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A Hybrid Algorithm Based on Computational Intelligence Methods for Adaptive House Energy Management System

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Abstract — **The increase in electricity consumption and future demand is a major issue of power companies around the world, and energy management is one of the best solutions to the outage of this problem. This paper proposed a two-stage energy management system for domestic house applications. The first step is a long-term plan, which is related to reducing energy consumption by effectively replacing equipment. In this way, a two-objective function optimization model is defined which benefits from an economic efficiency index. Also, a game theory model is utilized to consider the investor's idea which appears as a flexible coefficient to tune allotment capital of different appliances categories. The second step is the short term one, being linked to optimal and adaptive scheduling of appliances and is defined as a multi-objective function model with some fuzzy coefficient and owner comfort factors. This tool is essential for enabling customers to respond to real-time electricity prices and indicates various potentials for reducing energy consumption. Also, the paper's findings can assist power companies in reducing household electricity consumption, especially peak shaving. In long term and short term parts, separate specific scenarios are simulated which reflect 45.56% and 60.96% of energy consumption reduction, respectively.**

Index Terms — **Energy Management System (EMS); smart grid; power consumption; home appliance; multi objective optimization**

I. Introduction

NOWDAYS, power companies all over the world are facing many problems, such as severe power loss, increased power demand, lack of fuel and energy, and environmental pollutants [1]. The increase in demand for electrical energy has caused serious problems for power companies. According to reports from the US Department of Energy over the past 20 years, electricity demand and consumption have continued to grow by 2.5% every year [2]. The increase in power demand has led to serious grid congestion problems, and several major power outages occurred in recent years [3]. Apparently, these problems cannot be solved by the existing power grid [1].

To solve these problems, a new concept of the next electric power system has emerged, known to many as the smart grid. The smart grid is a modern electric power grid infrastructure for improved efficiency, reliability, and safety, with the smooth integration of renewable and alternative energy sources, through automated control and modern communication technologies [2, 4-6]. The smart grid consist of several components and measurement sensors, which are used to measure more real-time grid parameters, and will be sent to the control center in the next few years [7]. Most of these data can be displayed and sent through a communications media to plan and reposition the equipment. Customers can instantly match their energy intake with price information received, leading to anticipated improvements in power system control and operation [8,9].

A typical daily demand curve is divided into two or three parts: peak and off-peak prices; or peak demand, normal demand, and low demand prices. As a result, since peak demand only occurs within a small part of the day, the system is inherently non-optimal. In addition, an unusually heavy demand on the distribution grid can be a disastrous quiescence. Demand response is defined as the changes in the normal electrical energy consumed by the consumers in response to the changes in the electricity price over a period of time, or the incentive payments, to reduce energy consumption in the high price hours or in the high risks of system reliability [10, 11]. Therefore, demand response is divided into two types: price base and incentive base categories [10]. Demand response program's goals will be fully achieved when consumers respond to the sent prices. For this, there are two obstacles. The first one needs some proper structure for transmitting information from the upper layer to the consumer, while the other needs some proper mechanism for the consumer to respond to the received price message. The first problem can be solved by using advanced metering infrastructure (AMI), meanwhile, the main obstacle in the way of full implementation of demand response programs is the fact that many customers have not sufficient time to meet manually price responses or do not know its method [10]. The proposed solution is an automatic household load planning, in a way that consumer interests are considered. This subject is considered in some parts of the proposed method.

In the recent years, some auteurs, or individual creators with a distinctive style and vision, have studied the demand response issue in the power grid and especially the smart grid [12-16]. In the residential sector; however, power scheduling schemes have become the subject of many studies [17-19]. Amongst the issues that have been raised recently in the demand management issues, comfort level managed to attract the attentions of auteurs [16]. In demand response, appliances exhibit varying behaviors; some are elastic and adjust consumption in response to price changes, while others maintain a constant consumption level. Appliances are classified, into shiftable and non-shiftable categories [20]. Also, from the perspective of appliances' operational characteristics, The appliances are classified into interruptible and non-interruptible appliances [16].

Also, some auteurs focused on smart home energy management. A smart home energy management solution, proposed in [21], considers a detailed set of attributes related to energy management within a smart home. These attributes are then linked to each other by meaningful and useful relationships. In line with this, a fuzzy logic based smart home energy management is proposed in [22]. It classifies appliances based on their energy consumption patterns. In this respect, a fuzzy logic is then proposed to operate different classes of appliances. A bat algorithm (BA) based solution with exponential inertia weight is proposed to save energy in a smart home without deteriorating the user comfort [23]. Temperature, illumination, and indoor air quality are considered to account for user comfort.

The demand side management (DSM) programs are used in order to maintain the flexibility of the system by changing the consumption patterns of customers as well as controlling the loads of the main network [56]. They focused on the optimal planning of residential loads using the Binary Particle Swarm Optimization (BPSO) algorithm, and their aim is to minimize the monthly electricity cost of a typical household.

A study proposed an optimal charging and discharging schedule for a hybrid photovoltaic-battery system connected in the premises of a residential customer [57]. The scheduling strategy is formulated to minimize the electricity bill of the customer.

A smart energy community management approach which is capable of implementing P2P trading and managing household energy storage systems was presented in [58]. The proposed energy trading process was modeled as a Markov Decision Process (MDP). In addition, the fuzzy inference system makes it possible to use Q-learning in continuous state-space problems (Fuzzy Q-learning) considering the infinite possibilities in the energy trading process. They evaluate power consumption before and after using the proposed energy management system.

Looking at the research done on this subject, it seems that some auteurs used different techniques to help households to create a schedule for electricity consumption, mostly based on various tariffs and pricing schemes. An optimization strategy was proposed to use the performance of household appliances to minimize electricity costs [67]. In [68] optimal home appliance planning is provided due to the presence of electric vehicle and battery storage based on various tariffs. One study arranged a mixed-integer nonlinear programming model to save energy consumption [69]. A rule-based algorithm is proposed for home energy management to schedule home appliances [70].

In this paper, an innovative approach for domestic power consumption management has been introduced, which the logic comfort and social behavior of households is considered to reach a credible tool. In this paper, the electricity consumption management problem is discussed in two-time stages. One stage is related to a short-term plan (for example, daily), and the other stage is related to a long-term plan (for example, every year). Therefore, the proposed tool has two main parts: short term and long term management. In the long-term management, different viewpoints have been adopted on the issue of household energy management. Basically, energy management issues will not end by leaving or moving loads to reduce energy consumption. This part attempts to reduce power consumption by formulating long-term policies and effectively investing in household appliances optimization. In this stage, we are investigating the issue of high-efficiency appliances replacement that aims to reduce power consumption and reduce household costs. To this end, a mathematical model is proposed, which involves the family's social behavior, investment parameters and power consumption reduction issues. The customer's personal interest in investing in specific devices and the limited financial resources and the cost of repairs are facts that have complicated the issue. The subject is then developed using a collaborative game model, and finally use a two-step algorithm to optimize the obtained multi-objective function. The next major part of this paper relates to short-term planning, which is an innovative adaptive tool for reducing power consumption. Social behavior, lifestyle, home comfort, grid restrictions and appliance operation constraints are topics that should be considered, which led us to establish a multi-objective function model. In this process, different intelligent computational methods are used to optimization.

The rest of this paper is structured as follows. Section 2 contains an overview of the proposed energy management model. In addition, the long-term and short-term energy management system and the formulation of the problem are explained in detail. Case studies and simulation results are provided in Section 3, while Section 4 draws conclusions and makes recommendations for future work.

II. Household Energy Management System modeling

The overview of the proposed method is illustrated in Fig.1. The proposed energy management system has two main parts: long term and short term energy management systems. In the long term part, a game theory model is utilized to consider the investor's idea to tune allotment capital of different appliances categories. The result of implementing this idea is to obtain a two-objective function with definite constraints. Finally, in order to solve the problem, a two-step optimizer tool is proposed to obtain the best and economic annual investment options. The proposed method can provide the best possible investment points for the replacement of appliances. The second part is related to the short term program, which is modeled as a multi-objective function problem as well, and solved by the PSO algorithm. Some FISs and an owner comfort factor make two coefficients to tune the mentioned objective function, also desired data for this section can be collected from the home, the environment and the grid. This part of the proposed energy management system can find the best working time for any appliances that aims to achieve peak shaving and reduce household electricity costs. According to the description provided, the proposed energy management system in both short term and long term programs should be able to reduce electricity costs and keep household welfare as well. So, a household utility function is described as follows:

$$U = u(E_c, E_a, H_w) \tag{1}$$

Where U is households' utility function, E_c is electricity consumption cost, E_a is high efficiency appliances and H_w is household welfare. In order to reduce the cost of electricity, it is necessary to use appliances at low price times, while the other uses high-efficiency appliances. In addition, to maintain family welfare, home appliances need to be used at a more suitable time.

A. Long term energy management system

Long term household energy management system is the first part of the proposed method. This method can reduce household electricity consumption by determining the best choice among appliances to be replaced by its high-efficiency type. To achieve this goal, four main steps are provided. The first step is to define a mathematical model to identify those appliances that have higher economic efficiency due to replacement. For this purpose, an economic index is defined to estimate the efficiency resulting from replacing higher efficiency appliance instead of its old type. In the second step, to consider the owner's idea about investment in specific appliances category, a game theory model is employed. For this purpose, cooperative games with transferable utility are used to form coalition of these appliances to increase the possibility of selecting these items in the long-term program. Also, in this way owner may determine a maximum investment for next years. In the third step, according to the relations and models mentioned in the last two steps, a multi-objective function model is defined, which is solved by the non-dominated sorting genetic algorithm (NSGA)-II algorithm. The last step relates to the determination of the equipment that must be replaced in each year. The task was optimally done by using the particle swarm optimization algorithm (PSO) algorithm.

1) Low and high efficiency appliances modeling

Since the efficiency of appliances is proportional to their power consumption, so the calculation of the electricity consumption of appliance i in a specific time following equation is proposed:

$$W_{i,j}^k = P_i \times X_{i,j}^k \times \frac{t}{3600} \qquad \forall (i \in A_B \subseteq A, j \in T, k \in M) \tag{2}$$

Where P_i is power consumption of appliance i and $W_{i,j}^k$ is energy consumption of appliance i at time slot j in day k. Also, $X_{i,j}^k$ is binary matrix indicating the operation status of task for appliance i at time j, and t is duration of appliance operation index in time units (s or second). If A denote to home appliances set, then A_B is set of appliances for long term energy management program. Also, T is set of time slots in which time varying electricity prices, and M is set of all days in a month. Note that, since the appliance may be in circuit less than one complete slot, then above-mentioned relation gives electricity consumption of appliance i in a part of slot j. To calculate the electricity consumption of equipment during a day, the following equation is presented:

$$W_{i,k} = \sum_{j=1}^{m} W_{i,j}^k = \sum_{j=1}^{m} P_i \times X_{i,j}^k \times \frac{t}{3600} \qquad \forall (i \in A_B, j \in T, k \in M) \tag{3}$$

Where is $W_{i,k}$, energy consumption of appliance i in day k. In a similar way, to calculate the electricity consumption of appliance during a month, the following equation is prepared:

$$W_{i,l} = \sum_{k=1}^{30} W_{i,k} = \sum_{k=1}^{30} \sum_{j=1}^{m} P_i \times X_{i,j}^{k} \times \frac{t}{3600} \quad \forall (i \in A_B, j \in T, k \in M, l \in Y) \tag{4}$$

Where is $W_{i,l}$ energy consumption of appliance i in month l. Also, Y is set of all months in a year. According to the above-mentioned equation, to calculate the energy consumption of any appliance in low efficiency case during a month, and just needs to enter the power value of the appliance that has already used.

$$W_{i,l}^{old} = \sum_{k=1}^{30} W_{i,k}^{old} = \sum_{k=1}^{30} \sum_{j=1}^{m} P_i^{old} \times X_{i,j}^{k} \times \frac{t}{3600} \quad \forall (i \in A_B, j \in T, k \in M, l \in Y) \tag{5}$$

Where $W_{i,k}^{old}$, $W_{i,l}^{old}$ are energy consumption of old appliance i in day k and month l, respectively. Also P_i^{old} is power consumption of old appliance i. If low efficient appliance is replaced with the highly efficient type, the monthly energy consumption of new appliance will be calculated through the following equation:

$$W_{i,l}^{new} = \sum_{k=1}^{30} W_{i,k}^{new} = \sum_{k=1}^{30} \sum_{j=1}^{m} P_i^{new} \times X_{i,j}^{k} \times \frac{t}{3600} \quad \forall (i \in A_B, j \in T, k \in M, l \in Y) \tag{6}$$

Where, $W_{i,k}^{new}$, $W_{i,l}^{new}$are energy consumption of high efficiency appliance i in day k and month l, respectively. Also, P_i^{new} is power consumption of high efficiency appliance i. After determining the amount of monthly energy consumption of each appliance in both low and high efficiency cases, their annual consumption is defined as follows:

$$W_i^{old} = \sum_{l=1}^{12} W_{i,l}^{old} = \sum_{l=1}^{12} \sum_{k=1}^{30} \sum_{j=1}^{m} p_i^{old} \times X_{i,j}^{k} \times \frac{t}{3600} \quad \forall (i \in A_B, j \in T, k \in M, l \in Y) \tag{7}$$

Where W_i^{old} is annual energy consumption of low efficiency appliance i. Similarly, if low efficient appliance is replaced with highly efficient type, yearly energy consumption of the new appliance will be calculated through the following equation:

$$W_i^{new} = \sum_{l=1}^{12} W_{i,l}^{new} = \sum_{l=1}^{12} \sum_{K=1}^{30} \sum_{j=1}^{m} P_i^{new} \times X_{i,j}^{k} \times \frac{t}{3600} \quad \forall (i \in A_B, j \in T, k \in M, l \in Y) \tag{8}$$

Where W_i^{new} is annual energy consumption of high efficiency appliance i. The efficiency relation is defined to define an index for the effective energy consumption reduction of any appliance:

$$R_{i,l}^{eco} = \frac{\sum_{k=1}^{30} \sum_{j=1}^{m} \left(W_{i,j}^{k,old} - W_{i,j}^{k,new}\right)\rho_{j,k}^{R.T.P}}{C_i^{buy}} + \frac{\left(C_{i,l}^{old,repair} - C_{i,l}^{new,repair}\right)}{C_i^{buy}} \tag{9}$$

$$R_{i,l}^{eco} = \frac{\left(\sum_{k=1}^{30} \sum_{j=1}^{m} \left(W_{i,j}^{k,old} - W_{i,j}^{k,new}\right)\rho_{j,k}^{R.T.P}\right) + \left(C_{i,l}^{old,repair} - C_{i,l}^{new,repair}\right)}{C_i^{buy}} \tag{10}$$

$$\frac{\left(\left(\sum_{k=1}^{30} \sum_{j=1}^{m} P_i^{old} \times X_{i,j}^{k} \times t - \sum_{k=1}^{30} \sum_{j=1}^{m} P_i^{new} \times X_{i,j}^{k} \times t\ \right)\rho_{j,k}^{R.T.P}\right) + \left(\alpha C_{i,l}^{repair} - \beta C_{i,l}^{repair}\right)}{C_i^{buy}} \tag{11}$$

$$P_i^{difference} = P_i^{old} - P_i^{new} \tag{12}$$

$$R_{i,l}^{eco} = \frac{\left(\left(\sum_{k=1}^{30} \sum_{j=1}^{m} P_i^{difference} \times X_{ij}^{k} \times \frac{t}{3600}\right)\rho_{j,k}^{R.T.P}\right) + C_{i,l}^{repair,difference}}{C_i^{buy}} \quad (13) \tag{13}$$

Where $R_{i,l}^{eco}$ is economic efficiency of appliance i in month l, $\rho_{j,k}^{R.T.P}$ is electricity price for the slot j in day k and C_i^{buy} is cost of buying appliance i. Also $C_{i,l}^{old,repair}$, $C_{i,l}^{new,repair}$ are repair costs for low and high efficiency appliance i in month l, respectively. Note that, $W_{i,j}^{k,old}$ and $W_{i,j}^{k,new}$ can obtain from the equation 2 when old and new appliance power replaces to P_i variable. After some simplification and placement relation, (equation 10), (equation 11) can obtain. Also, if the difference in power consumption of appliance i before and after optimization is defined as $P_{i,}^{difference}$, and difference in repair cost of old and new appliance is defined as $C_{i,l}^{repair,difference}$, then the economic efficient equation can be rewritten as relation (equation 13). To obtain annual efficiency following relation is provided:

$$R_{i,y}^{eco} = \sum_{l=1}^{12} R_{i,l}^{eco} \tag{14}$$

Where $R_{i,y}^{eco}$ is economic efficiency of appliance i in year y. Then average economic efficiency can be obtained from the following equation:

$$R_i^{ave} = \frac{R_{i,y}^{eco}}{12} \tag{15}$$

Where R_i^{ave} is average economic efficiency for appliance i.

2) Effective parameters for investment

The purpose of the long term program is to find an optimal solution for the finance allocation problem considering the limited financial resources. The appliances that are selected should have more values of the economic efficiency index as presented in equation 15. But in addition to economic parameters, there are other parameters which are important for the owner and should be considered to have a better model of the problem. For example, a customer may wish to invest more in the specific category of device such as a set of basic appliances.

This paper uses the game theory model (cooperative game with transferable utility), to consider this issue. According to this game rule, if more investment is made in a specific appliances category (such as basic equipment), the customer will agree to allocate some additional funds next year. By using the Shapley value relationship, the coalitional game will earn the value of benefits for the coalition players, and the benefits should be fairly divided among them.

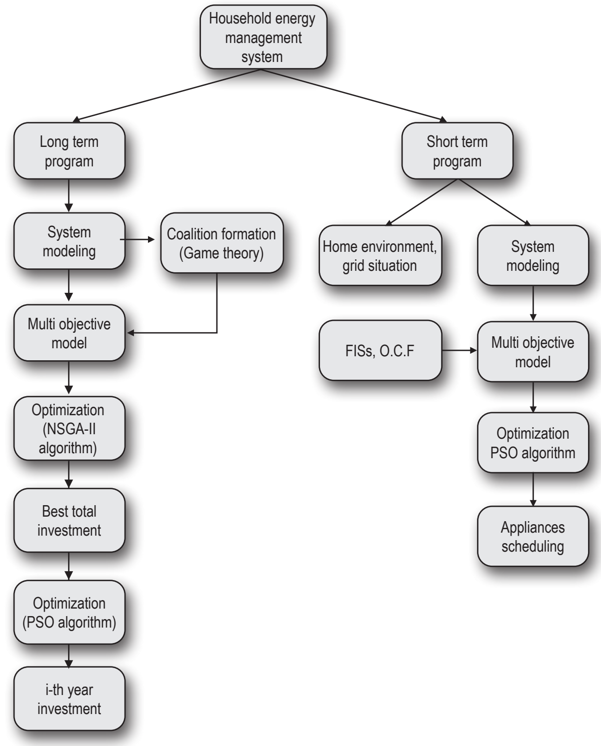

Fig. 1. Overview of the proposed method

3) Long-term energy management optimization modeling

The economic efficiency relations of appliances and effective parameters on investing were introduced in the previous sections. Customer behavior usually requires investment in areas with higher benefit (here is equal to economic efficiency index) and lower cost (here minimum investment cost), therefore this subject may model as a two objective function model. The first goal of the long term energy management problem is to maximize the economic efficiency index, while the investor idea is considered and modeled using a game theory. The relation is provided as follows:

$$\underline{F_1} = \lambda \sum_{p=1}^{r} X_p R_p^{ave} + (1-\lambda) \sum_{q=r+1}^{s} Z_q R_q^{ave} \quad \forall (p \in A_B^{SC} \subseteq A_B, q \in A_B^{S} \subseteq A_B) \tag{16}$$

Where X_p, Z_q are binary matrix indicating the investment or lack of investment for set of coalition supplements and coalition, respectively. Also λ is impact factor for coalition appliances. A and A_B are home appliances set and appliances set for long term energy management program. Then A_B^{SC}, A_B^{S} are set of coalition supplements and coalition, respectively. Note that R_p^{ave} and R_q^{ave} will be obtained from equation 15, when appliances p and q and their parameters are considered. By entering the λ coefficient in the objective function, try to set the weight parameter in the range of [0,1] to consider the owner's ideas, so as to make more investments in special categories. Although it may apparently seem that, these changes in the objective function by λ coefficient led the problem to non optimal results. But the use of game theory model and its rules guarantee to achieve optimal solutions. Above mentioned equation can also be expressed as a minimization problem:

$$F_1 = \lambda \sum_{p=1}^{r} -X_p R_p^{ave} + (1-\lambda) \sum_{q=r+1}^{s} -Z_q R_q^{ave} \quad (17)$$

Where I_p, I_q are matrix of investment for the set of supplements coalition and coalition appliances. The second objective function of the long term energy management system is included in investment cost minimizing and is presented as follows:

$$F_2 = \sum_{p=1}^{r} X_p I_p + \sum_{q=r+1}^{s} Z_q I_q \quad (18)$$

B. Short term energy management system

The proposed energy management system has two main parts, which the long term program was explained in the previous section. This section is linked to the short term energy management system, which has two main steps: the first step is related to appliances' recommendation degree identification as well as the owner's important factor determination. For this purpose, some fuzzy logic systems are used to identify the recommended level of using any electrical appliance during different hours of the day. The numbers of these Fuzzy Inference Systems (FIS) depend on the numbers and kinds of the home appliances, and are designed according to the related condition of appliances operation. The output of this part is a number ranging from 1 to 3, which is a degree of suitability time for using any appliance. These numbers indicate low recommendations, good recommendations, and best recommendations for using the appliance. Note that, these outputs do not mean that the devices certainly should be turned on or off. This factor only has an effect on the ultimate optimizer tool. The other factor is related to comfort factors that are determined by the owner and show a degree of suitability for the use of any appliances from their view. This factor is considered here aiming to increase the household comfort and the control of electricity consumption without force or loss of comfort. Finally, determining these two factors gives a value matrix which is used in the main optimizer. The second step is related to the main optimizer in which a PSO algorithm system is employed to solve a multi-objective function to determine the best working time of any appliances.

1) Owner comfort factor (O.C.F)

The household power management system should be based on owner comfort. If the owner has compelled feelings and comfort losses, he/she will not use it. In the proposed method, a comfort factor is designed to consider owner idea about using appliances in different hours a day. This factor should be determined by the owner and is a number between 0 to 3. A larger number indicates that the time to use the device is more appropriate, and vice versa.

2) Recommendation degree for using different home appliances

The structure of this part is based on use of different fuzzy systems. Because all appliances have different operation styles, different FISs are designed to determine their degree of recommendation. All of them have exclusive inputs, so specific sensors should be used to collect these data from home, outside and grid. The output of FISs is a number between 1 and 3, where a larger number indicates a more suitable time to use the device, and vice versa. These numbers and the owner's comfort factor will form a value matrix that will be used in the main optimization tool. Again, these last two factors cannot turn the device on or off, but only affect the final optimizer tool.

3) Affective factors on the power consumption of the household sector

There are some factors, which are effective in household power consumption. This refers to the amount or possible changes in the power consumption of the house due to changes in these parameters. Some of these are related to the power consumption amount of appliances, therefore they can be used as FISs inputs. The other factors deal with maximum household power consumption and have an effect on this parameter. The main purpose of this part is to make an adaptive optimizer tool, which is able to determine appliance scheduling according to the different household features. These factors include: house size, family education, number of households at time t, degree of urbanization, consumer desire, and alternative energy prices [24-55].

4) Calculating appliances' best working time

The main step of the proposed short term program relates to the optimization of appliances' working time. The purpose of this part is to minimize the household electricity cost considering their welfare. The equations 2 and 3 represent the electricity consumption of appliance i in a specific time slot and in a day, respectively. Then, to obtain energy consumption of any appliance which is present in short term program, these two equations are utilized with the appliances short term parameters. Next the following equation is presented to obtain household energy consumption during a week.

$$W_u^{Weekly} = \sum_{v=1}^{7} W_{u,v} = \sum_{v=1}^{7} \sum_{j=1}^{m} P_u \times X_{u,j}^{v} \times \frac{t}{3600} \quad \forall(u \in A_C, j \in T, v \in W) \tag{19}$$

Where $W_{u,v}$, W_u^{weekly} are daily and weekly energy consumption of appliance u. Also, W is set of all days in a week and A_c is set of appliances for short term energy management program. In addition, weekly consumption can be calculated through the following equation:

$$W_v^{Optimization} = \sum_{u=1}^{x} W_u^{Weekly} = \sum_{u=1}^{x} \sum_{v=1}^{7} \sum_{j=1}^{m} P_u \times X_{u,j}^{v} \times \frac{t}{3600} \quad \forall(u \in A_C, j \in T, v \in W) \tag{20}$$

Where $W_v^{Optimization}$ is weekly household electricity consumption. The cost can be calculated through the following equation:

$$C_v^{Optimization} = \frac{\left(\sum_{u=1}^{x} \sum_{v=1}^{7} \sum_{j=1}^{m} P_u \times X_{u,j}^{v} \times \frac{t}{3600} \times c\right)}{1000} \tag{21}$$

Where $C_v^{Optimization}$ is weekly household electricity cost and is spot electricity price.

5) Short-term energy management optimization modeling

The short-term energy management problem can be modeled as a multi-objective optimization problem. Customer behavior usually maximizes household welfare at the lowest cost of electricity. Family welfare here is defined as the use of any appliance at the desired time [47]. For example, if the optimizer tool, select the middle of the night for an appliance operation and it is not matched with household lifestyle, then it has an impact on the family welfare. Therefore, the matrix encompasses the summation of owners' significant factors, while the FISs output defines the value representing the presence of appliances in various time slots. Considering this household welfare's definition, the first objective of short term energy management problem can definitely maximize the welfare during a week. Note that, this model is considered as multi objective aim to present any appliance at the favorable times and avoid inappropriate timing. For example, the morning appliances set are placed in the objective function G_1 and they cannot select to work at noon time slots. Note that objective function G_5 is related to the appliances which have not specific operation time.

$$G_1 = \sum_{v=1}^{7} \sum_{u=1}^{x} \sum_{j=1}^{a} \left(V_{u,j}^{v,F.I.S} + V_{u,j}^{v,O.I.F}\right) X_{u,j}^{v,Morning} \tag{22}$$

$$G_2 = \sum_{v=1}^{7} \sum_{u=1}^{x} \sum_{j=a}^{b} \left(V_{u,j}^{v,F.I.S} + V_{u,j}^{v,O.I.F}\right) X_{u,j}^{v,Lunch} \tag{23}$$

$$G_3 = \sum_{v=1}^{7} \sum_{u=1}^{x} \sum_{j=b}^{c} \left(V_{u,j}^{v,F.I.S} + V_{u,j}^{v,O.I.F}\right) X_{u,j}^{v,Evening} \tag{24}$$

$$G_4 = \sum_{v=1}^{7} \sum_{u=1}^{x} \sum_{j=c}^{24} \left(V_{u,j}^{v,F.I.S} + V_{u,j}^{v,O.I.F}\right) X_{u,j}^{v,Night} \tag{25}$$

$$G_5 = \sum_{v=1}^{7} \sum_{u=1}^{x} \sum_{j=1}^{24} \left(V_{u,j}^{v,F.I.S} + V_{u,j}^{v,O.I.F}\right) X_{u,j}^{v,Variable\ time} \tag{26}$$

Where $V_{u,j}^{v,F.I.S}$, $V_{u,j}^{v,O.C.F}$ are matrix of F.I.S (fuzzy inference system) output and O.C.F (owner comfort factor) for appliance u at time j in day v. Also, $X_{u,j}^{v,Morning}$ is binary matrix indicating the operation status of task for appliance u at morning time j in day v.

6) Continuous operation:

Some appliances have continuous performance limitations. This subject is described as follows:

$$X_u(t_s) = 1 \rightarrow X_u(t_s, t_{s+1}, \ldots, t_e) = 1 \tag{27}$$

This means that if a specific device u starts at time t_s, its work should continue until the end of its function at time t_e.

7) Appliances consumption quota

Total energy consumption by appliance u along a week should be limited within a specific value, which is formulated as follows:

$$\sum_{v=1}^{7} \sum_{j=1}^{m} W_{u,j}^{v} \leq W_u^{Individual} \tag{28}$$

Where $X_u^{Individual}$ is energy consumption quota of appliance u. Total household electricity cost should be less or equal than the specified value. Above mentioned equation can be expressed in the form of cost. Also, if the effective factors of the household power consumption mentioned in section 2.1.2.3 are considered, the maximum allowable electricity consumption costs of any appliance can be obtained by the following equations.

$$\sum_{v=1}^{7} \sum_{j=1}^{m} W_{u,j}^{v} \times c \leq (W_u^{Individual}.c)(1+\gamma_u) \tag{29}$$

$$\sum_{v=1}^{7} \sum_{j=1}^{m} C_{u,j}^{v} \leq (C_u^{Individual})(1+\gamma_u) \tag{30}$$

$$\sum_{v=1}^{7} \sum_{j=1}^{m} C_{u,j}^{v} \leq C_u^{adaptive} \tag{31}$$

Where $C_u^{Individual}$, $C_u^{adaptive}$ are cost quota and adaptive cost for appliance u. Also, γ_u is coefficient between 0 to 1 indicating impact factors on the electricity consumption quota of any appliance.

8) Total cost

Household electricity consumption cost should be considered as a limited value, and if affective factors in total power consumption cost are considered, the following relation will be obtained.

$$\sum_{u=1}^{x} C_u^{adaptive} \leq (1+\delta) \times C_{base} \tag{32}$$

Where δ is coefficient between 0 to 1 indicating impact factors on household electricity consumption quota and C_{base} is base cost of household electricity consumption.

III. Simulation and results

A. Long term simulation

In order to evaluate the proposed long-term method, simulations were performed in the MATLAB environment. For this purpose, a family of four is considered whose behavior (Table 1). The possible range for the use of every appliance is mentioned in Table 2. Note that the total length of TV watching per day is based on the 1062/2010 instruction [59]. In order to estimate the air-conditioning operating time, the temperature-related statistics of Tehran in 2015 have been used [60].

In this case, three hours of operation is considered for the days with temperatures between 25-30°c, and ten hours of operation for the days with temperature between 31-35°c and twelve hours of operation for the days with a temperature of more than 35°c. According to the information in Table 2 and equations 7-8, the annual household electricity consumption is calculated, and the results are shown in Table 3. In addition, the price of low-consumption appliances and the daily running time of appliances are also given. It should be noted that electricity consumption of dishwasher, refrigerator and washing machine are based on 1059/2010, 1060/2010 and 1061/2010 Europe instructions [61-63], respectively.

In equation 11, the coefficient α has indicated the possibility of repairs' occurrence, which should be determined here. The failure prevalence rates in the first 3-4 years are indicated in Table 3 [64, 65]. To calculate the probability of failure by any appliance, it is assumed that the failure rate's probability of these appliances would annually be increased by the same rate. Since the proposed method uses spot electricity prices, the electricity prices will be collected from one of the power companies [66]. These prices have been used for those devices that have recognizable operation time (Table 2). (To simplify the simulation, it is assumed that the price is the same on all days of the year). Also, in some cases where the operating time of the equipment cannot be identified, the electricity price will be assumed to be 4.2 cents on average.

TABLE 1
Household behavior pattern

No.	Behavior	Hour	Persons number
1	Wake up	5:30 AM	4
2	Take a shower	5.45 AM	2
3	Eating breakfast	6.30 AM	4
4	Leave the home	7 AM	4
5	Children return	1 PM	2
6	Parents return and lunch	2.30 PM	2
7	Eating dinner	9.30 PM	4
8	Sleep time	11 PM	2

TABLE 2
Time frame for the use of appliances

No.	Appliances	Power consumption		Possible operation times
		High	Low	
1	Tea maker	2200	1500	6 AM
2	TV	125	28	6-7 AM, 6-10 PM
3	Rice cooker	860	550	2.30 PM
4	Pressure cooker	1000	700	2.30 PM, 9 PM
5	Aircon	690	450	According Ref [60]

TABLE 3
Home appliances operation information

No.	Appliance	Energy consumes		Appliance life	Repair cost	Total failure in the first 3-4 year	Price	Daily operation time/ instruction
		Low efficiency	High efficiency					
1	Refrigerator (337 liters)	307(A+)	166(A+++)	7	155-200	12%	1100	1060/2010
2	Tea maker (1.8 liters)	132	90	1.5	3.6	100%	90	10 Minutes
3	Rice cooker (1.8 liters)	258	165	5	4	20%	100	50 Minutes
4	Aircon 9000	952(A+)	621(A+++)	5	185-239	15%	1400	Some months
5	TV (32 inches)	225	50	5.5	122-158	8%	350	1062/2010
6	Dishwasher	295(A+)	235(A+++)	5	107-138	21%	850	1059/2010
7	Washing machine (8kg)	195(A)	136(A+++)	5.5	123-160	29%	920	1061/2010
8	Pressure cooker	180	126	5	6.8	20%	170	30 Minutes

TABLE 4
Appliances operation times

zone	Hour	Appliances	Weekly Consumption	α_1
1	6 am-8 am	Aircon, TV	17.92 [a]	0
2	8 am-1 pm	–	0	0
3	1 pm-5pm	Aircon, TV, IT	37.94 [b]	0.2
4	5pm-9pm	Aircon, TV, IT, Washing Machine	44.24 [c]	0.2
5	9pm-11pm	Aircon, TV, Dishwasher, IT	27.37 [d]	0.2
6	11pm-6am	Aircon	53.9 [e]	0

α1: Education level factor, z: Time zone
a: ((1.1*2)+ (0.18*2))*7, b: ((1.1*4)+(0.18*4)+(0.075*4))*7
c: ((1.1*4)+ (0.18*4)+0.9+(0.075*4))*7
d: ((1.1*2)+(0.18*2)+1.2+(0.075*2))*7, e: (1.1*7)*7

TABLE 5
The output of F.I.S and O.C.F of IT appliance

No	Appliance	t	Consumption per cycle	W Incorrect	$W_u^{Individual}$
1	Aircon	3600	1.1	146.3[a]	69.3[b]
2	TV	3600	0.18	15.12[c]	5[d]
3	Dishwasher	3600	1.2	8.4	6
4	Washing machine	3600	0.9	5.4	3.6
5	IT	3600	0.075	5.25[e]	2.52[f]

a: 20.9*7, b: 9.9*7, c: 2.16*7, d: 0.72*7, e: 0.75*7, f: 0.3*7*(1+0.2)

This situation can be considered when the owner is willing to invest more in a particular equipment group. In order to achieve this goal and increase its chances of winning, a coalition has been formed between these appliances. Here, let's consider a scenario where the initial credit limit for the first year is $1,000. The owner is willing to increase it by an additional $500 in the following year, on the condition that further investment is necessary for basic equipment. Also, the value of λ is assumed to be equal to 0.3.

After forming the coalition, and performing a simulation by means of NSGAII algorithms and making a Pareto front, then the solution nearer to the maximum credit ceiling (here $1500) would be selected as the best solution.

The result shows tea maker, rice cooker, and TV between non-coalition appliance and washing machine from the coalition set. The total cost will be equal to $1,460. These appliances must be replaced instead of their old types over two years, with the assigned credit. Then, in order to determine the items that must be replaced in the first year, the PSO algorithm will be used to simulate with the participation of all the devices that have been previously selected. Tea maker, rice cooker and TV were selected as the final winner to be bought in the first year, and washing machine is selected for the second year. The total costs for the first and second years are $540 and $920, respectively. The simulation results show that, the total amount of energy consumption of the four appliances is reduced from 810 KWh/year to 441 KWh/year. This is equivalent to an average reduction in energy consumption of 84% (the percentage reduction in energy consumption of any device is also marked separately). According to the results, TV has the greatest potential to reduce energy consumption (in the scenario examined). Also, the proposed method reduces the appliances' repair cost. The total annual repair cost of the four examined old appliances was $65.22, while the total repair cost of their new type was $12.73; an average reduction of 80.48%.

In addition to reducing household cost and increase investment motivation, the proposed method is able to reduce the cost of appliances repairs via effective investing in long-term plan. The possibility of appliance repair cost's reduction of each old and new appliance is shown in Fig. 3. According to the results, washing machine has the highest potential to reduce the repairs cost (in the examined scenario).

B. *Short term simulation*

In order to evaluate the proposed short term energy management model, a family of four is again considered here, According to this family's lifestyle, the appliances operation time has been categorized in six zones (Table 4).

In addition, some effective power consumption parameters are also determined here. As a sample, the coefficient of education level related to IT equipment is mentioned. Table 5 provides other parameters required in the formula. Also, incorrect values for energy usage (W Incorrect) and weekly energy quota of any appliance are represented. Some F.I.S are designed and simulated to determine the recommended degree of any equipment. As a sample the fuzzy rules table and the results of F.I.S outputs and O.C.Fs related to IT appliance are illustrated in Table 6, 7.

TABLE 6
The output F.I.S and O.C.F of IT appliance

		Electricity price		
		Low	**Medium**	**High**
Education level	Low	H. R	H. R	H. R
	Medium	Zero	L. R	H. R
	High	Zero	Zero	L. R

TABLE 7
The output of F.I.S and O.C.F of IT appliance

	Zone 1 Slot		**Zone 2 Slot**				**Zone 3 Slot**						**Zone 4 Slot**		**Zone 5 Slot**		**Zone 6 Slot**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
F.I.S	1.3	0.9	1.5	1.5	1.5	1.5	1.5	0.54	0.54	0.54	0.54	0.92	0.92	0.92	1.89	1.89	1.89	1.5	1.5	1.5	1.5	1.5	1.5	1.5
O.C.F	0	0	0	0	0	0	0	1	2	2	3	3	3	3	3	2	2	0	0	0	0	0	0	0

TABLE 8
The output results for IT appliance

	6 AM	7 AM	8 AM	9 AM	10 AM	11 AM	12 AM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	7 PM	8 PM	9 PM	10 PM	11 PM	12 PM	1 AM	2 AM	3 AM	4 AM	5 AM
Sun	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0
Mon	0	0	0	0	0	0	0	1	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0
Tues	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Wed	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0
Thurs	0	0	0	0	0	0	0	1	0	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0
Fri	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
Sat	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	0	1	0	0	0	0	0	0	0

Note that the six zones mentioned in Table 4 are divided in specific time slots which mentioned in table 7. For example, zone1 has 2 slots, starting from 6 AM to 8 AM. Then, any time slot has two coefficients related to F.I.S and O.C.F, as mentioned in section 2.1.2.5. After determining these parameters, the problem can be solved by using the PSO algorithm. As a sample, the output results of IT equipment are shown in Table 8. The number 0 indicates the time during which the appliance is not allowed to operate, and the number 1 indicates the allowed operating time. As shown in Fig.4, total weekly energy consumption before scheduling is 181.37 kwt, and after scheduling it is reduced to 70.81 kwh which is great improvement. Therefore, the proposed short-term program are able to reduce energy consumption by 60.96%. Again, note that these results are only related to that particular case study, and different scenarios may have different results.

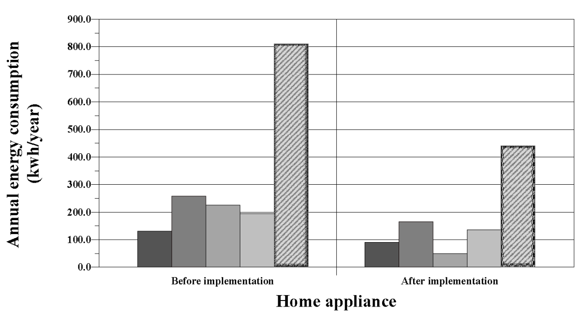

Fig. 2. Annual energy consumption before and after implementation of the proposed method

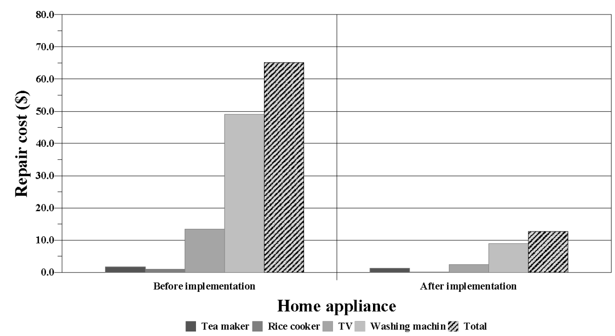

Fig. 3. Annual repair cost probability

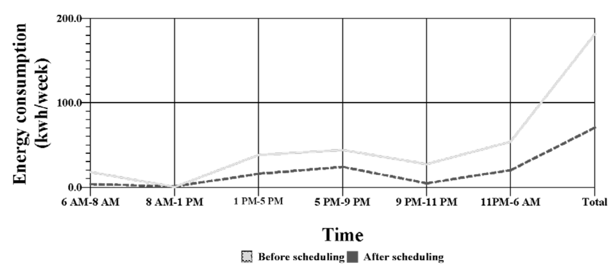

Fig. 4. The weekly energy consumption pattern

IV. CONCLUSION

In this paper, an adaptive energy management system for household applications based on computational intelligence methods has been described and evaluated. The proposed method pursues the objectives of electricity consumption management in both long-term and short-term sections. In the long-term program, a model is presented to reduce electricity consumption by optimally replacing appliances. In this way, issues such as social behaviors and investment parameters are also considered. The other part is the short-term plan, which is related to the meaningful balance between energy savings and household lifestyle. In order to do so, in the long term program an economic efficiency index is defined to find the most suitable appliance for replacement. In addition, the owner's desire for special investment is considered by using a game theory model. In short term program FISs and an O.C.F are considered which effects the energy consumption modeling and main optimizer procedure. It was demonstrated (through a case study simulation) that the proposed hybrid algorithm could reduce the domestic energy usage, and ensure an optimal task scheduling considering inhabitants' comfort. Future efforts will be mainly aimed at improving the energy management framework by taking into account more components and in a larger scale. In this way the energy management system will design a residential complex building considering of electric vehicles.

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