Building Energy Management through a Distributed Fuzzy Inference System

Pervez Hameed Shaikh [#1], Nursyarizal Bin Mohd Nor [#1], Perumal Nallagownden [#1], Irraivan Elamvazuthi [#1]
[#] Universiti Teknologi Petronas, Bandar Seri Iskandar 31750,
Perak, Malaysia
[1] engr.pervezhameed@gmail.com

***Abstract*—Buildings consume significant world's energy resources, approximately 32% of the total primary energy. The rapid depletion of energy resources, has imparted researchers to focus on energy conservation and wastage. The next generation of smart buildings is becoming a trend to cope with the needs of energy and environmental ease in buildings. This advances the intelligent control of building to fulfill the occupants' need. Intelligent system control for sustainable buildings is dynamic and highly complex. Building information accuracy with an effective controller scheme is a challenging task.**

This paper presents the fuzzy control system architecture (FCSA) for resolving the conflict of maintaining the inhabitants comfort index and the energy consumption in buildings. It also infers the graphical relationship between energy consumption and comfort parameters. With a distributed fuzzy inference system (FIS), control has been developed for temperature, air quality and artificial lighting comfort parameters. Model simulation has been carried out and control factors have been discussed. The FIS models have also been validated with implication of change function. The presented control system is capable of achieving energy conservation in the buildings.

Keyword-Fuzzy control, Energy management, Comfort management, Energy consumption, Sustainable buildings

I. Introduction

The alarming environmental threats and the depletion of fossil resources have increased the awareness of the need to decrease energy consumption for sustainable energy development [1]. Energy efficiency, thus, has become a requirement inside buildings for both climate preservation and economic stability. Around 80-90 % of inhabitants spend their utmost time in buildings [2]. Therefore, an occupant's satisfaction is highly dependent on the indoor ambient comfort. The building energy management is primarily concerned in attaining the maximum indoor environment comfort in contrast tp the least energy consumption. Attainment of indoor comfort, keeping in view the consumer's preferences, is an important aspect. This will certainly influence the efficiency of the occupants and ultimately energy consumption.

For reduction of power consumption and waste in buildings, an intelligent control system is needed, since energy consumption has been directly related to comfort and ultimately to operational costs. A building's indoor environmental primary comfort factors, according to the consumers' preferences are thermal, visual and indoor air quality [3]. Therefore, satisfaction of energy prerequisites in efficient buildings has been focused on by assuring operational requirements with the least possible energy cost and the most environmental protection.

An indoor building environment is quite sensitive to variations and will closely follow the change. The non-linear fuzzy linguistic mapping model of an input data set to a scalar output data will overcome this. A FIS contains four basic blocks: fuzzifier, rule sets, inference engine and defuzzifier. The general architecture is shown in Fig. 1. Initially, an input set of crisp data is accumulated and turned into a fuzzy set utilizing fuzzy linguistic variables and membership functions called fuzzification. An inference is developed based on the rule set and finally, the fuzzy output is mapped to crisp values using the membership function called defuzzification [4].

The study presents the implementation of fuzzy control system architecture (FCSA) using a fuzzy inference system. The control functions employed for attaining energy conservation and improved level of comfort included thermal, visual and air quality as parameters. In a building envelope, the indoor thermal is the temperature [3], visual means the brightness level and the CO_2 concentration represents the air quality; these are regarded to be the main comfort parameters [5]. The user's preferences need to be considered in the design of the controller. This research is primarily focused on building towards the inhabitant's comforts and energy efficiency through actuator control.

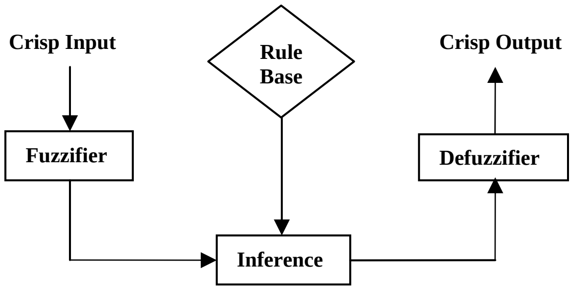

Fig. 1. Fuzzy Inference System

II. RELATED LITERATURE

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Primarily, building energy systems have been introduced for the monitoring and control of indoor environmental parameters to abate energy usage and cost. Buildings utilize substantial amounts of energy, predominantly electrical, and emit greenhouse gases (GHG) [6, 7]. Various decision support analysis techniques have been presented comprising optimum choices involving energy, environment, social and financial constraints [8, 9]. A framework for a building energy management system (BEMS) has been anticipated in [6, 10]. The authors considered the targets of enhanced energy efficiency, effective energy cost and the least amount of fossil fuel dependency with reduced emissions. Energy consumption, and a prediction method for data collection of inhabitants' activities and their movements along with their frequency was proposed. Furthermore, energy utilization of similar buildings in the same geographic neighborhood was explored in [11]. In [12], fuzzy logic control (FLC) has been developed for visual comfort. An illumination control system has been evaluated in the presence of daylight [13]. Whereas, [14] presented an airflow rate robust control approach. A building's air quality control has been employed with a fuzzy reasoning machine. A 3-D fuzzy model [15] has been deployed to represent overall comfort. The user decision-making model approach has been provided but has not been appropriately combined with comfort preferences. Several complicated control issues have been identified, whereas, real time control systems involve a network of controllers instead of a single unit. The proposed system employs a fuzzy expert system of local control to achieve the overall maximized comfort with less energy usage and waste. The distributed fuzzy controller system has been implemented in a general framework based on agents. Each FIS controller agent is regulated as a function of various sensors. The goal of consumer needs for building environmental comfort and custom adjustment of actuator devices releasing the tension of the manual control task was attained.

III. PROBLEM FORMULATION AND METHOD

The study aimed at providing an expert control system architecture for automated buildings which requires supply and control of energy keeping in view the interactions between the indoor environment and its residents. To cope with the energy demand of the building, the fuzzy expert system has been employed at an individual control level for sustainability and energy efficiency. The individual controls for each controlled parameter included temperature, illumination and CO_2 concentration. The input for the expert system is the standard comfort range, in which the consumer has the authority to set the desired comfort value. The instantaneous parameter value has been measured with sensors and has been fed back to the expert system for the desired amount of energy required to maintain the comfort. The proposed expert control architecture flow block is depicted in Fig. 2.

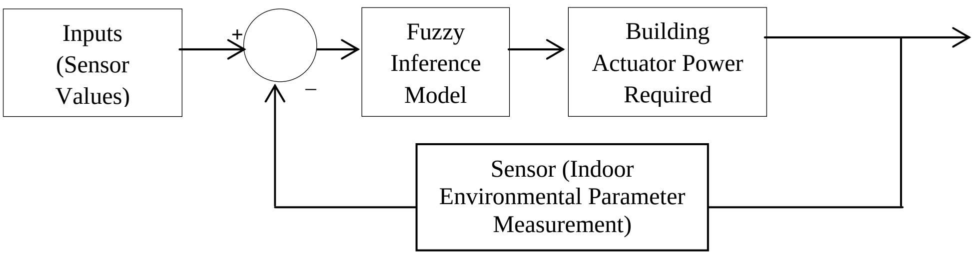

Fig.2. Automated building design structure

IV. Control System Architecture with Fuzzy

A. Heating Ventilation and Air Conditioning Control

In maintaining the inhabitants' working efficiency and gratification, thermal comfort plays an important role and possesses a high impact. Due to the subjectivity of thermal comfort, it is difficult to a state environmental and personal factor range. This is why the comfort index for thermal, commonly termed as Predictive Mean Vote (PMV), has been majorly established on heating, ventilation and air conditioning (HVAC) schemes. The index has been devised as a user's normal body consciousness. The mean temperature radiance, speed of air, outfit elements and humidity are in direct proportion to the temperature [14]. The PMV index prevails within the range of -3 to +3. This has a variation occurrence in between -0.5 and +0.5, and thus satisfies around 90% of the building dwellers [12]. The thermal comfort index has already been a prime feature in PMV index computation and the building's temperature has generally been specified with [5]. Both heating and cooling techniques are associated with a one unit system actuator. The fuzzy control knowledge base inference consists of two set strategies, one is comfort optimization and the second is energy consumption minimization. The input and output membership functions are depicted in Fig. 3; whereas, the 3-D expert control plot is depicted in Fig. 4. The knowledge base of the FIS system is shown in Table I.

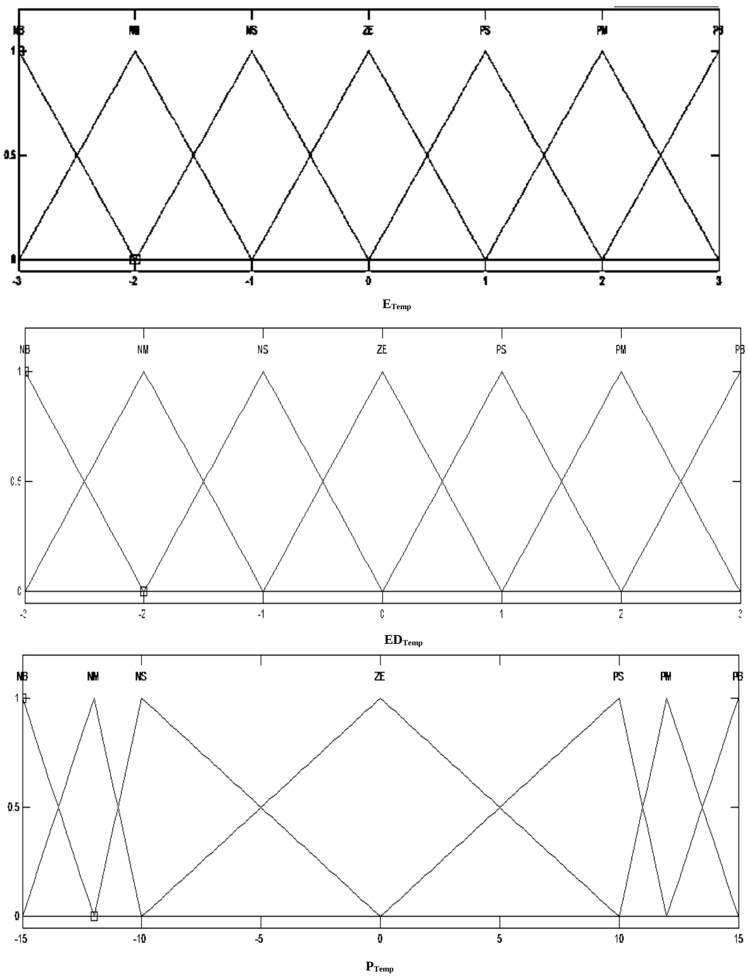

Fig.3. Fuzzy membership input and output functions for temperature.

TABLE I
Knowledge Base for FIS Temperature Controller

Power Required		E_{Temp}						
		NL	NA	NS	NE	PS	PA	PL
ED_{Temp}	NL	NL	NS	PS	PL	PL	PL	PA
	NA	NL	NA	NE	PA	PA	PL	PA
	NS	NL	NA	NS	PS	PA	PL	PA
	NE	NL	NA	NS	NE	PS	PA	PA
	PS	NL	NL	NA	NS	PS	PA	PA
	PA	NL	NL	NA	NA	NE	PA	PA
	PL	NL	NL	NL	NL	NS	PS	PA

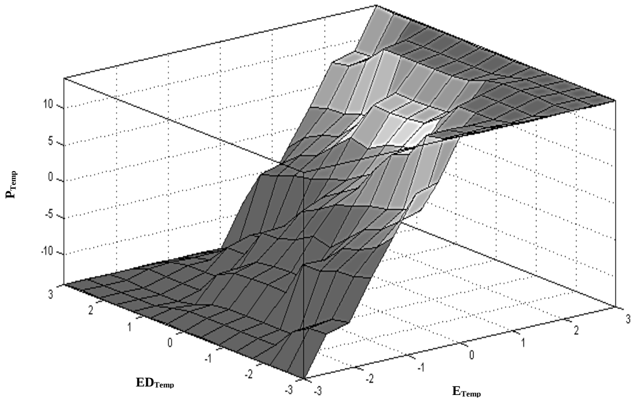

Fig.4. Fuzzy control surface control plot for temperature.

B. Artificial Illumination Control

Indoor building envelopes utilise 20-30 % energy in artificial electrical lighting. An attractive dynamic load management potential exists in controlling artificial lighting loads. The measure of the radiance level specifies the interior visual comfort [16].

Therefore, visual comfort provides luminance control in the lighting fixtures [17] measured in Lux. The measurement of glare, wall colour etc. are subjective and challenging parameters. The input and output membership functions are depicted in Fig. 5; whereas, the expert control plot is depicted in Fig. 6. The knowledge base of the FIS system is shown in Table II.

TABLE II
Knowledge Base for FIS Illumination Controller

Lighting						
	Small	SS	BS	OK	SB	Big
$P_{required}$	OFF	S	REG	SB	BB	ON

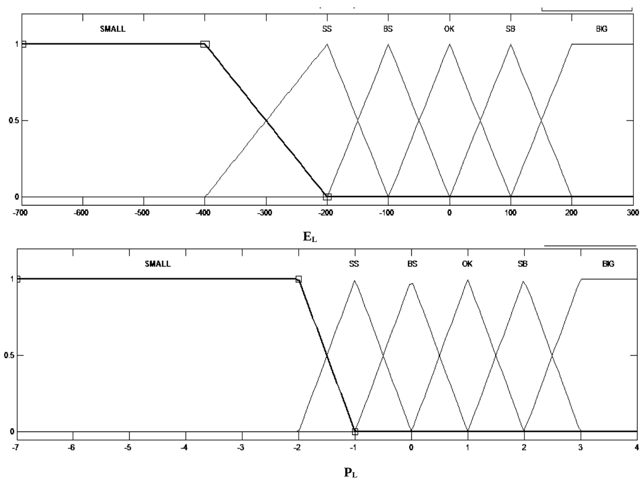

Fig.5. Fuzzy membership input and output functions for illumination.

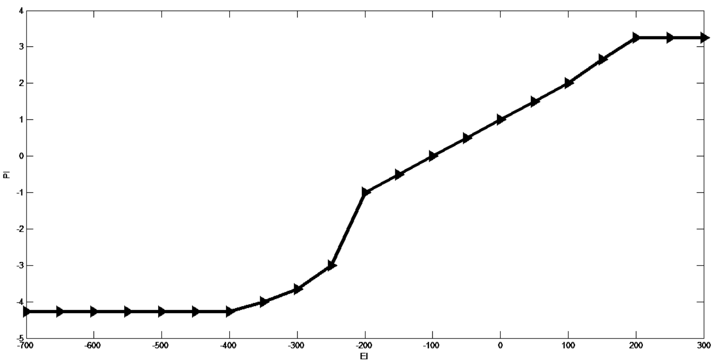

Fig.6. Fuzzy control plot for illumination.

C. Ventilation Control

Air quality control space has been specified with level of CO2 concentration and is predominantly subjective to the concentration of pollutants in the indoor environment [18]. This verily signifies various sources of pollution the existence of the dwellers in the building. Thus, in parts per million (ppm) CO2 concentrations is measured and has been represented as level index for air quality. The computation of power demand for ventilation or an exhaust fan system was done with the fuzzy inference system controller. The computed power then applied to the slave controller, air quality subsystem. In the local fuzzy controller, input is the error of the outdoor natural concentration and the internal set point through the consumer. Thus, the output is utilized for ventilation actuator control with the required electrical power. The input and output membership functions are depicted in Fig. 7, whereas the expert control plot is depicted in Fig. 7. The knowledge base of an FIS system is shown in Table III.

TABLE III
Knowledge Base for FIS Air-quality Controller

CO_2 Concentration						
	LOW	SL	OK	SH	BH	High
$P_{required}$	OFF	S	REG	SB	BB	ON

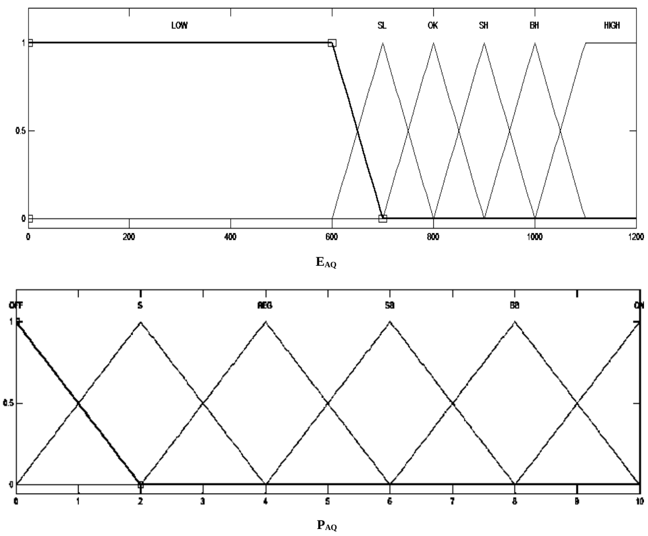

Fig.7. Fuzzy membership input and output functions for air quality.

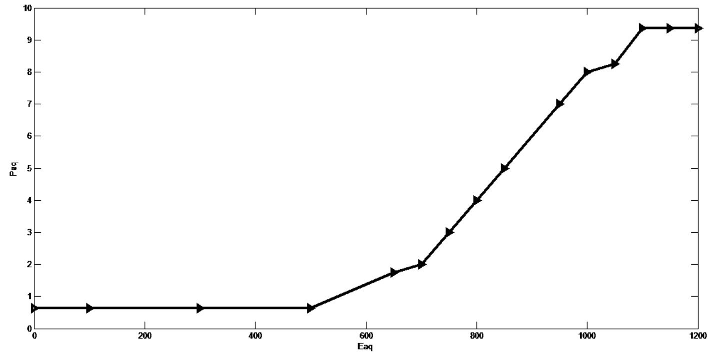

Fig.7. Fuzzy control plot for air quality.

V. Discussion of Results

The three distributed fuzzy controllers for temperature, illumination and air quality describe the control output surface. The 3-D plot of temperature in Fig. 3 depicts the actuator power requirement for both the heating and cooling systems combined. When the demand has moved in the positive direction, the cooling system is actuated, whereas, a negative demand activates the heating system to come into operation. The error (E_{Temp}) displays the direct proportion of the power requirement for both the cooling and the heating systems. Whereas, the error difference (ED_{Temp}) depicts an inverse proportional relation to the actuator power demand. The developed FIS model for thermal comfort has been validated employing trapezoidal and generalized polynomial based pi functions. The statistical data variance has been observed in Table IV. The deviation of trapezoidal and pi function has been obtained 0.7 and 0.23, whereas, the mean absolute percentage error contained is 6% and 2% respectively.

TABLE 4
FIS validation of thermal comfort

Parameter	Trapezoidal Function	Generalized Polynomial Based Pie Function
Sum of Squared Error (SSE)	12.29	1.32
Mean Squared Error (MSE)	0.49	0.05
Root Mean Square Error (RMSE)	0.70	0.23
Mean Absolute Percentage Error (MAPE)	0.06	0.02

The actuator power requirement of the lighting fixture shown in Fig. 6 provides a linear pattern of the control system. With a large error range, a steady high actuator power requirement occurs and vice versa with a decreasing error. The developed FIS model for visual comfort has been verified using trapezoidal and difference between two sigmoidal (dsig) functions. The statistical data discrepancy has been observed in Table V. The deviation of trapezoidal and dsig function has been obtained 0.02 and 0.20, whereas, the mean absolute percentage error contained is 7% and 3.7% respectively.

TABLE V
FIS validation of visual comfort

Parameter	Trapezoidal Function	Difference between two sigmoidal, Function
Sum of Squared Error (SSE)	0.01	0.84
Mean Squared Error (MSE)	0.00	0.04
Root Mean Square Error (RMSE)	0.02	0.20
Mean Absolute Percentage Error (MAPE)	0.07	0.37

While for ventilation, as shown in Fig. 7, the actuator requires a low steady power demand with a limited concentration of CO_2 occurrence. Whereas, as the concentration increases, power demand rapidly increases with the minute rise in the concentration. The developed FIS model for air quality comfort has been verified using trapezoidal and generalized bell functions. The statistical data discrepancy has been observed in Table VI. The deviation of trapezoidal and bell function has been obtained 0.04 and 0.08, whereas, the mean absolute percentage error is limited to 3% each.

TABLE VI
FIS validation of air quality comfort

Parameter	Trapezoidal Function	Generalized Bell Shaped Function
Sum of Squared Error (SSE)	0.03	0.11
Mean Squared Error (MSE)	0.00	0.01
Root Mean Square Error (RMSE)	0.04	0.08
Mean Absolute Percentage Error (MAPE)	0.03	0.03

VI. CONCLUSION

The comfort index of the inhabitants with regard to the power consumption in order to make a wise decision for energy management within a distributed control level has been shown in this study. An intelligent building control system utilizing fuzzy controller agents has been coordinated with intelligent coordinators. The intelligent FCSA provides an actuator sensor network for decision-making to maintain a balance between the occupant's comfort and the total power usage. The aims of learning and the weighted decision-making of consumer comfort preferences have been achieved to some extent. This will make consumers properly aware to take wise actions for energy consumption. The unforeseen behavioral relation with the used power and comfort has been inferred with the implication of the FIS control system. The inference models for each agent have also been validated with the implication of different membership function. The future work will be carried out on the system optimization, for the grid connected, constrained power supply and the inhabitant's interior environment comfort.

ACKNOWLEDGMENT

The authors thank and acknowledge Universiti Teknologi PETRONAS for carrying out this extensive research work.

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