Integrated Computer-Aided Engineering 15 (2008) 1–9 1
IOS Press

A fuzzy logic based efficient energy saving approach for domestic heating systems

José R. Villar[a,*], Enrique de la Cal[a] and Javier Sedano[b]
[a]*Computer Science Department, University of Oviedo, Spain*
[b]*Electromechanic Engineering Department, University of Burgos, Spain*

Abstract. This paper focuses on the designing of an energy saving method for a domestic heating system based on electrical heaters. A multi-agent system architecture with two fuzzy rule based systems has been used: a fuzzy model, to estimate the energy requirements and a fuzzy controller, to distribute the energy to all of the installed heaters. The aim is to reduce the energy spent for heating the house while maintaining the predefined comfort level. The proposal has proved valid in realistic simulations, although some revisions must be be carried out prior to integrating it into a microcontroller hardware. The real prototype must also be validated in real situations. This system is to be included in the local company's product catalogue.

1. Introduction

A local company marketed a new catalogue of dry electrical heaters in the last quarter of 2007. The total power installed in a domestic heating system in Spain easily surpasses 7 kW. When electrical heaters are used, the energy consumption generated could be higher than the common contracted power limit (for short, CPL). A Central Control Unit (CCU) must be designed in order to save energy and distribute it among the heaters in a building. In a preliminary work [21], a CCU -using two fuzzy rule based systems (FRBS) – was presented as valid for a certain type of houses. But as stated by Spanish regulations, the CCU must be valid for each of the five Spanish climate zones, that is, the CCU must be validated for each climate zone and season.

In this work, the design of the CCU is detailed and benchmarked for all of the Spanish climate zones. In this approach, the whole energy saving algorithm is integrated and distributed over the heaters and the CCU. The system has two objectives. First, the power consumption in a house – including the energy spent on heating- must be kept lower than the CPL. On the other hand, the comfort in the house should be reached.

This proposal includes a distributed architecture based on several distributed agents (the heaters) and a CCU using a wireless network. An Energy saving and Distributor Algorithm (EDA), which makes use of two FRBS, is responsible for accomplishing both objectives. Finally, the EDA determines how to distribute the available energy between the heaters in the house to achieve the desired comfort temperature level. The CCU carries out the EDA in collaboration with the installed heaters.

This work is organized as follows. In the following sub-sections the Spanish building regulations are outlined, and then the different building topologies and the complete problem are described. In Section 2 the Fuzzy Energy Saving Domotic System is analysed and explained. The experiments carried out and the obtained results can be seen in Section 3. Finally, the conclusions and proposals for future works are given in Section 4.

1.1. *The spanish regulations and the problem description*

In the first quarter of 2007, the Spanish parliament approved a new building regulation [7] (RITE). As a re-

*Corresponding author: Computer Science Department, University of Oviedo, Campus de Viesques s/n 33204 Gijón, Spain. E-mail: villarjose@uniovi.es.

ISSN 1069-2509/08/$17.00

sult, building methods have been updated [8]. This new regulation had many consequences, as it determined how new buildings must be accomplished [6]: materials, isolation, energy efficiency, ventilation rates, etc. In Spain, the LIDER software [9] has been developed and should be used to calculate the heating installation in a building: the number of heaters and their nominal power are fixed.

The RITE establishes 5 climate winter zones, named with a letter from A to E, where E represents the maximum in weather severity. A peculiar fact [7] is that in Spain only 3 of the 5 winter zones defined in the RITE are considered. Moreover, a number between 1 and 5, related with the summer weather severity, is also given. The combination of winter and summer severities determines the climate zone for each location in Spain.

1.2. The specified building topologies

The building topologies refer to all of the building parameters that influence the heating system. Such parameters include the type of house, the geometrical aspects, the inner partition, the materials, etc. For example, the building envelope could help in reducing the heating losses.

A set of specific geographic locations and building parameters has been chosen to validate the energy saving proposal. To determine the geographical locations, the provincial capital cities with the most severe climate have been chosen. Hence, the capitals of province that have been chosen are: Málaga (A3), Palma de Mallorca (B3), Santander (C1), Lugo (D1) and Ávila (E1). On the other hand, real state data has been analysed to determine the set of building materials and the different kind of buildings (building topologies). The building topologies considered in this work are presented in Table 1. In Fig. 1 an example of a Condo3 house with a possible indoor partition is shown.

1.3. The problem description

The main goal is the design of a heating system to distribute the available power without exceeding the CPL. The predefined comfort level in the house must also be reached. The heating system comprises the electrical heaters installed in all of the rooms in a house and the CCU. The range of the nominal powers for the heaters are 500, 1000, 1200 and 1500 Watts. The houses must comply with the Spanish regulations.

The inhabitants would establish the comfort level in the house or in a room by setting the predefined suitable environmental variables. In the case of this project, only the temperature in each room is considered because of economic reasons. Future works should consider other measurements, such as the humidity percentage. The different room temperatures are to be measured using the temperature sensors included in each heater. Although the temperatures measured in the heaters are noisy, a pre-process module is carried out in order to improve the measurement quality; the heaters designers introduced this pre-process module.

Even though there are devices for energy distribution – specifically, energy rationalizers, these devices distribute the energy consumption but do not consider the comfort level in the house. Consequently, it is necessary to introduce a new device, called CCU, which will be responsible for the saving and distribution of energy to the installed heaters; all of the devices will collaborate to achieve the goal. A measure of the current power consumption is needed to maintain the electrical power consumption below the CPL.

Some hints about costs are to be considered when deciding the system architecture. Firstly, the communications between devices should be wireless in order to reduce the cost of the installation, specifically, the communications must be managed by a Zigbee wireless network [15]. Secondly, the cost of configuring the system should also be low: the installer must configure the whole system in a limited period of time. The configuration must be as simple as possible, with a reduced set of parameters.

2. The fuzzy energy saving proposal

In Spain, the electrical heating power installed in a house easily surpasses 7 kW, despite the fact that the most common CPL in Spain is 4.4 kW. Moreover, there are always some small power devices drawing energy (the fridge, computers, etc.), so that the real instantaneous available power is lower than the CPL. At any moment a small power device can be switched on, for example, a microwave oven. The *available power* is the electrical power that can be distributed for heating at any moment, that is, the CPL minus the small power devices and lighting consumptions.

The available power will be distributed between the active heaters – those with temperature set point greater than 0–. The best power distribution is that which maximises the comfort level with the minimum electrical energy waste.

Table 1
The building topologies considered in the thermal study. All the topologies except for the Office include a living room, a kitchen and an entrance hall. Building type 2 includes 3 bathrooms. Then, for each topology subtype and geographic zone a thermal study must be carried out

Topology type	Topology subtype	Bedrooms	Area m2	Description
1	Condo1	1	35–45	A house in a condo or loft
	Condo2	2	65–75	A house in a condo
	Condo3	3	85–95	A house in a condo
2	Detached house	4	220–250	An individual isolated house, a cottage or a lodge
	Terraced house	4	200–220	A set of similar houses, side by side
3	Office	–	85–130	An office in an office building

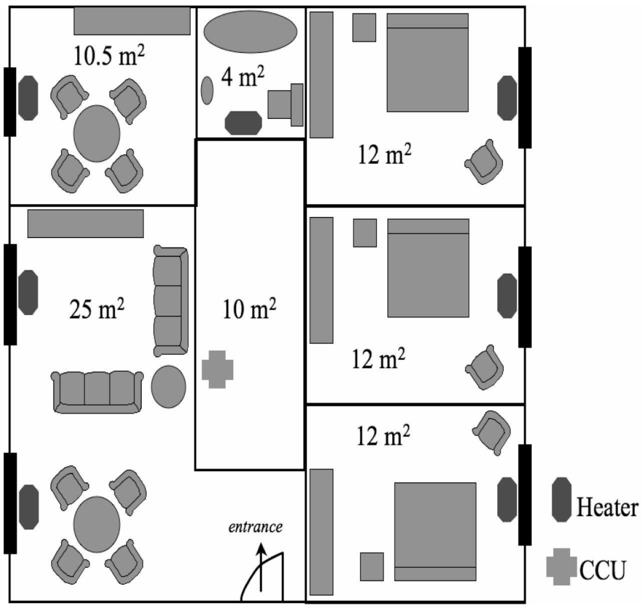


Fig. 1. An example of a Condo3 house design and the architecture schema. The heaters are the red boxes close to the windows. The CCU, which is in the corridor, is the energy saving device.

2.1. The solution schema

In this work, the multi-agent system outlined in Fig. 2 is proposed as a solution for the problem defined in the previous section. In short, the heaters send the CCU the temperature of the room and its nominal power. The CCU measures the instantaneous consumed current and the outdoor temperature. The CCU also stores the set point temperature profiles for all the rooms in the house, and the association between rooms and heaters. Finally, the CCU carries out the EDA for distributing the instantaneous power (*heating power*) for each heater. The *heating power* is the fraction of the nominal power that a heater is allowed to spend; the *heating energy* is the heating power by time unit.

The EDA makes use of two FRBS (a fuzzy model –FRBS-1– and a fuzzy controller –FRBS-2–) to fit the maximum power for each radiator. Fuzzy logic is chosen to manage the wide variety of topologies that the system must work with: the same algorithm must ensure the power distribution and the energy saving for many different cases. An FRBS is a Fuzzy inference system that allows to model with human interpretability [4]. An FRBS includes a Knowledge Base with two main parts: the fuzzy rule base and the database. The former includes the rules or relationships between the fuzzy partitions of each variable. The latter comprises the description of each membership function for each fuzzy partition.

A block diagram of the whole process is shown in Fig. 3. There are two stages in the solution: the design stage and the run stage. In the design stage, both the FRBS-1 and the FRBS-2 are generated. The FRBS-1 estimates the *required power* of a generic room. An FRBS-1 must be generated for each pair of climate zone and building topology (*configuration*). To generate the learning datasets for the FRBS-1 the simulation software tool HTB2 [18] has been used. The FRBS-2, which was designed *ad hoc*, calculates the *percentage of nominal power* for a heater given the room *temperature error* and the **energy error**.

The heater *required power* is the estimated instantaneous power that the heater must spend to heat up the room, that is, to maintain the comfort in the room. The *required energy* for a heater is its required power by time unit. The *energy error* is the difference between the required energy and the heating energy. The *temperature error* is calculated as the difference between the temperature set point and the room temperature.

Finally, the heating power for each heater is calculated while a balance of energy is achieved. The available power is distributed between the heaters according to their percentages of nominal power.

2.2. The MAS architecture

An MAS paradigm is considered to provide the heating system with a robust behaviour, as proposed in [5]. The MAS methodology used is that resembled in [14] and the FIPA specifications [19]. The MAS runs over a Zigbee wireless network. The EDA – distributed between the CCU and the heaters – directs the power output of all the heaters when the network is up. When the network is down, or when the CCU is out of service, all the heaters must act as normal stand-alone heaters until the system recovers. Figure 2 shows the schema of the MAS, where the data flows between heaters and CCU and the agent behaviours are included.

2.3. A fuzzy model for estimating the power requirements of a room

The required power of a room must be estimated in the EDA, but it is not possible to have a model for each different room. That is the reason why the behaviour of the heating dynamics in a *generic room* is modelled. The estimation of the required power of a generic room has to deal with uncertain dynamics due to several reasons. On the one hand, there is no volumetric information of any room in order to facilitate the installation and set up, only the number of installed heaters and their nominal power are given. On the other hand, heating up a room depends on the weather conditions, which are different for each climate zone. Finally, the occupancy profile, or the small power profile in each room introduces vagueness in the behaviour of a heating system.

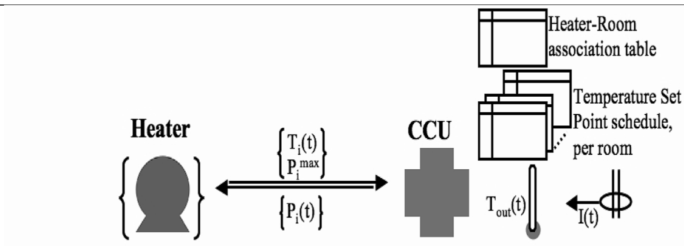
Fuzzy logic is a well-known technique for managing uncertainty [16]: an FRBS is used to confront the uncertainty in modelling the required power of a generic room (FRBS-1). Many different techniques have been used to obtain FRBS, such as genetic algorithms [2] or neural network [11]. Although there are similar works in the literature as in [22], these approaches are based on knowing the specific building in which the heaters will be installed and have not proved as valid in generic buildings and houses with electrical heaters.

Different fuzzy models have been tested to manage the problem uncertainty, specifically, the fuzzy regression models included in KEEL software tool [2]. It was found that no fuzzy regression model significantly outperforms the others when a configuration dataset is used. The ANFIS model [12] has been chosen to model the power requirements of a generic room because the ANFIS model has been proved as a valid model when the training dataset includes data from all kinds of events needed, and when it is to be used in short-mid term prediction [10,13]. The ANFIS model is a Sugeno type FRBS using a hybrid learning algorithm: the least square method and the back propagation gradient descent method.

The generation of the ANFIS model is shown in a block diagram in Fig. 3. The HTB2 simulations, the data set post-processing and the FRBS-1 ANFIS models training steps are described in the following subsections. The ANFIS model is generated using 5 fuzzy partitions for each variable -with triangular fuzzy membership functions except the outmost, which are trapezoids- and linear output. The input variables of the FRBS-1 are the instantaneous in-room temperature error and the temperature in-room given from the heater. The output of the model is the estimation of the required power of a generic room for a specific climate zone and topology.

2.3.1. Creating the data set from realistic simulations

As stated in [10,13], a sufficiently large dataset, including all situations and events to be modelled, is needed to successfully train an ANFIS model. The datasets must be gathered from simulations. The HTB2 is a well-known tool, suitable to analyse the dynamics of heating systems with concentrated parameter problems such as the one that concerns us [3,17]. The HTB2 is a totally parameterized simulation tool: the social behaviours and all the Spanish building regulations can be included for each simulation (materials, power installation, weather conditions, etc.).



Role	Behaviours	Role
Proactive	Control Action (Internal PID)	---
---	EDA algorithm	Proactive
Initiator	Subscribe Protocol **Joint**	Participant
Initiator/Participant	Contranet Protocol **JointByBridging**	---
Initiator	Propose Protocol **BridgeAHeater**	Participant
Participant	Contranet Protocol **SetPower**	Initiator
---	Propose Protocol **JointACCU**	Initiator/Participant
---	Propose Protocol **distributeAvailablePower**	Inititator/Participant

Fig. 2. The MAS architecture and the behaviours that are defined, including the role of the devices in each case.

To generate the dataset, each one of the topologies reflected in Table 1 must be defined, and a set of simulations for each season is carried out using realistic social profiles. For each configuration an FRBS-1 should be generated.

2.3.2. *The post-processing stage*

The HTB2 software generates a huge dataset. Each example in such dataset includes data from all rooms of the building. In order to avoid over-fitting the FRBS-1, this dataset must be post-processed to choose the relevant information and rearrange the data properly. First, a grouping step is run, rearranging the data in order to ensure that each line in the dataset contains data from only one room. Then the grouped dataset is re-sampled, so only relevant examples are taken into account. Relevant examples are those that include information of dynamics. For example, when a room set point temperature is 0 there is no need for it to be modelled, as it does not have information of the dynamics.

The outcome of the post-processing stage is the dataset for training and testing purposes, including the following data: the temperature in the room T_i, the room set point temperature profile T^{SP}, the nominal power installed in the room $P^{\max}$, the required power for the room heater ($)(), the outside temperature T_{out}, the occupancy rate of the room O_i, the light power consumption of the room L_i, and the small power devices consumption of the room S_i. The values of T^{SP}, T_{out}, O_i, L_i, and S_i are the same as those used in the HTB2 simulation. The ($)() and the T_i for each room of the building is the major outcome of the HTB2 simulations.

2.3.3. *The learning stage*

Although a preliminary experimentation was carried out with the KEEL tool, the final learning phase of the ANFIS FRBS-1 has been developed in Matlab [23]. The post-processing output dataset will be used in training and validation. It is stratified in a 10-fold cross validation schema; 10 ANFIS models are generated provided that the dataset is large enough to contain sufficient relevant information. The best suite model will be chosen. The ANFIS model will estimate the required power of a generic room for a given environment condition.

2.4. *The energy distribution algorithm*

The solution makes use of the concept of energy balance. A distribution algorithm is used, so each heater is given with a fraction of the available power that it is allowed to spend. If it is desired that the room reaches the comfort level then the heating energy must equal the required energy for each room, that is, there must be a balance between both energies. The energy balance is carried out over a predefined period of time in order to eliminate the accumulative errors. A predefined window of 20 minutes has been adopted, where the required power and the heating power are stored for each heater. This time window size is a compromise value: the higher the window size, the higher the RAM needed in the CCU. Finally, this slicing window will reduce the impact of both missing data and outliers.

It is important to consider the heaters thermal dynamics and capacity. A typical heater has a 6 minute period from cold to full power state. From full power to cold state typically takes 5 minutes. This means heaters do not heat with full power until the end of the dynamics. Also, they quickly cool down due to their low thermal capacity. In the distribution algorithm these facts must be taken into account. The former could be solved with a certain correction factor. The latter implies that the active heaters must always be assigned with a minimum heating power to keep them hot. This threshold must be determined empirically. Finally, to reduce the dynamic periods, the duty cycle must be reduced, provided it is large enough to allow the heaters to reach the steady state. This parameter must also be determined empirically, and it has been fixed to 3 minutes.

The adopted energy distribution algorithm is shown in the box diagram in Fig. 3, and its flow chart can be seen in Fig. 4. The first time the algorithm runs the initialization of the required energy (Er), the heating energy (Eh) and the energy error (ΔE) are carried out. The algorithm is run every minute. In each run, the required power (Pr) for each heater is estimated by means of the FRBS-1. Then, all of the energy variables are updated. When the duty cycle runs out the heating power (Ph) for each heater is calculated. The current power consumption (Pc) must be determined, and the available power (Pa) calculated as 0.85 times the CPL without the Pc. The FRBS-2 is used for computing the percentage of nominal power for each heater. Finally, the Pa must be distributed between the active heaters according to the Ph assigned to each one, and including the correction factors described previously. In this way, the Ph is updated every three minutes, while the rest of the variables Pr, Er, Eh and ΔE are updated every minute.

The FRBS-2 is a Mamdani fuzzy model with two inputs and one output. This FRBS-2 is used to manage the uncertainty introduced by some measures: the temperature error precision, the temperature error bias the energy error precision, etc. Each variable has three fuzzy partitions, with triangular fuzzy membership functions except the outmost –which are trapezoids. The fuzzy rule base is shown in Table 2. The temperature error in a room and the ΔE are the inputs. The output of the FRBS-2 is the percentage of nominal power to be assigned to the room heater. The variables partitions and the rules have been designed intuitively; following the ideas given by the experts. The inference method is the mean of the maximums. Future work will deal with the design of the FRBS-2 by means of hybrid learning techniques.

Table 2
The fuzzy rule base for the FRBS-2. A fuzzy partition scheme is used, with three partitions per variable

		ΔE		
		LOW	MEDIUM	HIGH
Temperature error	LOW	LOW	LOW	MEDIUM
	MEDIUM	MEDIUM	MEDIUM	HIGH
	HIGH	HIGH	HIGH	HIGH

2.5. *Rearranging the energy distribution*

One problem that arose was the fluctuation of the heating energy proposed by the EDA. Moreover, the electrical heaters are ON-OFF devices, so the power distribution assigned by the CCU cannot be a percentage but ON-OFF.

To solve this problem the energy distribution to all the heaters was rearranged. This rearrangement minimizes the number of ON-OFF switches for all heaters. The heating energy is distributed in an ON-state time slot, where the electrical heater performs with its nominal power. The remaining time of each period the electrical heater is in an OFF state and does not waste electrical energy. The ON slots for all heaters are arranged so the CPL is never surpassed and the amount of power assigned to each heater is accomplished. Once this algorithm runs then the outcome is sent to all heaters.

3. Experimentation and results

The experiments must validate the whole system, including both the FRBS-1 and the EDA for each of the configurations. As stated in RITE and Spanish Regulations, only 3 of 5 winter climate zones are sufficient to cover all the weather conditions in Spain. The system can be considered as valid when these two goals are achieved: the electrical power consumption in a building does not surpass the CPL and the comfort level is reached when sufficient power is available. To validate the system, the EDA power distribution is compared to that of the HTB2 in the two cases of having or not sufficient available power. In the former, the comfort level must be reached, in the latter the CPL must never be surpassed.

The experimentation is described as follows. Firstly, the HTB2 simulations to generate the datasets for each configuration are described. Then the datasets post processing and the ANFIS models learning stages are explained. Finally, the evaluation of the EDA in the Run Stage for each configuration is described and the results are commented.

3.1. The HTB2 simulation

A dataset for each configuration is generated. For each configuration several simulations were carried out. Each topology subtype has been duplicated to provide different building orientations and inner distribution in order to evaluate the robustness of the EDA and FRBS-1. The weather data was gathered from the middle of each one of the seasons – autumn, winter and spring – from the year 2007. As a result, each configuration requires 6 HTB2 simulations.

For the sake of simplicity, only results for one case – the test case – will be shown to avoid overrunning the reader with tables and figures. The reader must take into account that the same process shown below was carried out for each configuration, so an FRBS-1 for estimating the required power for each topology was obtained. The case to be shown corresponds to a configuration of a D1 climate zone city – specifically, the city of Lugo in the north-west of Spain – with a No. 1 building topology, considering the three topology subtypes -Condo 1 with 40 m^2, Condo 2 with 66 m^2 and Condo 3 with 90 m^2. The social profiles – that is, occupancy, lighting, etc. – and ventilation profile have been defined realistically. For each topology subtype a CPL was chosen according to the surface of the flat. The CPL was fixed to 3.3 kW for Condo 1, to 4.4 kW for Condo 2 and to 5.5 kW for Condo 3 flats and for the N$^\circ$ 3 building topology. For N$^\circ$ 2 building topology 7 kW is used.

3.2. The data sets post-processing and the ANFIS learning

All the data gathered from simulations is post-processed and the appropriate data sets for training and validating the system are obtained. For each configuration an FRBS-1 is obtained using the training data sets. To obtain an FRBS-1 a 10-fold cross validation schema is used, with 70% of the data for training and 30% of the data for testing. The mean square error is used to evaluate each ANFIS model. The best evaluated ANFIS model is chosen as FRBS-1.

In Fig. 5 the mean square error box plot for the test case is shown. As expected, the mean square error is higher than that obtained in preliminary work [21]. This is due to the fact that the latter was generated for a climate zone and building topology subtype, that is, it was a more specific problem. Consequently, the dataset generated for the preliminary work was smaller than for the current one and the post processing stage was carried out manually. In contrast, this work has automated the data post-processing ,and the data samples are chosen randomly between all the relevant examples. Attending to the box plot it can be concluded that the post-processing stage must be improved in order to obtain a better ANFIS model performance.

3.3. The run stage validation

In this stage, the performance of the EDA in each configuration is analyzed. The Run Stage is run with the post-processed datasets, one for each configuration. The aim is to evaluate which of the power distributions – the one from the EDA or the one from the HTB2- better accomplish the objectives.

The evolution of the power consumption in the test case -for the Condo2 in two different orientations and inner distributions- is shown in Fig. 6; the simulation time shown corresponds to a high-required power period where almost all the heaters should be ON. The energy balance is obtained, but the power distributions are quite different. The HTB2 is higher than the CPL and the EDA is fluctuating.

As shown in Fig. 7, if the small power devices consumption is added to the heating required power from HTB2 the total electrical power consumption is higher than the CPL, while this does not happen in the case of the heating power proposed by EDA, which was one of the main objectives.

Obviously, if the CPL is too low, then the EDA cannot guarantee that the system will reach the comfort level. Nevertheless, the lower the energy spent on heating -with respect to that proposed by HTB2- the higher the time needed to reach the comfort level with the EDA.

On the other hand, the performance of the system is not influenced by the season of the year, the different orientations of the flat or by the inner partition of the building: the EDA can reach the comfort level in any case provided there is enough heating energy available.

In several cases the heating power proposed by the EDA was not suitable, surpassing the power proposed from HTB2 (Fig. 8). When this is the case the system does not accomplish the energy saving objective. This problem always occurs when the heating system switches ON and the temperature error is relatively low. In these cases, the FRBS-1 over-estimates the power requirements, so the system provides more power than needed. It seems that the automated module must be enhanced to choose significant data. This is a very important item to be analyzed and developed in future work.

Finally, the second objective of the system is to reach the comfort level. The measure of comfort used is the temperature in a room, and a result for a room in the first Condo 2 in autumn is presented in Fig. 9. As can be seen, the room temperature reaches the temperature set point. Of course, the time needed to reduce the temperature error increases as the heating power is reduced, but it is not a significant rise.

4. Conclusions and future work

In this work, an energy saving system for a heating system is designed in order to reduce the power consumption while maintaining the comfort level in houses. The Spanish Regulations should be accomplished, and different climate zones, building topologies and seasons of the year have been taken into account.

An MAS approach is designed, where an FRBS-1 ANFIS model is used to estimate the required energy for a generic room and the EDA is used to calculate and to distribute the heating power to all the heaters. The EDA makes use of a fuzzy controller designed ad hoc. In preliminary works the proposed system was found valid for a specific configuration: a Condo house with three bedrooms in a city of a specific climate zone in Spain, for a certain week of the year.

The preliminary work has been extended to all the climate zones in Spain and common building topologies. The data set generated with the HTB2 simulations, which is too large, is post processed. It was found that the post-processing stage has a significant role for a proper training and validation data sets generation and has to be improved.

After the experimentation stage, the system has been found valid for the most common buildings and climate zones, reducing the consumed electrical power and avoiding surpassing the CPL.

Nevertheless, further work has to be done. It has been found that the FRBS-1 overestimates the required power in certain situations, especially when the system is almost in steady state and the temperature error is low.

Finally, two new proposals are postulated as future work. Firstly, new trends in FRBS modelling should be considered instead of the ANFIS or to obtain a fitter FRBS-2 [1]. Secondly, the required energy can be estimated in each electrical heater as its output in the local control loop. This approach would improve the robustness and the system integration. Also, the precision in the required energy estimation could be outperformed.

Acknowledgements

This research work has been funded by *Gonzalez Soriano, S.A.* -by means of the CN-08-028-IE07-60 FICYT research project – and by the Spanish Min. of Education, under the grant TIN2005-08386-C05-05.

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