VOT 74120

DEVELOPMENT OF AN ON-LINE AND INTELLIGENT ENERGY SAVING SCHEME FOR A COMMERCIAL BUILDING

(PEMBINAAN SYSTEM PENJIMAT TENAGA PINTAR SECARA BERTERUSAN UNTUK BANGUNAN KOMERSIL)

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PUSAT PENGURUSAN PENYELIDIKAN
UNIVERSITI TEKNOLOGI MALAYSIA

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Jabatan Elektrik Kuasa
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Abstrak

Di Malaysia, selama 2 dekad terakhir, permintaan untuk sektor komersil meningkat pada purata 7.5 peratus pada 1980an dan 7.7 peratus pada 1990an melebihi 5.9 peratus pertumbuhan GDP dan 7 peratus dari masa yang sama. Saat ini, sektor komersil telah menggunakan 19 peratus daripada jumlah penggunaan tenaga untuk semua sektor. Mengikut konteks bangunan komersil, penyaman udara ialah pengguna tenaga yang utama yang memakai 70 peratus tenaga elektrik sementara 30 peratus digunakan untuk lampu dan beban lainnya. Projek penyelidikan ini ialah merekabentuk dan membina sistem kawalan penyaman udara dan sistem kawalan penyusup cahaya luar. Fuzzy akan digunakan untuk menentukan nilai pasti dari isyarat kawalan yang bertujuan untuk mengenal pasti dan mengawas penggunaan tenaga secara efisien. Pembinaan skema pintar kawalan tenaga boleh mengawal penggunaan tenaga bangunan komersil dengan menggunakan pengawas secara berterusan.

DEVELOPMENT OF AN ON-LINE AND INTELLIGENT ENERGY SAVING SCHEME FOR A COMMERCIAL BUILDING

Abstract

(Keywords:…………..   )

In Malaysia, during the past two decade, demand for commercial sector grew rapidly, increasing at an average rate of 7.5 percent in the 1980s and 7.7 percent in 1990s, surpassing the GDP growth of 5.9 percent and 7 percent over the corresponding period. At present, the commercial sector has utilized 19% of the total energy usage for the all sectors. In the context of commercial building, the air conditioning is the main energy usage which consumes 70% of the electrical energy used while the remaining 30% used for lighting and other loads. This research project is to design and develop an Air Conditioning control system and external light infiltration control system. Fuzzy will be used to determine the definite value of control signal in order to identify and to monitor the energy usage in the efficient way. The development of this proposed energy intelligent control scheme would be able to control the energy consumption of the commercial building using on-line monitoring.

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Abstract

(Keywords: Energy saving, Fuzzy, Intelligent)

In Malaysia, during the past two decade, demand for commercial sector grew rapidly, increasing at an average rate of 7.5 percent in the 1980s and 7.7 percent in 1990s, surpassing the GDP growth of 5.9 percent and 7 percent over the corresponding period. At present, the commercial sector has utilized 19% of the total energy usage for the all sectors. In the context of commercial building, the air conditioning is the main energy usage which consumes 70% of the electrical energy used while the remaining 30% used for lighting and other loads. This research project is to design and develop an Air Conditioning control system and external light infiltration control system. Fuzzy will be used to determine the definite value of control signal in order to identify and to monitor the energy usage in the efficient way. The development of this proposed energy intelligent control scheme would be able to control the energy consumption of the commercial building using on-line monitoring.

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PSC -	Single Phase Compressor
ASHRAE -	American Society of Heating, Refrigerating and Air conditioning Engineers
PMV	Predicted Mean Vote
ADC	Analog to Digital Converter
LED	Light Emitting Diode
VCL	Visual Component Library
OOP	Object Oriented Programming
°	Degree
Ω	Ohm

CHAPTER I

INTRODUCTION

1.1 Introduction

"An On-line and Intelligent Energy Saving Scheme" can provide alternative options in developing strategies that contribute to the optional use of resources. Considerable improvement can be achieved in commercial sector. Further reduction in total energy consumption can be made possible by better load management and control.

Air Conditioning (AC) System consume more than 70% of the electrical energy used in P07 building Faculty of Electrical Engineering and 30% used for lighting and other power consumption according to the online monitoring record[1].

In human life, human always try to adapt with environment. It is shown that people always try to have a comfortable environment. It can be seen on the progress of planning design for activity places.

With air conditioning, it can be up grading human life into a better life in order to improve performance by giving a comfort place to conduct activities.

Average of human skin surface temperature in a tropical zone is 33°C [2]. This condition will be achieved if heat radiation is equal to heat produce. People would not suddenly feel the coldness if temperature is being changed in neutral band which is ± 1.5°C.

Because of that human body will react quickly if temperature is changing suddenly which caused blood stream become smaller, then the differences of outdoor temperature and indoor cooling temperature is preferable not further than 7°C [2].

In order to obtain temperature differences using temperature cooling setting which is from outdoor temperature changing and indoor activity, then it is necessary to control Air Conditioning Systems continuously.

In Universiti Teknologi Malaysia (UTM) especially FKE almost in every building is fully equip with Central Air Conditioning which type is "Water Cooled Packages Units" which is fully equip with Water Cooling Systems from Cooling Tower to every AHU and also fully equip with Split Air Conditioning.

Existed temperature control using conventional thermostat or manual thermostat is located in every split AC and AHU room. Thus this gives a different temperature control value from the set value which has been arranged because of outdoor temperature influence and air flow which always change and also because of conducted activity. That is why indoor temperature is lower than thermostat setting. To overcome this, it is necessary to control the AC continuously in order to achieve the comfort level. In this research, a control system which control a split AC in the FKE building; i.e. P07 3rd floor which in this case is "Bilik Mesyuarat Makmal Sistem Tenaga" will be developed by using Fuzzy Programmable Thermostat in order to improve AC performance and saving energy.

1.2 Objective

i) To design a fuzzy split air conditioning control system.
ii) To design an automated horizontal blind control in synchronization with lighting system.
iii) To identify the potential of energy saving.

1.3 Scope of Research

The scope of this research work is to develop an On-line and energy saving scheme for a commercial building. The work focuses on designing the control system for the room air conditioning system and lighting system using Fuzzy Logic Controller. The meeting room, Energy System Lab at P07, Faculty of Electrical Engineering will be used as a model where the research work will take place.

1.4 Outline Of The Project

Chapter Two is the literature review of the research. This chapter provides a review of some of the research that has been done which is related to this research.

Chapter Three explains the research methodology in this research.

The steps of research methodology are following :

Selection of a model room
On-line data capture
Optimization of conflicting parameters
Design of hardware
On-line implementation
Testing and validation
Costing Analysis

Chapter Four is the result and discussion of the project.

Chapter Five is the conclusion of the project and suggestion for further work of the project.

CHAPTER II

LITERATURE REVIEW

Many research works have been done on designing the controller for air conditioning and the lighting system. The designs, which have different capability in improving the use of air conditioning, are presented by the researchers in the journal paper. Among the papers which are related to these works are as follows:

2.1 An HVAC Fuzzy Logic Zone Control System and Performance Results [6]

Robert N. Lea, Edgar Dohman, Wayne Prebilsky, Yashvant Jani, outline of the conceptual design of a heating, ventilation, and air conditioning control system based on fuzzy logic principals is given. This system has been embedded in microprocessors with interfaces to the sensors, compressor, and air circulation fan and installed in a test building for performance evaluation. Over the last few years, several fuzzy logic controllers for temperature control [1, 2, 3, 4, 5, 6, 7] have been developed and reported in the literature. The first two references provide the details for temperature control in a heating, ventilation, and air conditioning (HVAC) system, developed by Togai InfraLogic and Mitsubishi in late 1989 and 1990. This system was designed to control temperature in commercial buildings and was reported to achieve a high comfort level with energy savings up to twenty-five percent. Fuzzy logic temperature control in non-HVAC systems has also shown to be very effective [5, 6] in simulation environments with a very complicated models of the plant. However, these controllers did not investigate the energy savings for the overall operations. Their goal was specifically to achieve higher performance from the given plant.

In reference 7, a fuzzy temperature controller that can adapt to the customer requirements has been developed for a residential home heating system. The controller was first developed in a simulation environment and then was implemented using a micro controller board. Control of the temperature is reasonably good and is shown to use less energy for the overall operation.

Another thermal control system based on fuzzy logic principals has been designed, implemented, tested and flown in a Space Shuttle flight in August, 1992 [8]. The system, referred to as the Thermal Enclosure System (TES) and Commercial Refrigerator/Incubator Module (CRIM) was developed by Space Industries, Inc., League City, Texas, and was used in control of temperature in protein crystal growth experiments on mid-deck Shuttle payloads. Commercially available off-the-shelf conventional control systems could not maintain the accuracy of +/-0.1 deg C over a 0-40 deg C range that the experiments required. The fuzzy logic controller, however, was able to control it well.

The fuzzy controller reported is being developed primarily with residential applications in mind although it will apply easily to commercial setups as well. The main emphasis is on the use of zone control, as well as the factoring in of relative humidity measurements, to maintain comfort level and save on energy usage by regulating the flow of air to the different zones. In the following paragraphs we will give a brief overview of the system design and results of testing the system in our laboratory in League City, Texas.

The fuzzy logic HVAC controller is being developed and tested by Ortech Engineering Inc. under a NASA/JSC Phase II SBIR contract. It has a functional flow diagram as shown in figure 1. This flow diagram differs from the conventional systems typically implemented in residential units. Typical conventional temperature control systems are based on a single input of temperature and a single output which controls the on/off state of the compressor and fan simultaneously. These types are known as SISO controllers and they do not take into account the comfort level to address in this project. It should be noted that the functional flow shown in figure 1 is not just another presentation of a multi-input multi-output (MIMO) controller broken into several SISO type controllers. It rather takes into account the comfort level via the measurement of relative humidity and generates an intermediate value of desired temperature. It also takes into account the effects of overall air circulation in the house. The main idea is to maintain an acceptable comfort level in the various areas of the house as needed rather than assumes a homogeneous environment and turns the compressor on and off based on the reading of one temperature sensor, as is the usual case.

Three sets of sensor inputs are available to the controller for each zone; relative humidity, temperature. And zone temperature set point. The testing facility consists of a variable speed compressor and fan as well as a fixed capacity-heating element installed in a six-room mobile home. Temperature and relative humidity from each zone are available on a continuous basis to the control system. The temperature set points for each zone can be programmed manually or can assume default values. Outputs of the controller are compressor speed, fan speed, and heat/cool/off (H/C/OFF) mode. In addition the system outputs vent positions for each zone to regulate the flow of air for comfort and energy efficiency. These input and output parameters have been given reasonable ranges, which determine the universe of discourse for the definition of the fuzzy membership functions.

Relative humidity, R_H, is quantified according to memberships in the fuzzy sets low, medium, and high, figure 2.a, which are input to the rule base in figure 2.b. This rule base has the function of computing an adjusted temperature setting based on the humidity in the facility. The underlying reason for the rule base is to exploit the fact that when humidity is low, people are comfortable at higher temperatures, as long as there is adequate air circulation, than they are when the humidity is high. Membership functions of low, medium, and high are assigned to the output of this rule base, desired temperature (D_Tmp), figure 2.c. D_Tmp is an internal variable which has an actual output range of approximately 23-26ºC, which is within the ASHRAE published comfort range[9] of 22-26ºC.

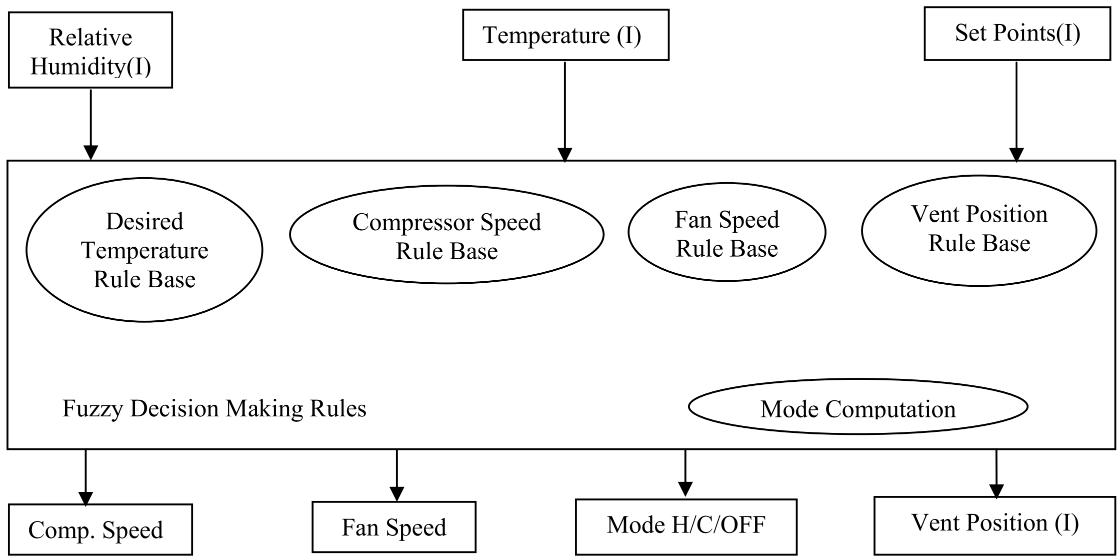


Figure. 1. Fuzzy Logic Controller with MIMO Controller Broken Into Several SISO Type Controllers.

The defuzzified value of D_Tmp and the actual sensed temperature are used to compute an internal variable, Error = Temp – D_Tmp. The membership of Error in N (negative), Z (zero), and P (positive) are computed according to the membership functions in figure 3.a. Fifure 3.b shows the Compressor Speed Rule Base which has temperature error as an input as well as relative humidity, R_H. From this rule base a fuzzy set denoting compressor speed is computed, and defuzzified using the membership functions in figure 3.c, to give the required speed level of the compressor in percent of maximum speed.

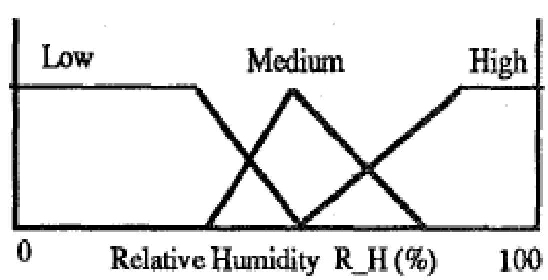


Figure 2.a

D_Tmp	Relative Humidity		
	low	med	high
	high	med	low

Rule Base for Desired Temperature

Figure 2.b

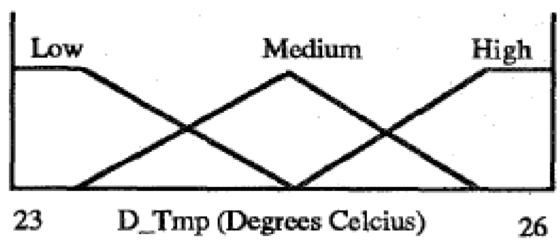


Figure 2.c

Similarly fan speed is computed from a Fan Speed Rule Base and membership functions for actual sensed temperature and relative humidity R_H. These membership values and rules are processed to produce a fuzzy set output for Fan Speed which is then defuzzified to yield a speed in units of percent of maximum fan speed.

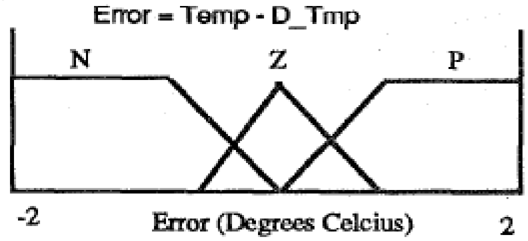


Figure 3.a.

Comp Speed		R_H low	R_H med	R_H high
Error	N	low	low	low
Error	Z	low	low	med
Error	P	low	med	high

Figure 3.b.

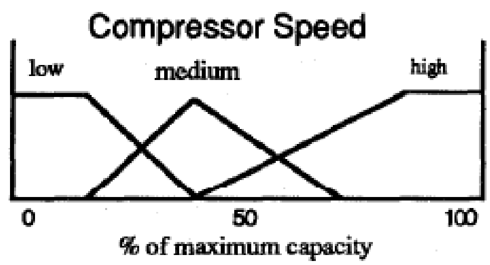


Figure 3.c

The system described above has been installed in the mobile home test bed and has been integrated with a data acquisition system for collecting data for performance analysis of the controller for use in tuning and further design. The system has performed well in maintaining the comfort level as specified by the comfort zone chart, section 8, ASHRAE Fundamentals Handbook[9], based on temperature and relative humidity parameters. An example of the results is shown in figure 4 which shows the temperature ranged from a low of approximately -4ºC at night to a high of approximately 5ºC during the day. The Zone 1. heat parameter, figure5, shows when heat was being delivered to the zone (1 is on, 0 is off). This Zone was selected for concentration since it is the farthest from the heat source. As is noted, in figure 5, it is cycling on and off during the period.

Figure 5 also shows the heat flags for zones 3 and 4. Zone 3 heat was off for the most of the period, while Zone 4 heat was on for a large part of the time which is consistent with the fact that temperature was lower in Zone 4 than in Zone 3 throughout the period as can be observed in Figure 4.

Figure 6 shows the zones 1,2, and 3 heat flag for two hours on another afternoon when the outside temperature was in the vicinity of 5ºC. It is seen that the Zone 1 heat flag is cycling on and off at regular intervals. However, the Zone 3 and Zone 4 flags came on very short and infrequent intervals. During this period the door to Zone 1 was open and consequently the warm air from Zone 1 was being dispersed throughout the zones 3 and 4 which are between Zone 1 and the air return.

Note also in figure 7 that temperature were being maintained in the three zones at a comfortable level during this period. It may be argued that it is a little warm in Zone 3, but with the trailer configuration, and with the door to Zone 1 open as it was during this data period, it is virtually impossible to control Zone 3 and 4 with precision since air from Zone 1 is going to circulate through both zones as it moves to the return vent.

Figure 8 shows the maximum and minimum temperatures for zones 1, 3 and 4 for still another early morning four hour segment when the outside temperature was approximately -4ºC. During this period the door to Zone 1 was closed. Figure 9 shows the temperature for each zone during the time period. Figure 10 shows Zone 1 heat cycling on and off at a regular frequency. Also note in figure 9 that zones 3 and 4 temperatures are now maintained at a very good level since with Zone 1's door closed they are not so noticeably affected by the air from that zone as they were in the previous example. This forces Zone 4 to call for heat on a regular basis in order to maintain its desired temperature as can be seen in figure 10. Zone 3 is still being heated from Zone 4's vent as they are fairly close together.

The current system utilizes zone control to regulate the temperature to the proper comfort level in each of six zones. The current version of the zone control monitors temperature and humidity and decides a compressor and fan speed setting for the particular zone. Since we are dealing with a single fan circulation system, we cannot change fan or compressor speed to a particular zone. Hence we set the compressor and fan speed to a fuzzy set function of the requested speeds of all zones requiring air flow. Proper flow to the individual zones is controlled through cycling of the vents from open to closed.

The addition of the zone controller has improved comfort throughout the trailer. Data collected and analyzed has shown that temperature is held within a comfortable region in all zones. We have not had time to assess the energy impact, but expect energy usage to be very efficient. In fact it would be surprising if it is not better due to the more efficient circulation of the air. It is possible, however, that a fair comparison will be very difficult to do since, by the nature of a controller without zone control, we normally have consistent variations in temperature from room to room which are not controlled. Since we are trying to heat and cool the house for comfort, we could experience larger energy usage in some cases.

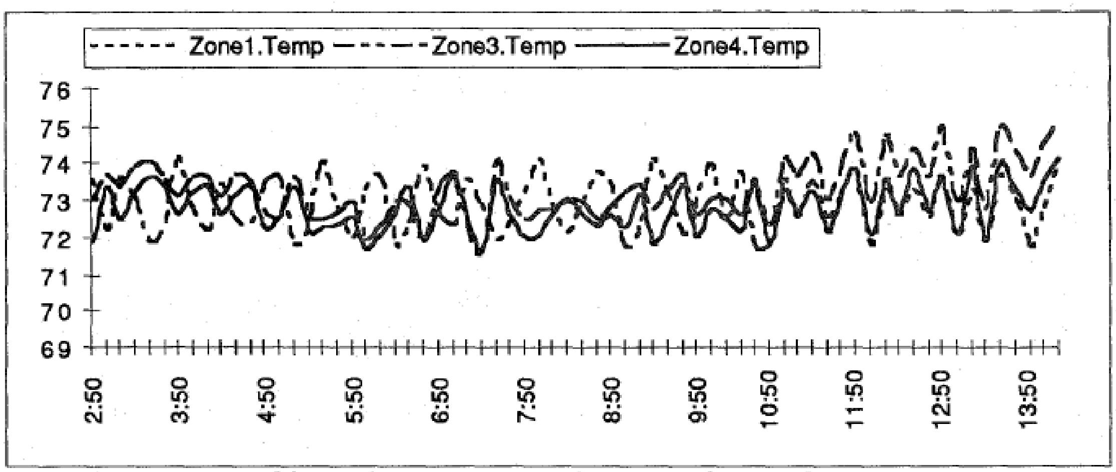


Figure 4. Temperatures for Zones 1,2, and 3

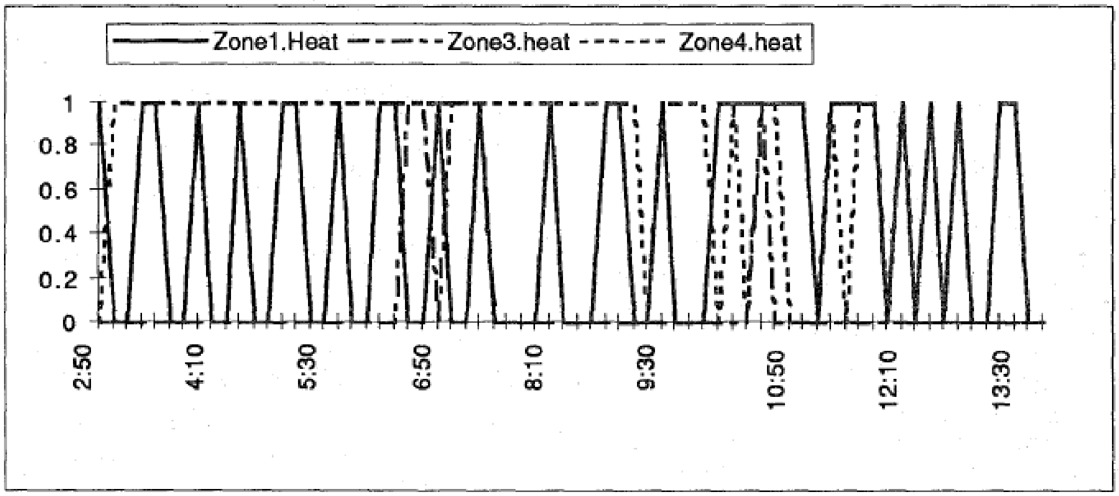


Figure 5. Zone1, Zone3, and Zone4 heat_flgs.

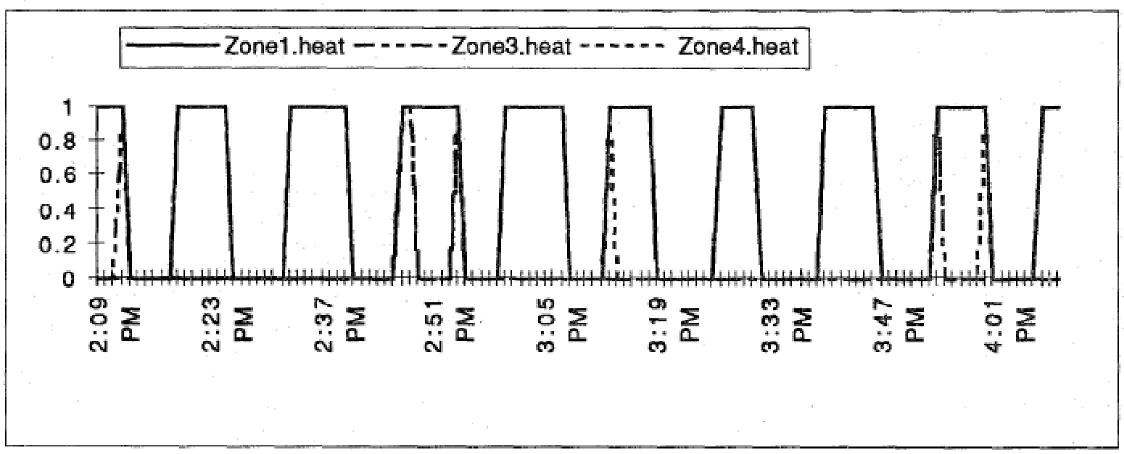


Figure 6. On/Off cycling of heater for zones 1, 3 and 4.

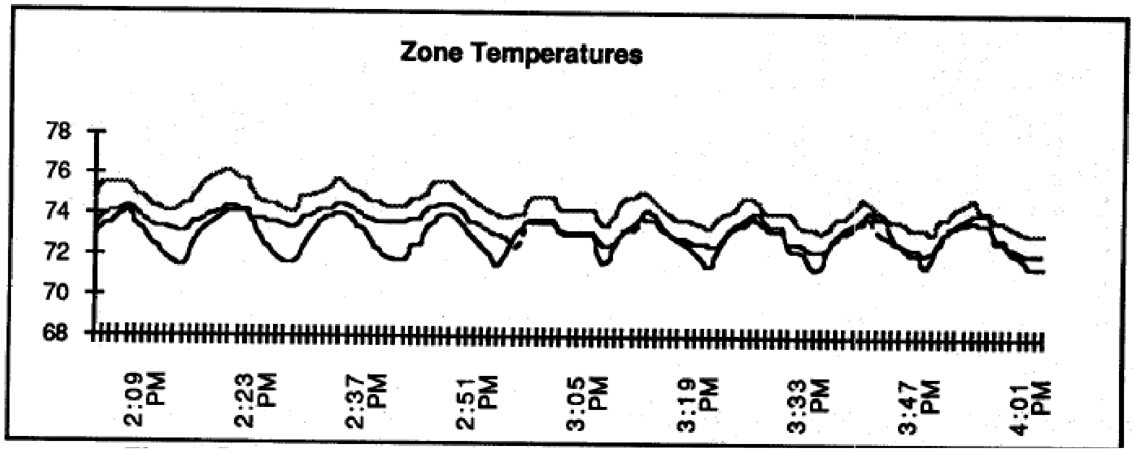


Figure 7. Zone1-bottom graph, Zone3-top graph, Zone4-middle graph.

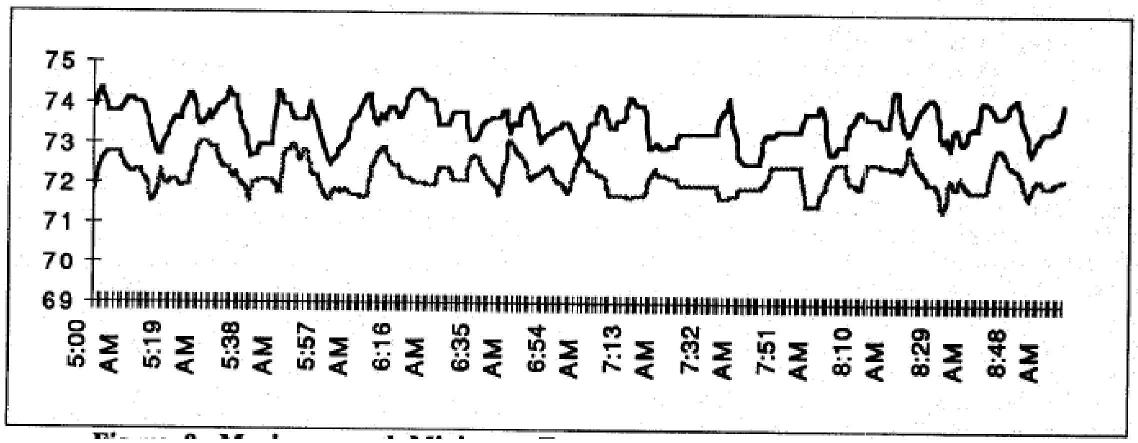


Figure 8. Maximum and Minimum Temperature

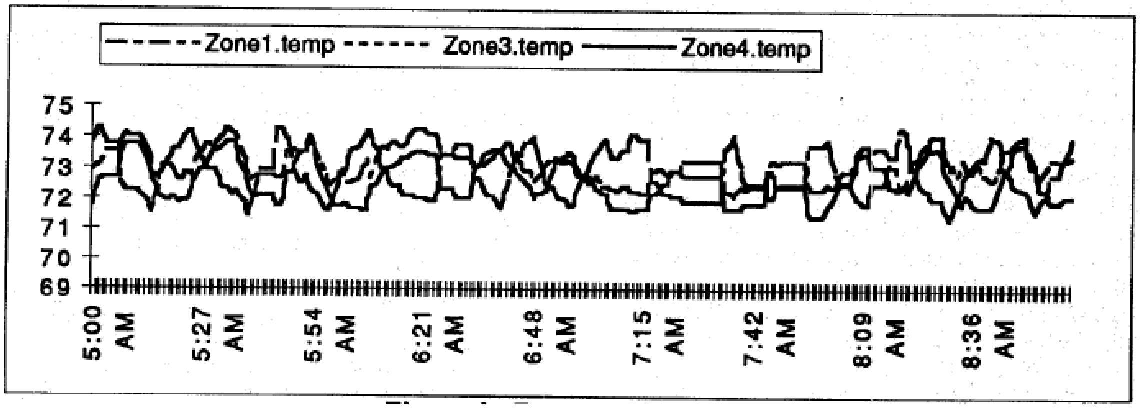


Figure 9. Zone Temperatures

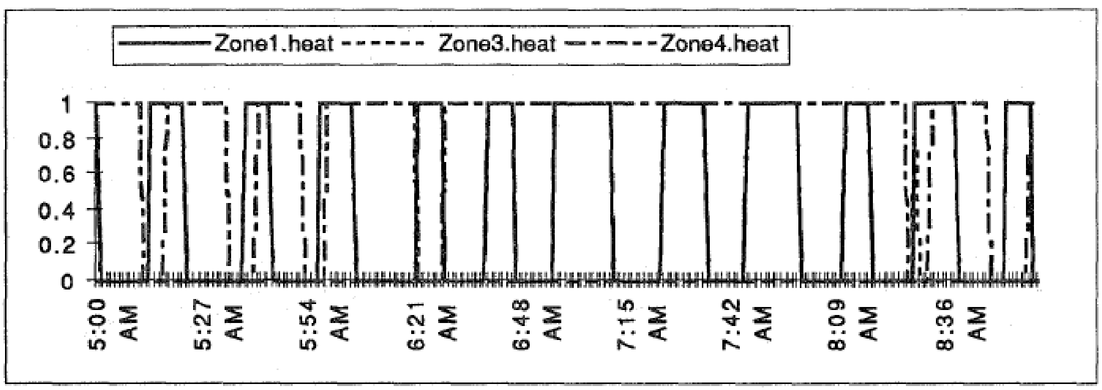


Figure 10. Zone Heat Flags

Later versions of the controller will address the problem of large variations of the temperature in different zones due to conditions such as occupancy, activity, and air circulation system configuration. Real savings could result from a modified version of the zone controller which will add the activity processing from motion detectors. With this modification the system will not only be able to avoid cooling one part of the trailer too much, but will also increase the level of required cooling when the zone is not occupied. It will not turn the system off to an occupied zone, since relative humidity control will still need to be maintained, but will increase the setpoint for that zone significantly. Similarly, for comfort reasons, if a high activity level is detected in a zone the setpoint will be lowered since high activity levels lead to higher relative humidity and increased temperature due to radiation.

Although our laboratory makes use of a variable speed fan compressor, we are focusing on the more usual situation that occurs in home air conditioners, or even commercial systems, in which variable speed compressors do not exist due to the expense. We feel that with a multi-speed circulation fan, with say three speeds, we could achieve good results in comfort and energy use performance, and as a result create a system which would be relatively inexpensive to install in a new home or to retrofit to an existing home. We will also simulate a system with single speed fan to see if the cost of multi-speed fan installation is justified by increased performance.

Initial results indicate that the system will work well from a comfort level standpoint. It also seems intuitively clear that by monitoring different zones, and regulating the air flow into these various zones by shutting off flow to zones where it is not needed and diverting the air into other zones, will make dramatic differences in energy use.

It also clear that the system we are building can be easily adapted to a chilled water system such as may exist in many commercial and state buildings. The logic would be essentially the same but would require different control devices such as valves, possibly, for regulating the flow of chilled water, as opposed as to varying the compressor speed.

2.2 A Fuzzy Control System Based on the Human Sensation of Thermal Comfort [4]

Maher Hamdi and Gérard Lachiver, Unlike the majority of the existing residential Heating, Ventilating and Air Conditioning (HVAC) control systems which are considered as temperature control problems, this paper presents a new HVAC control technique that is based on the human sensational of thermal comfort.

The proposed HVAC control strategy goal is not to maintain a constant indoor air temperature but a constant indoor thermal comfort. This is realized by the implementation of a fuzzy reasoning that takes into account the vagueness and the subjectivity of the human sensation of thermal comfort in the formulation of the control action that should be applied to the HVAC system in order to bring the indoor climate into comfort conditions. Simulation results show that the proposed control strategy makes it possible to maximize both thermal comfort of the occupants and the energy economy of HVAC systems.

Creating thermal comfort for occupants is a primary purpose of Heating, Ventilating and Air-Conditioning (HVAC) industry. In this context, there is a growing interest in the formulation of thermal comfort models that can be used to control HVAC systems [2, 3, 5, 10]. In spite of these theoretical studies, it is practically impossible to use the available mathematical models in the design of HVAC control systems because of three main reasons. First, thermal comfort calculation requires complex and iterative processing which make it impossible to implement in real-time applications. Second, the human sensation of thermal comfort is rather vague and subjective because its evaluation changes according to personal preferences. Finally, the thermal comfort sensation depends on several variables, which are difficult to measure with precision and at low cost. The thermal comfort is a non-linear result of the interaction between four environmental-dependant variables (air temperature, air velocity, relative humidity, mean radiant temperature) and two personal-dependant variables (the activity level and the clothing insulation) [2]. To compute a value of the indoor thermal comfort level, the environmental variables must be measured at a location adjacent to the occupant and the activity level and the clothing insulation must be known. In most applications, this is not possible.

To overcome these problems, some studies proposed simplified models of thermal comfort to avoid the iterative process. Such controllers have been proposed where simplified thermal sensation indexes have been calculated on the basis of significant modifications of the original thermal comfort models. Many researchers carried out that the assumptions under which the simplifications are made are difficult (or impossible) to reach in residential buildings and they are valid only in laboratory conditions. Fanger and ISO proposed in [2, 8] to use tables and diagrams to simplify the calculation of the thermal comfort sensation in practical applications. This method necessitates manual selection of the environmental variable setpoints that will create optimal indoor thermal comfort. From a practical point of view, this solution is difficult to use because it requires detailed knowledge of the HVAC control techniques.

The present paper investigates a new approach to resolve the above-mentioned problems by using fuzzy modeling. The main advantage of fuzzy logic controllers as compared to conventional control approaches resides in the fact that no mathematical modeling is required for the design of the controller. Fuzzy controllers are designed on the basis of the human knowledge of the system behavior. Since the human sensation of thermal comfort is vague and subjective, fuzzy logic theory is well adapted to describe it linguistically depending on the state of the six thermal comfort dependent variables. In the present work, fuzzy logic is used to evaluate the indoor thermal comfort level and to indicate how the environmental parameters should be combined in order to create optimal thermal comfort. The fuzzy rule base is formulated on the basis of learning Fanger's thermal comfort model, which is considered as the most important, and common used one [2].

This paper is organized as follows. First the problem limitation of HVAC conventional control strategies is exposed. Then, the design of the thermal comfort fuzzy system is described and applied to the control of the indoor climate of a single zone building. Finally, the superiority and the effectiveness of the proposed fuzzy system is verified through computer simulation using MATLAB® and TRNSYS® algorithms.

Recently, it has been pointed out that controllers that directly regulate human's thermal comfort have advantages over the conventional thermostatic controller [1, 3, 4, 9]. The main advantages are increased comfort and energy savings. In addition, thermal comfort regulation provides a comfort verification process. Although mathematical models are available to predict the human sensation of thermal comfort [2, 5], only the air temperature and the relative humidity are controlled in the majority of the conventional residential HVAC systems. The thermal comfort level and the other variables are difficult to quantify and therefore not used in classic control techniques. Presently, thermal comfort is ensured by the occupants who have to adjust the air temperature setpoint depending on their perception of the indoor climate. This practice is found to be inadequate to satisfy occupants desire to feel thermally comfortable. Occupants sitting near sunny windows or underneath air conditioning ducts or under hot and humid conditions will find the HVAC control strategy based only on air temperature is not adequate.

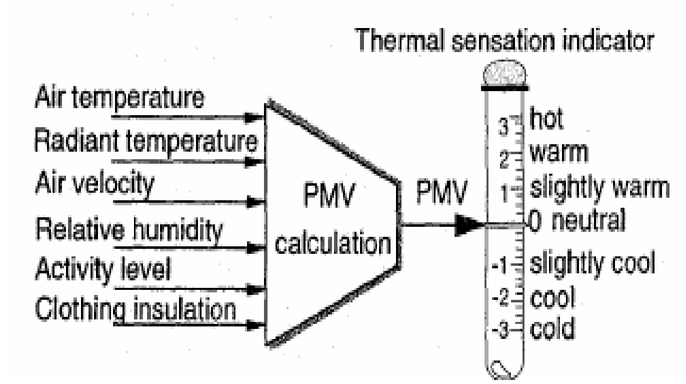


Figure. 11. PMV and thermal sensation

Over the past decades, numerous studies of thermal comfort have been achieved. The widely accepted mathematical representation of thermal comfort is the predicted mean vote (PMV) index [2]. This index is a real number and comfort conditions are achieved if the PMV belongs to the [-0.5, 0.5] range [2, 8]. Fig. 1 shows the subjective scale used to describe an occupant's feeling of warmth or coolness. However, since the human sensation of thermal comfort is a subjective evaluation that changes according to personal preferences, the development of a HVAC control system on the basis of the PMV model had proven to be impossible [1, 4, 9]. In fact, all classical techniques, including adaptive optimal controllers, requiring a crisp determination of the comfort conditions, are not suitable for handling this problem.

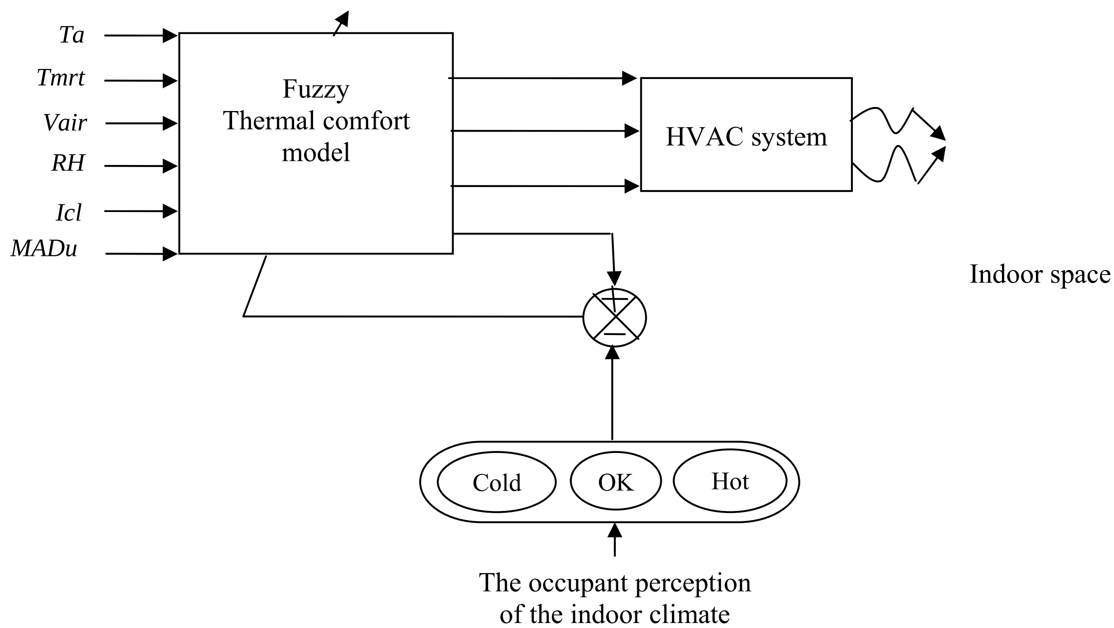


Figure 12. TCL-based Control of HVAC system

Even if the vagueness and the subjectivity of thermal comfort are the main obstacles in its implementation in classical HVAC controllers, fuzzy logic is well suited to evaluate the thermal comfort sensation as a fuzzy concept. The comfort range can be therefore evaluated as a fuzzy range rather than a crisply defined comfort zone. Presently, the fuzziness is not eliminated with the conventional HVAC control techniques, it is simply ignored by these conditions, the HVAC control system goal is to maintain a desired air temperature in a given indoor space. However, in everyday life, what is desired is not constant air temperature but constant comfort conditions. The fuzzy modeling of thermal comfort could be of importance in the design of such a control system that regulates thermal comfort level (TLC) rather than temperature levels. The control strategy based on comfort criteria will regulate the thermal comfort-influencing factors to provide thermal comfort in the indoor space. The TCL-based fuzzy controller establishes the desired setpoint values of the environmental variables to be supplied to the HVAC system and distributed in the building to create a comfortable indoor climate.

The Thermal Comfort Levels (TCL)-based fuzzy system starts with the evaluation of the indoor thermal comfort level depending on the state of the six parameters: air temperature (*Ta*), relative humidity (*RH*), air velocity (*Vair*), mean radiant temperature (*Tmrt*), the activity level of occupants (*MADu*) and their clothing insulation (*Icl*). Then, if the estimated thermal comfort level is out of the comfort range, the control algorithm will provide the air temperature and the air velocity set points that should be supplied to the HVAC system in order to create indoor thermal comfort. Fig.12 shows the block diagram of the HVAC control system based on the TCL.

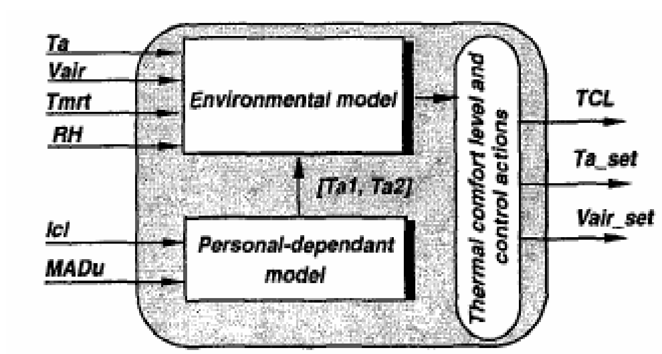


Figure. 13. TCL-based fuzzy sytem

Once the TCL is calculated, it is compared to the user's actual thermal sensation in order to improve the fuzzy approximation of the specific user's thermal comfort level (UTCL) on-line. So that, with time the fuzzy model of thermal comfort sensation exactly matches the specific occupant's actual thermal sensation. The on-line adaptation of the thermal comfort model is justified by the fact that each occupant possesses different attributes that will affect his or her thermal comfort due to biological variance. This adjustment is realized by changing the fuzzy state of the activity level of the occupant to take into account his or her specific metabolic rate.

The proposed architecture of the TCL-based fuzzy control system has two main advantages. It is equipped with an on-line comfort verification process and the possibility of the occupants-participation in the formation and the definition of the comfort range according to their personal-preferences. These characteristics could be of importance in the development of modern HVAC systems by using thermal comfort sensors to quantify the user's degree of thermal comfort/discomfort.

The fuzzy thermal comfort system is composed of three main subsystems which are interconnected as shown in Fig.13. The personal-dependant model is used to approximate the air temperature range [Ta1, Ta2] around which the users should be in thermal comfort according to the state of the activity level and the clothing insulation. This subsystem uses the triangular membership functions given in Fig.14 to describe the input and output variables. The fuzzy rule base shown in table 1 represents the set of fuzzy rules that are activated to evaluate the optimal temperature range.

Table 1. Fuzzy evaluation of the temperature range in which the thermal sensation is neutral

		Activity level		
		Low	***Medium***	***High***
Clothing insulation	***Light***	Very High	High	Medium
	Medium	High	Medium	Low
	Heavy	High	Low	Very Low
	Very heavy	Medium	Low	Very Low

The 12 fuzzy rules are expressed such as:

- IF the clothing insulation is Light AND the activity level is Low THEN the air temperature range should be Very High.
- IF the clothing insulation is Heavy AND the activity level is High THEN the air temperature range should be Very Low.

etc

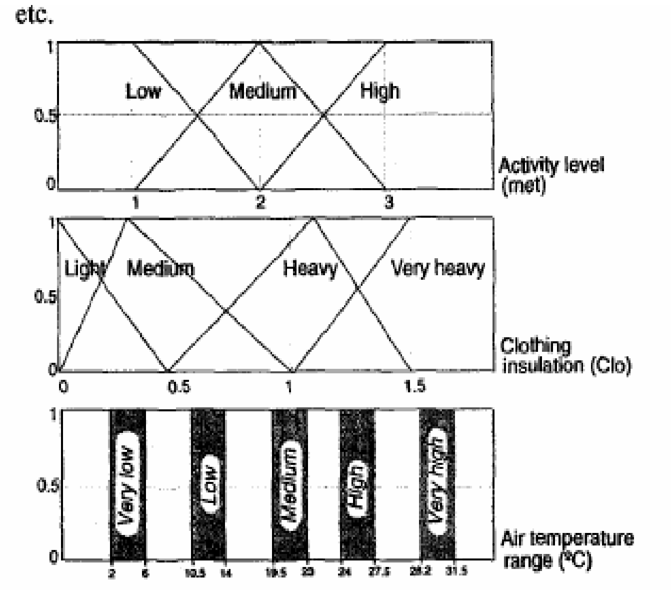


Figure. 14. Membership functions used in the personal-dependant fuzzy subsystem

Once the air temperature range is evaluated, it is supplied to the environmental model to determine the air temperature and the air velocity setpoints that will create indoor thermal comfort. The next subsections describe how to derive these two parameters for any combination of the four environmental variables.

The air temperature setpoint that will provide indoor thermal comfort is estimated according to the state of the air velocity, the mean radiant temperature and the relative humidity. This is realized in two steps. First, the air velocity is used to evaluate the air temperature setpoint for *RH* = 50%. Then, the air temperature setpoint is adjusted to compensate any deviation of the relative humidity from 50%. To this end, δT/δTmrt and the operative temperature (Ta0), which is the optimal temperature that will create thermal comfort when RH = 50% and Tmrt=Ta, are Tmrt=Ta, are estimated by using the membership functions and fuzzy terms (V1,….,V7), (T1,….,T7) and (ΔT1,….ΔT7) as shown in Fig.15. The fuzzy rule base represents the effect of the air velocity and the mean radiant temperature on the necessary air temperature that should create optimal thermal comfort. For a given air velocity, if the mean radiant temperature in a room is altered, e.g. due to changed outdoor conditions, or to crowding, or because lights are turned on, a different air temperature setpoint is required to maintain the indoor thermal comfort. This statement is transformed into a fuzzy reasoning composed of the following seven fuzzy rules:

- IF Vair is V1 THEN Ta0 is T1 and (δT/δTmrt) is ΔT1
- IF Vair is V2 THEN Ta0 is T2 and (δT/δTmrt) is ΔT2
- IF Vair is V3 THEN Ta0 is T3 and (δT/δTmrt) is ΔT3
- IF Vair is V4 THEN Ta0 is T4 and (δT/δTmrt) is ΔT4
- IF Vair is V5 THEN Ta0 is T5 and (δT/δTmrt) is ΔT5
- IF Vair is V6 THEN Ta0 is T6 and (δT/δTmrt) is ΔT6
- IF Vair is V7 THEN Ta0 is T7 and (δT/δTmrt) is ΔT7

The first rule can be interpreted as if the air velocity is very low, the operative temperature is close to Tal and an increase in the mean radiant temperature by 1ºC must be compensated for by a decrease of the temperature by 1ºC. However, the required air temperature increases and the δT/δTmrt falls with rising velocity. The deffuzification process is done using the centre of area method and the air temperature setpoint is therefore calculated as:

$$Tset = Ta0 + (Tmrt – Ta0).\ \delta T/\delta Tmrt \qquad (1)$$

The air velocity setpoint required to maintain thermal comfort conditions is evaluated by using the mean air temperature ((Ta + Tmrt)/2) as the input of the fuzzy subsystem. If the mean air temperature is in the temperature range [Ta1, Ta2], then the air velocity may vary between 0.1 – 1.5 m/s. The same membership functions of Fig.15 are used to describe the mean air temperature and the velocity setpoint. The fuzzy rule base used to evaluate the air velocity setpoint according to the mean air temperature state is deduced on the basis of analyzing the effect of each of them on the human sensation of thermal comfort. In all seven fuzzy rules are selected and expressed as:

- IF the mean air temperature is T1 THEN Vair is V1
- IF the mean air temperature is T2 THEN Vair is V2
- IF the mean air temperature is T3 THEN Vair is V3
- IF the mean air temperature is T4 THEN Vair is V4
- IF the mean air temperature is T5 THEN Vair is V5

- IF the mean air temperature is T6 THEN Vair is V6
- IF the mean air temperature is T7 THEN Vair is V7

Once the fuzzy rules are evaluated, the air velocity setpoint to calculated by using the centre of area method in the defuzzification step.

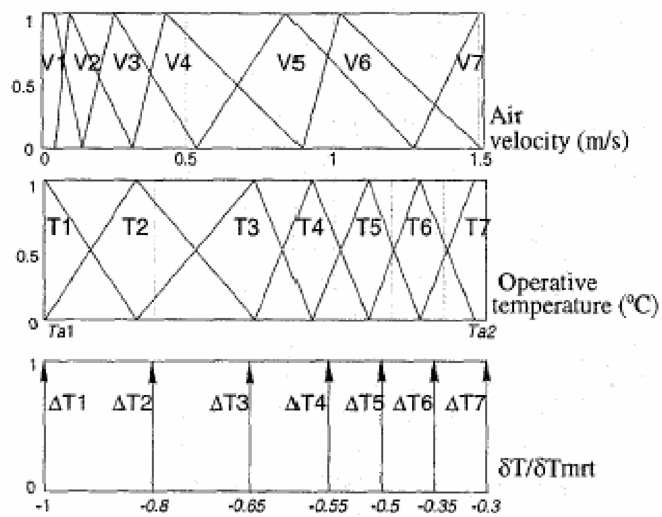


Figure. 15. Membership functions used to evaluate the optimal air temperature setpoint.

The effect of the relative humidity on the air temperature and the air velocity setpoints is relatively moderate since a change from absolutely dry air (RH = 0%) to saturated air (RH=100%) can be compensated for by a velocity increase Δv = 0.1 m/s or a temperature decrease of 1.5 ºC. These statements are added to the environmental model to adjust the output variables when the relative humidity deviates from 50%.

The TCL-based fuzzy system has been successfully tested for the control of HVAC system. Simulation results for the control of a single room climate are investigated. For numerical simulations, TRNSYS® algorithm which is a common used tool in the study of the interactions between the thermal environment and buildings and MATLAB® algorithm are used to verify the effectiveness of the proposed thermal comfort level fuzzy system.

Fig. 16 shows the outdoor temperature profile (a January day) and heat gains that the building was subject to. These included gains due to climatic factors such as solar gains and to lighting and machines. The profiles of the activity level of the occupants and their clothing insulation used in the simulation is given in Fig.17. Fig.18 shows a full day's simulation result of the TCL-based fuzzy system when applied for heating mode. It shows the air temperature setpoint in the top graph, the temperature tracking in the centre and the thermal comfort level in the bottom graph. These simulation show that the TCL-based fuzzy system is able to adjust the necessary air temperature setpoint to maintain the indoor thermal comfort as soon as the personal-dependant variables change.

In order to verify the superiority and the effectiveness of the proposed thermal comfort fuzzy system, two commonly used conventional techniques are simulated for the same indoor and outdoor conditions: night setback and constant setpoint thermostat system. For night setback, the thermostat setpoint was simulated at 70 F (21.1 C) from 6 a.m. to 10 p.m. and at 60F (15.6 C) from 10 p.m. to 6 a.m (Fig. 19). On the other side, the thermostat setpoint was simulated at 70F (21.1 C) for constant setpoint system (Fig. 20). The air temperature tracking and the resulted thermal comfort level of the occupants versus the hour of the day are given in figures 9 and 10.

For comparison purposes, the performance of the three HVAC control systems are studied. Table 2 gives the number of hours-per-day in which the occupants are comfortable (the thermal comfort level is in the [-0.5, 0.5] comfort range), the energy consumption and the percentage energy savings for each of the above-studied systems. The heating energy consumption is calculated by the integral of the simulated system energy demand when operating in the heating mode. Savings in energy consumption where determined by subtracting the totals obtained with the TCL fuzzy system and the night setback system from the totals obtained with the constant setpoint thermostat.

Table. 2. Performance of the three HVAC control systems for one day simulation

	Number of comfort hours [per-day]	Energy consumption	Savings
Constant setpoint thermostat	5 hours a day	8.25 kWh	
Night setback thermostat	10 hours a day	7.10 kWh	14 %
TCL- based fuzzy system	24 hours a day	6.6 kWh	20 %

This study shows that the TCL-based fuzzy control system provides better thermal comfort of the users with the possibility of energy savings. However, the night setback technique provides energy savings at the expense of the occupant's thermal comfort since the thermal sensation is out of the comfort range 10 hours per a day. The TCL fuzzy system is able to maintain the thermal comfort level in the comfort range during all the day even if the consumed energy is lower than that required by the classical techniques. Finally, it is important to note that the thermal comfort level is out of the comfort zone when the constant thermostat setpoint is used.

A new HVAC control strategy that regulates indoor thermal comfort levels is presented. Fuzzy logic is applied to the evaluation of the air velocity and the air temperature setpoints that should be supplied to the HVAC system in order to create indoor thermal comfort. The design of the thermal comfort-based fuzzy system is realized by extracting knowledge from Fanger's thermal comfort model. The architecture of the proposed control system allows easier evaluation of the indoor climate by using linguistic description of the thermal comfort sensation which make it simpler to understand and to process than having to solve iteratively a complex mathematical model. The simulation results show that the control based on thermal comfort levels provided by thermostatic control techniques.

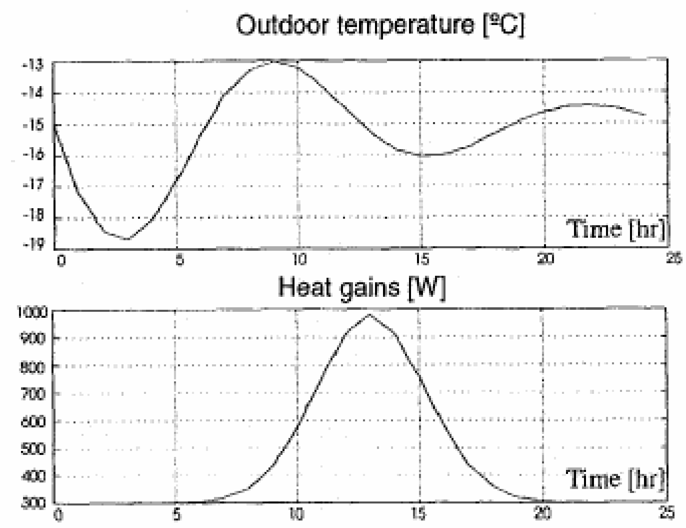


Figure. 16. Outdoor temperature and heat gains

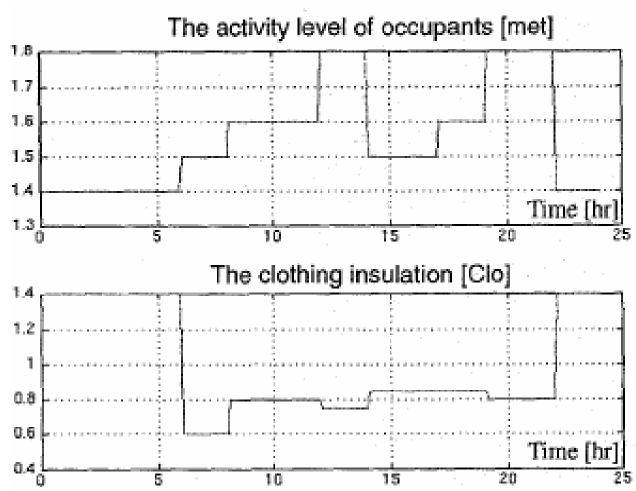


Figure.17.The personal-dependant parameters profiles during simulation (for 1 day)

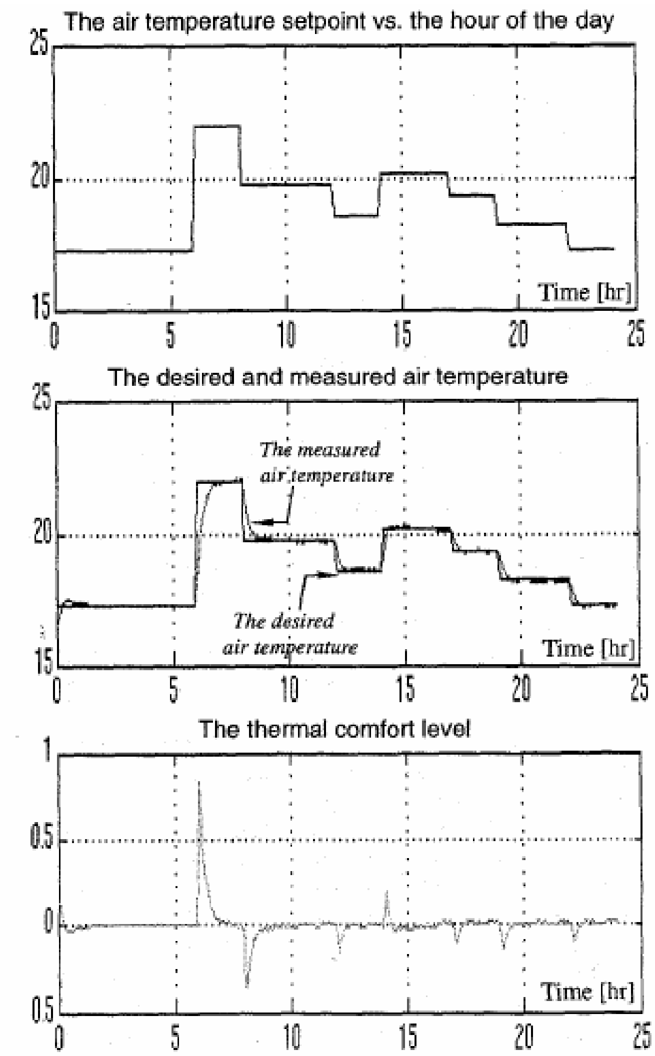


Figure. 18. Simulation results of the HVAC control system based on comfort level for heating mode.

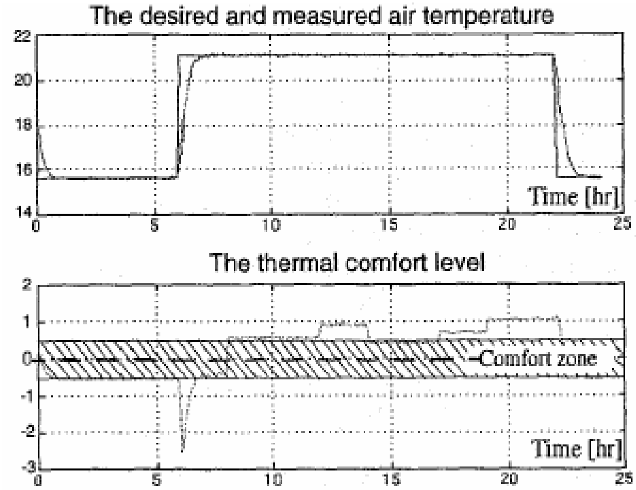


Figure.19. Simulation results of the HVAC control system based on night setback technique

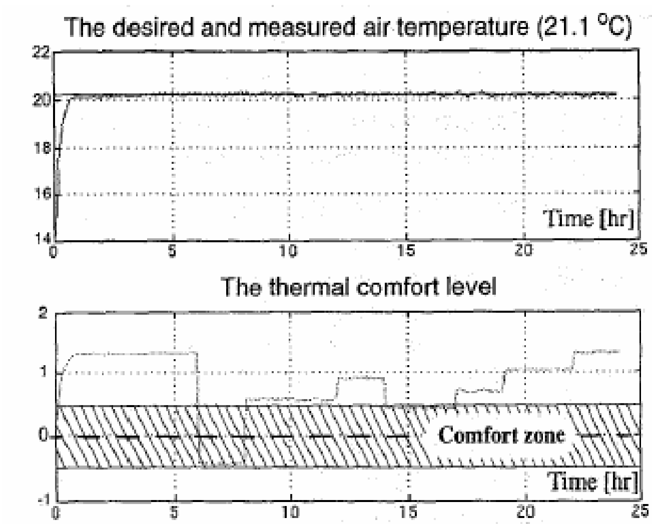


Figure. 20. Simulation results of the HVAC control system with constant thermostat setpoint

2.3 A New Fuzzy-based Supervisory Control Concept for The Demand-responsive Optimization of HVAC Control Systems [2]

H.-B. Kuntze and Th. Bernard, In many cases the user of multi-variable control systems is interested in operating them in a demand or event-responsive manner according to various, sometimes opposing performance criteria. E.g. within well isolated low-energy houses there is an increasing requirement to coordinate the control of heating, ventilation and air conditioning systems (HVAC) in such a way that both economy and comfort criteria can be considered with a user-specific tradeoff. In order to find an on-line solution of this multi objective process optimization problem, a new supervisory control concept has been developed at IITB. By means of a simple slide button the user is enable to choose his individual weighting factors for the economy and comfort criteria which are taken to optimize the reference commands of heating and ventilations of the room occupancy. The performance of the fuzzy-based multi objective optimization concept, which has been implemented and is being trialled in a test environment at IITB is analyzed and discussed by means of practice-relevant simulation results.

Due to the energy crisis and legal energy conservation requirements within the last decades in construction engineering more and more insulating building materials and construction techniques have been developed and introduced. By these measures a remarkably high energy saving has been achieved, however at the cost of a diminished natural air exchange within the buildings. In order to guarantee a sufficient air quality and living comfort it is compelling to introduce more and more controlled ventilation besides controlled heating facilities.

The demand-responsive coordination of both control loops is a tough problem for untrained users. On the one hand he is free to choose the reference commands of heating and ventilation control in such a way that his individual cost and comfort criteria are satisfied. On the other hand the climate state response within the living room in interaction with the outside climate is very complex and nonlinear. Thus the user will hardly comprehend all the consequences of his operations with respect to cost and comfort criteria. Obviously, there is an increasing demand on the HVAC (heating, ventilating and air conditioning) market for a user-friendly integrated control and monitoring concept of heating and ventilation control systems which is optimizable with respect to the individual comfort and economy requirements of the user.

In order to solve the multiobjective on-line optimization problem at the IITB a new fuzzy-logic supervisory control concept has been developed [1] which can be applied in principle to comparable problems in different industrial areas. Interestingly enough fuzzy-based optimization concepts have been almost exclusively applied to off-line planning and assistance problems in the area of operations research (cf. e.g. [2]). In the HVAC area fuzzy-logic approaches are mainly restricted to heating control problems [3].

The fuzzy-based supervisory control concept considered within this paper is not constrained only to the HVAC applications but can be adapted to various industrial processes. Especially in the steel and glass industry [4] there is an increasing demand to control processes optimally in terms of contradictory performance criteria (e.g. productivity versus product quality).

The climate dynamics within offices and living rooms is more complex as it seems to be at first sight. Thus, both the comfort perception as well as the energy consumption depends on the essential climate state variables such as temperature T_i, relative humidity φ_i and CO_2-concentration CO2i as reference gas of air quality. The climate state will be disturbed by different measurable or non-measurable influences of the outside climate as well as of the room occupancy. Measurable disturbance inputs are e.g. temperature T_o , relative humidity φ_o and CO_2-concentration $CO2_o$ outside as well as the presence of persons within the room. Non-measurable mainly stochastic disturbances are the heating flows, water vapor sources, air draft as well as CO_2-emissions caused by present person (cf. fig. 21).

For controlling the room climate in terms of T_i, φ_i and $CO2_i$ first of all controllable heating and ventilation facilities have to be installed. However, while the T_i can be selectively controlled e.g. by radiators φ_i and the $CO2_i$ are strongly coupled with each other. Thus, the air exchange rate AER which can be controlled by fans or tilting windows as auxiliary control variable.

As regards a feedback-control of T_i as well as φ_i or CO2, of rooms in the past different efficient concepts or products have been proposed (cf.e.g. [5]). Much less considered has been the supervisory control problem of T_i, φ_i and $CO2_i$.

The supervisory control concept introduced in this paper is based on the approach that the user chooses the performance requirements in terms of economy and comfort but not, as usual, the reference values of heating and ventilation controllers. By means of a simple slide button ("economy-comfort slider") he/she is enable to select the weighting factor λ ($0<\lambda<1$) of his individual comfort and economy requirement. If he/she is only interested in minimizing the heating costs he/she will choose $\lambda \rightarrow 0$. Vice versa he/she will select $\lambda \rightarrow 1$ if he/she prefers a comfortable living climate. Normally he/she tries to achieve a tradeoff within the range $0<\lambda<1$.

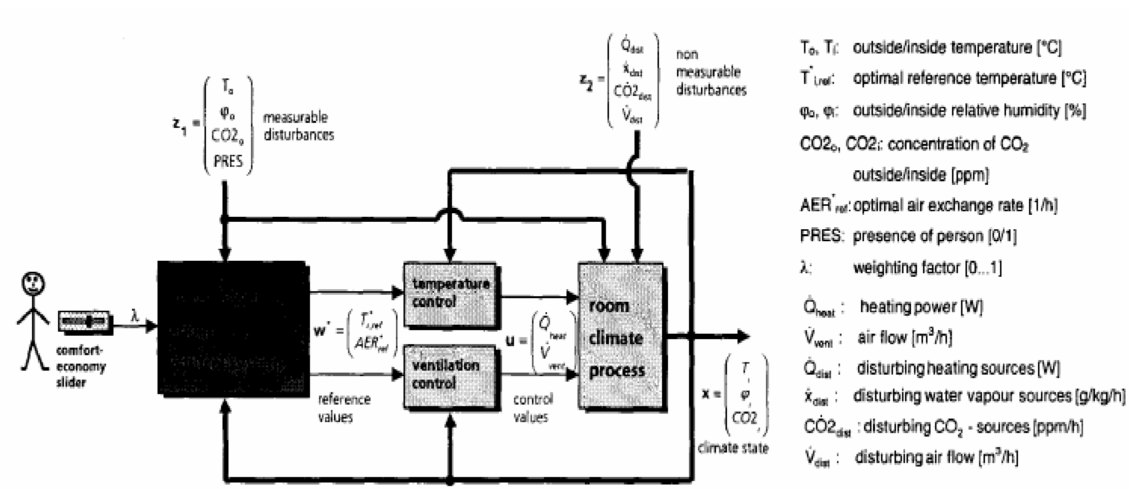


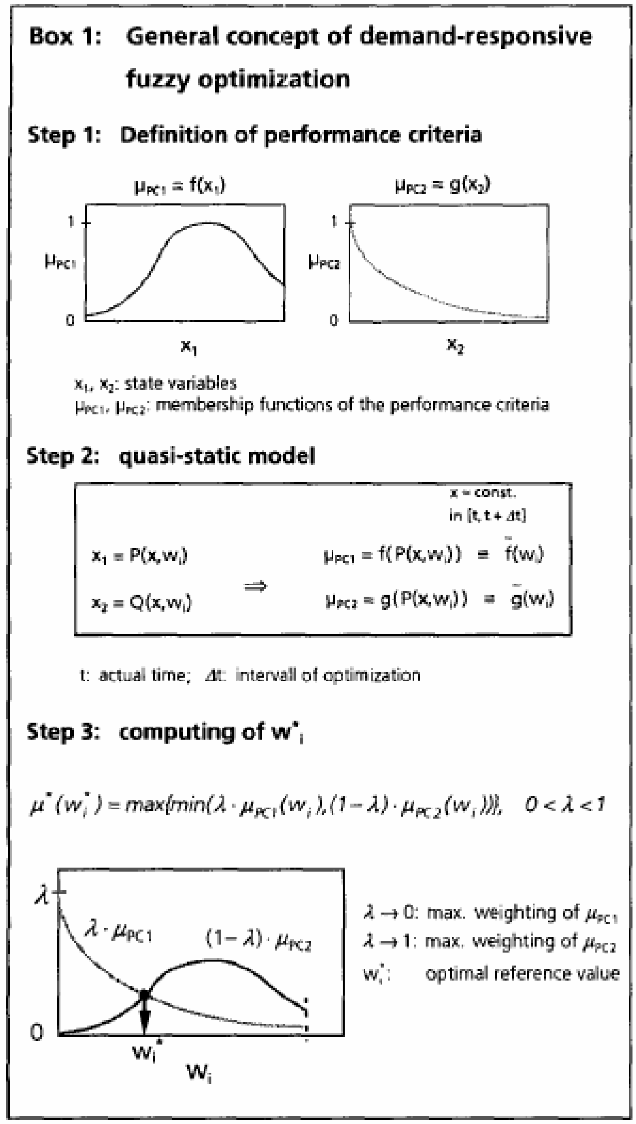
Figure. 21. The fuzzy based supervisory control and monitoring system for indoor temperature and sir exchange rate is superimposed to the temperature and ventilation control loops.

Based on the arbitrarily selected cost-comfort weighting, factor λ as well on the measured inside climate state (T_i, φ_i, $CO2_i$), outside climate state (T_o, φ_o, $CO2_o$) and the room presence rate (PRES) in the supervisory control system the optimal reference values of inside temperature control ($T^*_{i.ref}$) and of air exchange rate AER^*_{ref} are computed (cf. fig. 21). The multiobjective optimization of both reference values is based on a fuzzy-algorithm which will be derived in the following chapter.

In addition to the above nominal operation mode depending on special daytimes, seasons or events heuristic control elements can be inserted. E.g. in the absence of persons or during the night time an economy mode can be set automatically.

A controlled process will be considered in which the state variables x are completely controllable by the reference values w. Moreover, it will be assumed that the process will be controlled in terms of two different, sometimes contradictory performance criteria.

The aim is optimize the reference value w in a balanced way with respect to both criteria while the user can arbitrarily select his individual weight factor. For solving this multiobjective optimization problem a concept has been developed which can be structured into three steps. For better understanding of the following the optimization of only one reference value w_i in terms of two performance criteria will be considered (cf. box 1).



In the first step two performance criteria PC_1 and PC_2 will be defined by the fuzzy-membership functions φ_{GK1} and φ_{GK2} which depend only on one state variable. Since the performance criteria provide a diffused evaluation of process quality which is especially in climate processes very realistic for solving the multiobjective optimization problem, the theory of fuzzy decision making [7], [8] can be applied. It is based on the idea to consider the normalized performance criteria as fuzzy membership functions which can be optimized by introducing max-min operators. Physical constraints can be easily considered by setting the membership functions in the “forbidden” value ranges to zero.

In the second step a static or dynamic model is introduced which describes the relation between state variables x depending on both performance criteria and the reference value w_i to be optimized. Assuming the approximation that the process behaves quasi-stationarily in the considered optimization interval both performance criteria can be described in terms of the reference value w_i to be optimized.

In the case of strongly nonlinear processes the modeling may sometimes be difficult. However, for the fuzzy description containing some uncertainty in the majority of cases it is sufficient to use a simplified physical model in terms of few significant parameters.

In the third step by using a max-min operation the desired optimal reference value w^*_I will be obtained. By introducing the weighting parameter λ the individual importance of both performance criteria is considered. In the special cases $\lambda \rightarrow 0$ and $\lambda \rightarrow 1$ only one of both performance criteria PC1 and PC2 is optimized.

The multiobjective optimization approach for one output w^*_I outlined above can be easily enlarged to several outputs w^* if a weakly coupled MIMO process is considered of heating and ventilation control loops can be assumed.

For solving the optimization problem in a first step useful performance criteria of comfort and economy depending on $T_{i, ref}$ and AER_{ref} have to be defined.

Obviously, there are no universal models which can realistically describe the human comfort perception. In the HVAC technology, however, the limits of comfort in terms of temperature and air quality are well defined [6]. According to these standards the perceived temperature $T_{o\varphi}$ should be within the range 20…22ºC, the relative humidity φ_i between 30% and 70% and the CO_2-concentration $CO2_i$ down to 1000ppm. Since these parameters are only blurred recommendations it is useful to represent them by fuzzy-membership functions e.g. according to fig.22. Obviously, the shown fuzzy-membership functions μ_{comf} in terms of T_{op}, φ_i and $CO2_i$ represent the human-like comfort evaluation much better then step – like membership functions (dotted lines) of the classical binary logic. Moreover, the Fuzzy-parameters can be easily matched to individual user criteria.

The cost of inside temperature and air exchange rate results directly from the required heating power. Thus, a membership function is required which describes the economy rate of the HVAC in terms of heating power. A decreasing exponential function which can be easily parameterized by simple model equations is sufficient (cf. box 2). In accordance with reality the membership functions show a decrease of economy in terms of increasing inside temperature and air exchange rate as well as of decreasing outside temperature.

Box 2: Calculation of economy membership functions μ_{eco} in terms of T_i und AER

General approach: $$\mu_{eco} = e^{-\dot{Q}_{heat}/\dot{Q}_{nom}}$$

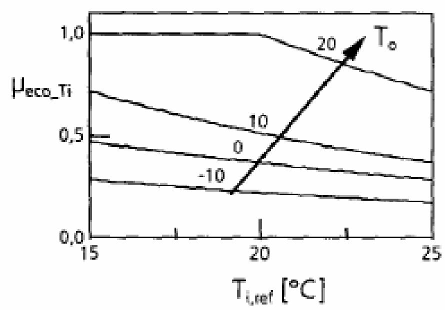
$\dot{Q}_{heat}$: heating power, $\dot{Q}_{norm}$: nominal power

For the inside temperature T_i:

$$\dot{Q}_{trans} = k \cdot A \cdot (T_{i,ref} - T_o)$$

$$\dot{Q}_{nom} = k \cdot A \cdot \Delta T_{nom} = const.$$

$$\Rightarrow \quad \mu_{eco\_Ti}(T_{i,ref}) = e^{-(T_{i,ref} - T_o)/\Delta T_{nom}}$$



$\dot{Q}_{trans}$: heating losses by transmission [W]

ΔT_{nom}: nominal temperature-difference [K]

k: coefficient of heat transission [W / m²K]

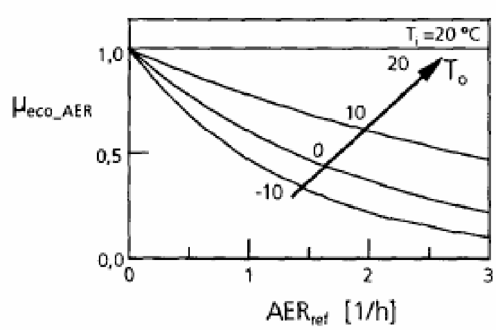
A: wall surface [m²]

For the air exchange rate AER:

$$\dot{Q}_{vent} = c \cdot \rho \cdot V \cdot AER_{ref} \cdot (T_{i,actual} - T_o)$$

$$\dot{Q}_{nom} = c \cdot \rho \cdot V \cdot AER_{nom} \cdot \Delta T_{nom}$$

$$\Rightarrow \quad \mu_{eco\_AER}(AER_{ref}) = e^{-AER_{ref} \cdot (T_{i,actual} - T_o)/AER_{nom}/\Delta T_{nom}}$$



$\dot{Q}_{vent}$: heating losses by ventilation [W]

AER_{nom}: nominal air exchange rate [1/h]

c: heat capacity of the air [J / kg / K]

ρ: air density [kg / m³]

V: room volume [m³]

After the definition of comfort and economy criteria according to chapter 3.2.1 and 3.2.2 the reference inside temperature $T_{i,\, ref}$ can be optimized. As regards the comfort criterium the direct dependence on $T_{i,\, ref}$ is defined by the membership function μ_{comf} (cf, fig. 22). The optimmizable relation between the economy membership function μ_{eco} and $T_{i,\, ref}$ can be derived from the model-equations (cf. box 2). Based on $\mu_{comf}(T_{i,\, ref})$ the optimization of $T^*_{i,ref}$ is obtained by min-max operations. The resulting dependence of the optimized reference temperatures $T^*_{I,ref}$ on the weighting factor λ and the outside temperature T_o is shown in fig.23.

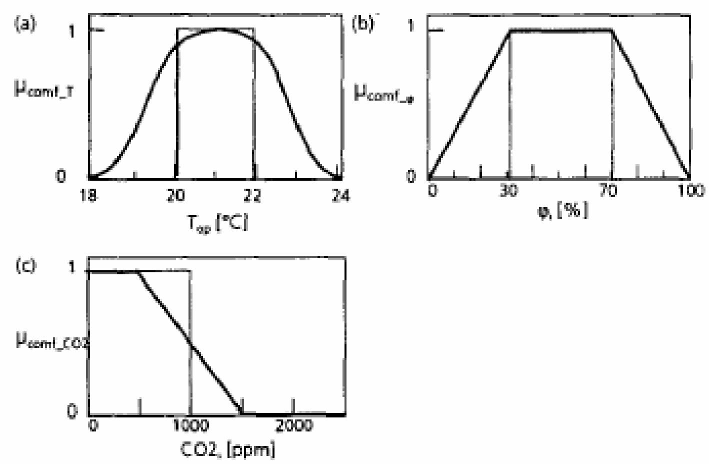


Figure. 22. Heuristic membership functions μ_{comf} in dependence of the perception temperature T_{op} (a), the relative humidity φ(b) and tbe CO_2 – concentration (c). Dotted lines are the membership functions based on binary logic.

The optimization of the air exchange rate AER_{ref} is somewhat more complex than the temperature optimization. While the economy criterium depends in a straightforward way on AER_{ref} to be optimized (cf. box 2) the comfort criterium is defined only in terms of CO_2-concentration $CO2_i$ and relative humidity φ_i but not directly in terms of AER_{ref}. The dynamic behaviour of $CO2_i$ and φ_i in terms of AER_{ref} which is disturbed by humidity- and CO2-sources (e.g. men) has to be considered in the optimization procedure.

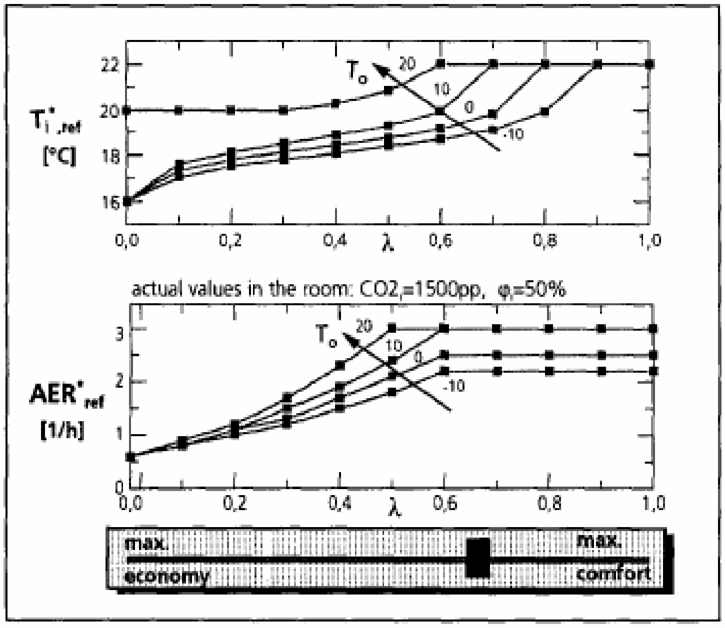


Figure. 23. Dependence of the optimal indoor temperature $T^{o}_{I,ref}$ and the air exchange reference AER^{o}_{ref} on the slider position λ and the outdoor temperature T_o.

Contrary to the static optimization of $T_{i,\,ref}$ in the optimization of AER_{ref} the transition dynamics have to be additionally considered. By means of an internal predictive model the time response of $CO2_i$ and φ_i is simulated and optimized at each sampling instant (e.g. every 5 minutes) over a prediction horizon (e.g. 15 minutes) in terms of the control variables AER_{ref} and the initial values of the measured variables $CO2_i$ and φ_i.

Thus contrary to the feedforward optimization of $T_{i,\,ref}$ (cf. chapter 3.2.3) a dynamic feedback optimization is applied to obtain AER^{*}_{ref} according to the concept of predictive functional control [9]. The internal model used for the feedback optimization which describes the dynamics of $CO2_i$ and φ_i in terms of AER_{ref} and internal disturbances, represents a nonlinear differential equation (cf. box 3). By means of that internal model for a desired dynamic response (e.g. low pass first order, time constant τ) the comfort membership function μ_{comf} can be described in terms of AER_{ref}.

Box 3: principle of dynamic feedback optimization with internal predictive model (e.g. CO_2 behaviour)

system behaviour:

$$\dot{CO2}_i = -AER_{ref} \cdot (CO2_i - CO2_o) + \dot{CO2}_{dist}$$

required dynamic response (low pass):

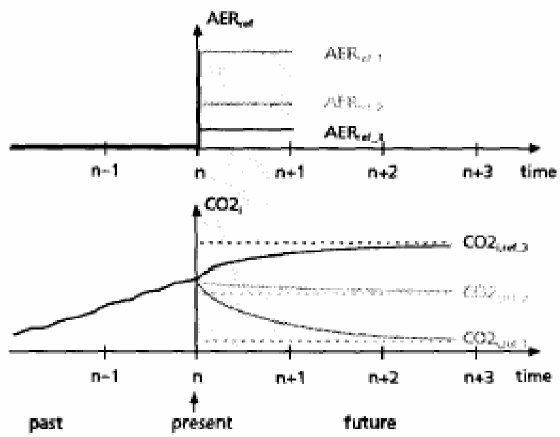
$$\dot{CO2}_i = -\frac{1}{\tau} \cdot (CO2_i - CO2_{i,ref})$$

$$\Rightarrow \quad CO2_{i,ref} = CO2_i + \tau \cdot \dot{CO2}_{dist} - \tau \cdot AER_{ref} \cdot (CO2_i - CO2_o)$$

$CO2_{i,ref}$: internal reference value

τ: time transition constant from $CO2_i$ to $CO2_{i,ref}$

prediction of system behaviour:



In order to combine $\mu_{comf}(CO2_i)$ and $\mu_{comf}(\varphi_i)$ a resulting membership function can be achieved by applying a min-operator. Finally the optimal value AER^*_{ref} results from a max-min operation of $\mu_{comf}(_{AERref})$ and $\mu_{eco}(_{AERref})$.

From the resulting nonlinear function of AER^*_{ref} in terms of the weighting factor λ the strong influence of outside temperature T_o can be seen (fig. 23). Since the outside humidity φ_o depends strongly on T_o the saturation limit of AER^*_{ref} depends on T_o as well. Just this dependence demonstrates the advantage of the proposed supervisory control concept over the non-coordinated operations of a user who hardly comprehends all the consequences of his heuristic control actions with respect to economy and comfort. The minimal value $AER^*_{i,\,ref} = 0{,}6/h$ in the case of highest economy (λ = 0) results from the limit value $CO2_i \leq 1500$ ppm recommended for comfortable air quality in living rooms [6].

In order to investigate system behaviour and performance of the fuzzy-based supervisory control concept under almost realistic conditions as regards the building physics or the climate scenario a simulation model has been generated in a MATLAB/SIMULINK software environment. The physical main structure as well as the essential influence variables are provided by fig. 21. The conventional ventilation and heating control loops which are subordinated to the fuzzy control system are assumed to have PI-behaviour. A sampling interval of Δt = 6 minutes was chosen. The considered building physics are characterized by a room volume of V = 50 m^3, a discretization of walls by five layers, an outside wall of a 20 cm brick layer and an isolation layer of 5 cm (k = 0.54 W/m^2k), inside walls of 15 cm brick layers (k = 1.82 W/m^2k) as well as one window (k = 2.0 W/m^2k). As regards disturbances internal heating sources Q_{int} = 100 W/Person, a CO_2 generating source of $CO2_{dist}$ = 10 Liter/h/person, a water vapour source of x_{dist} = 40g/kg/h/person as well as a constant temperature of neighbouring rooms $T_{neuighbour}$ = 15 ºC have been assumed.

From a great manifold of various simulation scenarios one example which represents the course of a typical winter day assuming three different adjustments of the fuzzy-based comfort-cost slider is considered in figure. 24. In order to demonstrate the fuzzy system response with respect to changing room occupancy and to the corresponding disturbances beginning at 8:00 a.m. the room presence is successively increased by 1 person per 2 hour cycle. At 6:00 p.m. all five persons leave the room.

The time response of inside temperature in fig.24 underlines the strong influence of different adjustments of the comfort-cost slider on the temperature reference value $T^o_{i,ref}$. It varies within a range which was defined by the chosen comfort membership function. For the slider positions "max. comfort", "medium" and "max. economy" it means $T^o_{i,ref}$ = 22 ºC, about 20 ºC and 18 ºC respectively. Moreover, the influence on the actual room presence PRES can be clearly seen. If the room is empty the fuzzy-optimization is deactivated, a constant set point $T^o_{i,ref}$ = 15 ºC is chosen.

From the time response of the air exchange rate AER_{ref} an automatic adaption with respect to altering room occupancy is visible. In the slider position “max. comfort” the ventilation is activated soon after the presence of the first person in order to maintain the defined CO_2-comfort level of 500 ppm. The strong dependency between temperature and relative humidity can be seen as well. The cold inflowing air from outside becomes considerably less humid when heated. Therefore the slider position “max.comfort” represents a tradeoff between the comfort demand with respect to CO_2-concentration and relative humidity while the CO_2-rate increases up to 700 ppm. Vice versa in the slider position “max. economy” the ventilation is not activated before the CO_2-concentration achieves the defined threshold of 1500 ppm. Then the relative humidity remains in an uncritical range.

Based on numerous simulations of various realistic scenarios of building physics and climate it could be proved that a considerable reduction of energy costs can be achieved by the optimally coordinated fuzzy-supervisory control of heating and ventilation systems. In the considered case in fig. 24 the required heating energy of 13.3 kWh at slider position “max comfort” can be reduced by more than 70 % at 3.7 kWh if the slider position “max. economy” is chosen.

In this paper a new fuzzy-based supervisory control concept for HVAC systems is presented. It enables the untrained user to easily and optimally operate his/her home heating and ventilation control facilities according to his/her individually weighted comfort and economy objectives. The performance with respect to energy saving and comfort improvement is demonstrated by different realistic simulations. On-going R&D activities deal with the implementation of the fuzzy concept in a marketable building automation and control system and with the experimental investigation in a demonstration center at the IITB. The modification of the fuzzy-based supervisory control concept to completely different multivariable industrial processes will be the subject of further research.

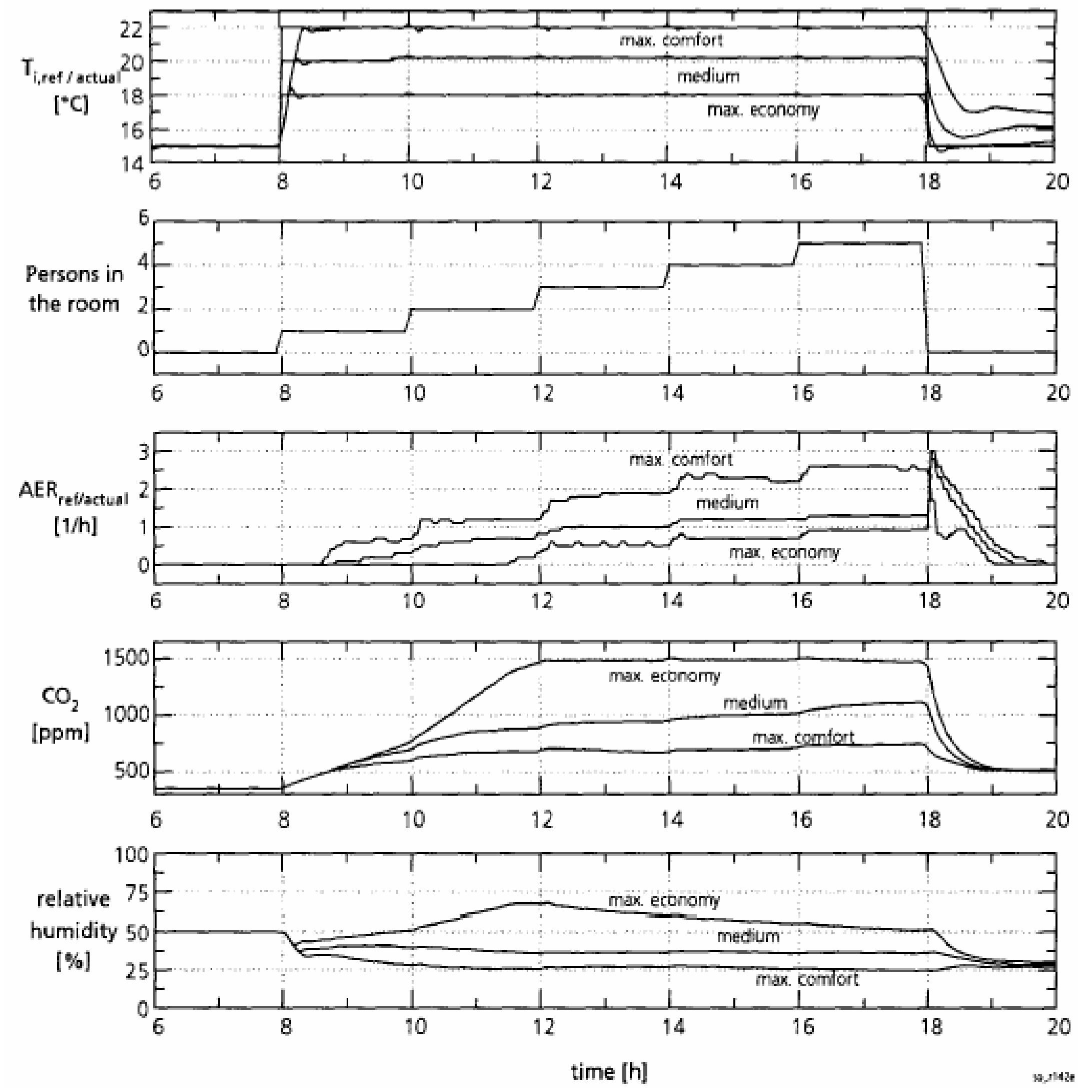


Figure. 24. Simulation at slider positions „max economy" (λ = 0.01), „medium" (λ = 0.5) and „max comfort" (λ = 0.99).

2.4 Application of Fuzzy Control in Naturally Ventilated Buildings for Summer Conditions [5]

M. M. Eftekhari, L. D. Marjanovic, The objective of this work is to develop a fuzzy controller for naturally ventilated buildings. Approximate reasoning has proven to be in many cases more successful control strategy than classically designed controlled scheme. In this paper the process of designing a supervisory control to provide thermal comfort and adequate air distribution inside a single-sided naturally ventilated test room is described. The controller is based on fuzzy logic reasoning and sets of linguistic rules in forms of IF-THEN rules are used. The inputs to the controller are the outside wind velocity, direction, outside and inside temperatures. The output is the position of the opening. A selection of membership functions for input and output variables are described and analyzed. The control strategy consisting of the expert rules is then validated using experimental data from a naturally ventilated test room. The test room is located in a sheltered area and air flow inside the room, the air pressures and velocities across the openings together with indoor air temperature and velocity at four locations and six different levels were measured. Validation of the controller is performed in the test room by measuring the air distribution and thermal comfort inside the room with no control action. These data are then compared to the air temperature and velocity with the controller in action. The initial results are presented here, which shows that the controller is capable of providing better thermal comfort inside the room.

There is currently a growing worldwide interest in low-energy building design. An important aspect of this is the goal of maximizing the effectiveness of the environmental control provided by the building envelope and minimizing the use of mechanical plant, especially in cooling systems. Much attention has been focused on taking advantage of natural ventilation; however, as it is driven by forces which are primarily of an uncertain nature, there is need to control the resulting airflow in order to maintain comfortable conditions. The ability to effectively control the indoor environment would considerably enhance the use of natural ventilation in buildings.

Current practice in naturally ventilated buildings is mainly manual control of openings or seasonal operation [1]. The use of negative feedback control for natural ventilation systems is inhibited by the difficulty of defining a representative sensed variable. In addition to the feedback loop some rule-based enhancement are required to take account of particular external conditions.

The principal objective in controlling the thermal environment in occupied spaces is to minimize the discomfort throughout the occupied region of the space. In most situations in which conventional feedback control is used, the air is well mixed and the variation in comfort conditions within the space is relatively small, so the signal from a single temperature sensor can be used as the controlled variable. In naturally ventilated spaces the air temperature and speed vary significantly with position and the form of their distribution also varies with the external conditions and with the position of the window or other control flow element.

The complexity of the problem suggest that a rule based control system would be most appropriate. A fuzzy control is particularly suited for controlling systems that cannot be easily mathematically modeled, but can be described by experts.

The primary objective of this research was to develop a fuzzy rule based controller, which can vary the resistance of ventilation opening in order to minimize the deviation from the desired comfort conditions. Rules were developed based on performed simulations [2,3] and available expert knowledge. The control strategy consisting of the expert rules is then validated using experimental data from a naturally ventilated test room. The test room is located in a sheltered area and air flow inside the room, the air pressures and velocities across the openings together with indoor air temperature and velocity at four locations and six different levels were measured. Validation of the controller is performed in the test room by measuring the air distribution and thermal comfort inside the room with no control action. These data are then compared to the air temperature and velocity with the controller in action. The initial results are presented here, which shows that the controller is capable of providing better thermal comfort inside the room.

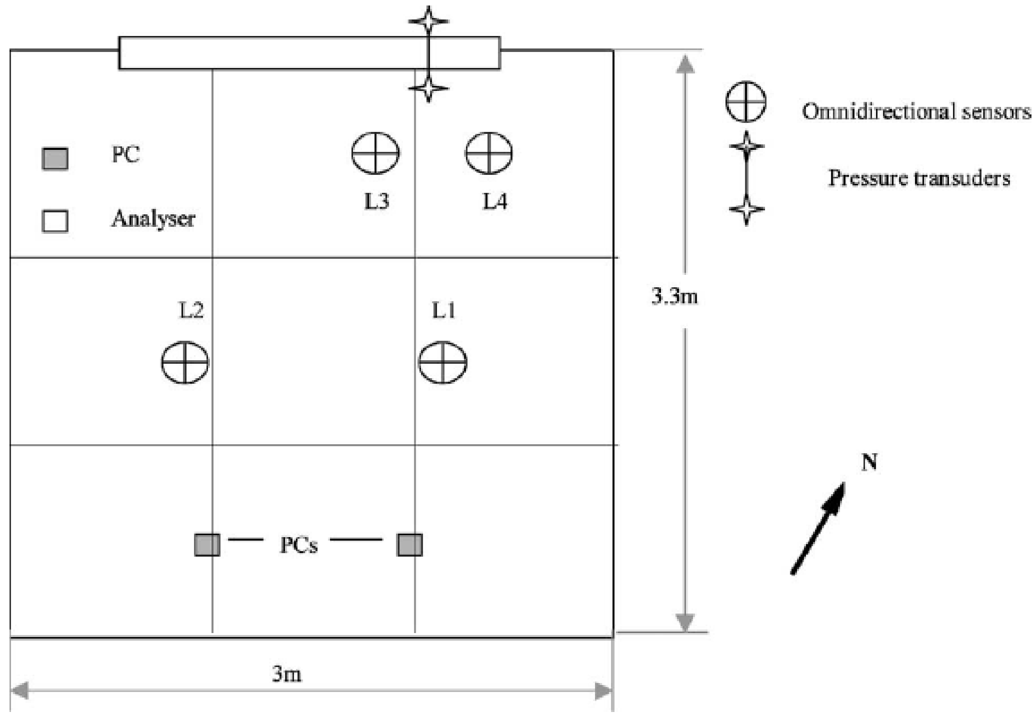


Figure. 25. The location of the sensors inside the test room and across the louvre

An existing portable cabin of light mass is used as a test room for natural ventilation at Loughborough University, located in a sheltered area. The room is fitted with four sets of horizontal slats metal louvers, and tracer gas measurements technique were carried out [4] demonstrated that a minimum ventilation of 8 l/s per person was achieved inside the test room what corresponds to opening level of 23% in respect to maximal opening position. To measure the indoor air flow distribution the room was divided into four zones and for each zone the temperature and velocity stratification were measured. During summer the internal heat loads inside the room were three computers, one flow analyzer and two fluorescent luminaries. Due to the sheltered position of the test room there was no solar gain into the room. During the experiments the size of the opening at the top and bottom was 0.07 and 0.12m2, respectively, with a 1.25m distance between the centre of the openings. Details of the *U*-values and the thermal capacity of the test room was described fully elsewhere [4].

Due to the sheltered nature of the test room, the external environmental weather conditions local to the test room were measured. Weather station sensors were mounted locally which measured the wind velocity, direction, outside air temperature, humidity and pressure. Inside the room mean air velocity and temperature were measured. The total pressure at top and bottom levels inside and outside across the louvers was recorded using low-pressure differential transducers. The reference pressure for all pressure measurements was the static pressure inside the room taken at approximately 1 m from the floor. Multichannel flow analyzer was used for the measurements of the inside air temperature and velocity at four locations and six levels above the floor. The positioning of indoor sensors is shown in Fig. 25.

The linguistic description of the dynamic characteristics of a controlled process can be interpreted as a fuzzy model of the process. A set of fuzzy control rules can be derived using experimental knowledge. This approach avoids rigorous mathematical models and is consequently more robust than a classical approach in cases which cannot be or are with grate difficulties precisely modeled mathematically.

The fuzzy logic controller's goal is to achieve thermal comfort inside the naturally ventilated room. Based on outside condition and inside temperature (inputs) the position of the openings (output) will be adjusted. The typical design scheme of an open loop fuzzy controller [5] which is used is shown in Fig. 26.

The basis of a fuzzy or any fuzzy rule system is the inference engine responsible for the inputs fuzzification, fuzzy processing and defuzzification of the output.

In fuzzy control applications to heating and air conditioning systems the usual number of membership functions describing input variables and actuating signals is between 3 and 7. Logic behind three membership functions is that in most cases it is enough to describe quantities or changes as "small", "moderate" or "big". In the case of further expenditure of subsets gets further divided into new three subset ("very big", "positive big" and "big" or "very very small", "very small" and "small"). The exception can be ambient temperature, which is often described with four membership functions.

Based on comfort criteria and specific aspects of natural ventilation membership functions for the input and output variables are defined. In Fig.27, the input variable inside temperature is described in terms of linguistic variables as “low”, “acceptable” and “high”. Since it is important to establish the relationship between the inside and outside temperature, the minimum number of linguistic variables describing outside temperature should be also three. Membership function describing input variable outside temperature is presented in Fig. 28.

Wind velocity of 7 m/s in natural ventilation applications is marked as a critical one after which all openings should be closed. Changes in wind speed over a moderate range does not influence air velocity inside single-sided ventilated space as much as it does for a cross ventilation. This has been confirmed by performed measurements and simulation in a test room. This argumentation led to a conclusion that one membership function describing very strong wind would be enough.

In natural ventilation applications the recording of any rain presence is compulsory. Opening should be closed or in a safe position in the case of rain detection as well. Membership functions describing wind velocity and rain presence are shown in Figs. 29 and 30, respectively.

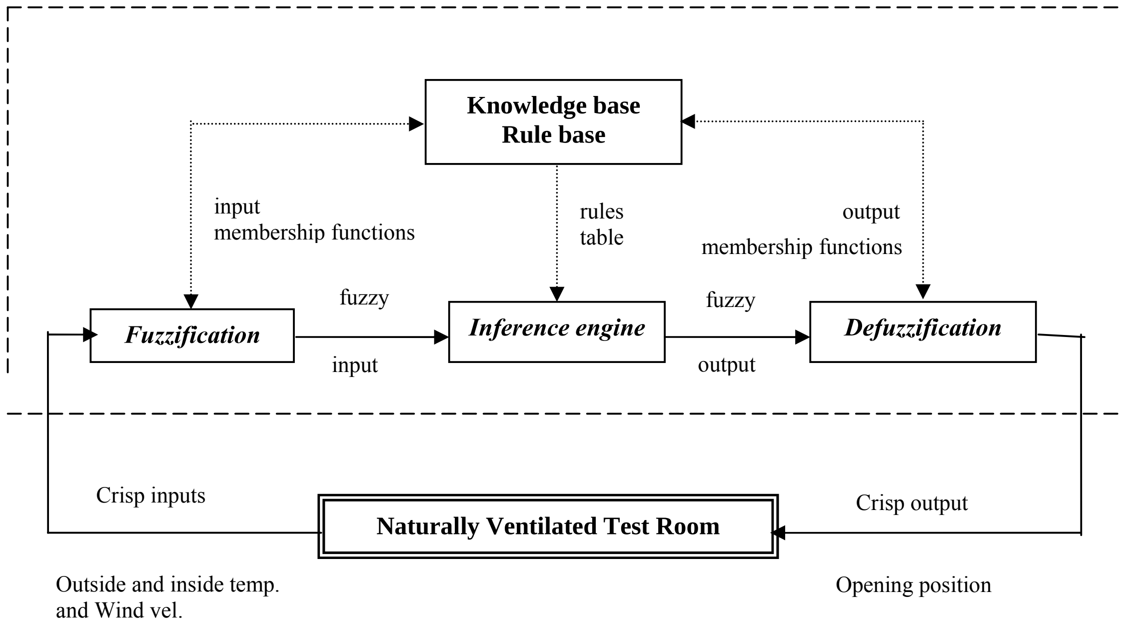


Figure.26. Basic Configuration of Fuzzy Logic Controller

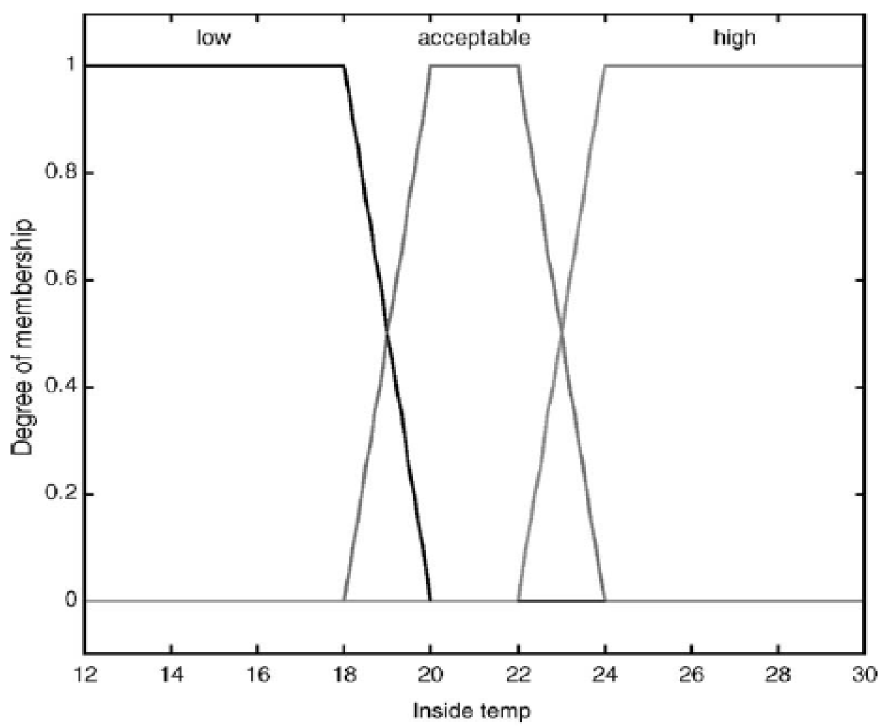


Figure.27. Membership functions for inside temperature.

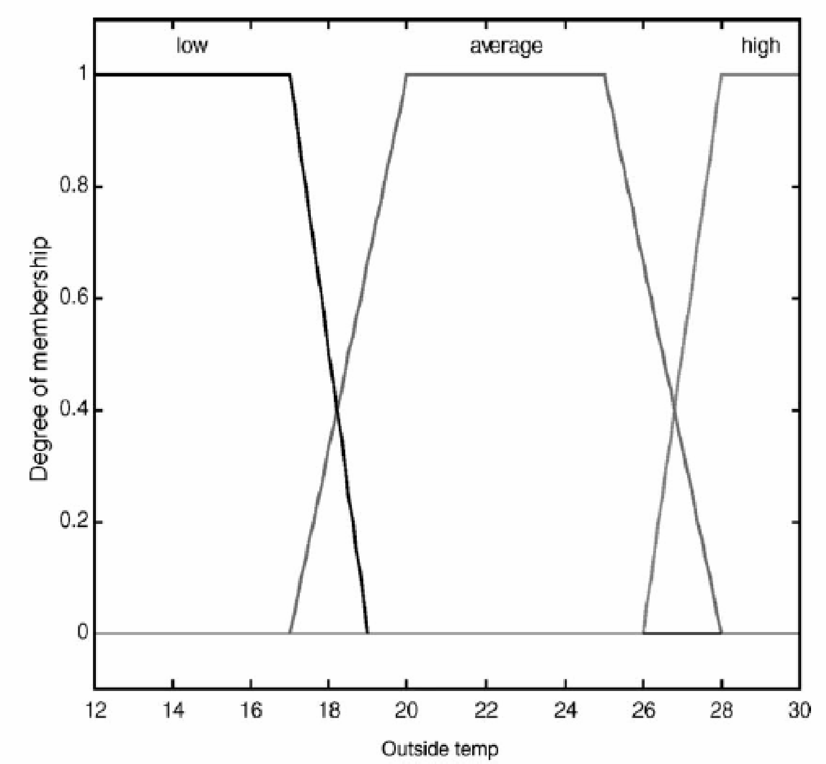


Figure. 28. Membership functions for outside temperature.

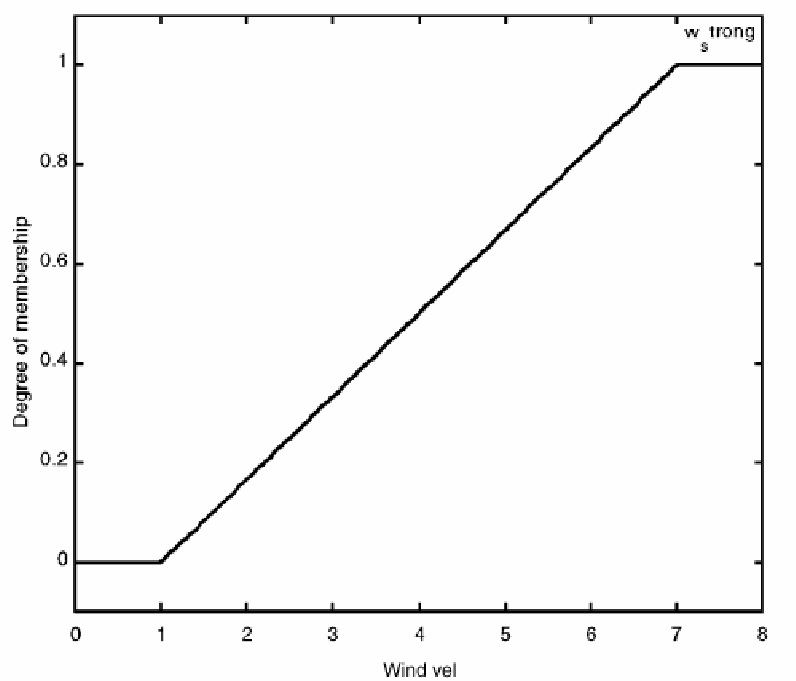


Figure. 29. Membership function describing wind velocity.

Control element in the case of natural ventilation only is the opening position. As any other ventilation control element it should have some predetermined nominal position which would correlate with min ventilation requirements. In respect to the nominal position, the area of the openings (output) can increase or decrease, as presented in Figure.31, allowing more or less air to enter the space depending on environmental conditions.

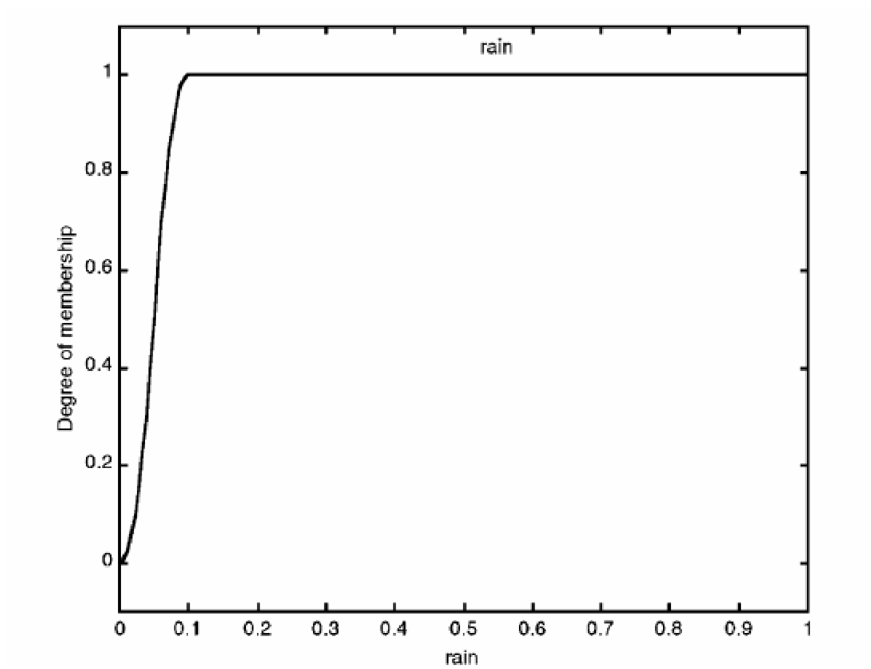


Figure. 30. Membership function describing rain.

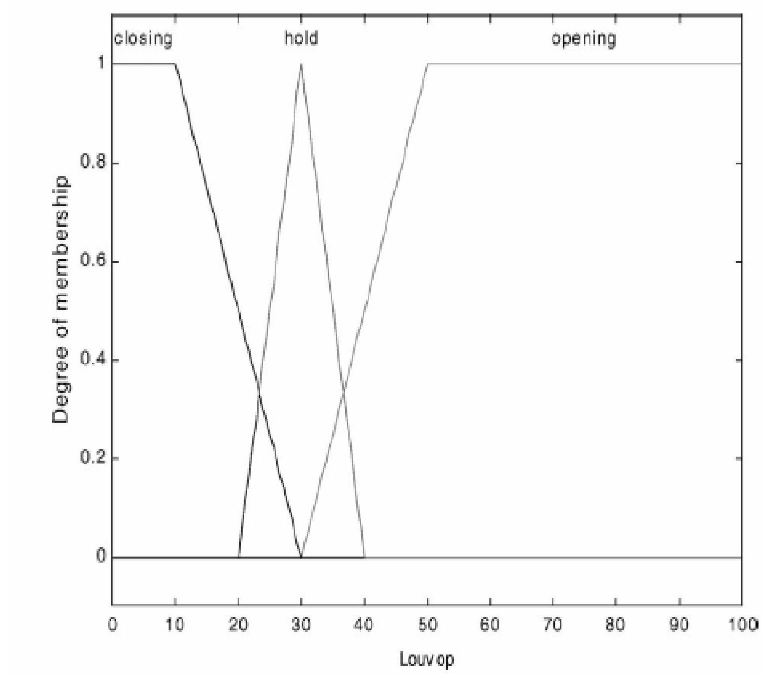


Figure. 31. Membership functions for linguistic variables describing opening position

Table.3. Fuzzy rules for natural ventilation, simple solution

Fuzzy rules for natural ventilation, simple solution

IF	Wind velocity is vvstrong	OR	Is raining	THEN	Louvre opening is closing
IF			Inside temperature is acceptable	THEN	Louvre opening is hold
IF	Outside temperature is low	AND	Inside temperature is low	THEN	Louvre opening is closing
IF	Outside temperature is not low	AND	Inside temperature is low	THEN	Louvre opening is opening
IF	Outside temperature is high	AND	Inside temperature is high	THEN	Louvre opening is closing
IF	Outside temperature is not high	AND	Inside temperature is high	THEN	Louvre opening is opening

While the differential equations are the language of conventional control, IF-THEN rules about how to control the process are the language of fuzzy control. Fuzzy rules serve to describe the quantitative relationship between variables in linguistic terms. Instead of developing a mathematical model of a single-sided natural ventilated space, a different approach has been adopted and knowledge based system is implemented. The system aims to make the correct decision about how to move the louvers according to environmental conditions. For summer conditions that practically means that as long as outside temperature is smaller than inside the outside air should be let in to allow cooling.

Several rule bases of different complexity have been developed for the controller. One possible set of rules for input variables defined in Figs. 27-30 is given in Table 3.

The number of rules in the controller will depend on the total number of linguistic variables. It is certainly possible to describe in more details at least some of the input variables. In describing outside temperature universe for summer conditions there is obviously a room for more than three membership functions. Description of the outside temperature with five membership functions as “very low”, “low”, “average”, “high” and “very high” is presented in Fig. 32.

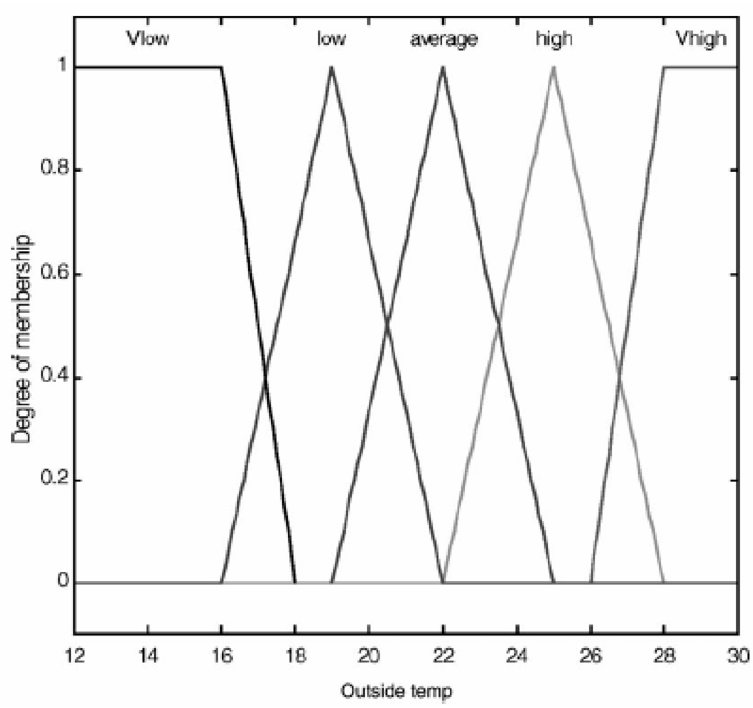


Figure. 32. Outside temperature and the corresponding five membership functions

If the outside temperature is described by five membership functions that allows controller not only to detect the difference between the outside and inside temperature but also to evaluate its magnitude. In that case it is logical to allow different levels of louver opening and closure. The louver position described by four membership functions is presented in Fig. 33. New membership function “closed”, is introduced in order to make a difference between closure due to security reasons (rain or wind) and closure due to temperature difference.

For these new membership functions, a new set of IF-THEN rules was developed, which is given in Table.4.

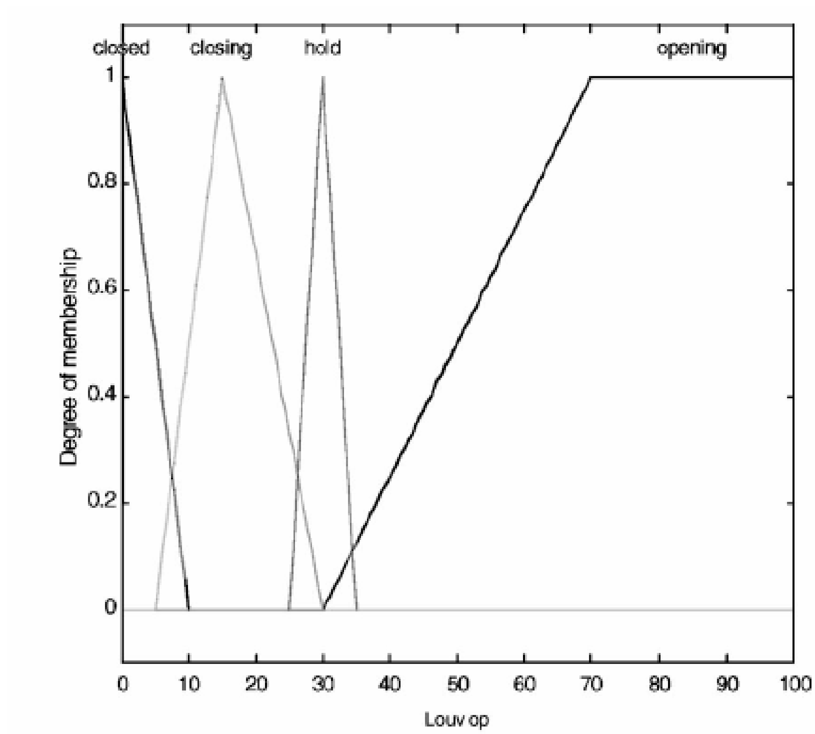


Figure. 33. Louvre opening and the corresponding four membership functions

In this particular case the fuzzifier was very simple; the real input was fuzzified according to appropriate input membership function [9].

The inference engine applies Mamdani min-max method. A single fuzzy IF-THEN rule assumes the form

IF x is A and y is B THEN z is C

where A, B and C are fuzzy sets. In IF-THEN rules the term following the IF statement is called the *premise* or antecedent and the term following THEN is called the *consequent.* Degree to which premise is true is called the degree of applicability of the premise part usually denoted as β and calculated as t-norm: $\beta = A_1 (x_1) \text{ t } B_1 (x_1)$. Fuzzy controllers in general have more than one rule. Depending on the input values some rules are fired and some are not. Each fired rule produces the fuzzy set output. Overall fuzzy output is obtained by applying the s-norm operator on all rule outputs: $C = C_1 \text{ s } C_2 \text{ s } \ldots \text{ s } C_{n \text{ rules}}$. Depending on the definition of t and s norms used to process fuzzy IF-THEN rules, there are many proposed methods in the literature. The most common used is direct Mamdani method. In this method the final output membership function for each output is the union (maximum operator) of the fuzzy sets assigned to that output after scaling their degree of membership according to corresponding premise degree of applicability using min operator for t-norm.

The defuzzifier uses the centre of area method to compute the crisp values needed to drive the actuator:

$$z_{COA} = \frac{\sum_{j=1}^{n_{rules}} C_i(z_j) z_j}{\sum_{j=1}^{n_{rules}} C_i(z_j)}$$

where $C_i(z)$ are the membership function values of each rule and z_j the support values of the quantization levels.

The weather data for the tests performed on 19 June 1998 (test 1) and 22 June (test 2) with the wind directly towards the openings (windward) are shown in Fig. 34. The measured temperatures for all four locations across the room during the test are shown in Fig. 35. The average inside temperature on all locations during the tests 1 and 2 was 25.6 and 22.34 ºC respectively.

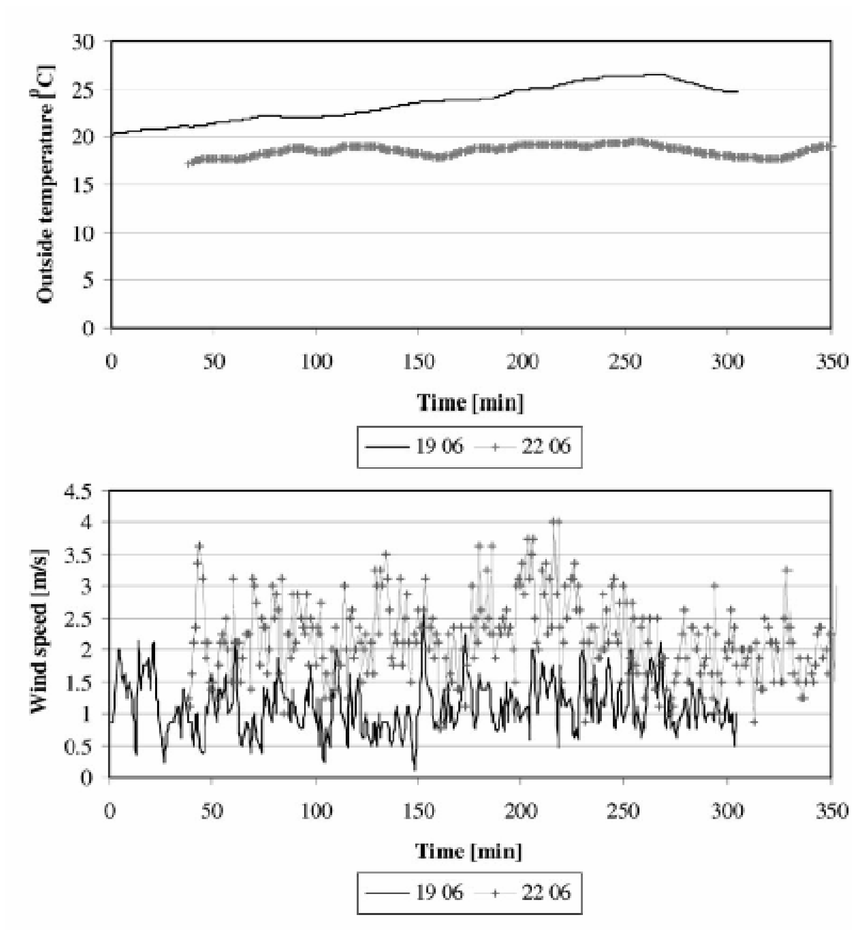


Figure. 34. The outside conditions for the test on 19 and 22 June

Table. 4.

Fuzzy rules for natural ventilation, model 2

IF	Wind velocity is vvstrong	OR	Is raining	THEN	Louvre opening is closed
			Inside temperature is acceptable	THEN	Louvre opening is hold
IF	Outside temperature is very low	AND	Inside temperature is low	THEN	Louvre opening is closed
IF	Outside temperature is low	AND	Inside temperature is low	THEN	Louvre opening is closing
IF	Outside temperature is average	AND	Inside temperature is low	THEN	Louvre opening is opening
IF	Outside temperature is high	AND	Inside temperature is low	THEN	Louvre opening is opening
IF	Outside temperature is very high	AND	Inside temperature is low	THEN	Louvre opening is opening
IF	Outside temperature is very high	AND	Inside temperature is high	THEN	Louvre opening is closed
IF	Outside temperature is high	AND	Inside temperature is high	THEN	Louvre opening is closing
IF	Outside temperature is average	AND	Inside temperature is high	THEN	Louvre opening is opening
IF	Outside temperature is low	AND	Inside temperature is high	THEN	Louvre opening is opening
IF	Outside temperature is very low	AND	Inside temperature is high	THEN	Louvre opening is opening

The control Model 2 was used to test the fuzzy rules shown in Table 2. Simulation was performed for several different possible levels of inside temperatures chosen according to Inside Temperature membership functions and for outside conditions (outside temperature and wind velocity) for both tests. The results for inside temperature of 19, 21 and 23 ºC for both tests are given in Figs. 36 and 37, respectively.

For inside temperatures below 19 ºC the opening positions were similar to that of temperature of 19 ºC as shown in Figs. 36 and 37. In the case of test 1 when outdoor temperature is considerable “high”, and the inside temperature “low”, the louvers are open more depending on the wind speed. For the test 2 when outdoor conditions when outdoor temperature is relatively low, with the further drop outdoor temperature louvers would be closing down. For temperature higher than 23 ºC the controller behavior is similar to that of inside temperature of 23 ºC.

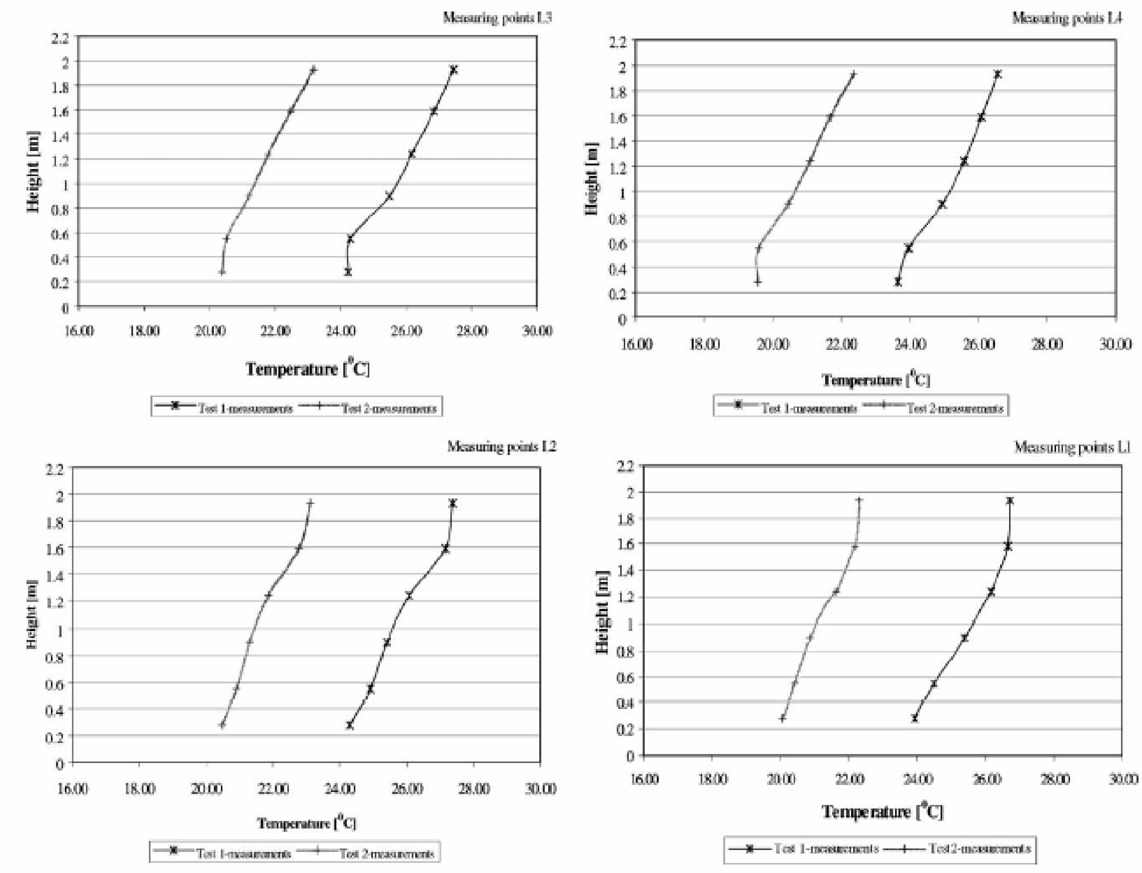


Figure. 35. The temperature variations with height at all four locations.

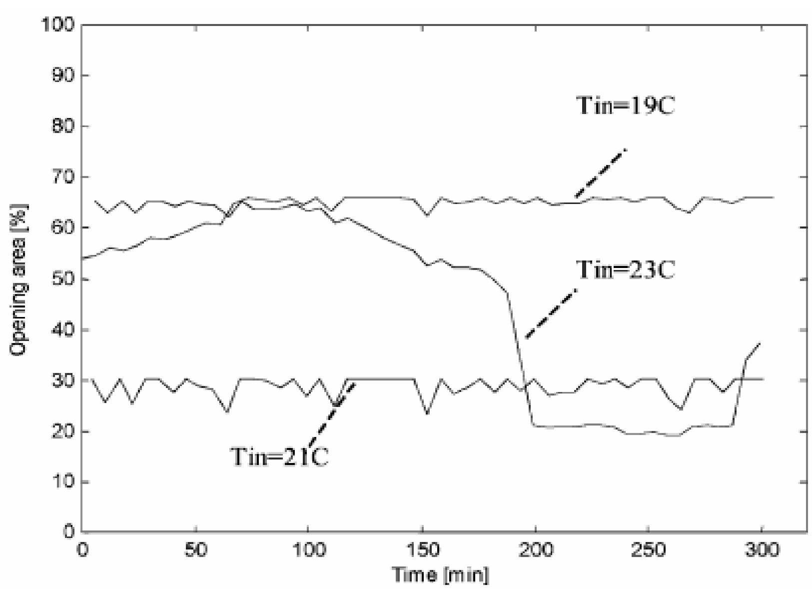


Figure. 36. Simulated louver opening for the test 1 outside conditions and different inside temperatures.

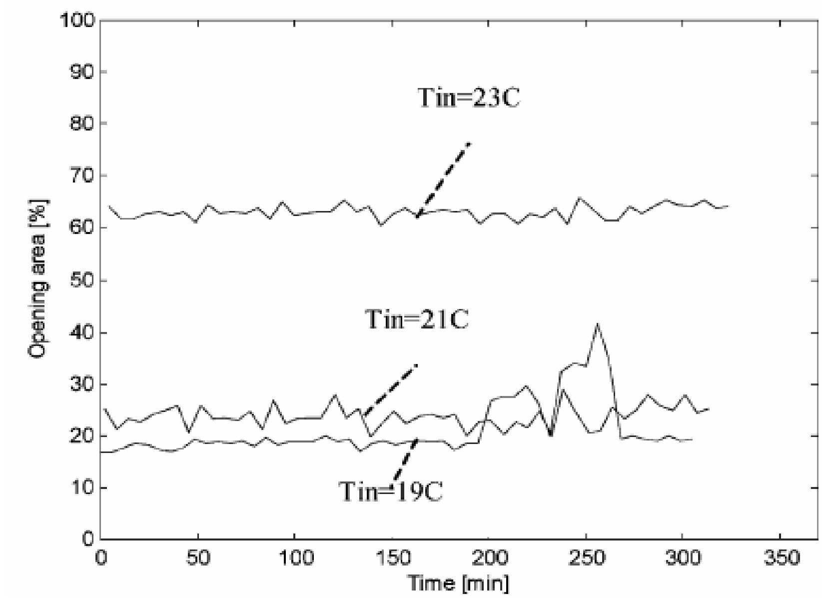


Figure. 37. Simulated louver opening for the test 2 outside conditions and different inside temperatures.

It was found that the critical inside temperature after which fuzzy controller Model 2 would increase the opening area in respect to nominal position is 22 ºC, as shown in Fig. 38.

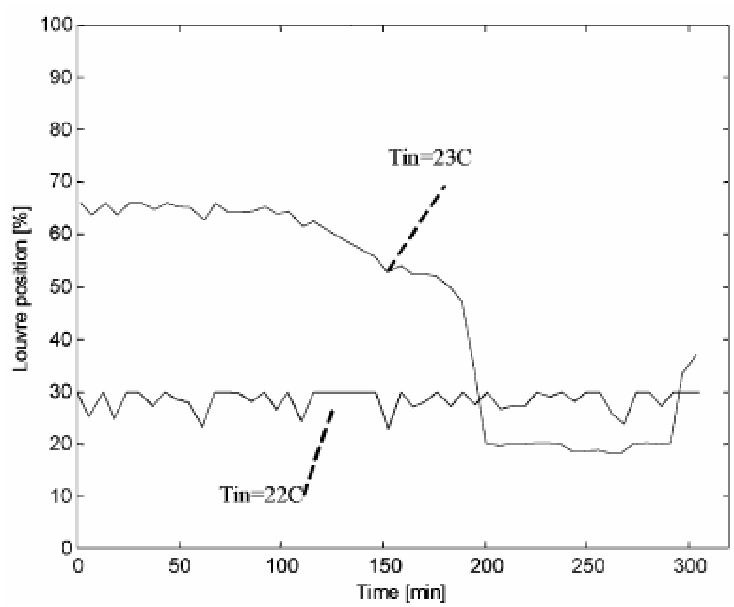


Figure. 38. Simulated louver opening for the case of fuzzy control model 2 (Table 2).

On the 19 June no control action upon the position of the louver which was kept constant (around 23%) resulted in high internal temperature of 25.6 ºC. Based on weather data recorded during that test and the average inside temperature both fuzzy control models were compared. The control Model 1 was based on three membership functions for outside temperature and opening positions. The control Model 2, used 5 and 4 membership functions for outside temperature and opening positions respectively. Simulation was performed under MATLAB programming surrounding and the results are presented in Fig. 39.

Comparing the results for the measured inside temperature of 25.6 ºC, using both Model 1 and Model 2 controllers, showed that the Model 2 with more membership functions and therefore larger number of IF-THEN rules, will provide better control action. Simulation results suggested that a fuzzy controller would increase opening area with an increase in outside temperature in order to raise inside temperature levels.

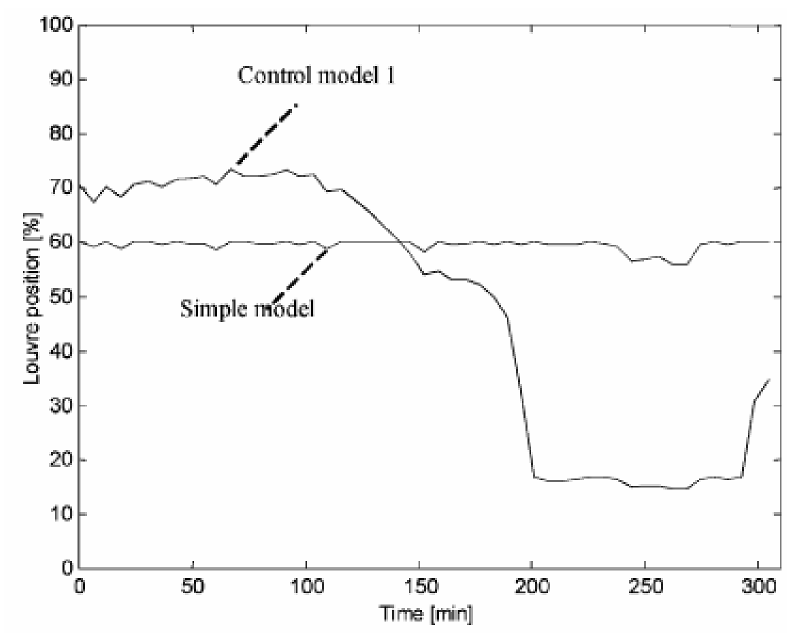


Figure.39.Simulated louver opening for the case of input data recorded during test 1

Two fuzzy control models were developed, using different membership functions. The results for the measured inside temperature of 25.6 ºC, using both Model 1 (Table 1) and Model 2 (Table 2) controllers, showed that the Model 2 with more membership functions and therefore larger number of IF-THEN rules, was more responsive to the changes in outside conditions. However, the simulation results indicated that both controllers are capable of responding to the changes in outside condition by adjusting the opening positions. The opening areas were decreased once the outside temperature was greater than inside, but control Model 2 resulted in decreasing openings to a minimum level. Such decision appears to be a better solution, considering that relatively high outdoor temperature levels combined with too high ventilation rate could lead to higher inside temperatures.

The control Model 2 with more membership functions and therefore larger number of IF-THEN rules was tested using different inside temperatures and outside conditions. The results showed that the controller is capable of adjusting the opening positions with changes in inside and outside conditions.

2.5 Thermal and Daylighting Performance of An Automated Venetian Blind and Lighting System in A Full-Scale Private Office [1]

E.S. Lee, D.L. DiBartolomeo, S.E. Selkowitz, Dynamic envelop/lighting systems have the potential to optimize the perimeter zone energy balance between daylight admission and solar heat gain rejection on a real-time basis, and to increase occupant comfort. Two side-by-side full-scale offices in Oakland, California were built to further develop and test this concept. An automated venetian blind was operated in synchronization with a dimmable electric lighting system to block direct sun, provide the design workplane illuminance, and maximize view. The research program encompassed system design refinements, energy measurements, and human factor tests. In this study, it present lighting energy and cooling load data that were monitored in this facility over the course of a year. Significant energy savings and peak demand reductions were attained with this automated venetian blind/lighting system compared to a static venetian blind with the same dimmable electric lighting system. Correlations between key weather parameters and cooling end uses under the full range of weather conditions of this sunny, moderate climate. Energy efficiency estimates were conservative since experience shows that conventional daylighting control systems and manually operated shading devices are rarely used effectively in real world applications.

The category of 'dynamic' window technologies encompasses numerous conventional components such as motorized louvers, Venetian blind, and shades, as well as more advanced glazing systems such as switchable electrochromics, thermochromics, polymer dispersed liquid crystal glazings, and electrically heated glazings. These building envelope technologies offer promising energy-efficiency opportunities and the potential to provide higher quality work environments. Substantial research has been devoted to passive heating applications, with dynamic window systems working as heat exchange systems. Computer simulations, laboratory tests, or reduced-scale field tests document the energy benefits associated with this application; e.g. automated between-pane Venetian blinds controlled by temperature and solar position.

For climates with high daylight availability and building types that are cooling load dominated, dynamic window technologies coupled with daylighting controls, window technologies that possess a broad range of daylight transmission and solar heat gain rejection properties can be used to actively optimize daylight, reduce electric lighting loads, and reduce the respective solar and lighting heat gains at perimeter zones of commercial buildings. Less research has been devoted to such systems. While there are dynamic shading or dimmable lighting systems commercially available today, there are no commercially available today, there are no commercially available, dynamic window systems that are designed to operate in synchronization with the lighting system. We have summarized simulation studies that have been conducted on the electrochromic device coupled with daylighting controls. Other researchers demonstrated a similar control strategy using external Venetian blinds and a dimmable electric lighting system in a test cell and a full-scale occupied building. There are no comprehensive field-monitored performance data that quantifies the energy benefits of both systems working interactively.

In this study, it present results from a full-scale testbed demonstration that was conducted over the course of a year in two side-by-side, fully furnished but unoccupied test rooms located in a federal office building. The entire scope of work included further refinements to a dynamic Venetian blind/lighting system, energy measurements, and human factors tests. These tests different from earlier reduced-scale field tests in that the system design was iteratively tuned to solve and accommodate full-scale, observable issues such as venetian blind behavior, motor noise, and occupant preferences. The rooms were fully instrumented to collect data on cooling load, lighting energy consumption, system operation, and environmental quality. The energy results are documented here.

This research is part of a larger multi-phase research and development program whose primary objective was to develop integrated building envelope, daylighting, and lighting systems. The large variation in solar radiation due to diurnal and seasonal changes of sun and sky conditions is a major cause of both high energy use and peak demand, and of occupant discomfort. However, there is an optimum cooling and lighting energy balance between the envelope and lighting energy balance between the envelope and lighting system that can be used to advantage to reduce this large variation: daylight can be used to advantage to reduce this large variation: daylight can be used to offset lighting energy use and the heat gains associated with the electric lighting system, but the admission of too much daylight introduces solar heat gains that can increase cooling loads associated with the window system. By taking an integrated systems approach to combining disparate components, greater energy savings can be attained with improved occupant comfort over conventional design practice.

Simulation results from early studies revealed the potential of this concept. In California, our energy simulation models predicted that 500-800 MW of peak electricity demand can be saved with this integrated approach over business-as-usual practice for new construction and partial retrofit of office buildings alone by the year 2005. Since lighting and cooling in commercial buildings constitute the largest portion of peak electrical demand, promotion of such integrated systems can also become a cost-effective option for owners and utilities.

DOE-2 building energy simulations were used initially to model actively controlled Venetian blinds with daylighting controls, 'manually' operated shading systems (activated every hour when glare or direct sun was detected), and advanced electrochromic glazings. Total annual energy savings of 16-26% were attained with the Venetian blind/lighting system compared to an unshaded low-E spectrally selective window with daylighting controls in Los Angeles, California. The energy impact of predictive control algorithms was also investigated in detail.

Field tests using the dual chamber calorimeter Mobile Window Thermal Test (MoWiTT) facility indicated that the automated Venetian blind/lighting system with a less than optimal control algorithm was still more than twice as effective at reducing peak solar gains under clear sky conditions controls, while providing the same level of useful daylight. A separate year long test was also conducted in a 1:3 reduced-scale test cell to determine the lighting energy savings potential of the automated Venetian blind/lighting system and to further develop the control algorithm and hardware solution under real sky conditions. Lighting energy savings of 37-75% were attained with the dynamic system compared to a partially closed, static blind with the same lighting control system for south to southwest-facing windows on clear sunny days.

In terms of evaluating comfort and environmental quality, a RADIANCE visualization simulation study was conducted to evaluate visual comfort associated with a dynamic electrochromic glazing. The dynamic window was able to control the window, interior task, and remote surface luminance levels to within recommended practice standards over the course of a clear, sunny day in Phoenix, Arizona. The clear and tinted static glazings were not.

The full-scale test bed facility completed the development process of the prototype system by enabling us to test and evaluate the design in full-scale. New energy-efficient technologies must be well tested and proven before they are introduced to the building industry, to ensure performance and to reduce real and perceived risk. Through limited tests in actual buildings, performance data can be provided to industry, utility program managers, or design professionals who need data to asses the aesthetics, cost and energy performance of the technology. This test bed demonstration was both R&D facility to help answer research questions and a limited proof-of-concept test, allowing practical ‘bugs’ to be worked out of an innovative building system.

The full-scale Oakland Federal Building test bed demonstration facility was designed to measure the electric lighting power consumption and the cooling load produced by the window and lighting system under realistic weather conditions. The facility consisted of two side-by-side rooms that were furnished with nearly identical building materials and furniture to imitate a commercial office-like environment (Figs. 40-42). Each test room was 3.71 m wide by 4.57 m deep by 2.68 m high (12.17 ft x 15 ft x 8.81 ft). The southeast-facing windows in each room were simultaneously exposed to approximately the same interior and exterior environments between the two rooms could be compared.

Because this facility was installed in an existing commercial office building and in built-up urban area, a limited number of external conditions was measured. A datalogging station located on the roof of a five-story adjacent building wing monitored global and diffuse horizontal exterior illuminance, horizontal global solar radiation, and outdoor dry bulb temperature (shielded from solar radiation). Interior measurements included horizontal workplane illuminance, vertical illuminance, power consumption of all plug loads and mechanical equipment, cooling load, interior air temperatures, and other information pertaining to the status of the dynamic window and lighting system.

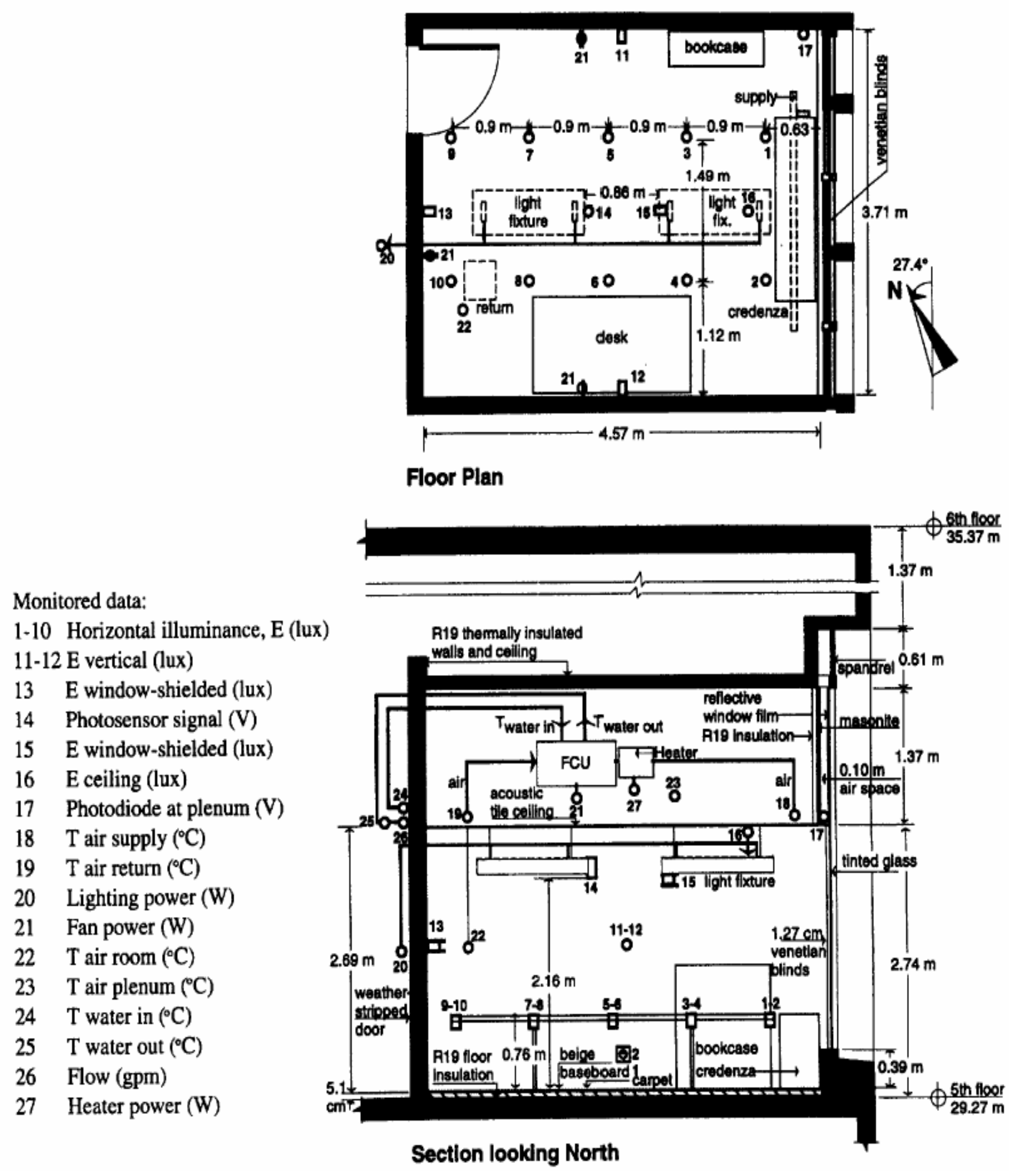


Figure. 40. Floor plan and section view of full-scale test room.

Identical automated Venetian blind/lighting systems were installed in each room so that the position of the prototype and base case systems could be interchanged. Both test rooms were located in the southeast corner of a larger unconditioned, unfinished space (213 m^2, 2300 ft^2) on the fifth floor of a 18 story tower. Room A was located to the east of Room B and was subject to slightly more early morning shading from an adjacent east building wing. The building was located at latitude 37º4'N, longitude 122º1'W. The testbed windows faced 62.6º east of true south. Both windows' view were obstructed by five to eight-story buildings one city block away and by several 24-story buildings three to six city blocks away (Fig. 43). These obstructions did not cause direct solar shading of the test rooms after 0745 from the spring to autumnal equinox.

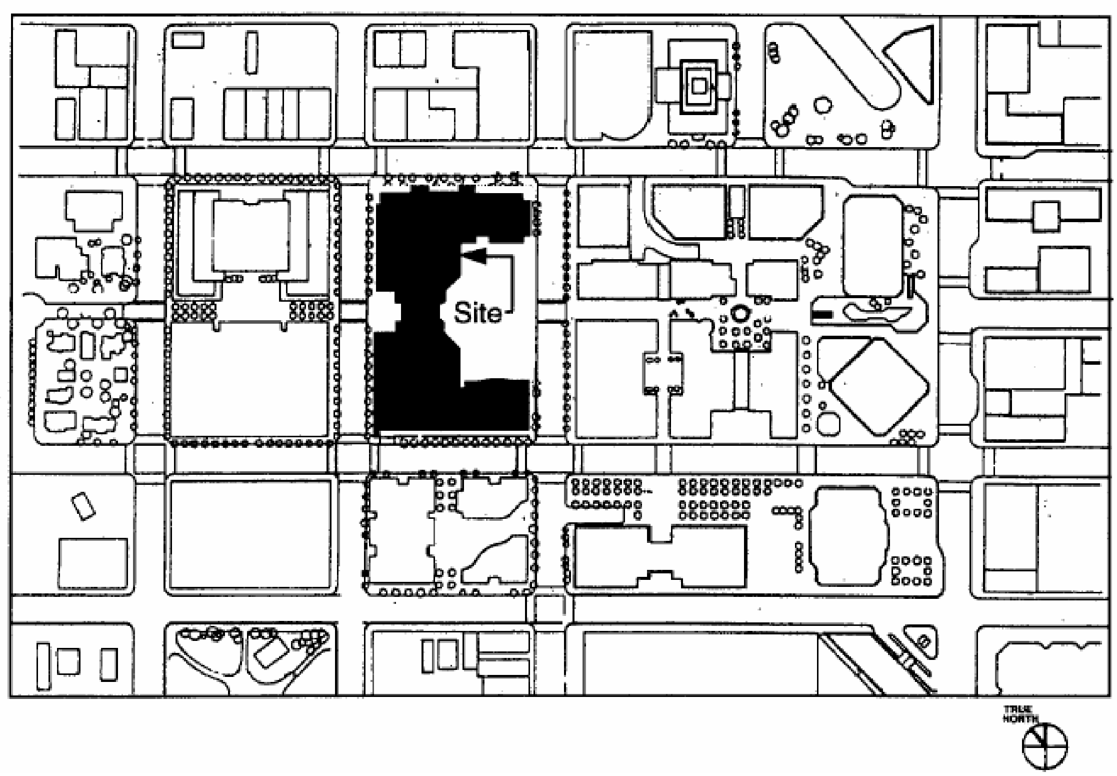


Figure. 41. Site plan (Oakland, CA).

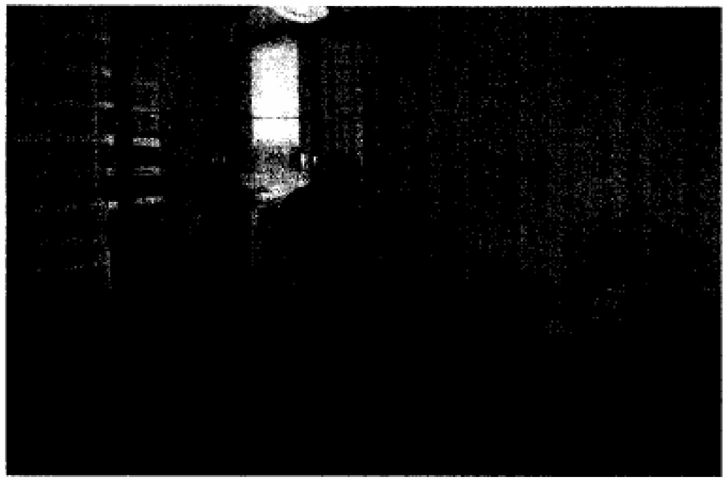


Figure. 42. Interior view of testbed

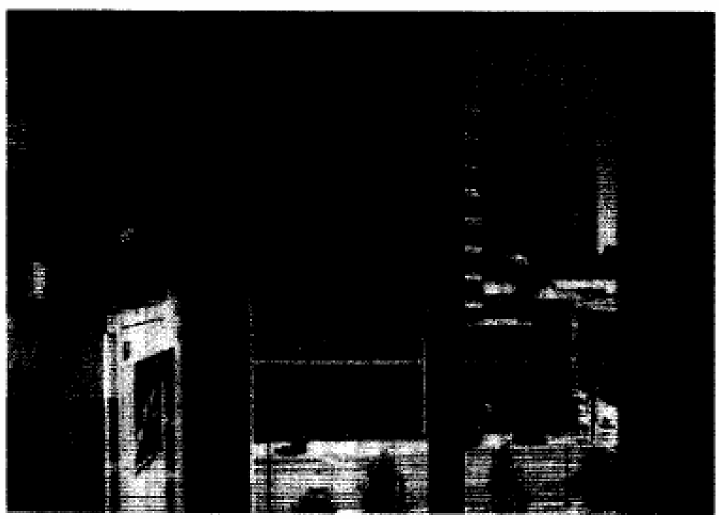


Figure. 43. View of surrounding outside the testbed window.

A 0.127 m (0.5 in.)-wide, curved slat, semi-specular white aluminum Venetian blind was fitted in a white painted wood frame and placed 0.127 m (0.5 in) away from the interior face of the existing glazing system. The blind covered the entire vertical height of the window and was not retractable, only the angle of the slats could be altered. A small direct current motor drive at the base of the window blind was used to alter blind angle in synchronization with the lighting controls via National Instruments Lab View computer control.

Two pendant indirect-direct (~95%, 5%) fixtures with four T8 32 W lamps, continuous dimmable electronic ballasts, and a shielded photosensor were used in each room (Fig. 44). The two fixtures were placed along the center line of the window with the first fixture spaced 0.61 m (2 ft) from the window wall and the second spaced 0.86 m (2.82 ft) apart. The photosensor was placed at one end of the second light fixture and flush with the bottom of the fixture, 2.08 m (6.8 ft) from the window wall. The ballast were rated to produce 10% light output for a minimum power input of 33%. The lighting power density was 14.53 W/m^2 (1.35 W/ft^2).

For the base case system, the Venetian blind was set to one of three fixed, static positions throughout the day to simulate 'manual' operation: 45º (nearly closed), 15º (partly closed), or 0º (horizontal), where a positive blind angle is defined from the horizontal plane with the slats inclined downwards for a ground view from the interior. For the base case with no daylighting controls, the electric lights were set to full power throughout the day. For the base case with daylighting controls, the lighting system was designed to supplement daylight, if available, to provide an average design iluminance of 510 lux at the horizontal workplane area located 2.44-3.35 m (8-11 ft) from the window wall and 0.74 m (2.42 ft) on either side of the centerline of the test room. If there was sufficient daylight to displace all electric lighting, the lights were shut off after a 10 min delay. The lighting control system was installed and commissioned with a prototype ballast controller so that there was a proportional response to available daylight every 30 s.

For the prototype dynamic system, the Venetian blinds were activated every 30 s to block direct sun and maintain the daylight design illuminance of 540-700 lux at the average workplane area, if daylight was available. If there was no direct sun present and daylight illuminance levels were within design parameters, the blinds were set to maximize view (horizontal). The range of motion for the blind was restricted to 0-68º to limit sky view glare, where at 60º the slats are just touching and at 68º the slats are squeezed shut to the mechanical limit of the Venetian blind system. Diffuse daylight was still admitted at 68º. The daylighting control system was the same described for the base case system.

Data were collected for 14 months from 1 June 1996 to 31 August 1997. The prototype system was developed iteratively over the year to refine control system algorithms and hardware operations according to observations in the field. Additional system parametrics were performed to address particular issues raised by the human factors study or to characterize and improve system performance. Although these system parametrics were monitored, data in this study are presented for the same prototype control system throughout the year.

For energy and load monitoring, data were sampled every 6 s then averaged and recorded every 6 min 0600-1900 and every 20 min from 1900-0600 (standard time) by Campbell Scientific CR10 dataloggers. Weather data, collected on a nearby roof, were sampled and recorded every 1 min by a CR10 datalogger.

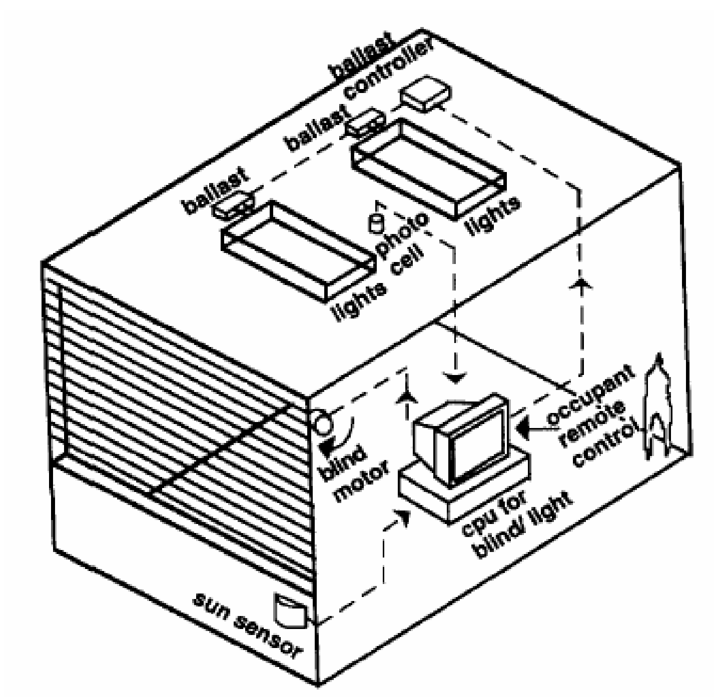


Figure. 44. Schematic of automated Venetian blind/lighting system.

Electric lighting power consumption was measured in each test room with watt transducers (Ohio Semitronics GW5) that were accurate to 0.2% of reading. The daily lighting energy use was defined as the sum of 6 min data over a 12h period defined by 0600-1800. To determine the comparability of data between the two rooms, the same Venetian blind and lighting configuration was set in both rooms then the resulting daily lighting energy use was compared periodically throughout the year.

Daily lighting energy use of Room A was found to correlate to within -6 or -19 Wh (1%, n = 2) of Room B when both rooms had the same fixed blind position, and to within -12 ± 46 Wh (2.6 ± 5.4%, n = 25) when both rooms were operating with the dynamic system. Room A was subject to slightly lower solar exposure than Room B for the same window and lighting configuration due to its position relative to the exterior surroundings. A comparison of the two rooms revealed that during some hours, the daylight illuminance in Room A was a maximum of ~10% lower than Room B. However, these differences in average daylight illuminance levels at the workplane did not necessarily correlate to differences in lighting energy use between the two rooms, since the reading at the photosensor determined lighting power consumption.

Cooling load measurements result from a net heat balance on each well-insulated test room, where the interior air temperature was maintained at a constant level (±1 ºC) by an electric resistance heater and a building chilled water liquid-to-air heat exchanger. Flow rate and inlet and outlet temperatures were measured. Individual three-speed fan coil units (McQuay TSH-081F) with modified electronic controls (to modulate the fixed speed settings) and two-stage electric duct heaters (Delta Flo DH) were placed in the plenum of each test room to deliver air at adequate temperature and volume to meet the load. A linear slot diffuser (Titus ML-39) was located near the window, the return was located in the back of the room. Building chilled water was delivered the cooling coils in each test room through a controlled circuit using a 2 cm (0.75 in) two-way control valve and valve actuator (Honeywell ML7984). The chilled water flow rate was maintained within 0.048-0.189 m^3/s (0.75-3.0) gpm. A booster chilled water pump (Grundfos UP26-96F) was used to maintained differential pressure. Control of the fan coil unit was based on a return air temperature sensor located in the plenum above the return air grille. Stand-alone PID controllers (TCS/Basys Controls SD1000) with separate heating and cooling outputs were used for room temperature control. The cooling outputs was used to control the two-way proportioning valve. Heating output was controlled with zero-crossing triac (low noise) power controllers.

High stability thermistors (YSI 46016, <0.01 ºC drift at 70 ºC for 100 months) were individually calibrated and placed in thermowells in the supply and return chilled water line. A turbine flowmeter (Hoffer 3/8", linear flow range 0.75 – 7.5 gpm) was placed in the filtered supply chilled water line and calibrated against a reference flowmeter periodically. Thermistors (YSI 44018, ± 0.15 ºC) were placed in the plenum, return air grille, and supply air grilled to monitor plenum and room air temperature. The mechanical system was designed to allow the measurement of cooling loads to within ± 3% of reading and electric power consumption (Ohio Semitronics watt transducers, GW5) from the fans, receptacles, and heating coils to within ± 1% of reading.

The test rooms were constructed to minimize heat transfer out of and into each room in order to isolate the measured cooling load to that imposed only by the window and electric lighting system. The walls and plenum ceiling were well insulated to prevent thermal bridging. Carpeting (1.3 cm, 0.5 in.), plywood (1.3 cm), and rigid insulation (R12, 0.47 W/m^2 K) were applied over the existing concrete decking floor. All penetrations through the walls and ceiling were caulked and sealed, and weatherstripping was applied to the door. Within the plenum, ducts and chilled water lines were insulated (R12, 0.47 W/m^2 K) from the point of penetration to the fan coil unit. Since the window head height extended 1.37 m (4.5 ft) above the finished acoustical tile ceiling, a highly reflective window film (3M P18-AR, SHGC = 0.23) was applied to the glazing in the plenum then insulated with R19 batt insulation applied to the interior face of the glazing.

The cooling load contribution of the window and electric lighting system was calculated for each 6 min interval by summing the measured cooling load (based on measured flow rate and inlet and outlet temperatures) and the heating and fan energy use (assuming 100% conversion to heat). The daily cooling load was determined by the sum of this 6 min data over a 12 h period defined by 0600-1800. Because of the inherent complexity introduced by the central plant mechanical system, no conversions were made from cooling load to energy use. The average hourly cooling load was determined for each room by the average of 6 min data over the hour. The peak cooling load and hour were defined by the test room with the higher average hourly cooling load over the 12 h period. Several filters were applied to the data. If the room air temperature of Room A or B was found to be outside of the range defined by 21.1 ± 1.0 ºC (69 – 71 ºF) for more than 10% of the 12 h period, the day's data were discarded. If the time stamps between the two room datalogging systems were found to have drifted by more than 3 min, the data were also discarded.

Nighttime mechanical system calibration tests and tests conduction with the mechanical system off were used to ascertain the comparability between the two rooms given instrumental error, differences in construction, the rooms' relative position to the exterior and interior environment, and the mechanical systems' operation. Additional daytime tests were conducted periodically throughout the year with the same Venetian blind and lighting configuration set in both rooms to determine test room comparability.

The daily cooling load of Room A was found to correlate to within 87 ± 507 Wh (0.5 ± 5.0%, n = 33) of Room B when both rooms had the same fixed or dynamic blind position and the cooling load exceeded 1.5 kWh but was less than 5 kWh. Less accuracy of the turbine flowmeters at low flow rates was the source of the larger error at the lower cooling loads. Loads less than 1.5 kWh, typical of overcast cool weather conditions, were not analyzed. Loads between 1.5 to 5 kWh are presented with the proviso that there is more error associated with these data.

Oscillations between the heating and cooling system with a period of 8 – 12 min were found to occur on occasion when the system was transitioning between heating or cooling modes in order to maintain the defined air temperature deadband of ± 1 ºC within each test room. With 6-min data collection, the peak load was estimated by averaging over the hour interval. As such, peak loads (>0) of Room A were found to correlate to within – 24 ± 114 W (-0.6 ± 6.4%, n = 23) of Room B when both rooms had the same fixed blind position and to within 5 ± 68 W (0.4 ± 6.0%, n = 31) when both rooms were operating with the dynamic envelop/lighting system.

The comparative data for the base case static Venetian blind defined with and without daylighting controls, because daylighting controls are presently used in only a small percentage of U.S buildings. Daily lighting energy, daily cooling load, and peak cooling load data are given for the entire year in Figs. 45 – 47, Tables 5, 6, and 7 give the average daily cooling load and lighting energy reductions for the daylit case by season, where seasons were defined by the days falling within 1.5 months of the day of the equinox or solstice.

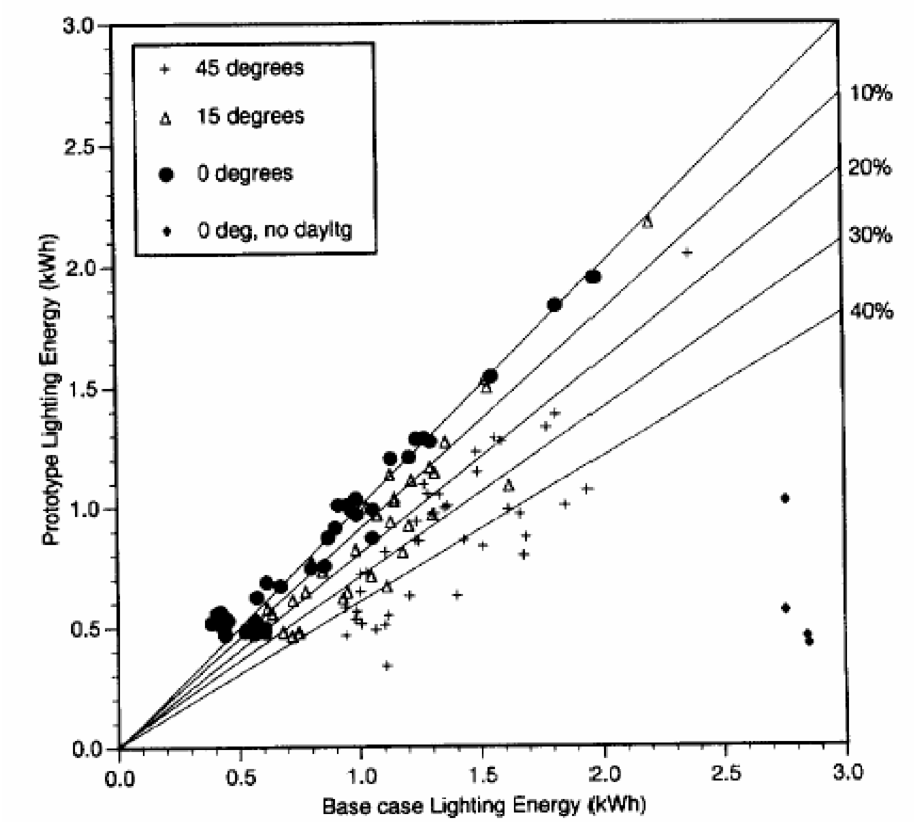


Fig. 45. Daily lighting load (kWh) of the base case and prototype venetian blind/lighting systems, where the base case was defined by three static blind angles, 0º (horizontal), 15º, and 45º. Diagonal lines on the graph show percentage differences between the base case and prototype. Both cases were defined by the prototype continuous dimming lighting control system or, within a limited set of tests, the lighting control systems with no dimming controls ('no dayltg'). Lighting

power density is 14.53 W/ft^2), glazing area is 7.5 m^2 (80.8 ft^2), and floor area is 16.96 m^2 (182.55 ft^2). Data were collected from June 1996 to August 1997. Measurement error between test room is 12 ± 46 Wh (2.6 ± 5.4%).

If both the base and prototype have the same daylighting control system, then daily lighting energy savings and cooling load reductions resulting from the dynamic blind were roughly proportional to the degree of the static blind's openness and its relation to solar position. To clarify, we show how the dynamic system saves energy compared to both the 0º and 45º static blind with the same daylighting controls on typical clear days (Figs. 48 and 49, 15 and 18 August 1996).

On August 15, the dynamic system achieved substantial reductions in cooling load (21%) and peak cooling load (13%) and good reductions in lighting energy use (21%) compared to the static 0º system. Cooling load reductions were the result of the dynamic system's control over solar heat gains. Lighting energy reductions were due to the illuminance control strategy of the dynamic system. Note how the dynamic Venetian blind closed at 0700 then started to open at 1100 to maintain a constant daylight illuminance at the workplane as daylight availability changed. After 1430, the dynamic blind moved to the horizontal position to maximize view and daylight admission. With the dynamic Venetian blind, average illuminance levels at the back of the room were well controlled in the morning hours to within 500 to 1000 lux (the blinds were closed to the mechanical limit when illuminance exceeded the 700 lux design level), while the static 0º system resulted in illuminance levels of 1000 to 2500 lux. Visual and thermal comfort may be compromised with the static system.

On August 18, the dynamic system achieved significant lighting energy reductions (46%) but small reductions in cooling load (4%) and peak cooling load (8%) compared to the static 45º blind. The partly closed blind was able to control solar gains as well as the dynamic blind. However, the static system could not meet the design workplane illuminance with daylight. Fluorescent lights were turned on at 1210, approximately 2.5 h earlier than the dynamic system. On both days, spikes in the Venetian blind angle, seen in the figures, were due to hysteresis or oscillations in the Venetian blind motorized control system; this problem was solved in later tests.

In general, lighting energy savings were achieved through the optimal response of the dynamic Venetian to changing exterior daylight levels, primarily in the mid-afternoon when the sun was out of the plane of the window and when exterior daylight illuminance levels were diminishing. The prototype blind was able to maintain a higher level of illuminance for a longer period than the partly closed blind. Overcast and partly cloudy conditions resulted in less lighting energy savings; e.g. the daily lighting energy use of the prototype blind on October 24, a heavily overcast day, was 2046 Wh/day with savings of only 14% compared to the 45º blind.

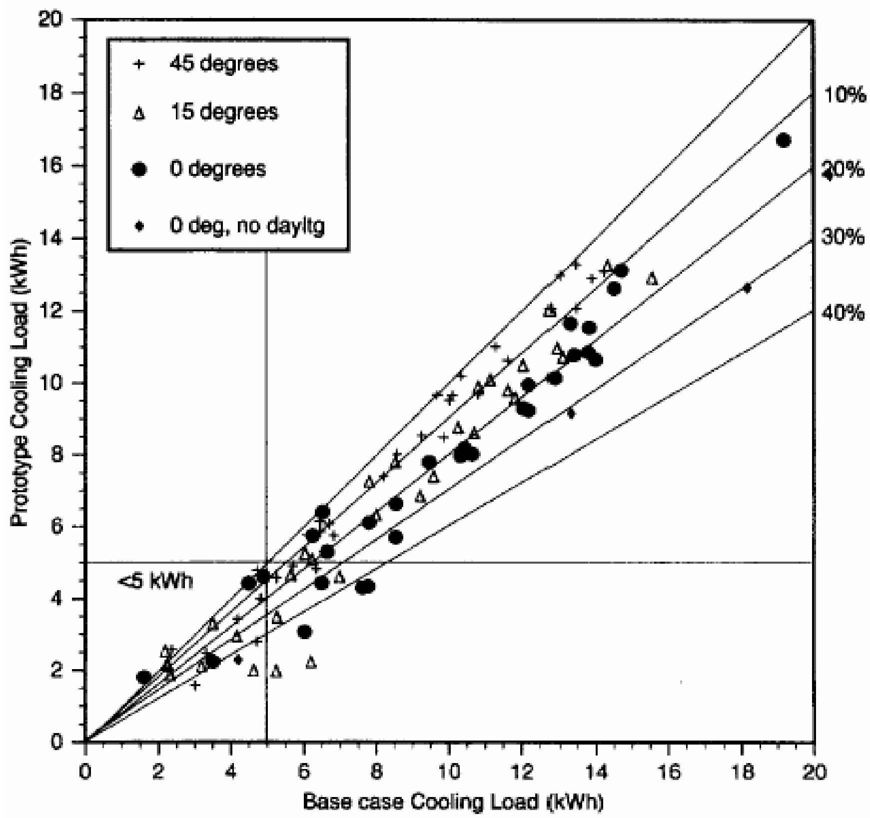


Figure. 46. Daily cooling load (kWh) of the base and prototype Venetian blind/lighting systems, where the base case defined by three static blind angles, 0º (horizontal), 15º, and 45º. Measurement error between rooms for loads greater than 5 kWh was 87 ± 507 Wh (0.5 ± 5%), and for loads within 1.5 – 5 kWh was 534 ± 475 Wh (15 ± 12%). Diagonal lines on the graph show percentage differences between the base case and prototype. Both cases were defined by the prototype

continuous dimming lighting control system or, within a limited set of tests, the lighting control systems with no dimming controls ('no dayltg'). Lighting power density is 14.53 W/m² (1.35 W/ft²), glazing area is 7.5 m² (80.8 ft²), and floor area is 16.96 m² (182.55 ft²). Data were collected from June 1996 to August 1997.

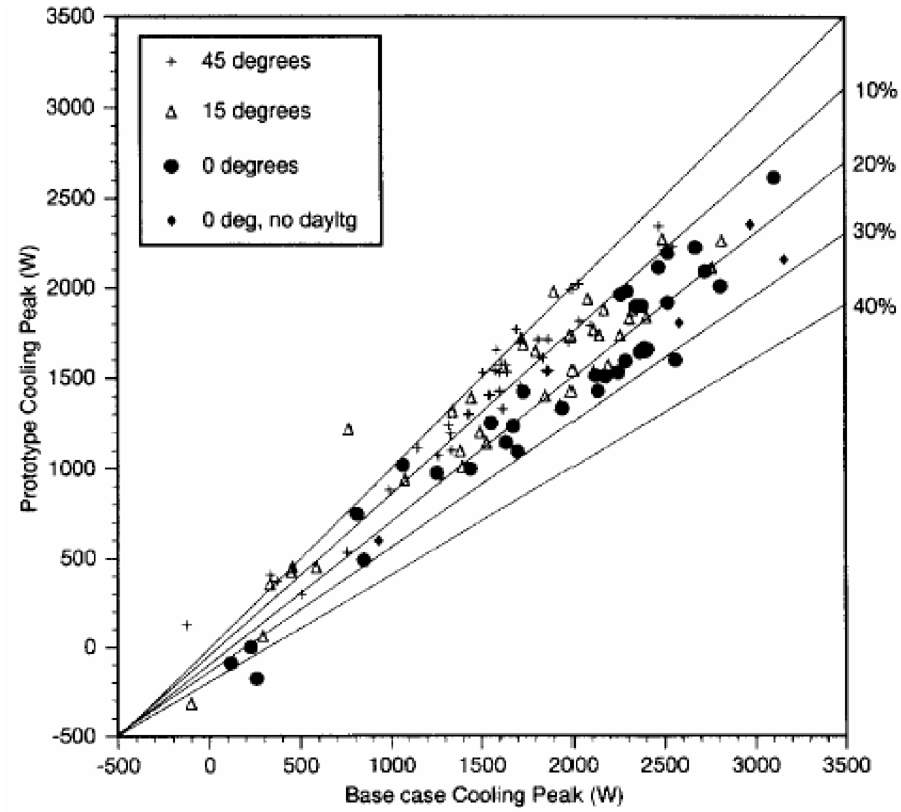


Figure. 47. Peak cooling load (W) of the base case and prototype Venetian blind/lighting systems, where the base case was defined by three static blind angles, 0º, 15º, and 45º. Measurement error between room was -24 ± 114 W (-0.6 ± 6.4%). Diagonal lines on the graph show percentage differences between the base case and prototype. Both cases were defined with the prototype continuous dimming lighting control system, or within a limited set of tests, with no dimming controls ('no dayltg'). Lighting power density is 14.53W/m² (1.35 W/ft²), glazing area is 7.5 m² (80.8 ft²), and floor area is 16.96 m² (182.55 ft²). Data were collected between June 1996 and August 1997.

Table. 5.

Average daily lighting energy use (Wh) of the dynamic and static Venetian blind with dimmable daylighting controls

Static blind angle (deg)		Vernal equinox	Summer solstice	Autumnal equinox	Winter solstice
45°	n	9	8	18	4
	E_{vgh} (klux)	41 ± 8	55 ± 7	43 ± 11	27 ± 5
	Dynamic	932 ± 198	511 ± 89	944 ± 335	1185 ± 81
	Static	1276 ± 224	1070 ± 149	1486 ± 357	1459 ± 135
	Δ (Wh)	344 ± 63	559 ± 152	542 ± 223	274 ± 75
	% Δ	27% ± 5%	52% ± 9%	37% ± 12%	19% ± 4%
15°	n	12	14	3	4
	E_{vgh} (klux)	40 ± 8	56 ± 10	43 ± 5	20 ± 8
	Dynamic	878 ± 204	647 ± 191	949 ± 376	1586 ± 432
	Static	1018 ± 208	872 ± 340	1027 ± 408	1599 ± 446
	Δ (Wh)	140 ± 85	225 ± 180	77 ± 38	13 ± 23
	% Δ	14% ± 8%	22% ± 17%	7% ± 2%	1% ± 1%
0°	n	13	11	6	5
	E_{vgh} (klux)	37 ± 9	56 ± 10	47 ± 16	21 ± 7
	Dynamic	968 ± 244	526 ± 62	766 ± 234	1495 ± 365
	Static	961 ± 249	472 ± 74	855 ± 207	1483 ± 388
	Δ (Wh)	−7 ± 32	−55 ± 82	89 ± 81	−13 ± 37
	% Δ	−1% ± 4%	−14% ± 19%	11% ± 10%	−1% ± 3%

Values are expressed in average ± standard deviation.
Average error of measurement between test rooms is −12 ± 46 Wh (−2.5 ± 5.4%), n = 25.
E_{vgh} = average daily horizontal global illuminance (klux).

Table. 6.

Average daily cooling load (Wh) of the dynamic and static Venetian blind with dimmable daylighting controls

Static blind angle (deg)		Vernal equinox	Summer solstice	Autumnal equinox	Winter solstice
45°	n	4	8	13	all data
	E_{egh} (W/m^2)	5584 ± 910	6642 ± 1011	5542 ± 427	< 5 kWh
	T_{dbt} (°C)	20.1 ± 1.6	26.2 ± 3.6	25.0 ± 1.4	
	Dynamic	5961 ± 1068	10 887 ± 1734	8646 ± 3023	
	Static	6957 ± 854	11 538 ± 1591	9259 ± 3129	
	Δ (Wh)	997 ± 406	651 ± 624	614 ± 251	
	% Δ	15% ± 7%	6% ± 6%	7% ± 3%	
15°	n	7	12	3	all data
	E_{egh} (W/m^2)	5271 ± 782	6932 ± 492	4621 ± 1193	< 5 kWh
	T_{dbt} (°C)	21.0 ± 3.7	24.8 ± 3.6	24.1 ± 4.1	
	Dynamic	6110 ± 3010	9444 ± 2330	6749 ± 3278	
	Static	8170 ± 3032	10 878 ± 2698	8418 ± 3163	
	Δ (Wh)	2060 ± 706	1434 ± 697	1669 ± 622	
	% Δ	28% ± 16%	13% ± 5%	22% ± 11%	
0°	n	10	11	5	all data
	E_{egh} (W/m^2)	4685 ± 871	6247 ± 2151	5346 ± 1403	< 5 kWh
	T_{dbt} (°C)	20.3 ± 3.5	28.4 ± 11.0	24.3 ± 1.9	
	Dynamic	5873 ± 2622	10 586 ± 3002	8650 ± 2454	
	Static	8371 ± 2314	12 727 ± 3203	10 711 ± 3764	
	Δ (Wh)	2498 ± 853	2141 ± 715	2061 ± 1432	
	% Δ	32% ± 16%	17% ± 6%	17% ± 11%	

Values are expressed in average ± standard deviation.
Average error of measurement between test rooms is 87 ± 507 Wh (0.5 ± 5.0%), n = 33.
All daily cooling loads were greater than 5 kWh in at least one test room.
E_{egh} = total daily global horizontal irradiance (W/m^2).
T_{dbt} = average daily exterior dry-bulb temperature (°C).
Seasons defined by 1.5 months before and after equinox or solstice date above.

Table. 7.

Average peak cooling load (W) of the dynamic and static Venetian blind with dimmable daylighting controls

Static blind angle (deg)		Vernal equinox	Summer solstice	Autumnal equinox	Winter solstice
45°	n	8	8	16	4
	E_{egh} (W/m^2)	615	834	771	494
	T_{dbt} (°C)	20.5 ± 1.7	27.1 ± 3.7	26.1 ± 3.2	18.8 ± 1.7
	Dynamic	1502 ± 185	1734 ± 198	1573 ± 423	1104 ± 213
	Static	1686 ± 210	1852 ± 211	1708 ± 464	1304 ± 173
	Δ (W)	184 ± 110	118 ± 163	135 ± 101	200 ± 135
	% Δ	11% ± 6%	6% ± 8%	8% ± 5%	15% ± 11%
15°	n	11	13	3	1
	E_{egh} (W/m^2	568	792	510	469
	T_{dbt} (°C)	21.4 ± 3.6	25.6 ± 4.1	25.1 ± 4.4	21.5 ± 0.0
	Dynamic	1389 ± 473	1725 ± 363	1696 ± 106	1430 ± 0
	Static	1785 ± 584	1993 ± 471	2151 ± 41	1993 ± 0
	Δ (W)	396 ± 164	268 ± 230	456 ± 146	563 ± 0
	% Δ	22% ± 6%	13% ± 10%	21% ± 6%	28% ± 0%
0°	n	11	11	6	3
	E_{egh} (W/m^2)	748	826	627	401
	T_{dbt} (°C)	22.8 ± 3.3	28.6 ± 11.2	25.0 ± 1.8	20.0 ± 4.9
	Dynamic	1673 ± 302	1809 ± 413	1431 ± 601	1079 ± 74
	Static	2235 ± 320	2365 ± 400	1811 ± 864	1593 ± 136
	Δ (W)	562 ± 197	557 ± 152	379 ± 330	514 ± 85
	% Δ	25% ± 8%	24% ± 7%	18% ± 11%	32% ± 3%

Average error of measurement between test rooms is −24 ± 114 W (−0.6 ± 6.4%), n = 23.
Standard error is 51 ± 112W (2 ± 7%).
E_{egh} = maximum peak hourly global horizontal irradiance (W/m^2) of n days.
T_{dbt} = average peak hourly exterior dry-bulb temperature (°C).

Cooling load reductions were achieved principally by the control of direct transmitted solar heat gains and to a lesser degree, by reduced heat gains from the electric lights. The more closed the static base case blind system with respect to direct solar radiation, the lesser the savings achieved by the prototype system: average daily cooling reductions of 6-15% (45º static blind) and 17-32% (0º static blind) were achieved across seasons by the dynamic blind compared to the static blind.

On clear sunny days, peak lighting demand was the same in both cases since the design illuminance setpoint was exceeded during the peak period, causing the lights to shut off. Peak cooling loads occurred in the early to mid-morning hours when the sun was in the plane of the window and again reflects largely the difference in direct transmitted solar heat gains resulting from the average hourly blind position (Fig. 47 and Table 7). Average peak cooling load reductions of 118-

200 W or 6-15% (45º tilt angle) and 379-562 W or 18-32% (0º tilt angle) were achieved across seasons by the dynamic blind compared to the static blind. This hourly average load reduction is a measure of both the instantaneous load reduction and the benefit from active control derived from the previous 1-2 h given lightweight, steel-frame construction.

A dynamic Venetian blind and dimmable electric lighting system was designed to optimize daylight admission and solar heat gain rejection in real-time, while accommodating other occupant considerations. A full-scale testbed facility consisting of two side-by-side, southeast-facing private offices was used to determine the energy savings potential of this system compared to a static Venetian blind system with and without dimmable daylighting controls in the moderate climate of Oakland, California. Cooling loads due to the window and electric lighting system and lighting energy use were monitored every 6 min throughout the day, as well as other control and performance parameters such as interior illuminance levels and status of the dynamic blind.

Conservatively, average daily cooling load reductions of 7-15% (45º blind angle) and 17-32% (0º blind angle) were achieved across seasons by the dynamic system over a static Venetian blind with the same dimmable lighting control system. Average daily lighting energy reductions of 19-52% (45º blind angle) and -14 to + 11% (0º blind angle) were achieved across seasons as well. Cooling data generally reflect sunnier, warmer weather since discarded the monitored day if the daily cooling load was less than 1.5 kWh. Lighting energy reductions are reported for monitored data taken over the course of a year.

CHAPTER III

METHODOLOGY

3.1 Methodology

The following are the steps of research methodology.

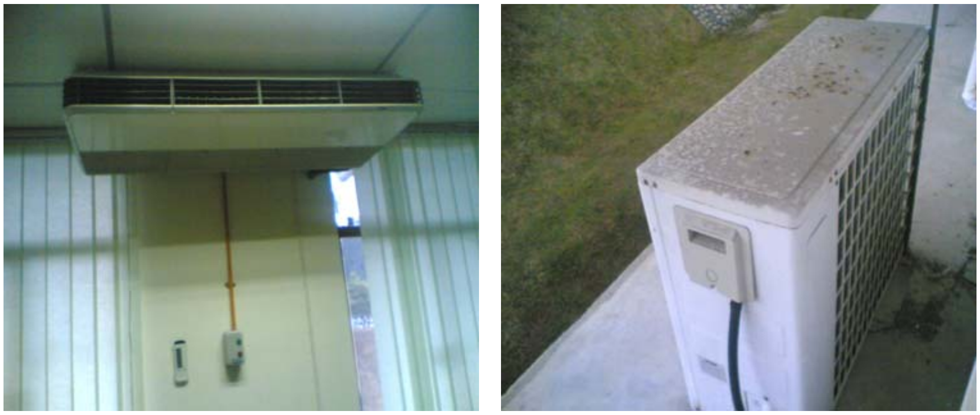
1. **Selection of a model room:** In this project, the prototype or model room is "Bilik Mesyuarat Makmal Sistem Tenaga" (Meeting Room of Energy System Lab) of Block P07, Faculty of Electrical Engineering, UTM, Skudai. This room has split type air conditioners which using a conventional thermostat and the windows in this room are always covered with conventional curtains.
2. **On-line data capture:** Sensors, transducers, data acquisition cards, interfaces and PC will be installed in the model room to acquire at suitably spaced intervals the indoor illumination level (lux), temperature, humidity, wattage at each power consumption point and also the outdoor (ambient) temperature, and humidity.
3. **Optimization of conflicting parameters:** A model will be developed and programmed for on-line analysis of the captured data. This will then update the exact lux and comfort level required in the room at any instant of time so that no condition of over or under illumination as well as cooling prevails in the room. The modeling and analysis will be done using fuzzy method instead of conventional mathematics.

4. **Design of hardware:** (i) The on-line controller of sunlight infiltration will be designed and fitted on suitable window. On that window, a moveable motor operated adjustable screen that will be regulated by the designed on-line controller will replace the conventional curtain. (ii) Either one or all the split type air conditioners will be provided with programmable thermostat. This thermostat will be design to accept on-line the decisions from the optimization algorithm.
5. **On-line implementation:** The optimizing algorithm's decision will be implemented through controlling the external sunlight admittance and adjusting the thermostat setting of the air conditioners.
6. **Testing and validation:** The developed scheme will be tested at various parts of different days under a wide spectrum of weather and sunshine conditions. If necessary, the algorithm and design of controllers will be modified so that acceptable illumination, comfortable room temperature and remarkable energy saving are obtained.
7. **Costing Analysis:** Analysis will be done to determine the energy saving potential, payback period and life cycle cost to be incurred when the developed scheme is implemented in (i) the selected room and (ii) all other similar rooms of P07 Block.

3.1.1 Problem Statement

3.1.1.a Split – System Residential Air – Conditioning Systems [9]

The split-system residential air-conditioning system adds a condenser, which includes the compressor and condenser fan to the existing furnace. Figure 49 shows a picture of the components of a typical split-system air conditioner.



(a) ***(b)***

Figure.48. a. The furnace is the part of the split-system residential air conditioner inside the room. b. The condenser unit is part of a split-system residential air conditioner and is outside the room. Figure 48a shows the furnace part of the system that is inside the room and has the evaporator fan and the transformer to provide control voltage to the coil of both the evaporator fan relay and compressor contactor. The thermostat that controls the system is mounted on an interior wall in the room. Figure 48b shows the condenser that is outside the room and contains the compressor, condenser fan, and controls.

Specification of the air conditioning unit:

Brand : York

Model : YSL30B-AFAA

S/No : MJGL10214

Refrigerant : R22 1, 85 kg

Volt /Ph/Hz : 220-240/1/50

Nominal watt : 3000 W

Nominal Amp : 14, 5 A

a.1. The Main Components of The System

The air conditioner is Figure 8 shows a wiring diagram of the split-system air conditioner, and Figure 9 shows a ladder diagram of the system. The electrical diagrams that the condensing unit is powered by 230 VAC, and the control circuit for the system is powered by 24 VAC. The top part of the ladder diagram shows the components that are mounted in the condensing unit. The system uses a single-phase compressor that is wired as a PSC motor. A current relay can be used with a start capacitor if the compressor requires additional starting torque. (Note: The diagram shows where the start capacitor and relay go if they are used, otherwise the compressor is connected as PSC motor). The condenser fan is also powered with 230 volts and is also wired as a PSC motor. Since the compressor for this unit sits outdoors, it has a crankcase heater to keep the compressor pump warm so that oil does not migrate into the evaporator coil inside the house.

The main control for this system is the compressor contactor whose contacts close to provide voltage to the compressor. The 24-volt coil of the compressor contactor is connected to the low-voltage control circuit, where it is energized by the thermostat connected in series with it. Other components in this system include the external overload and run capacitor for the compressor.

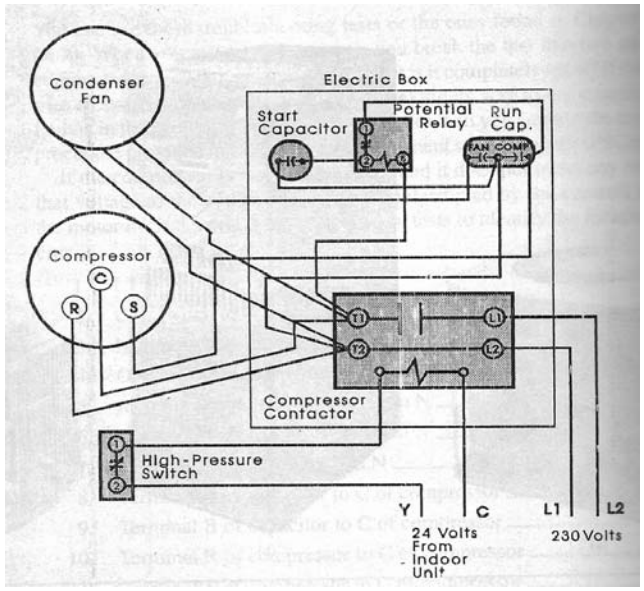


Figure 49. A wiring diagram for a split-system air-conditioning unit with the evaporator fan in the furnace, and the compressor and condenser fan in the condensing unit outside the house.

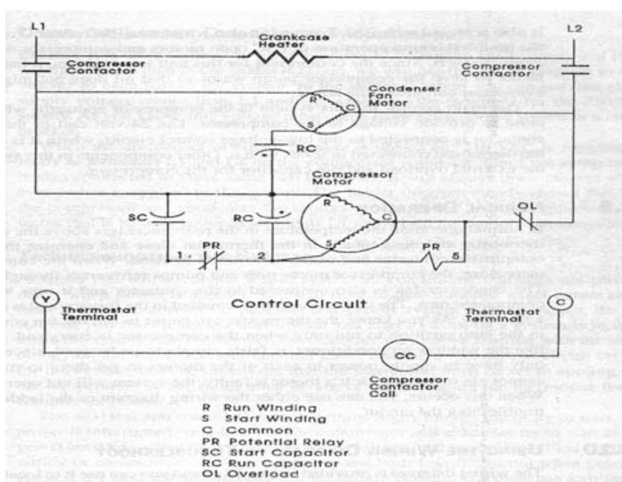


Figure 50. Ladder diagram for split-system air-conditioning unit

a.2. Normal operation of split air conditioner

In normal operation the temperature in the room increases above the setting on the thermostat and the contacts in the thermostat close and energize the coil of the compressor contactor and cause its contacts to close. When the compressor contacts close, the compressor motor runs and pumps refrigerant through the system.the condenser fan is also connected to the contactor and it runs whenever the compressor runs. The evaporator fan is mounted in the furnace and is controlled by a fan relay. The thermostat can be set to run the fan continously or in the auto position to run only when the compressor is energized. This system, like the window air conditioner, is fairly simple to understand, since the controls only have to support power to each of the motors to get them to run. If voltage cannot get to a motor or if a motor is faulty, the system will not operate correctly. When this occurs, you can use either the wiring diagram or the ladder diagram to troubleshoot the circuit.

a.3. Interior Comfort Condition

Room climate plays a significant role in the well being and working capacity of human beings. Observation has revealed an air quality range within which people generally feel at their best. The study of comfort is to determine the comfort level for a room. Clothing, age, gender, habits and type of work are the factors influence comfort.

There are few thermal comfort studies done in Malaysia before the 1990s. For indoor design conditions for air-conditioned space, the comfort range suggested by the Ministry of Energy Telecommunications and Posts (1989) and the Malaysian Department of Standards (2001) for nonresidential buildings is 23ºC – 26ºC. However despite the available guidelines for energy efficiency, anyone familiar with the Malaysian scenario would find that most air-conditioned buildings especially offices and hotels in Malaysia are overcooled.

The comfort zone used by most engineers in designing air-conditioning systems is normally based on those recommended by ASHRAE. However, due to the high relative humidity in Malaysia, the figures recommended by ASHRAE, particularly in relation to relative humidity may not be easy to accomplish. Based on the present study it was found that the thermal comfort zone is in the temperature range of between 23°C to 25°C and relative humidity of between 74 to 83 percent, which differ slightly from the ASHRAE thermal comfort zone. The ASHRAE thermal comfort zone for summer is in the temperature range of between 22°C to 27°C and relative humidity of between 30 to 60 percent. Comparison with the Predicted Mean Vote (PMV) thermal comfort sensation scale shows a slightly different result.

Due to this, in this project, the temperature of the air in a room must be maintained at such a level that people in the room are not feeling too hot or too cold. The minimum comfort temperature is set 23°C and the maximum comfort temperature is set 25°C.

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3.1.1.b Illumination Levels [3]

The amount of light that illuminates a surface is measured in lumens per square foot or footcandles. Table 1 shows selected illumination level ranges as recommended by Public Works Department or Jabatan Kerja Raya (JKR) Malaysia. Note that these values are recommended for the performance of a specific task and that a room with various task areas would have various recommended illumination levels.

Table. 8. Recommended Illumination Level for Selected Areas (JKR Standard)

Area	Illumination (Lux)
Laboratories (general)	500
General office with mainly clerical task and typing office	500
Deep plan general office	300
Business machine and typing	300
Filling room	300
Conference room	300
Executive office	300
Computer rooms	500
Punch card rooms	600
Drawing offices drawing boards	600
Reference table and general	300
Print room	300

3.1.1.c Fuzzy Logic [8]

Fuzzy logic is one of the artificial intelligence (AI) involves the development of algorithms that derived from human and animal intelligence. Fuzzy logic has capabilities such as learning, reasoning, generalization, adaptation, reproduction and so on. Fuzzy logic techniques have made their way into many domestic and industrial products and provide solution to many difficult engineering problems.

(1) Fuzzy Logic Control Method

Fuzzy logic controller (FLC) is a classification of modern control system based on fuzzy logic rules. Fuzzy control based on logic model, which presented resembles human decision making with its ability to control a process. Fuzzy control is calculating control signal according to input signal and output signal in linguistic variable. It is explained below:

If *e* and *de*, so *u*

With : *e* : error

de : delta error

u : fuzzy control signal output

In Fuzzy logic control system there is 4 processes need to be considered, those processes are:

1. **Fuzzification.** Fuzzification mapping non-fuzzy input value to fuzzy input value. Generally, it is explained as Xz = fz (x) where x is input value, Xz is fuzzy variable and fz is fuzzy control. Fuzzification involved distribution functions of fuzzy membership variable using triangle distribution is given in fig. 51. Input value limit, which is converted to fuzzy value, is (-R, +R).

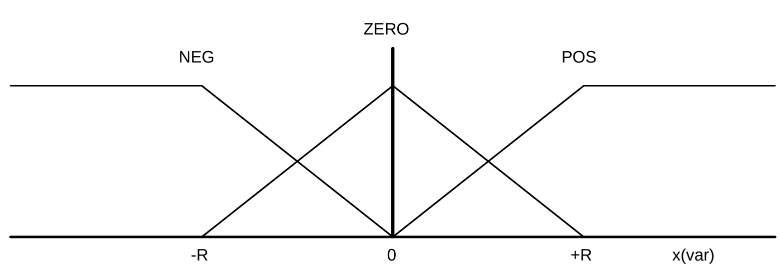


Figure. 51 . Diagram block of fuzzification function

2. **Basis of knowledge.** In this fuzzy logic control typical learning of control plan is principal knowledge. It consists of Data Basis, a linguistic and manipulated data of control method definition. Rule Base is explanation of dynamic characteristic input plan by linguistic base on expert experience. In examples:

a. **If** V constant and $\Delta V = 0$, **then** output constant
b. **If** V high and ΔV = pos, **then** output high
c. **If** V low and ΔV = pos, **then** output low
d. **If** V low and ΔV = neg, **then** output high

3. **Inference.** Inference process is interpretation of rules in fuzzy operation method basis. Inference is simulating human decision base on logic method. This part will decide which control signal need to be generated base on fuzzy logic rule. 3 fuzzy sets rule is given below.

Table. 9. fuzzy sets rule

Acceleration value $d\Delta V$			
	N (neg)	Z (zero)	P (pos)
N (neg)	N	N	Z
Z (nol)	N	Z	P
P (pos)	Z	P	P

That rule is generally explained in basis method for 2 inputs and 1 output as follows:

Method 1 :

If ΔV = N and $d\Delta V$ = N Then u = N
If ΔV = N and $d\Delta V$ = Z Then u = N
If ΔV = N and $d\Delta V$ = P Then u = Z
If ΔV = Z and $d\Delta V$ = N Then u = N
If ΔV = Z and $d\Delta V$ = Z Then u = Z
If ΔV = Z and $d\Delta V$ = P Then u = P
If ΔV = P and $d\Delta V$ = N Then u = N
If ΔV = P and $d\Delta V$ = Z Then u = P
If ΔV = P and $d\Delta V$ = P Then u = P

4. **Defuzzification.** Defuzzification is fuzzy value mapping into non-fuzzy value. In this case changing control signal (u) into non-fuzzy values (u_0). Because the signal object is non-fuzzy. A lot of method is used for fuzzification, i.e.: centre average defuzzification.

$$U_0 = \frac{\sum_{j=1}^{n} \mu_j(\mu).u}{\sum_{j=1}^{n} \mu_j(u)}$$

where, U_0 :non-fuzzy value u_j : average fuzzy value

$\mu_j(u)$: membership of fuzzy value

figure 52 is the diagram block of an on-line and intelligent energy saving scheme for the commercial building based on fuzzy logic controller.

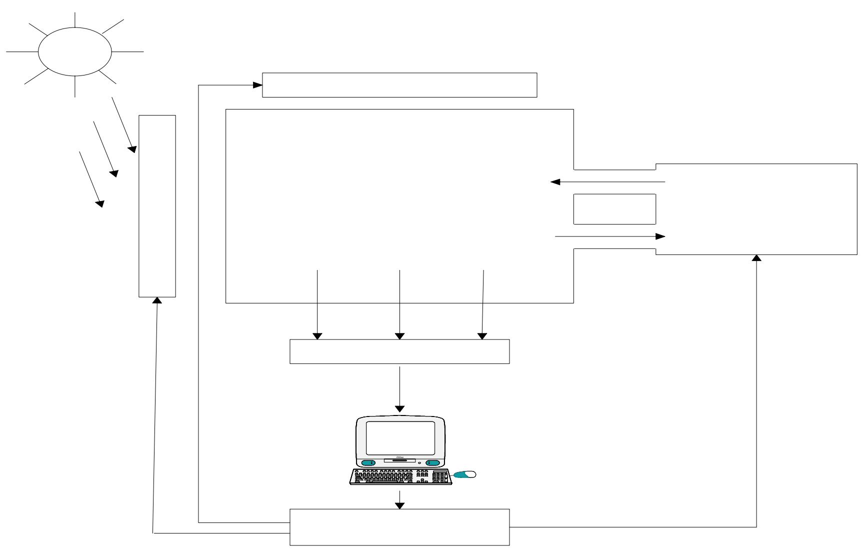


Figure. 52. Block Diagram of an On-line and Intelligent Energy Saving Scheme for a Commercial Building

3.2. Programmable Thermostat

This chapter describes the architecture of air conditioner controller which is programmable thermostat. All the circuits regarding to this project are described one by one. This project is developed based on several methods done with step by step. In the first step, all information which is relevant to this project was gathered. The information includes interface using parallel port and how to use Borland Delphi software itself. This step needs to be done to make sure the flow of the project runs smoothly. The next step is testing the hardware components to make sure it is compatible and match the software.

3.2.1. Testing procedures

Next, process of determining the output using parallel port is tested. It is tested using several a simple LED driving circuit. The only components needed are one LED and one 470 ohm resistors which are connected in series. The resistors is needed to limit the current taken from parallel port to a value which light up acceptably normal LEDs and is still safe value (not overloading the parallel port chip). In practical case the output current will be few milliamps for the LED, which will cause a typical LED to somewhat light up visibly, but not get the full brightness.

Then, the circuit is connected to the parallel port so that one end of the circuit goes to one data pin and another one goes to any of the ground pins. Figure below shows the circuit diagram using 8 LEDs. The software controlling is easy. When bit 1 is sent to the datapin where the LED is connected, that LED will light. When bit 0 is sent to that same datapin, the LED will no longer light.

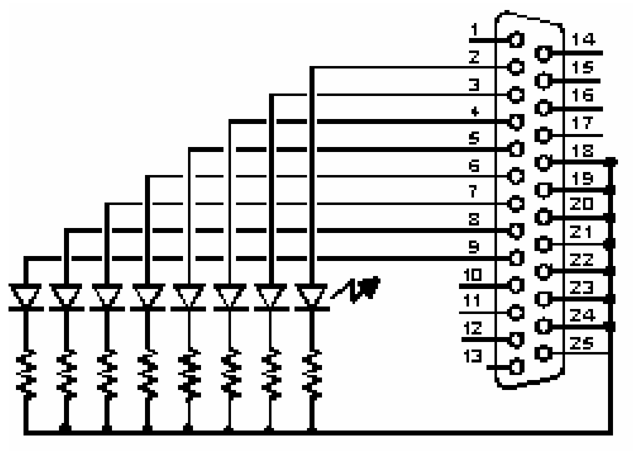


Figure. 53. Simple LED Driving Circuit Diagram

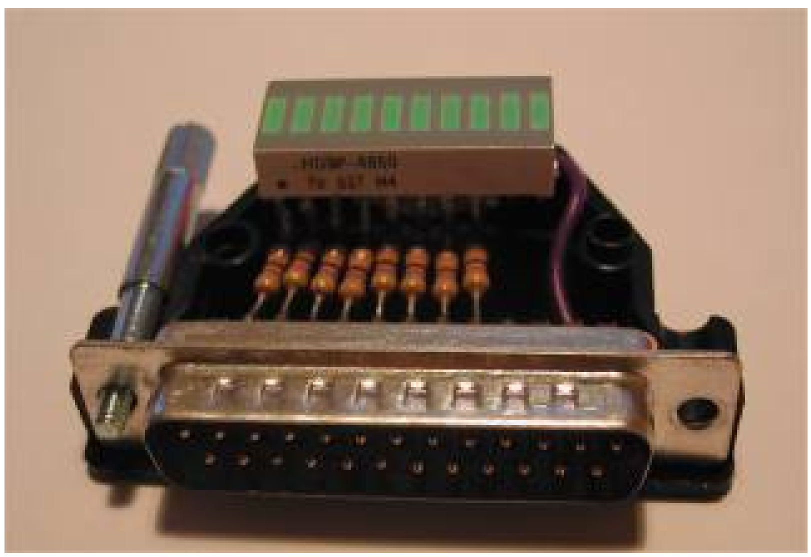


Figure. 54: Simple LED Driving Circuit

The next step is to implement the project coding using Borland Delphi software based on the method of controlling (automatic and manual). After the coding is settled, testing on each methods are done based on the coding whether each method can be implement and the output results are same as expected. It is tested on the simple LED driving circuit as in Figure 54 before applying it on the control circuit.

After the output testing resulting in desired expectation, the process of assembling hardware parts into project board and testing the control circuit were done. The control circuit consists of several devices such as optocoupler, relay, transistor, diode and resistors (470 Ω and 4.7K Ω). The schematic diagram of the circuit is shown in Figure 53. Figure 54 shows the control circuit used in this project..

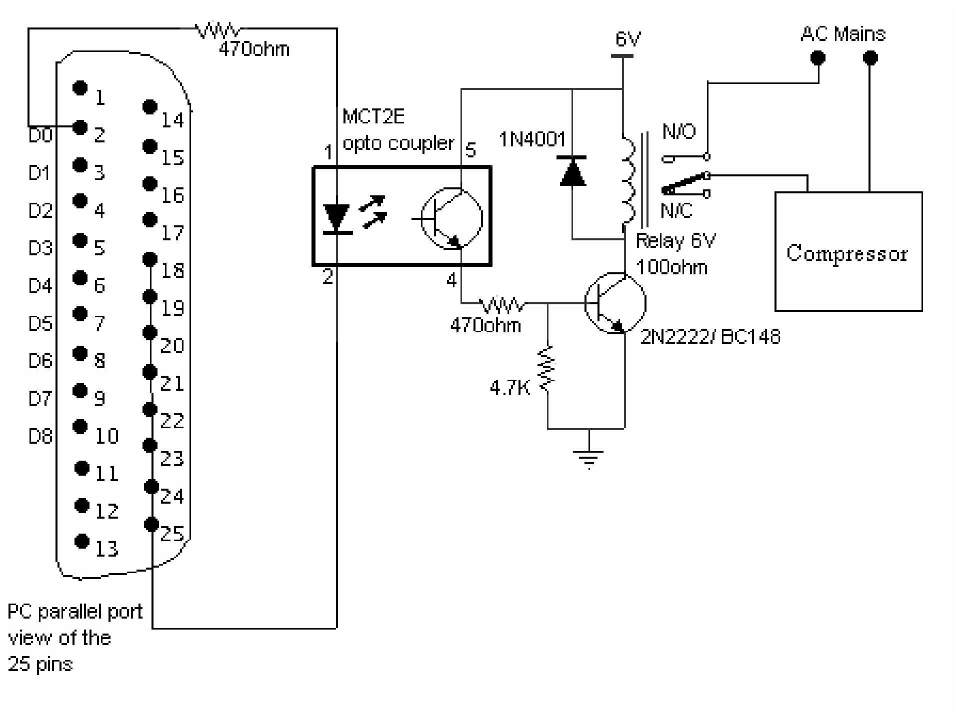


Figure.53. Programmable Thermostat Diagram

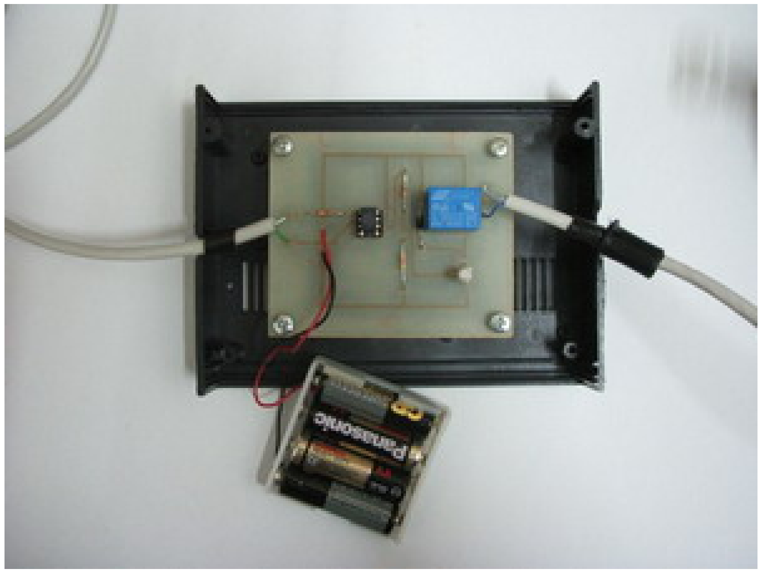


Figure. 54. Programmable Thermostat

3.2.2. Operation of the Designed Programmable Thermostat

Project coding using Borland Delphi 6.0 is the most important part in this project where in this coding, it can be divided into two parts which are automatic function and manual function.

In automatic controlling function, the coding will implement process based on input data from parallel port at 888 decimal addresses. This input data is received based on the signal deviation that occurs at temperature transducer before being sent to (ADC) circuit. (ADC) is responsible to convert the analog signal to digital signal before transmitting it to parallel port. At certain temperature, temperature transducer will produce signal in certain voltage and this signal will be transmitted to parallel port in a digital form. Then the software coding will analyze the data whether it is acceptable to on the compressor of the air conditioner or not. When the room temperature is higher than the maximum set point temperature (25°C), the coding will detect the difference and bit ‘0’is sent to the control circuit. Then the control circuit will send a signal out to the air conditioner compressor to turn it on. Otherwise, when the temperature is lower than the minimum set point (23°C), bit ‘1’ is sent to the control circuit and thus the air conditioner compressor is turned off.

In manual controlling function, it depends on the user whether he or she wants to use standard function or on-off function. In standard function, user can turn on and off the compressor whenever needed. User only has to press the buttons (compressor on) and (compressor off) on user interface at the monitor screen. By using programmable thermostat, it allows user to set the temperature for the compressor to be turned on and off. When the temperature is set, then compressor will be turned on and off according to the temperature given and this operation stays continuous. While the compressor is turned on, the temperature will be based on the set point temperature which is between 23°C and 25°C. The flow for on-off procedures are the same with automatic function procedures except the user has to set the time manually before the air conditioner operates. Figure 55 shows the project flow chart diagram.

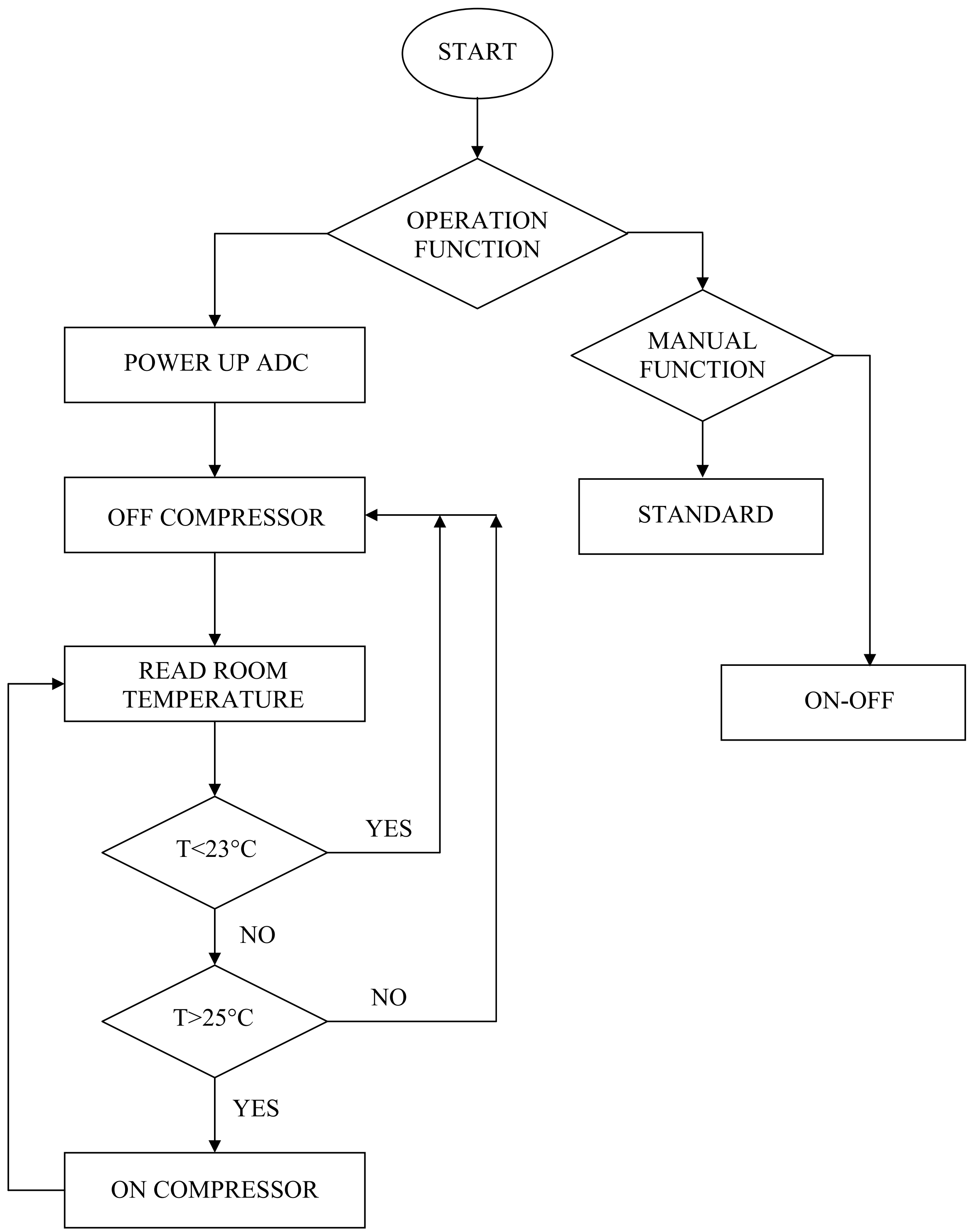


Figure. 55. Project Flow Chart

3.3. Software Development

3.3.1. Introduction to Borland Delphi

Borland Delphi is a sophisticated Windows programming environment, suitable for beginners and professional programmers alike. Using Delphi you can easily create self-contained, user friendly, highly efficient Windows applications in a very short time - with a minimum of manual coding.

Delphi provides all the tools needed to develop, test and deploy Windows applications, including a large number of so-called reusable components.
Borland Delphi, in its latest version, provides a cross platform solution when used with Borland Kylix - Borland's RAD tool for the Linux platform.

Delphi's roots lie in Borland's Turbo Pascal, introduced in the mid-1980s. Object Pascal, the object-oriented extensions to Pascal, is the underlying language of Delphi. The Visual Component Library, or VCL, is a hierarchy of Object Pascal objects that allow you to design applications. A better way of describing Delphi is an Object Pascal-based visual development environment.

3.3.2. Borland Delphi 4

Delphi 4 gives solid foundation of Borland's Object Pascal plus the visual application building characteristics of products such as Visual Basic. In the world of simpler, more visual interfaces, the first real player to show up was Visual Basic (VB). These new interfaces enable the software developer to visually construct the user interface using the mouse, rather than constructing it in code and then having to compile and run the code to see what it looks like.

Delphi offers real flexibility for the developer. Delphi possesses its own native version of ActiveX control, called a Visual Component Library (VCL).the (VCL) is a repository of visual components that developers can use to create Delphi application.

All the components in the (VCL) are displayed on the toolbar so they are easily accessible to the user.

3.3.2. Event Driven Programming

Delphi 4 is an event driven programming language that all its applications are constructed around the concept of events. Delphi 4 is very easy to program the events and the response to these events. The events are subroutines or procedures that are fired in response to specific conditions. There are many common events like clicking buttons and close forms or windows. This concept enables user to execute many events with one single procedure because an event can eventually trigger other events. It is different with traditional programming that run the codes in straight line or one direction.

3.3.3. Object Pascal and Object Oriented Programming

Object-oriented programming is a powerful way to approach the task of programming. Although high-level language such as C provides structured programming, it eventually comes to a complex situation when the programs grow larger. Object Pascal provides OOP and this make Delphi a powerful tool for programming. OOP requires the implementation of three qualities in a programming language: inheritance, polymorphism and encapsulation.

3.3.4. Delphi 4 Development Environment

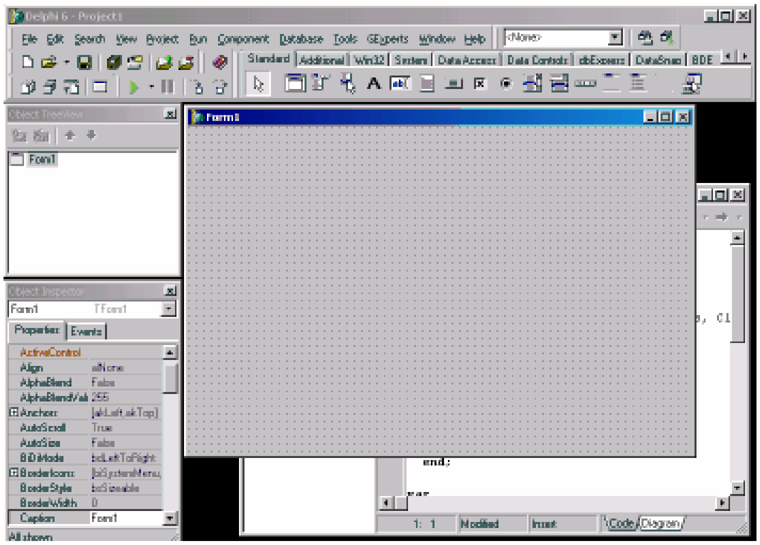


Figure. 56. Delphi IDE

When Delphi starts,(it could even take one full minute to start depending on the hardware performance) the user will be presented with the IDE: the user interface where the user can design, compile and debug Delphi projects. Like most other development tools (and unlike other Windows applications), Delphi IDE comprises a number of separate windows.

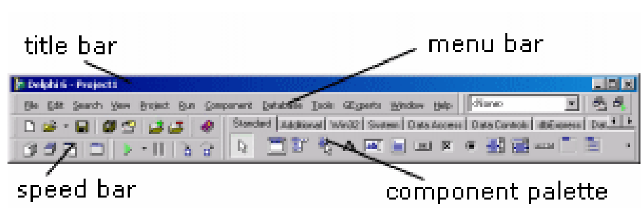


Figure. 57. Menus, toolbars

The main window, positioned on the top of the screen, contains the main menu, toolbar and Component palette. The title bar of the main window contains the name of the current project. The menu bar includes a dozen drop-down menus. The toolbar provides a number of shortcuts to most frequently used operations and commands such as running a project, or adding a new form to a project. To find out what particular button does, point the mouse "over" the button and wait for the tool tip. As you can see from the tool tip (for example, point to [Toggle Form/Unit]), many tool buttons have keyboard shortcuts ([F12]). The menus and toolbars are freely customizable.

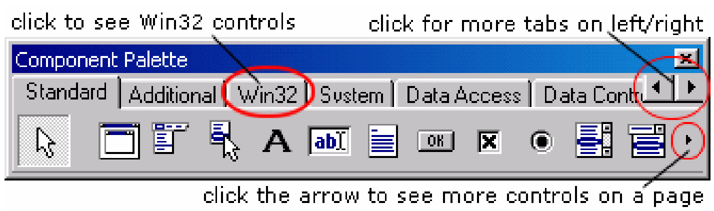


Figure. 58. The Component Palette

Any window in a standard Windows application contains a number of different (visible or not to the end user) objects, like: buttons, text boxes, radio buttons, check boxes etc. In Delphi programming terminology such objects are called controls (or components). Components are the building blocks of every Delphi application. To place a component on a window, drag it from the component palette. Each component has specific attributes that enable the user to control the application at design and run time.

Depending on the version of Delphi, starting with more than 85 components at disposal and can even add more components later The components on the Component Palette are grouped according to the function they perform. Each page tab in the Component palette displays a group of icons representing the components used to design the application interface. For example, the Standard and Additional pages include controls such as an edit box, a button or a scroll box.

To see all components on a particular page, (for example on the Win32 page) simply click the tab name on the top of the palette. If a component palette lists more components that can be displayed on a page an arrow will appear on a far right side of the page allowing the user to click it to scroll right. If a component palette has more tabs (pages) that can be displayed, more tabs can be displayed by clicking on the arrow buttons on the right-hand side.

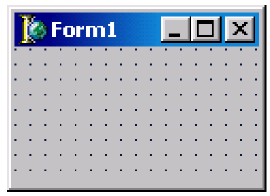


Figure. 59. Form1 window

Each time Delphi starts, a new project is created that consists of one empty window. A typical Delphi application, in most cases, will contain more than one window - those windows are referred to as forms. In our case this form has a name, it is called Form1. This form can be renamed, resized and moved, it has a caption and the three standards minimize, maximize and close buttons. A Delphi form is a regular Windows window.

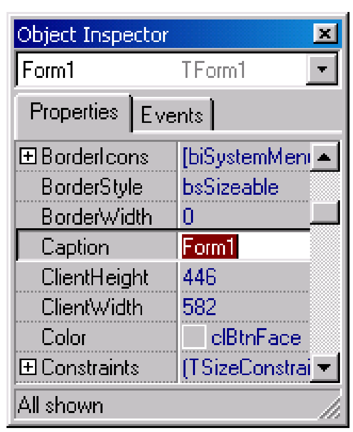


Figure. 60. The Object Inspector

Each component and each form has a set of properties such as color, size, position, caption that can be modified in the Delphi IDE or in the code, and a collection of events such as a mouse click, key press, or component activation for which the user can specify some additional behavior. The Object Inspector displays the properties and events (note the two tabs) for the selected component and allows the user to change the property value or select the response to some event.

For example, each form has a Caption. To change the caption of Form1 first activates the form by clicking on it. In the Object Inspector find the property Caption. Note that it has the 'Form1' value. To change the caption of the form simply type the new text value, like 'My Form'. When the user press [Enter] the caption of the form will change to My Form. Note that some properties can be changed more simply, the position of the form on the screen can be set by entering the value for the Left and Top properties or the form can be simply dragged to the desired location.

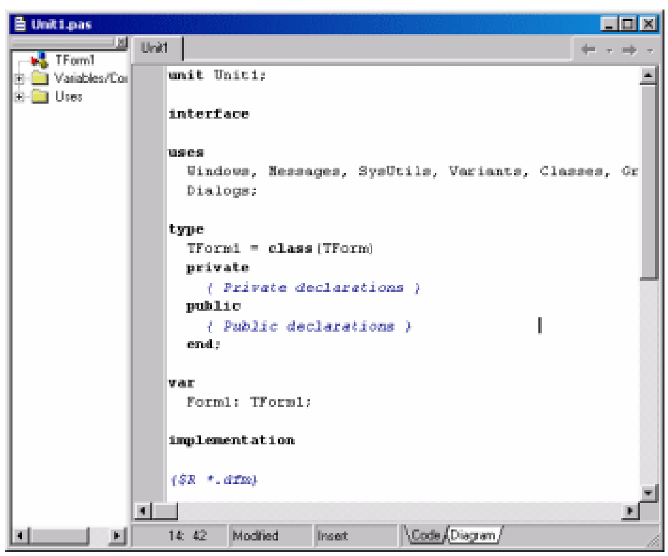


Figure. 61. Unit1.pas - the Code Editor window

The edit window provides the mechanism for the developer to input the Delphi code. The Delphi code editor is a full-featured editor, with color syntax highlighting, brief style editor commands and the ability to undo. The window's title bar displays the name of file currently being viewed. The tabs along the top of the window indicate the page or source files.

3.3.5. Coding Development

Coding development for this project is divided to several small parts so that code writing, testing and fault detection is easier to be done.

Parts involved were:

a) Routine to control on-off compressor automatically based on the data input from status port.

b) Routine to control on-off compressor manually.

3.3.5.a Routine to control on-off compressor automatically based on the data input from status port.

In controlling the compressor automatically, the coding is build using *if-then* statement. When the user chose to operate the compressor automatically, the coding will start on or off the compressor depending on the data (temperature) from temperature transducer and compared it with set point temperatures.

The coding using *if-then* statement to control the compressor automatically is shown below:

```
if temperature > 25 then
begin
PortOut (888,1);
end else
begin
if temperature < 23 then
begin
```

```
        PortOut (888,0);
        end;
        end;
```

3.3.5.b.Routine to control on-off compressor manually.

In manual controlling function, there are two types of controlling which are standard and on-off timing. The coding to control the compressor on and off using standard type is shown below:

For compressor on:

```
        begin
        PortOut (888,1);
        end;
```

For compressor off:

```
        begin
        PortOut (888,0):
        end;
```

The coding to control the compressor on and off using on-off timing type is as follows:

```
if BT3.Caption = 'Stop' then
    begin
    BT3.Caption:= 'Start';
    Timer1.Enabled:= False;
    Timer2.Enabled:= False;
```

```
      Label19.Caption:= 'Stopped';
      Label20.Caption:= 'Stopped';
      end else
      begin
      BT3.Caption:= 'Stop';
      Timer1.Enabled:= true;
      PortOut(888,1);
      fStopTime:= Now + EncodeTime (StrToIntDef (Ed1.Text, 0), StrToIntDef
      (Ed2.Text, 0), StrToIntDef (Ed3.Text, 0), 0);
      ReportTimeRemaining;
      Timer1.Enabled:= True;
      end;
   end;
end;
```

CHAPTER IV

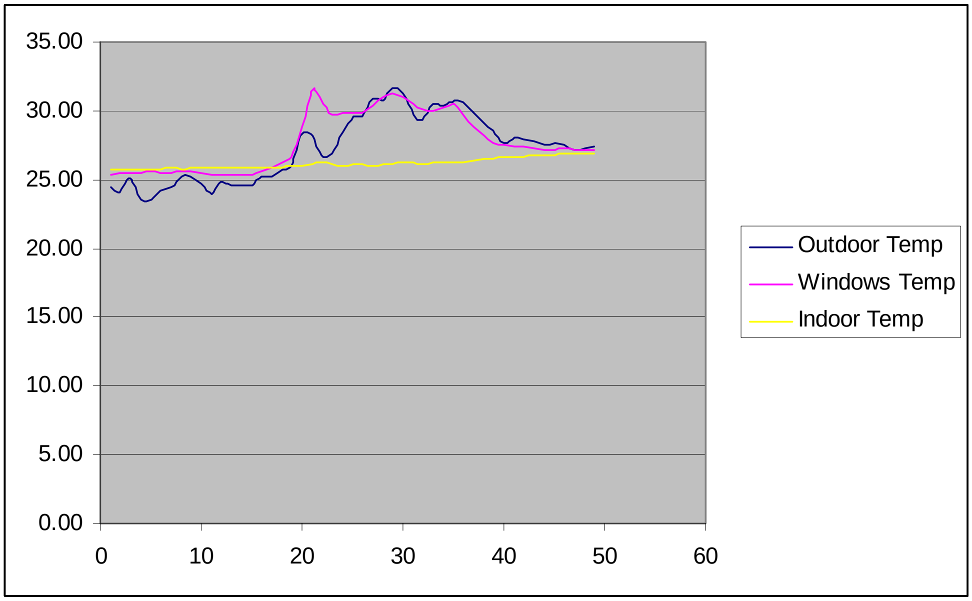
RESULT AND DISCCUSIONS

4.1 Introduction

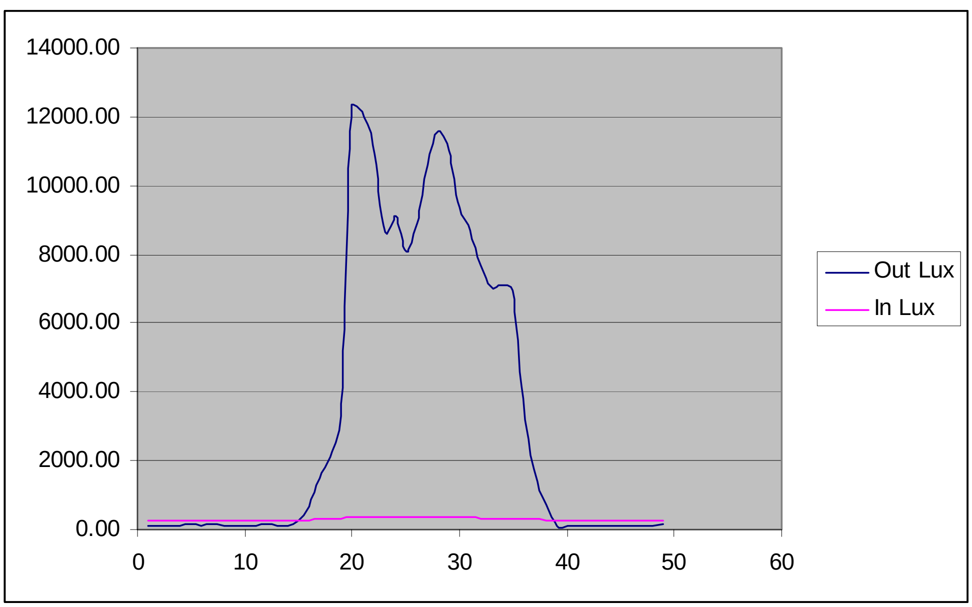
This data is taken 24 hours and every 5 minutes from 1200 PM. The parameter are : outdoor temperature, window temperature, indoor temperature, outdoor lux, and indoor lux. The data also taken in different type of weather and also different type of conditions. In the model room, the window is always covered with tinted glasses.

4.2 Tinted Glass, No Blind, All Lamps On

Time	Outdoor Temp	Windows Temp	Indoor Temp	Out Lux	In Lux
00.00 - 00.30	25.58	25.89	26.12	154.43	287.23
00.35 - 01.00	25.44	25.86	26.14	146.65	288.47
01.05 - 01.30	25.47	25.86	26.16	145.81	287.33
01.35 - 02.00	25.29	25.82	26.17	150.84	287.58
02.05 - 02.30	25.32	25.79	26.18	138.27	286.61
02.35 - 03.00	25.31	25.78	26.19	145.81	286.80
03.05 - 03.30	25.13	25.76	26.21	138.27	287.23
03.35 - 04.00	25.16	25.74	26.21	138.27	287.58
04.05 - 04.30	25.07	25.73	26.21	142.46	287.23
04.35 - 05.00	24.92	25.69	26.23	150.84	287.33
05.05 - 05.30	24.94	25.65	26.23	146.65	287.32
05.35 - 06.00	24.73	25.61	26.24	142.46	287.58
06.05 - 06.30	24.80	25.58	26.24	150.84	288.56
06.35 - 07.00	24.80	25.59	26.25	155.03	288.29
07.05 - 07.30	25.09	25.69	26.25	754.21	296.69
07.35 - 08.00	25.67	26.07	26.28	2007.00	317.46
08.05 - 08.30	26.67	26.62	26.32	3716.53	341.75
08.35 - 09.00	28.54	27.68	26.39	6259.84	377.86
09.05 - 09.30	28.73	28.64	26.47	8279.45	417.63
09.35 - 10.00	31.46	29.72	26.57	10743.10	456.63
10.05 - 10.30	32.13	30.95	26.69	13144.00	460.00
10.35 - 11.00	32.40	31.21	26.78	12988.83	501.76
11.05 - 11.30	32.96	31.77	26.88	13583.98	515.59
11.35 - 12.00	33.00	31.81	26.98	14702.67	547.15
12.05 - 12.30	31.73	31.83	27.06	12909.35	519.49
12.35 - 13.00	31.92	31.81	27.18	12322.13	505.91
13.05 - 13.30	33.00	31.80	27.27	12544.80	500.63
13.35 - 14.00	32.05	31.57	27.33	8019.63	421.18
14.05 - 14.30	28.17	29.18	27.30	2426.02	319.32
14.35 - 15.00	27.08	27.99	27.27	921.80	293.43
15.05 - 15.30	27.03	27.54	27.25	804.48	292.10
15.35 - 16.00	27.35	27.52	27.25	1324.05	301.59
16.05 - 16.30	27.59	27.69	27.26	2095.00	313.56
16.35 - 17.00	27.63	27.80	27.27	2066.50	313.61
17.05 - 17.30	29.98	27.71	27.29	1797.50	311.60
17.35 - 18.00	26.75	27.57	27.30	1689.42	311.27
18.05 - 18.30	26.72	27.48	27.30	1101.14	299.88
18.35 - 19.00	26.36	27.21	27.30	498.61	288.20
19.05 - 19.30	26.49	27.03	27.30	165.92	282.23
19.35 - 20.00	26.29	26.93	27.29	155.03	282.35
20.05 - 20.30	26.09	26.89	27.28	159.22	282.53
20.35 - 21.00	26.20	26.89	27.27	140.78	283.50
21.05 - 21.30	26.34	26.91	27.27	135.76	282.86
21.35 - 22.00	26.22	26.89	27.26	142.46	282.09
22.05 - 22.30	26.02	26.76	27.26	167.60	282.18
22.35 - 23.00	25.97	26.72	27.26	163.41	283.95
23.05 - 23.30	29.99	26.71	27.25	155.03	282.79
23.35 - 24.00	26.06	26.71	27.24	165.92	283.18



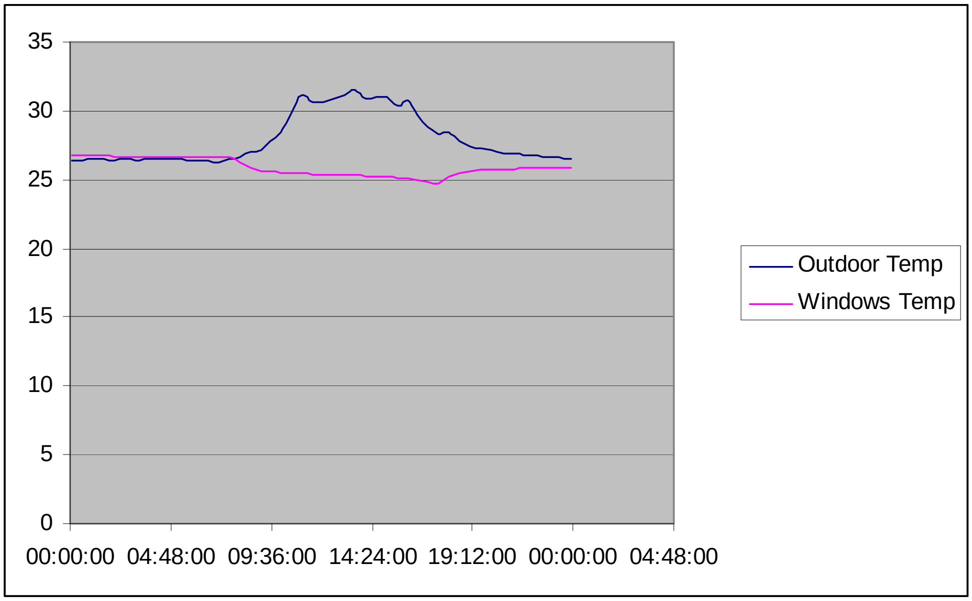
Graphic. 1. Temperature of outdoor, windows, indoor when there is no blind on the window and the lamps is on



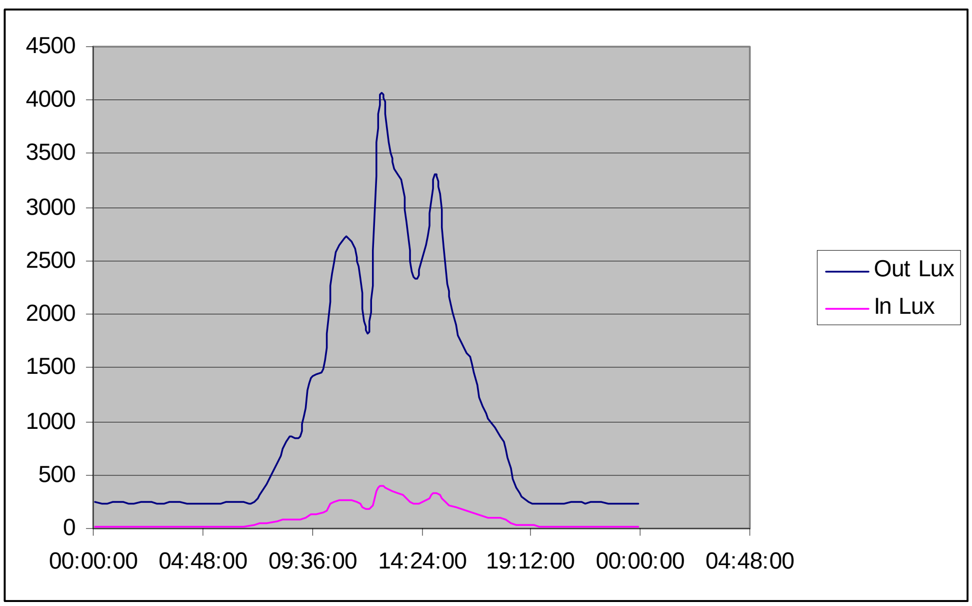
Graphic. 2. Outdoor lux and indoor lux when there is no blind in on the window and the lamps is on

4.3 Tinted Glass, No Blind, All Lamps Off

Time	Outdoor Temp	Windows Temp	Indoor Temp	Out Lux	In Lux
00:05:00	26.43	26.77	150.84	244.70	24.47
00:35:00	26.32	26.75	150.84	239.40	23.94
01:05:00	26.45	26.73	125.70	244.70	24.47
01:35:00	26.47	26.71	125.70	239.40	23.94
02:05:00	26.41	26.70	150.84	244.70	24.47
02:35:00	26.47	26.69	150.84	244.70	24.47
03:05:00	26.42	26.66	150.84	234.00	23.40
03:35:00	26.56	26.65	125.70	244.70	24.47
04:05:00	26.55	26.64	125.70	239.40	23.94
04:35:00	26.48	26.64	125.70	239.40	23.94
05:05:00	26.47	26.63	125.70	239.40	23.94
05:35:00	26.40	26.63	125.70	239.40	23.94
06:35:00	26.34	26.61	150.84	244.70	24.47
07:05:00	26.30	26.59	226.26	255.30	25.53
07:35:00	26.49	26.58	1055.90	420.20	42.02
08:05:00	26.62	26.20	1960.90	611.70	61.17
08:35:00	27.02	25.87	3494.50	867.00	86.70
09:05:00	27.16	25.66	3519.60	861.70	86.17
09:35:00	27.79	25.62	7164.90	1404.20	140.42
10:05:00	28.46	25.53	7114.60	1484.00	148.40
10:35:00	29.86	25.49	13802.00	2489.30	248.93
11:05:00	31.13	25.53	14757.00	2728.60	272.86
11:35:00	30.59	25.39	14581.00	2537.20	253.72
12:05:00	30.62	25.36	9905.20	1872.30	187.23
12:35:00	30.93	25.36	19383.00	4015.80	401.58
13:05:00	31.17	25.34	16668.00	3425.40	342.54
13:35:00	31.59	25.36	16140.00	3180.80	318.08
14:05:00	30.84	25.22	11740.00	2351.00	235.10
14:35:00	31.02	25.22	13098.00	2643.50	264.35
15:05:00	31.04	25.19	15109.00	3303.10	330.31
15:35:00	30.38	25.05	10282.00	2159.50	215.95
16:10:00	30.77	25.06	8396.80	1739.30	173.93
16:35:00	29.71	24.93	6787.80	1537.20	153.72
17:05:00	28.82	24.86	4726.30	1138.30	113.83
17:35:00	28.28	24.74	4273.80	941.50	94.15
18:05:00	28.40	25.17	2941.40	744.70	74.47
18:35:00	27.84	25.46	829.62	383.00	38.30
19:05:00	27.45	25.59	201.12	250.00	25.00
19:35:00	27.23	25.70	100.56	239.40	23.94
20:05:00	27.10	25.71	125.70	239.40	23.94
20:40:00	26.95	25.76	150.84	234.00	23.40
21:10:00	26.84	25.79	175.98	244.70	24.47
21:35:00	26.81	25.81	150.84	239.40	23.94
22:05:00	26.75	25.81	150.84	244.70	24.47
22:35:00	26.70	25.86	125.70	239.40	23.94
23:05:00	26.64	25.87	150.84	239.40	23.94
23:35:00	26.57	25.90	125.70	234.00	23.40
23:55:00	26.51	25.91	125.70	234.00	23.40



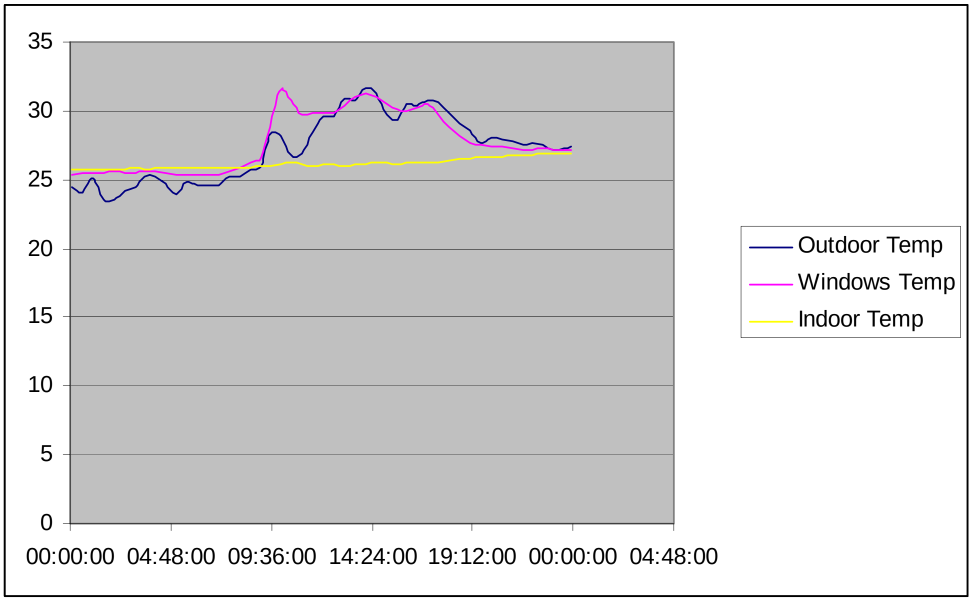
Graphic. 3. Temperature of outdoor, windows, indoor when there is no blind on the window and the lamps is off



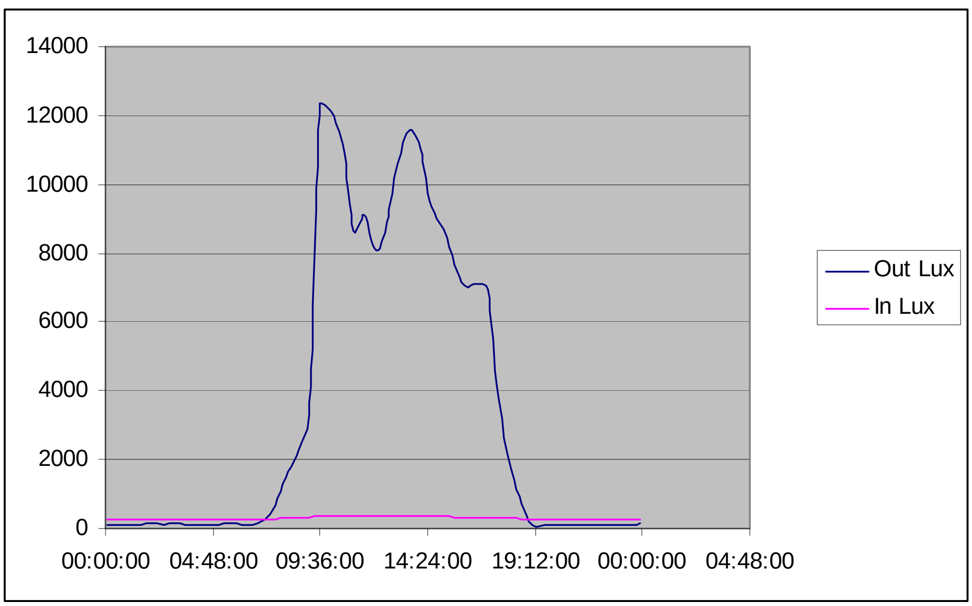
Graphic. 4. Outdoor lux and indoor lux when there is no blind in on the window and the lamps is off

4.4 Tinted Glass, With Blind, All Lamps On

Time	Outdoor Temp	Windows Temp	Indoor Temp	Out Lux	In Lux
00:05:00	24.42	25.37	25.77	125.70	273.93
00:35:00	24.05	25.48	25.77	125.70	275.52
01:05:00	25.05	25.42	25.78	100.56	277.12
01:35:00	23.56	25.52	25.78	125.70	276.06
02:05:00	23.55	25.56	25.79	150.84	277.12
02:35:00	24.20	25.54	25.76	125.70	278.18
03:05:00	24.50	25.50	25.80	150.84	276.06
03:35:00	25.17	25.57	25.79	125.70	275.52
04:05:00	25.24	25.56	25.80	125.70	276.06
04:35:00	24.77	25.49	25.80	125.70	276.06
05:05:00	23.95	25.32	25.82	125.70	276.59
05:35:00	24.81	25.39	25.85	175.98	276.06
06:05:00	24.62	25.40	25.85	125.70	278.18
06:35:00	24.53	25.39	25.86	125.70	278.18
07:05:00	24.64	25.41	25.86	251.40	277.65
07:35:00	25.18	25.56	25.89	653.64	282.97
08:05:00	25.24	25.85	25.90	1508.40	287.23
08:35:00	25.77	26.24	25.92	2086.60	292.01
09:05:00	25.94	26.59	25.94	3318.50	303.18
09:35:00	28.33	28.84	26.01	12319.00	373.39
10:05:00	28.13	31.54	26.18	12143.00	365.95
10:35:00	26.74	30.76	26.26	11187.00	361.69
11:05:00	26.90	29.72	26.18	8623.00	342.54
11:35:00	28.44	29.90	26.04	9100.70	348.39
12:05:00	29.60	29.80	26.08	8069.90	341.48
12:35:00	29.65	29.83	26.07	8924.70	346.80
13:05:00	30.91	30.36	26.04	10584.00	357.44
13:35:00	30.71	31.00	26.17	11564.00	366.48
14:05:00	31.67	31.29	26.12	11011.00	363.29
14:35:00	31.26	31.02	26.19	9352.10	352.12
15:05:00	29.66	30.46	26.21	8698.40	347.33
15:35:00	29.34	30.16	26.18	7692.80	330.31
16:05:00	30.54	29.95	26.28	7039.20	326.05
16:35:00	30.41	30.25	26.22	7089.50	329.25
17:05:00	30.77	30.55	26.30	6963.80	329.78
17:35:00	30.57	29.68	26.29	3796.10	302.12
18:05:00	29.80	28.81	26.39	1759.80	288.82
18:35:00	29.12	28.19	26.50	729.06	274.46
19:05:00	28.53	27.72	26.54	125.70	272.86
19:35:00	27.63	27.53	26.61	125.70	271.80
20:05:00	28.05	27.45	26.65	125.70	272.86
20:35:01	27.95	27.36	26.70	125.70	271.27
21:05:00	27.79	27.28	26.74	125.70	271.27
21:35:00	27.60	27.21	26.77	125.70	270.21
22:05:00	27.66	27.20	26.80	125.70	272.33
22:35:00	27.50	27.26	26.84	125.70	269.14
23:05:00	27.19	27.19	26.83	125.70	270.74
23:35:00	27.30	27.11	26.83	125.70	272.86
23:55:00	27.47	27.11	26.83	150.84	272.86



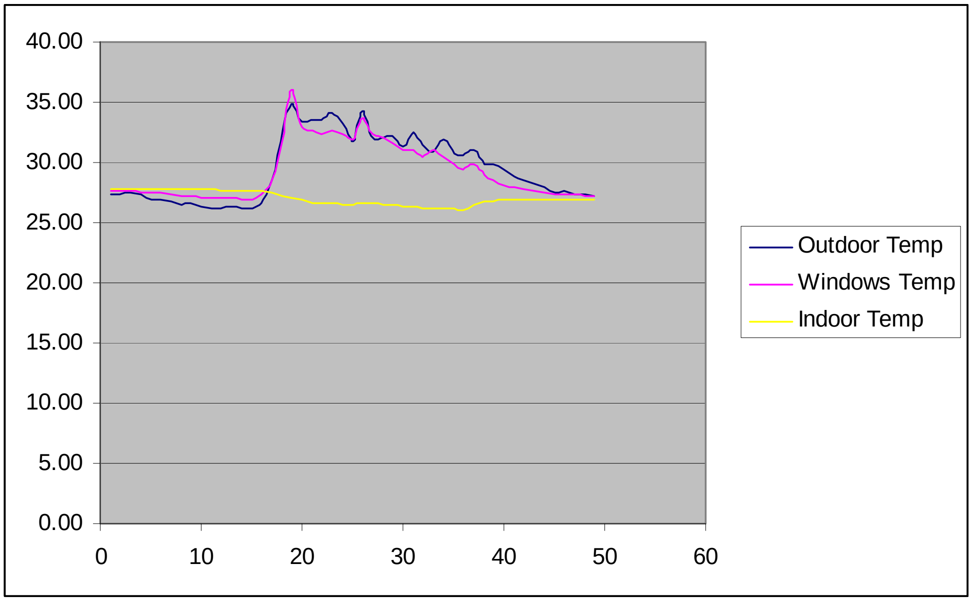
Graphic. 5. Temperature of outdoor, windows, indoor when there is blind on the window and the lamps is on



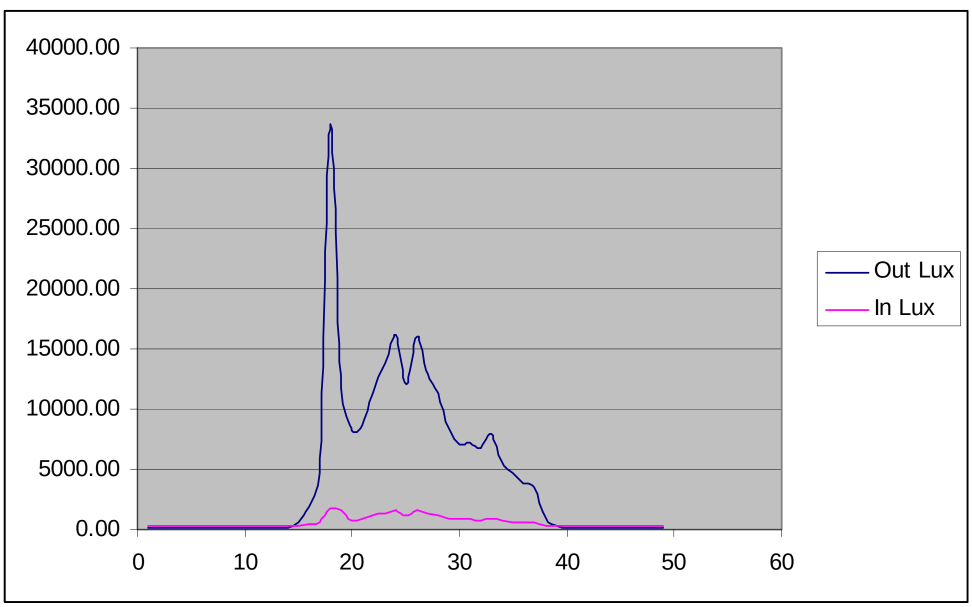
Graphic. 6. Outdoor lux and indoor lux when there is blind in on the window and the lamps is on

4.5 Tinted Glass, With Blind, All Lamps Off

Time	Outdoor Temp	Windows Temp	Indoor Temp	Out Lux	In Lux
00:00:00	27.39	27.69	27.82	175.98	255.30
01:05:00	27.46	27.60	27.82	201.12	250.00
01:35:00	27.30	27.56	27.81	201.12	250.00
02:05:00	26.90	27.45	27.80	175.98	250.00
02:35:00	26.98	27.43	27.79	175.98	250.00
03:05:00	26.74	27.35	27.78	175.98	255.30
03:35:00	26.43	27.23	27.76	175.98	250.00
04:05:00	26.58	27.19	27.75	175.98	260.60
04:35:00	26.37	27.12	27.74	150.84	250.00
05:05:00	26.17	27.05	27.73	175.98	255.30
05:35:00	26.22	27.04	27.71	175.98	255.30
06:05:00	26.26	27.00	27.69	150.84	250.00
06:35:00	26.23	26.94	27.68	175.98	250.00
07:05:00	26.22	26.96	27.66	553.08	287.20
07:35:00	26.62	27.37	27.66	1860.40	383.00
08:35:00	32.63	31.94	27.14	33637.00	1718.00
09:05:00	34.84	36.02	27.05	11715.00	1579.70
09:35:00	33.36	33.01	26.92	8170.50	776.60
10:05:00	33.52	32.69	26.69	8623.00	898.90
10:35:00	33.59	32.36	26.65	11313.00	1106.40
11:05:00	34.13	32.64	26.59	13827.00	1372.30
11:35:00	33.27	32.40	26.52	16190.00	1563.80
12:05:00	31.76	31.97	26.52	11992.00	1228.70
12:35:00	34.30	33.68	26.66	16014.00	1553.10
13:05:00	32.10	32.39	26.58	12947.00	1276.60
13:35:00	31.99	32.07	26.54	11363.00	1164.90
14:05:00	32.16	31.65	26.45	8447.00	936.10
14:35:00	31.35	30.98	26.37	7039.20	824.40
15:05:00	32.55	31.04	26.31	7164.90	835.10
15:35:00	31.43	30.39	26.24	6838.10	792.50
16:05:00	30.86	31.06	26.25	7919.10	867.00
16:35:01	31.84	30.49	26.20	5656.50	707.40
17:05:00	30.75	29.84	26.12	4650.90	606.40
17:35:00	30.55	29.39	26.06	3771.00	547.90
18:05:00	31.07	29.80	26.54	3544.70	547.90
18:35:00	29.89	28.99	26.77	854.76	324.50
19:05:00	29.80	28.46	26.82	276.54	255.30
19:35:00	29.34	28.10	26.84	201.12	244.70
20:05:00	28.77	27.87	26.86	201.12	260.60
20:35:00	28.53	27.73	26.90	201.12	250.00
21:05:00	28.21	27.61	26.93	201.12	255.30
21:35:00	27.96	27.51	26.95	201.12	244.70
22:05:00	27.55	27.41	26.97	175.98	250.00
22:35:00	27.60	27.34	26.95	175.98	250.00
23:05:00	27.32	27.29	26.96	175.98	255.30
23:35:00	27.30	27.21	26.97	175.98	255.30
23:55:00	27.27	27.18	26.96	175.98	255.30



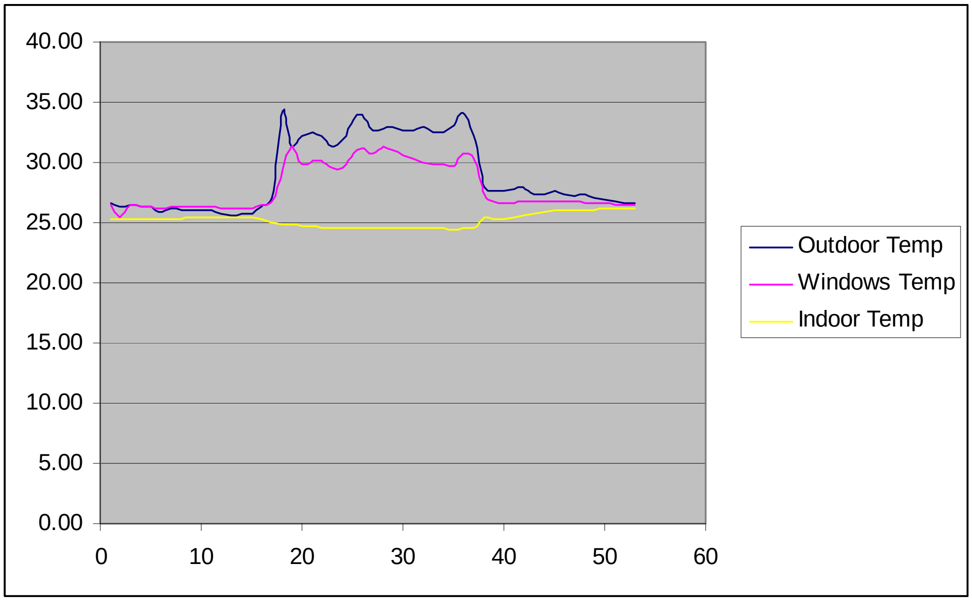
Graphic. 7. Temperature of outdoor, windows, indoor when there is blind on the window and the lamps is off



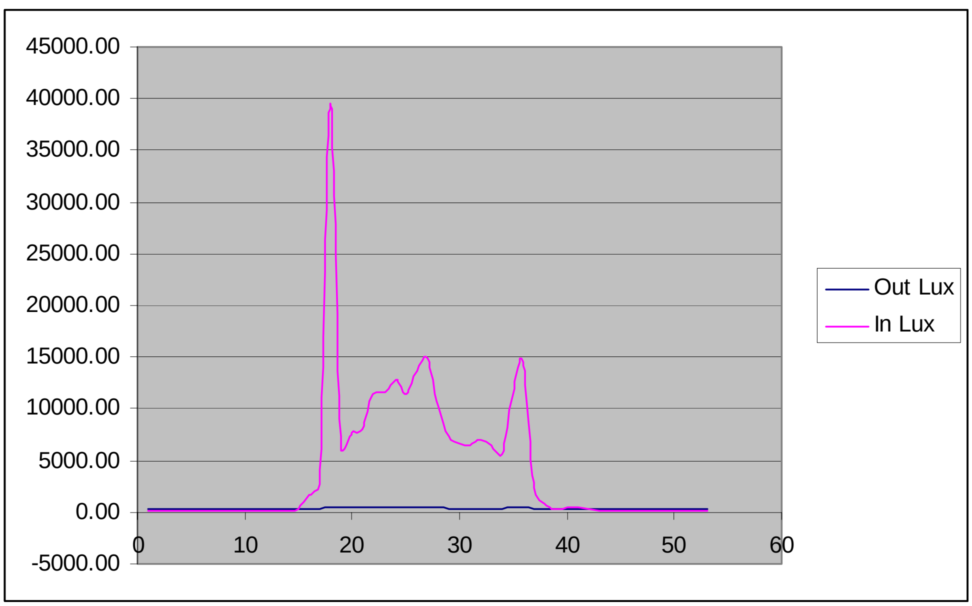
Graphic. 8. ***Outdoor lux and indoor lux when there is blind on the window and the lamps is off***

4.6 Tinted glass, No blind, All Lamps On, AC On

Time	Outdoor Temp	Windows Temp	Indoor Temp	Out Lux	In Lux
00:00:00	26.57	26.45	25.27	281.91	125.70
00:35:00	26.31	25.38	25.29	283.50	100.56
01:05:00	26.45	26.40	25.30	281.91	125.70
01:35:00	26.31	26.35	25.31	282.44	125.70
02:05:00	26.26	26.37	25.33	283.50	100.56
02:35:01	25.83	26.25	25.34	280.84	125.70
03:05:00	26.11	26.34	25.35	281.38	150.84
03:35:00	26.06	26.31	25.36	281.91	150.84
04:05:00	25.99	26.34	25.37	280.31	150.84
04:35:00	26.07	26.31	25.38	281.38	150.84
05:05:00	25.98	26.29	25.38	281.38	125.70
05:35:00	25.78	26.16	25.38	285.10	125.70
06:05:00	25.62	26.15	25.39	283.50	125.70
06:35:00	25.71	26.14	25.38	280.84	125.70
07:35:00	26.34	26.53	25.36	298.40	1759.80
08:05:00	27.10	26.80	25.00	317.01	2690.00
08:35:00	34.22	29.46	24.89	443.07	39470.00
09:05:00	31.34	31.33	24.86	395.73	6134.20
09:35:00	32.20	29.81	24.71	403.71	7642.60
10:05:00	32.48	30.11	24.73	404.78	7944.20
10:35:00	32.27	30.22	24.62	469.14	11388.00
11:05:00	31.34	29.50	24.63	478.71	11539.00
11:35:00	31.96	29.54	24.53	502.11	12872.00
12:05:00	33.52	30.72	24.63	464.35	11439.00
12:35:00	33.90	31.19	24.60	534.03	13676.00
13:05:00	32.69	30.71	24.56	547.86	14833.00
13:35:01	32.77	31.28	24.62	447.86	10207.00
14:05:00	32.87	30.96	24.53	392.01	7315.70
14:10:00	32.58	30.62	24.51	381.90	6662.10
14:15:00	32.60	30.33	24.52	379.78	6435.80
14:25:00	32.88	29.99	24.53	384.56	7014.10
14:30:00	32.54	29.89	24.53	379.24	6435.80
14:35:00	32.52	29.79	24.51	370.20	5656.50
15:05:00	33.11	29.75	24.43	484.03	11238.00
16:05:00	32.19	30.31	24.53	322.33	2287.70
16:35:00	28.01	27.39	25.40	291.48	603.36
17:05:00	27.66	26.71	25.27	288.29	326.82
17:35:00	27.59	26.57	25.25	287.23	527.94
18:05:00	27.83	26.65	25.46	289.35	402.24
18:35:00	27.87	26.71	25.66	285.63	251.40
19:05:00	27.42	26.71	25.78	284.57	150.84
19:35:00	27.39	26.71	25.88	281.38	100.56
20:35:00	27.38	26.71	25.98	283.50	125.70
21:05:00	27.26	26.78	26.03	280.84	150.84
21:35:00	27.35	26.69	26.07	280.31	150.84
22:05:00	27.12	26.61	26.09	282.97	125.70
22:35:00	26.96	26.58	26.12	284.03	100.56
23:05:00	26.82	26.51	26.15	282.97	125.70
23:55:00	26.63	26.47	26.20	284.57	125.70



Graphic. 9. Temperature of outdoor, windows, indoor when there is no blind on the window, the lamps is on, and the Air-Conditioner is on



Graphic. 10. . Outdoor lux and indoor lux when there is no blind on the window, the lamps is on, and the Air-Conditioner is on

CHAPTER V

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Generally, project's objective to design a control circuit that controls the operation of an air conditioner automatically and manually has been achieved. In this project, the control circuit is called 'Programmable Thermostat'. Even though there are already programmable thermostats created in market, but this one is different. It only consists of a circuit which acts more like a switch in order to on and off the compressor. Method of control depends on the user to choose whether the compressor functions automatically or manually.

Through systematic usage of the compressor, the cooling load can be reduced and thus, energy can be conserved. Air conditioner will operate economically by using a proper control system. Instead of just air conditioner, this control circuit can also be used in controlling other electrical appliances such as television, lighting and others.

By combining automatic window blind controller with lighting controller, the performance of the energy saving is increased. Automatic window blind controller is used to control the sunlight infiltration while the lighting controller is operated when the intensity of the room is not adequate to the standard lux of the room. By combining this system, the optimum energy saving is achieved.

5.2. Recommendation

Implementing fuzzy logic controller into this project would make it more efficient and easier. Fuzzy logic is one of the Artificial Intelligence Control Design Techniques and it is widely used as controller throughout the world. Many industrial and consumer products using fuzzy logic technology have been built, especially in Japan. There are different incentives to use fuzzy logic. Among them are:

a) Industrial AC systems use fuzzy logic to minimize energy consumption. The implementation of complex control strategies optimizes that the set values for the heater, cooler, and humidifier shall be set in a certain load state

b) Car AC systems use fuzzy logic to estimate the temperatures at the head of the driver from multiple indirect sensors.

c) Home AC systems are much simpler. They do not contain a humidifier and can only either cool or heat at one time. They use fuzzy logic for robust temperature control.

If using fuzzy logic, inputs and output are needed. In this case, fuzzy logic system uses four input variables which are:

a) Difference between set and room temperature (Temp_Error).
When the difference between set temperature and room temperature is very large, the fuzzy logic system increases the signal so the desired temperature is reached faster

b) Time differentiated set temperature (dTemp_by_dt)
The set temperature signal is differentiated with a time constant of 30 minutes. The fuzzy logic system uses this signal to understand when the user wants the AC to cool down a room quick

c) **Number of set temperature changes (Changes)**

This input signal is used to identify a user who tries to set the room temperature very precisely

d) **Brightness in the room (Brightness)**

If direct sunlight hits the room, the set temperature is automatically reduced. During the day or when lights are on in the room, the set temperature is slightly increased.

The fuzzy logic controller does not require any modification of the AC itself. Hence, by replacing existing temperature controllers, even old air conditioner can be upgraded. By also controlling the ventilation, an even more improved performance could be reached.

The usage of Borland Delphi software took a longer time in executing a command. By using other appropriate software which is faster and using new technology might produce a better performance to the system.

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