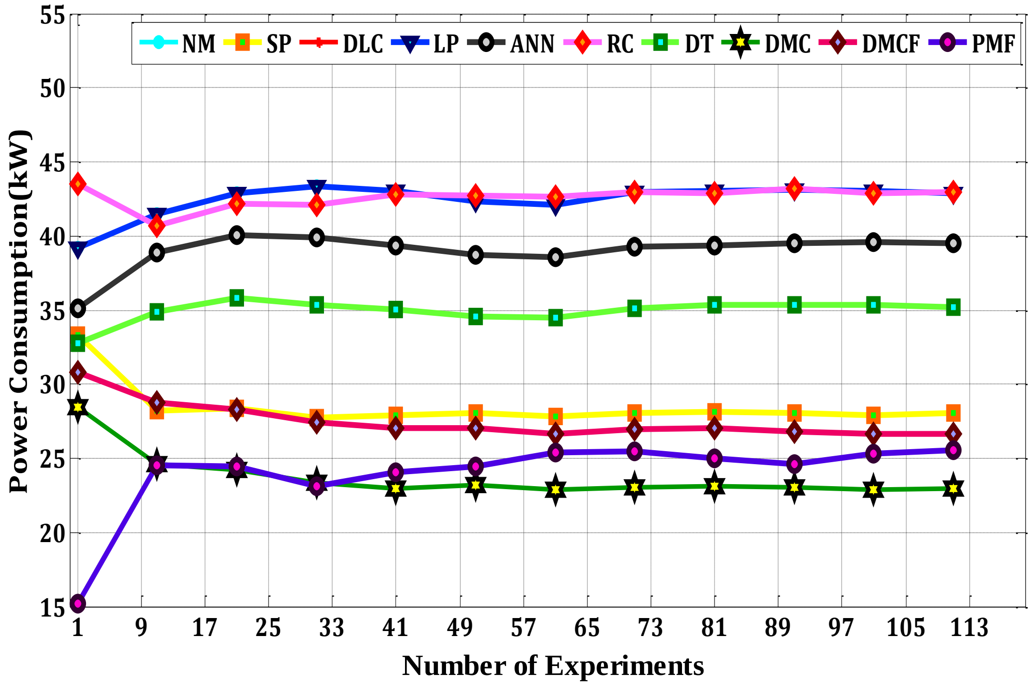
Repetitions: 120 per each experiment.

Below are presented some charts that show the results obtained for each response variable according to the design of experiments. The response variables define the performance of each management criteria to several type and number of equipments to manage. To perform a statistical analysis was used three types of graphic techniques, these are: cumulative average, box plots and multiple comparison test. However, in some cases the confidence intervals overlap hence any difference can conclude with given confidence level. In this case is requires an analysis of variance (ANOVA) in order to establish if the means have significant difference. After of the analysis of variance it is necessary implement a test that allow to identify which means are different and furthermore carry out a comparison between a means group. In this proposal was used multiple comparison test named Tukey-Kramer to identify the means significantly different. In this design was not considered the method proposed by Fisher or least significant difference (LSD) because when a large number of means to compare this method can reject the null hypothesis ($H_0: \mu_1 = \mu_2$) even when no significant differences.

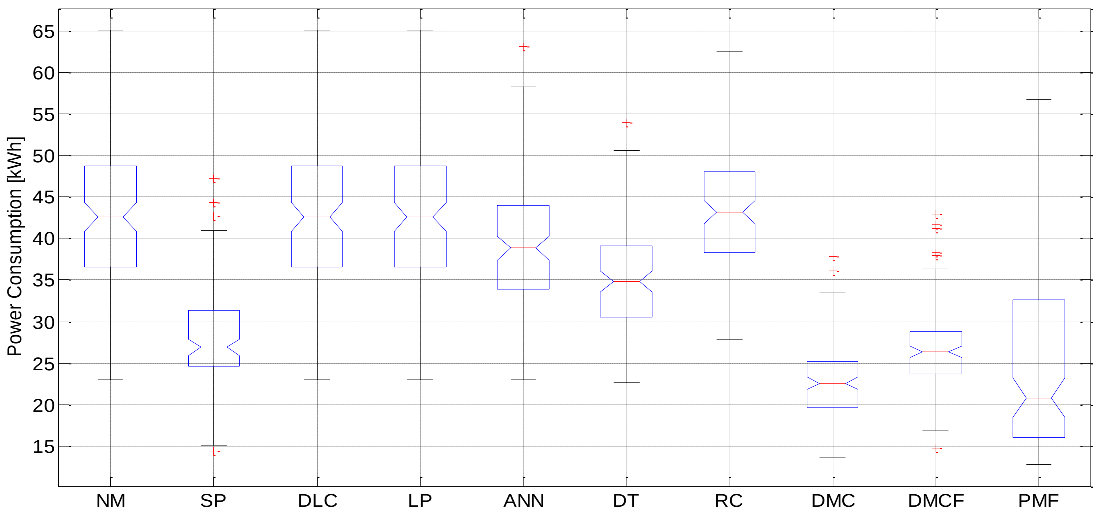
### 6.1.1. Power consumption

Dynamic manager (based on consumption, based on comfort and based on priority list) and other management criteria (LP, DLC, DT, SP, ANN) of electric energy demand presented a reduction of power consumption. This variable brings information about the scope in terms of power consumption savings for each management criteria tested.

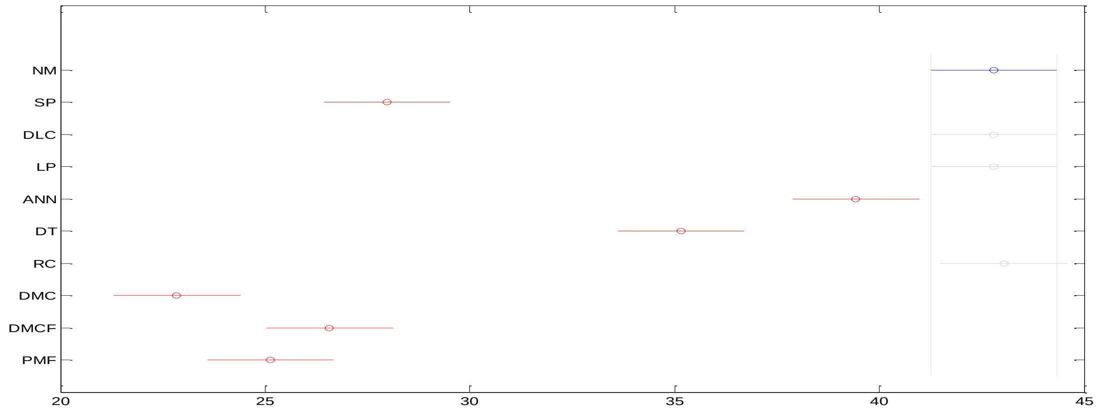
- **With one equipment**



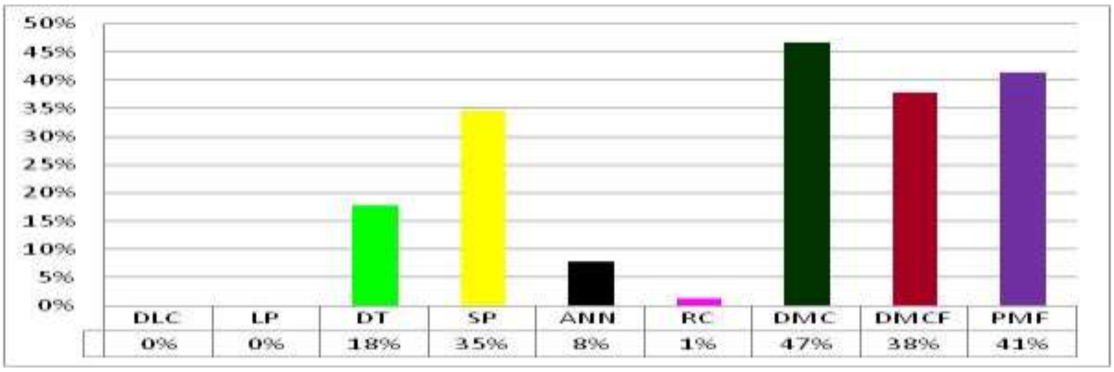

6.1-2 Cumulative average for *PS* with one equipment (PC).




6.1-3 Box plot for *PS* experiments with one equipment (PC)



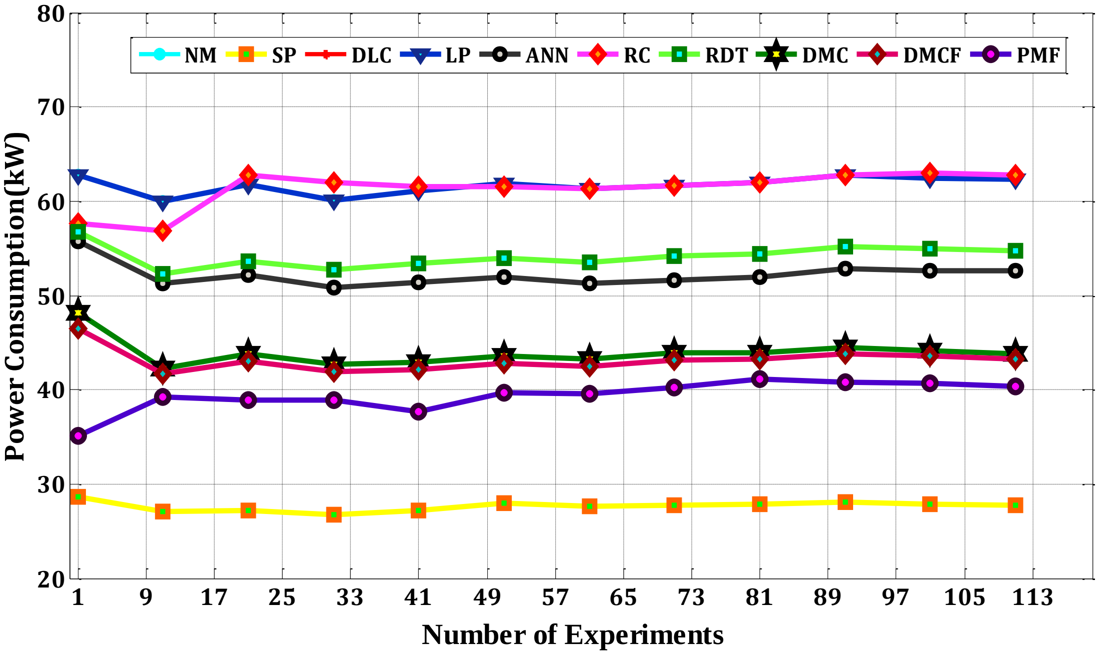
6.1-4 Multiple comparison test for *PS* experiments with one equipment (PC)



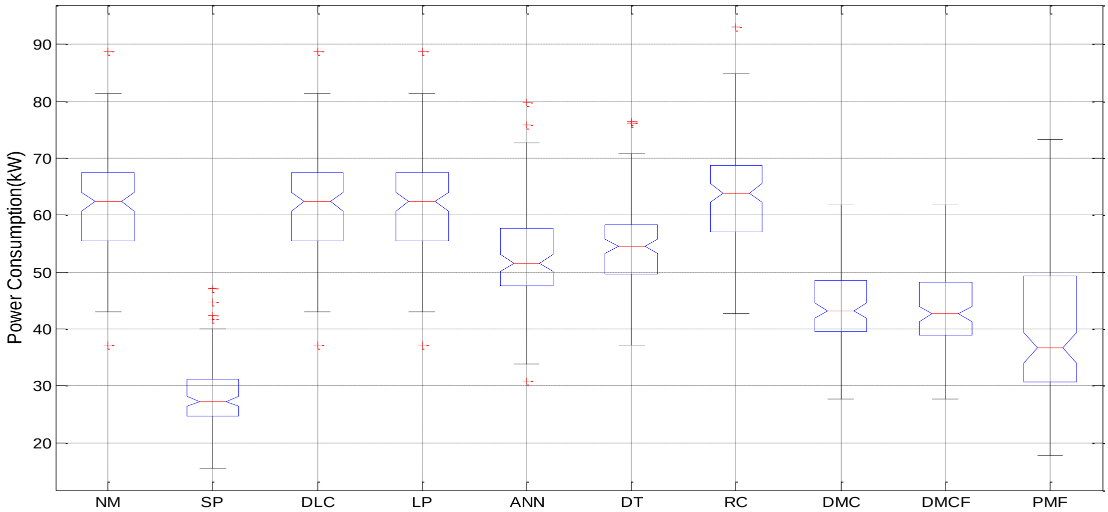
6.1-5 Power consumption savings ranking with one equipment (PC)

Fig. 6.1-2 and 6.1-5 show that the *DM* has the less power consumption in comparison that other criterion when the equipment to manage is the computer.

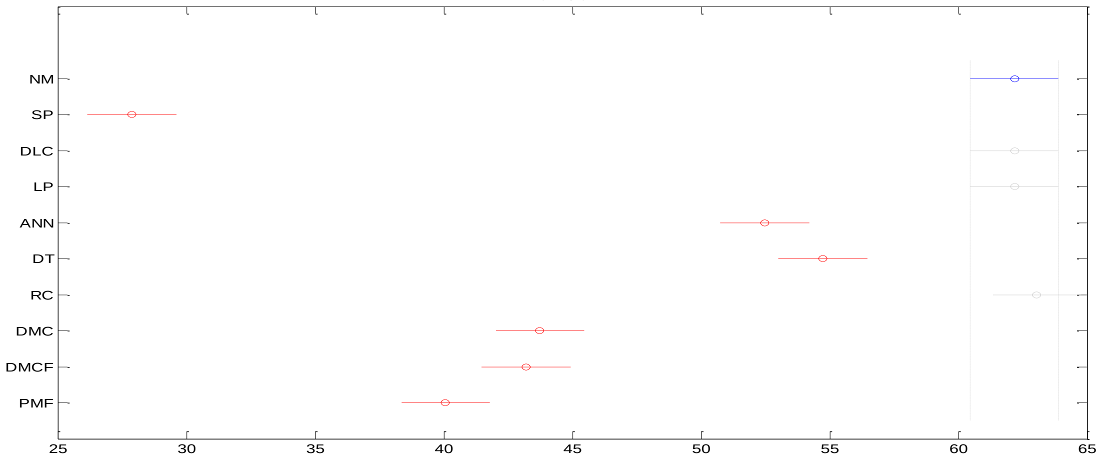
- **With two equipments**



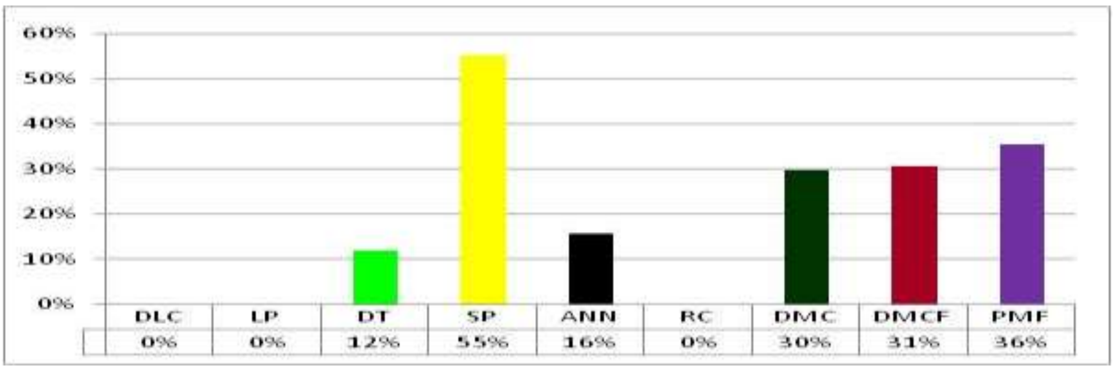
6.1-6 Cumulative average for *PS* with two equipments (computer and television)



6.1-7 Box plot for *PS* experiments with two equipments (computer and television)

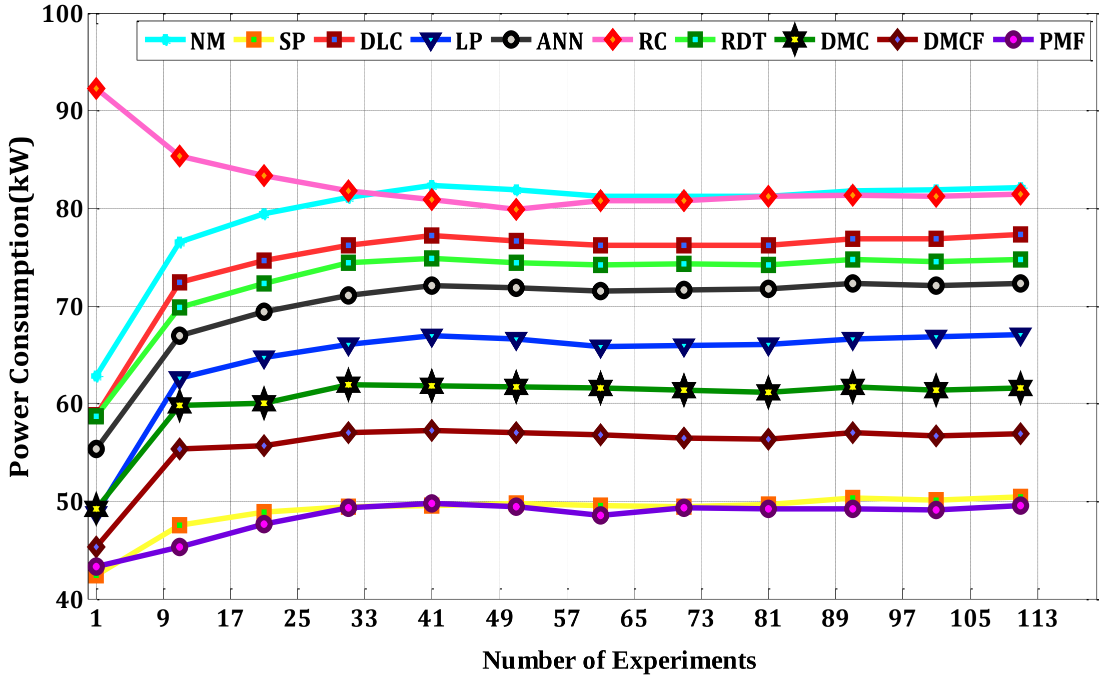


6.1-8 Multiple comparison test for *PS* experiments with two equipments (computer and television)

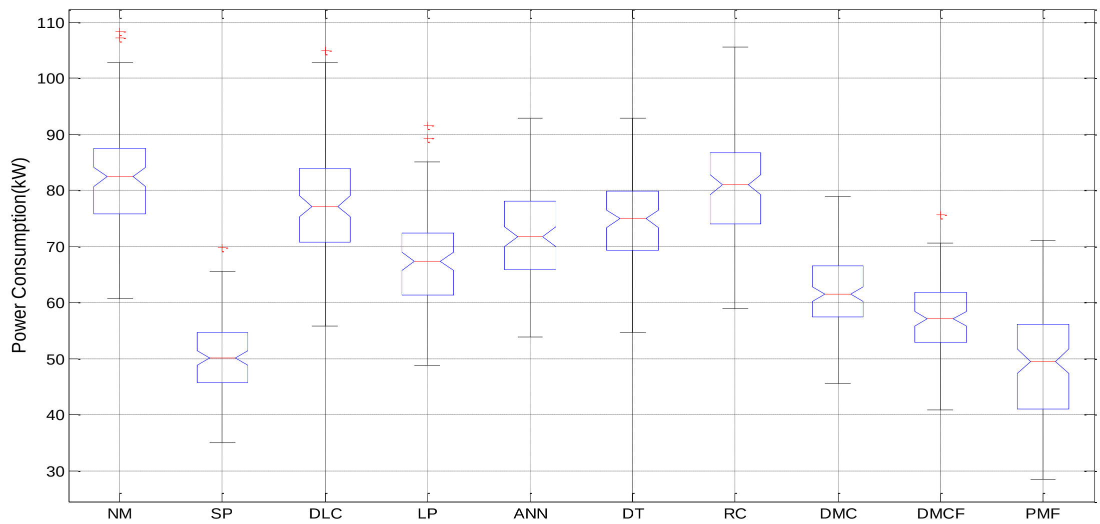


6.1-9 *PS* ranking with two equipments (computer and television)

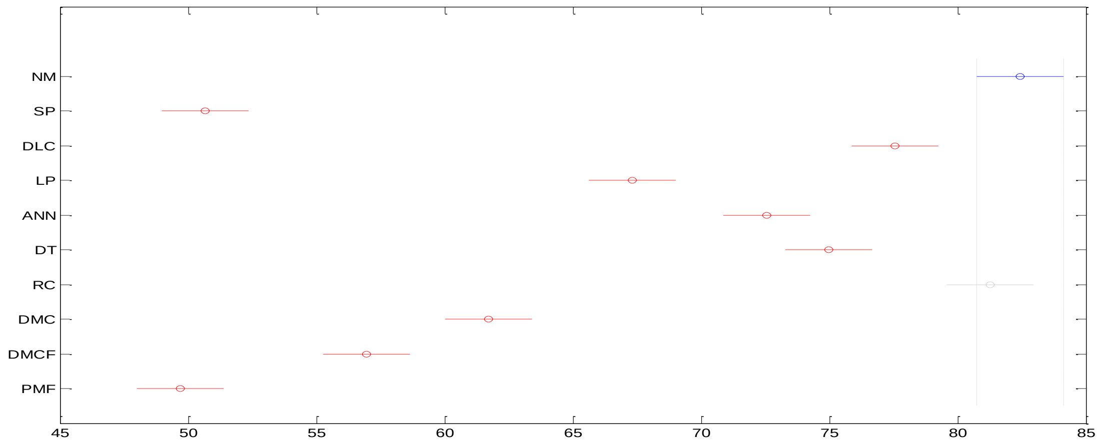
- <u>**With three equipments (computers, televisions, air conditioners)**</u>



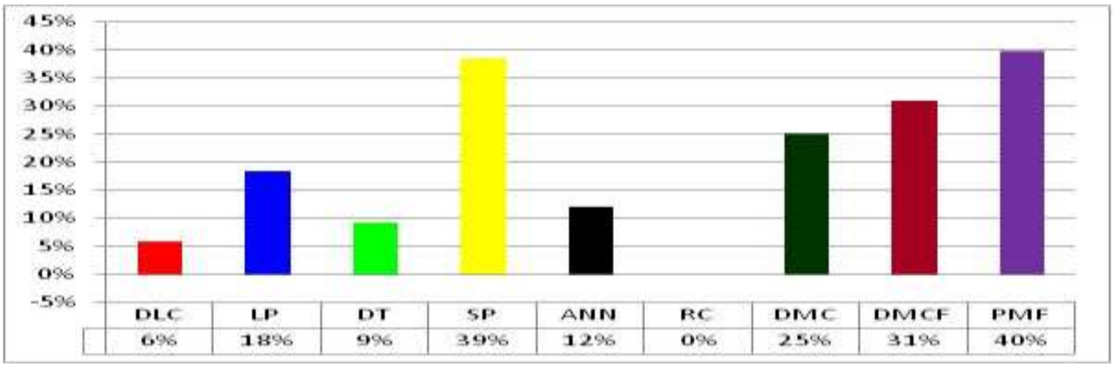

6.1-10 Cumulative average for *PS* with three equipments (computer, television and air conditioning)




6.1-11 Box plot for *PS* experiments with three equipments (computer, television and air conditioning)

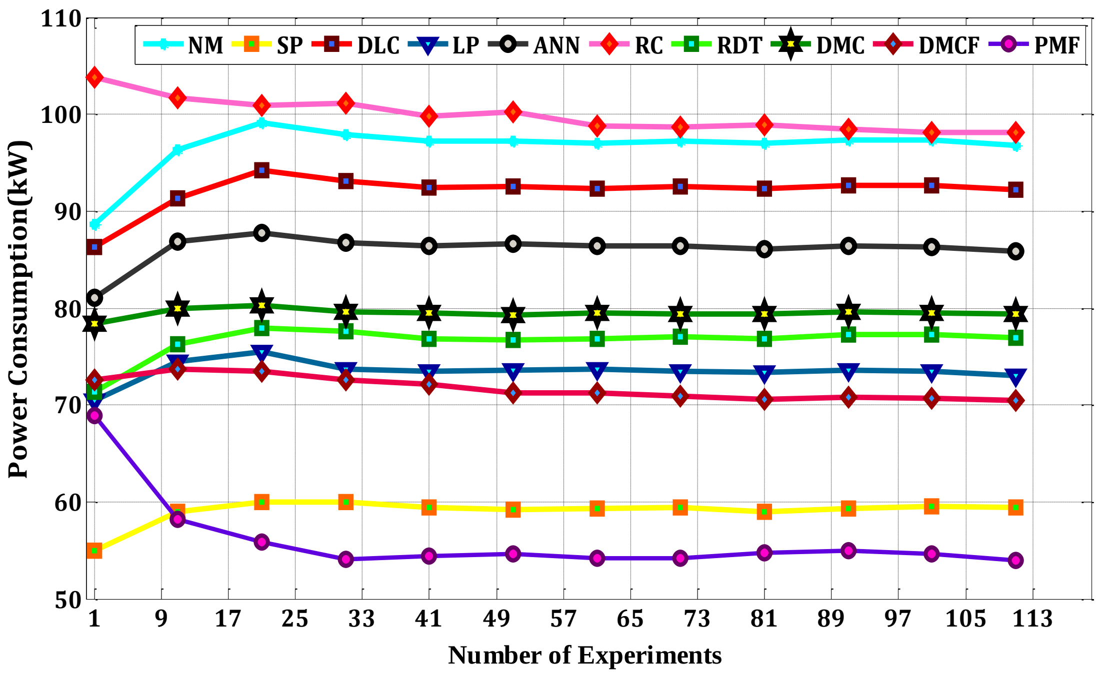



6.1-12 Multiple comparison test for *PS* experiments with three equipments (computer, television and air conditioning)

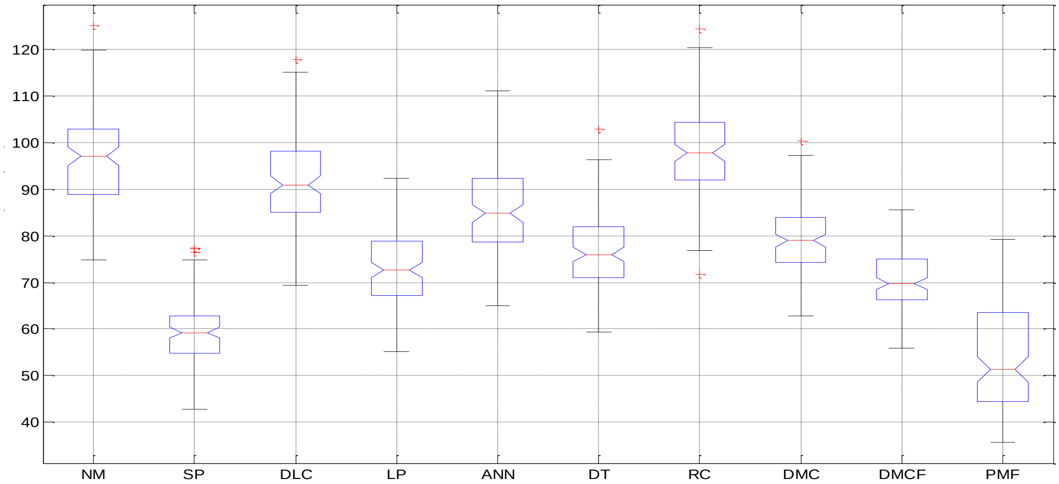



6.1-13 *PS* ranking with three equipments (computer, television and air conditioning)

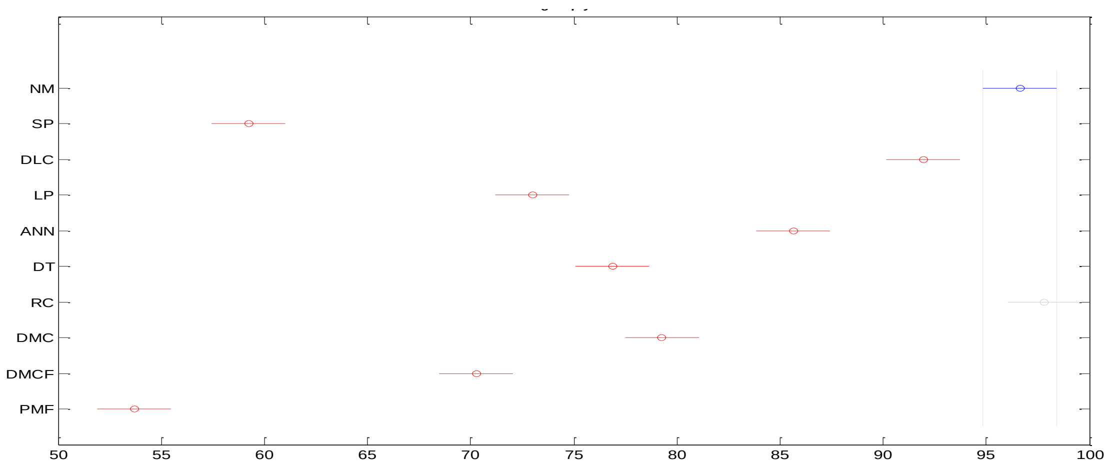
- **With four equipments (computers, televisions, air conditioner and luminaries).**



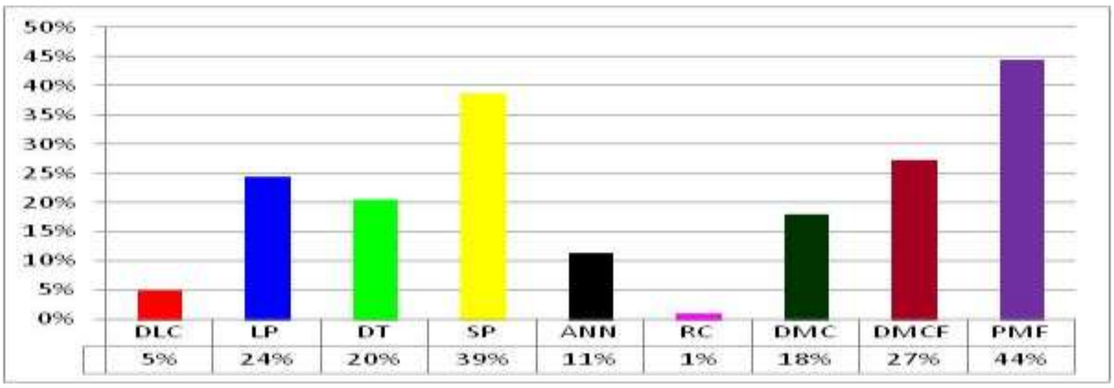

6.1-14 Cumulative average for *PS* with four equipments (computer, television, air conditioning and luminaries)



6.1-15 Box plot for *PS* experiments with four equipments (PC, TV, AC and luminaries)



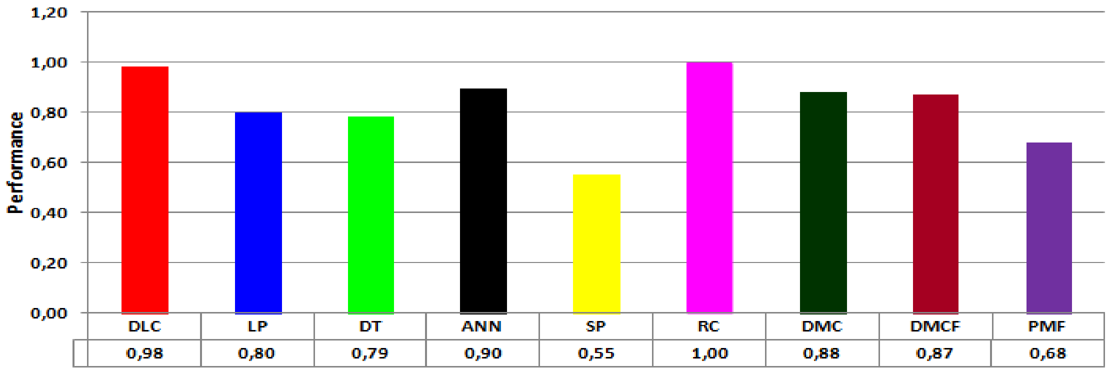
6.1-16 Multiple comparison test for *PS* experiments with four equipments (computer, television, air conditioning and luminaries)



6.1-17 Power consumption savings ranking with four equipments (computer, television, air conditioning and luminaries)

### 6.1.2. Time no off

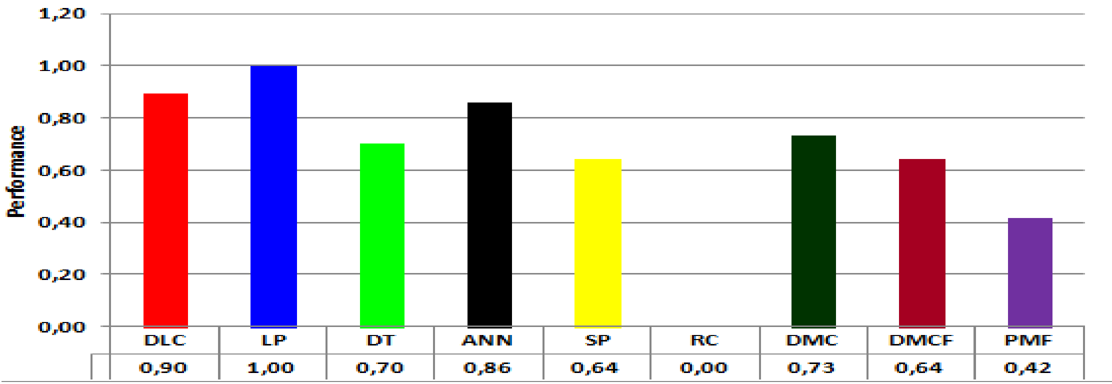
The addition of this variable allows to establish and asses the criteria with greater availability of operation for the equipments in general. In this item it is notable the performance of some criteria as DLC, ANN, DMC and DMCF. Fig. 6.1-18 shows that scheduled programming presents a low level of productivity.




6.1-18 Time no off ranking

### 6.1.3. Equipments states invariability

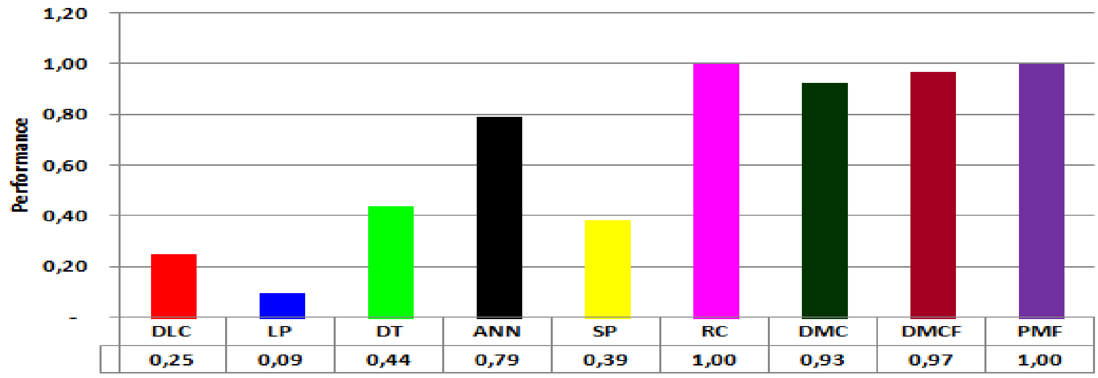
The lifetime of equipments can vary according to the rate of change (On-Off). LP, DLC and ANN present a less rate change than the other criterion; likewise PMF and DMCF show a balance in this case (see Fig. 6.1-19).




6.1-19 Equipments states invariability ranking

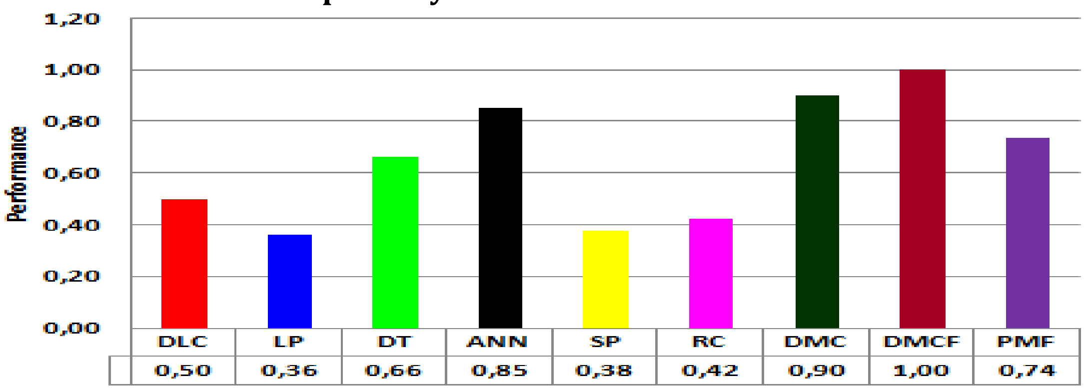
### 6.1.4. Equipment management regularity

This aspect it is very important because indicates that availability of management during all analysis day. Fig 6.1-20 shows a behavior top for the case of the DMC, DMCF, PMF and RC; however in latter case (RC) this management is not always suitable.



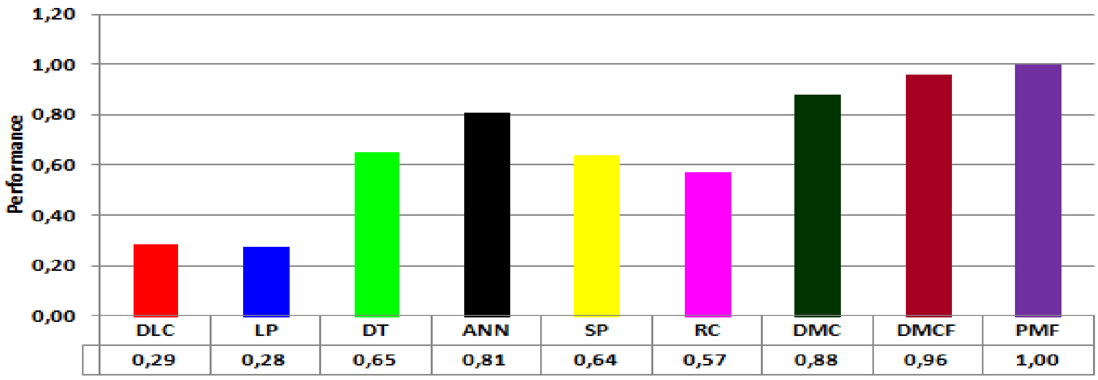

6.1-20 Equipment management regularity ranking

### 6.1.5. Environment adaptability




6.1-21 Environment adaptability ranking

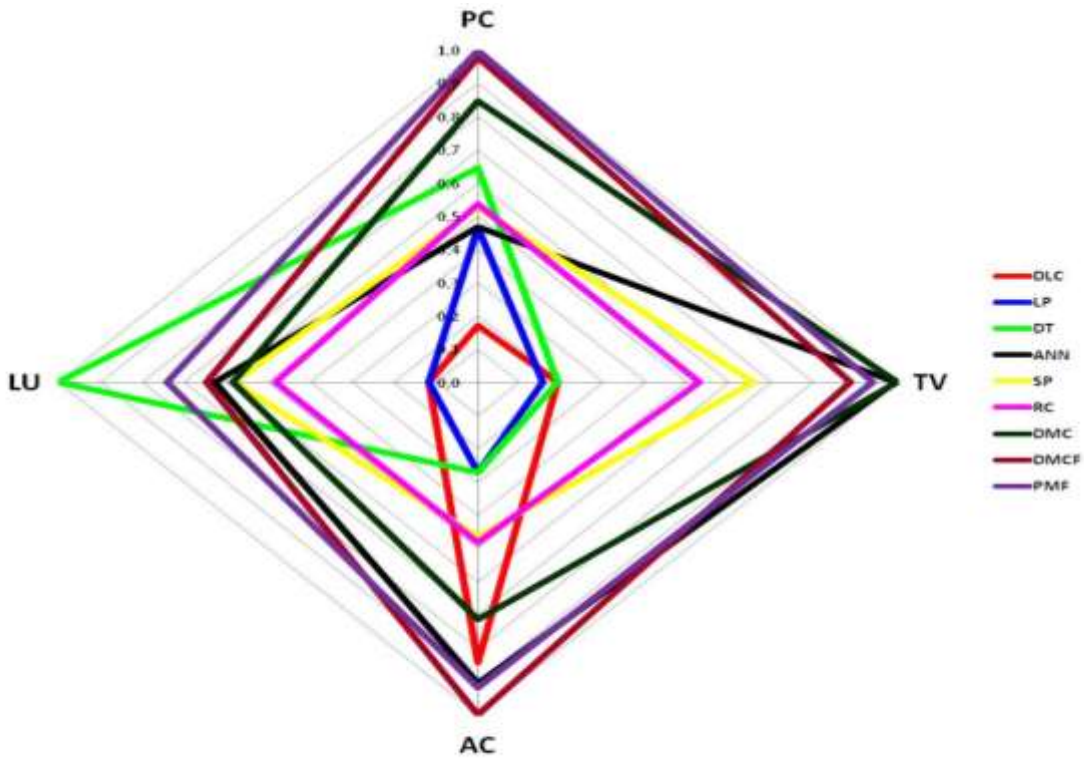
### 6.1.6. User adjusted suitability




6.1-22 User adjusted suitability ranking

Fig. 6.1-22 shows an analysis for each criterion where it is indicates the more suitable for each one of equipments within of the environment. In this case PMF presents a suitable behavior for the four equipments, while DMC and DMCF are good for the case of televisions, air conditioner and computer.

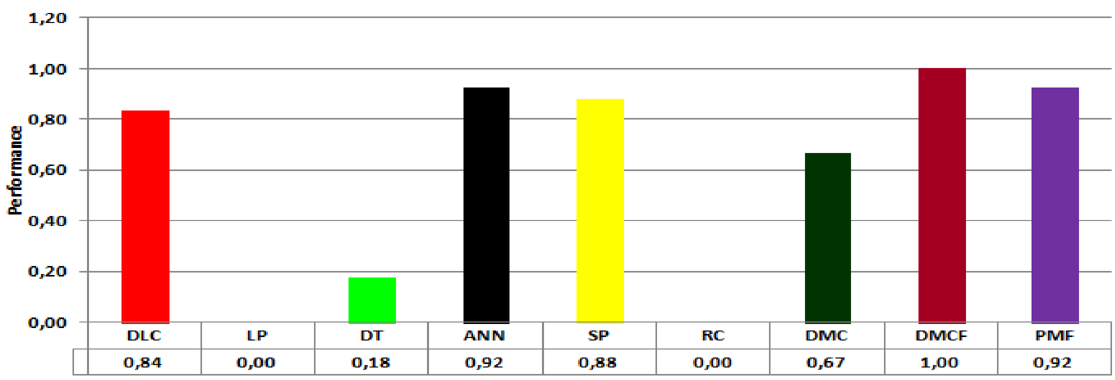
Fig. 6.1-23 shows a suitability evaluation taking into account the performance shown by each criterion during the management carried out to the equipments.




6.1-23 User adjusted suitability evaluation

### 6.1.7. Uniformity to diversity equipment

DMC and ANN presented a uniformity level more stable that other criteria, while LP and PMF are correlated directly with the equipments type to manage.




6.1-24 Uniformity to diversity equipment ranking

### 6.1.8. Energy Audit

Fig. 6.1-25 shows the results of experiments design for the energy audit process. In this case was varied the model and characteristics of each equipment to evaluate the response of audit process in terms of power consumption.

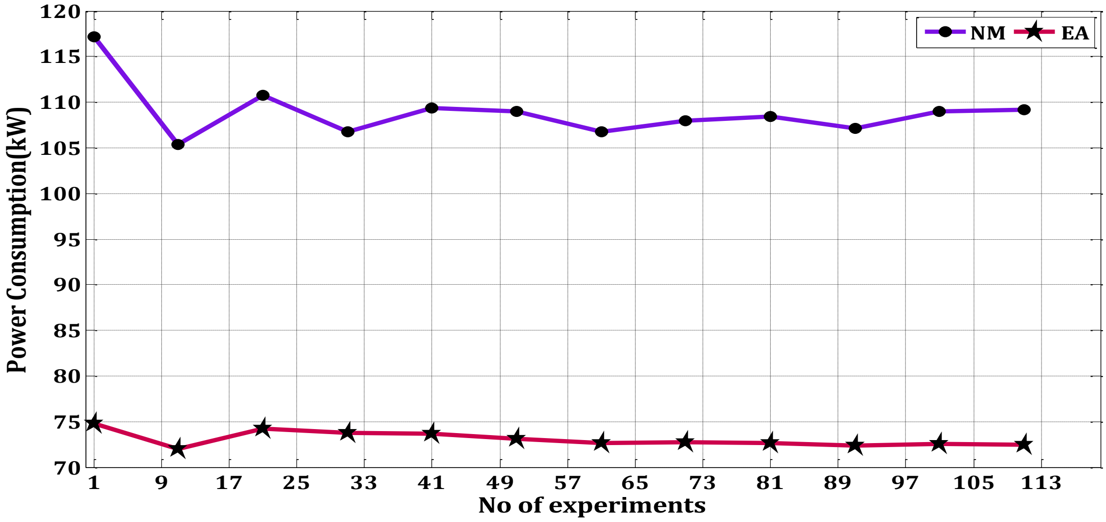



Fig. 6.1-25 Cumulative average for *PS* applying energy audit with four equipments (computer, television, air conditioning and luminaries)

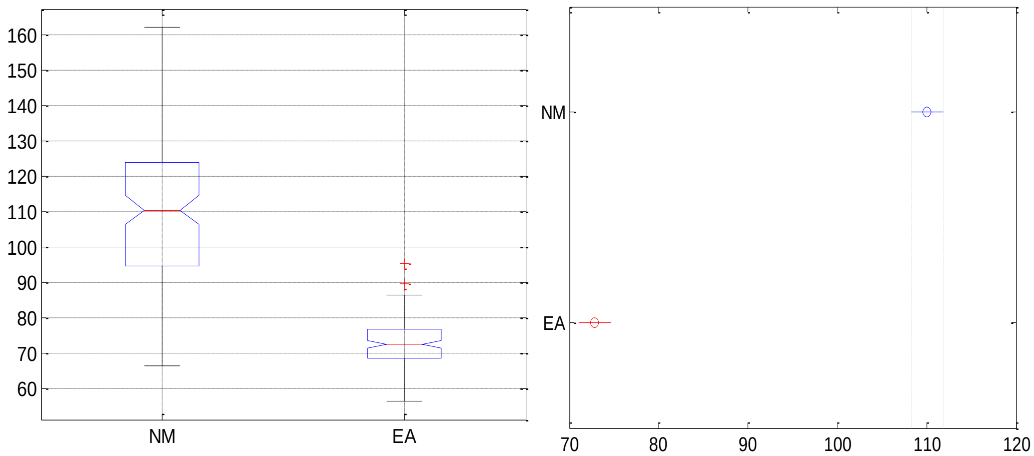



Fig. 6.1-26 (*left)*Box plot for power consumption savings experiments (energy audit) and *(right)* multiple comparison test for power consumption savings experiments (energy audit)

## 6.2. Analysis of Results

Direct load control and load priority only were configured to manage some type of equipments, according to this, they are not able to provide power savings in all cases (see Fig. 6.1-2 and Fig. 6.1-6).

In *Scheduled programming* the customer interaction during the management is poor, due to the control program based on an on/off preset. This depends on the programming of on/off and also does not allow management during the time in which tasks are executed within the building. The results show a limited management actions planned without consideration of changes in user behavior.

This criterion is not suitable in buildings that operate 24 hours a day. In this case of study it was programmed a time off of 10 hours.

Differential tariff presented similar behavior during the management of three equipments, however, its improved performance when luminaries were incorporated within the equipments to manage. Likewise, this criterion was integrated to two inference engine for the case of luminaries and computer; hence, it is notable that presents more power savings when these types of equipments are incorporates.

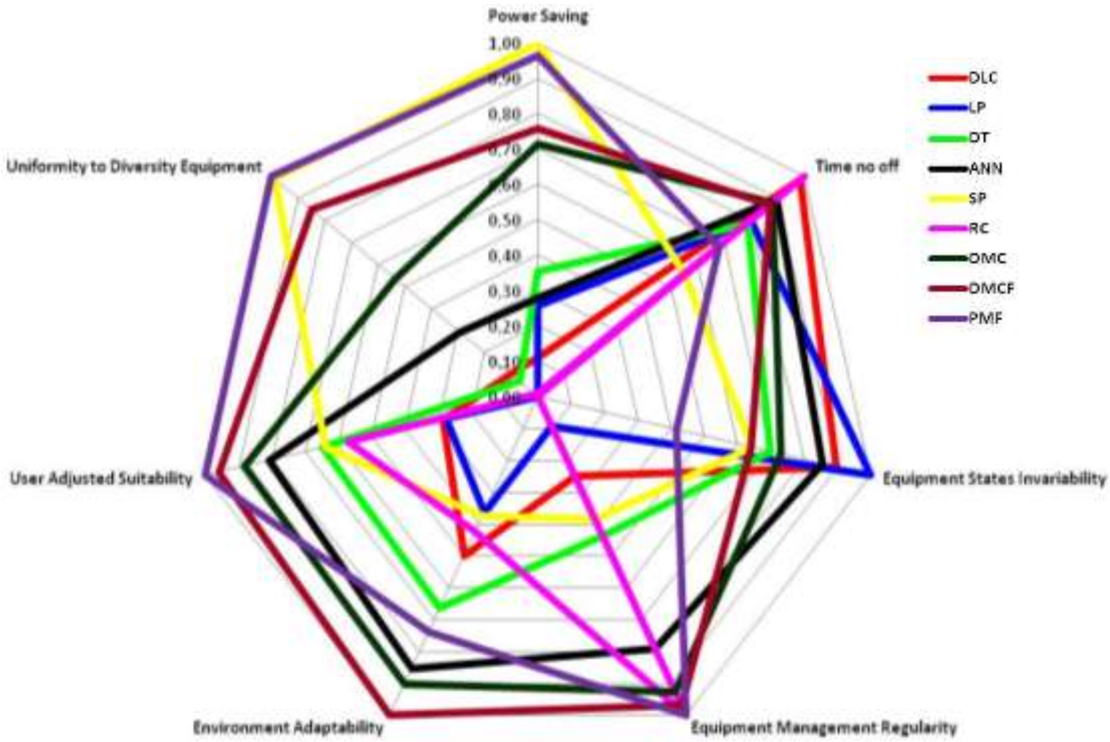
Management criteria of electric energy demand using neural networks allows maintaining a performance close to 10% savings of electricity even when the type of equipment varies. The suitable performance of this method is due to the model of efficient policies shown in Section 2.1 and Section 5.3.5.

The dynamic manager based on priority list only considerate the customer criteria to evaluated selection of each one of criteria (SP, DLC, ANN, LP and DT). The results for this criterion showed a major power saving in comparison the other criteria when the type of equipments to manage was higher than three. However, it is important considerate that selection criterion depends on a threshold of power savings too, which allows selecting the other criteria in the priority list. It is clear then that this criterion has in some cases a correlation with the criterion with higher power saving, as shown in Fig. 6.1-2.

Dynamic manager based on consumption presents higher power savings that some criteria as DLC, LP and ANN when the type of equipments to manage in less than three. This criterion is based on adjustment of power consumption curve proposed by dynamic manager. In this case, the selection of each of the criteria depends on the degree of similarity in consumption compared to that proposed by the intelligent system. The performance of this criterion was suitable and stable for all of cases of study reaching an average of 20 kW of power savings.

In dynamic manager based on comfort was achieved greater power saving in comparison the other intelligent approach (Dynamic manager based on consumption, ANN, DT and DLC). This approach seeks selecting the criterion with higher degree of similarity in functional states proposed by intelligent system, in order to guarantee customers comfort.

Finally, random criterion does have significance difference with non management in terms of power consumption savings due to shortcomings in the selection criterion.




6.2-1 Radar chart to evaluate the management criteria of energy electric demand with the response variables.

Fig. 6.2-1 allows analyzing the performance of each one criterion considerate in this proposal. This graph allows easy identification and assessment of each criterion according to the scopes and constraints presented.

# Chapter 7

# Conclusions and Future Works

*This chapter summarizes the main conclusions arisen of the analysis and discussion of the results reported in this work. The chapter also reviews the dissertation's scientific contributions and then discusses promising directions for future research and applications in certain topics in which the work of this thesis can continue. Finally, some concluding remarks are drawn.*

## 7.1. Conclusions

The results and analysis carried out during this proposal has allowed highlighting the characteristics of each criterion taking into account the response variables discussed in section 6.1. However, the main goal in this proposal is reaching power consumption savings with impact customer comfort; hence it is necessary consider the performance of all proposed approach. According to the concept of energy efficiency presented in Section 2.1., this proposal is suitable because allows reaching power saving levels without impact the comfort of user (e.g., temperature and illuminance) such as showed in Fig. 5.4-2. Likewise, the energy audit process is a good complement for the selection of each criterion because it allows reaching power savings near to 33%.

*DLC* incorporates qualitative and subjective assessment of comfort, allowing greater user interaction with the system, unlike the management approach based on schedule. This criterion has a control action in the load with higher contribution at the consumption, which for the case study, corresponded to the air conditioning.

The results obtained through the criterion based on a *priority list* have an acceptable behavior during the peak hours of consumption, allowing mitigates excessive consumption during those moments of the demand curve. This type of criterion is similar in some aspects to the scheduled programming criteria due to turn off the equipments that it is not considers as priority during peak hours, i.e. that the management is performed considering only the on and off states.

Management criteria of electric energy demand using neural networks respond according to the conditions object studio environment. The profile of computer use becomes powerful variable to provide adequate savings, since it enables the state of the device without affecting the user's work. The data base of training for this criterion was obtained applying considerations of efficient operation of equipments as shown in section 2.1.

Dynamic manager based on priority allows reaching power saving and uniformity level similar to the scheduled programming but improving some characteristics as environment adaptability, equipment management regularity, user adjusted suitability and time no off.

Dynamic manager based on consumption presents a suitable behavior in comparison to others criteria proposed by state of art; however in comparison to the other two proposals presents a performance less in uniformity, suitability and power saving.

Dynamic manager based on comfort provides opportunities of power savings even without the necessity of shut off completely the equipment in a long period of time. Furthermore, some characteristics relevant for the management as environment adaptability, user adjusted suitability and uniformity to diversity equipment are suitable in comparison to other criteria.

## 7.2 Main Contributions

This thesis presents a computational tool oriented to evaluated strategies for energy efficiency, specifically related to the operation and technologic characteristics of the some equipment as computer, television, luminaries and air conditioner. In this case, the suitability of this management model proposed is evaluated according to response variables presented in section 6.1. Our approach presents a better performance in suitability, productivity, adaptability and regularity in comparison to the conventional non-intelligent management techniques.

This thesis makes the following contributions in energy efficiency problems related to electric energy:

- *An intelligent approach for the dynamic selection of several demand management criteria of electric energy (load priority, direct load control, differential tariff and neural networks) for the power consumption management taking into account energy efficiency polices and customer preferences as selection based on priority, selection based on consumption or selection based on comfort.*
- *To improve the energy efficiency in an environment, it is developed a computational tool that integrates a stage of energy audit (diagnosis) and demand management of electric energy using fuzzy logic, neural networks and genetic algorithms.*

## 7.3 Future Research and Directions

The development of strategies focused on minimizing the power consumption within of an environment considering the customer comfort represent an aspect interesting towards to the integration with a smart grid. The application of efficiency policies requires a methodology capable of identifying and managing several loads connected to the power grid. Opportunities related to replace of those equipments with inefficient operation were evaluated through of the energy audit process. Furthermore the integration of several demand management criteria for electric energy provides suitable results in terms of power consumption savings and comfort. In this thesis all the above considerations were taking into account; however some aspects even can be improvement, hence below they are present some topics to review for future works.

- Developing others decision algorithms based on some criteria as reliability, costs and availability.

- Incorporating new topics of evaluation within of energy audit focused on identify bad habits of power consumption, failed in isolation and bad distribution of equipments e.g., luminaries.
- Testing the proposed algorithms using real-time data from the sensors (exogenous variables, e.g., temperature, illuminance, presence).
- Implement the proposed management model for energy efficiency with several types of equipments.
- Extrapolate this approach to multiple environments.

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