Intelligent Simulation Model for Energy Saving Integrated Lighting Schemes in Buildings

THESIS

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List of Abbreviations / Symbols

AHU	Air Handling Units
ANFIS	Adaptive Neuro Fuzzy Inference System
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
BACnet	Building Automation and Control Network
BAS	Building Automation System
BMS	Building Management Systems
CCFL	Cold Cathode Fluorescent Lamp
CFL	Compact Fluorescent Lamp
CIE	Commission Internationale de L′Eclairage
CRI	Colour Rendering Index
DALI	Digital Addressable Lighting Interface
DDC	Direct Digital Control
DEWA	Dubai Electricity and Water Authority
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
DIFC	Dubai International Financial Center
DSM	Demand Side Management
EIB	European Installation Bus
EPAct2005	Energy Policy Act of 2005
FCU	Fan Coil Units
FIS	Fuzzy Inference Systems
FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
GD	Gradient Descent
HID	High Intensity Discharge
HVAC	Heating, Ventilation and Air-Conditioning
IDMP	International Daylight Measurement Programme
IESNA	Illuminating Engineering Society of North America
LED	Light Emitting Diode

LEED	Leadership in Energy and Environmental Design
LON	Local Operating Network
LonWorks	Local Operating NetWorks
LSE	Least Squares Estimates
MEED	Middle East Economic Digest
MF	Membership Function
NFS	Neuro Fuzzy System
PID	Proportional-Integral-Derivative
PIR	Passive Infra Red
PLC	Programmable Logic Controller
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PROFIBUS	PROcess FIeld BUS
PWM	Pulse Width Modulation
Relux Pro	Relux Professional
RMSE	Root Mean Squared Error
RTP	Real Time Pricing
SAD	Seasonal Affective Disorder
SHGC	Solar Heat Gain Coefficient
SSL	Solid State Lighting
TCP/ IP	Transmission Control Protocol / Internet Protocol
TRY	Test Reference Year
UAE	United Arab Emirates
UDI	Useful Daylight Illuminance
UGR	Unified Glare Rating
USGBC	United States Green Building Council
VCP	Visual Comfort Probability
$\hat{G}$	Adaptive network function
$\overline{W_i}$	Normalised firing strength of input vector *i*
Δ	Spacing between points
C_{as}	Annual savings due to retrofit
C_i	Initial cost of lamp and fixtures plus the automatic shut off control
D	Number of points mapped

E_a	Horizontal outdoor illuminance with a uniformly overcast sky
E_i	Horizontal illuminance (in lux) at the point of interest in the given interior
E_s	Set illuminance level as desired by the user
G	Inverse mapping
hgl	Heat gain due to lighting
H_{op}	Average daily hours of operation
k	Discrete time instant
m	Number of membership functions on each input
n	Number of inputs in fuzzy inference system
N_f	Number of fixtures
N_t	Number of tube per fixture
O^j	Output of *j*th layer
p	Real number defined in the illuminance profile
P	Future time for prediction
P_e	Unit price of electricity
r	Tolerance range for the occupant
S	Set of total parameters
S_1	Set of premise parameters
S_2	Set of consequent parameters
$u(k)$	Control signal generated at k
W_l	Wattage of the luminaires
$x(t)$	Illuminance value at time t
$y(k)$	State at time k
$y_d(k+1)$	Future desired state
z	Overall output

Chapter 1

Introduction

1.1 Introduction

In the modern societies, much of life is spent in buildings. In the case of office buildings, the productivity of the employee is of paramount importance to the employer and negative impacts of the work environment cannot be tolerated (Henze 2001). The same is true for occupants of residential buildings also as a comfortable environment enhances the physical, psychological and mental well-being of the occupants. As a result of this, sophisticated lighting control systems have become an integral part of all modern constructions. These systems when designed properly can not only provide excellent comfort for the occupants but also decrease energy consumption in a building. Given restrictions that comfort conditions in the interior of the building are satisfied, it becomes obvious that the problem of energy consumption is a multidimensional one (Dounis and Caraiscos 2009). Scientists from a variety of fields have been working on this problem for a few decades now; however, essentially it remains an open issue (Dounis and Caraiscos 2009). Many techniques have been deployed to design systems that fulfill this difficult-to-achieve dual goal. One of the approaches has been to utilise various methods and tools to accurately capture a building's characteristics so as to provide a reliable basis for the control of its behaviour (Mistry and Nair 1993). By collecting information about the past behaviour of building's subsystem, the control scenario can be enhanced. This is achieved by optimising the various control options by exploring different possibilities using advanced computational performance simulation algorithms.

The notion that a building is to be treated as a static and passive physical model is no longer true. There are geographical, environmental factors which influence the external parameters of the building system. The occupancy factors influenced by presence, occupants' mood, emotions and behaviour determine the internal profile of the system. While the occupancy factors cause the system fluctuation rapidly, the thermal inertia of the building causes the changes to take place over a significant time scale. This whole process makes the system exhibit a complex, dynamic behviour which is difficult to capture, define and hence model. This research starts from the idea that a dynamic control process in a building can be modelled by combining simulation with machine learning and the region is well-equipped to support the modern and sophisticated lighting control options.

1.2 Objectives

The major objectives of this research is identified as follows:

1. Study of the existing energy saving and control schemes available in lighting subsystems and of building automation.

2. Understanding the soft computing tool for energy efficient control of building's lighting subsystems using advanced computational performance simulation algorithms.

3. Identifying and evolving a suitable intelligent simulation model for allowing flexible adaptation to the dynamic environmental and user preferences.

In this thesis, Dubai as a region is identified as a platform capable of supporting the sophisticated lighting control scenario and a model is obtained combining simulation and neuro-fuzzy system. A simulation model alone can not capture the system's dynamic behaviour accurately and the training by neuro-fuzzy system enhances the control process. This combination of simulation and machine learning has been explored by previous researchers (Chang 2000, Gullemin and Morel 2001) to define a building process but we use a specific class of intelligent systems called Adaptive Neuro Fuzzy Inference System (ANFIS) for the learning process.

The following section summarises the literature survey on an overall basis of the research topic. The individual chapters contain detailed literature on the specific topics of discussion.

1.3 Brief Literature Review

To meet with the first objective of the research, we explore Dubai as a region and we identify the existing energy saving and control schemes available at present. In the Gulf States, although there is small amount of research and writing that is relevant to the use of conservation measures, there is a need for such methodologies due to their economic and environmental benefits (Radhi, 2008). In the recent past, the effect of glazing and code compliance on Air-Conditioning systems was presented by Omar and Al-Ragom (2002). Iqbal and Al-Houmoud (2007) have analyzed alternative energy conservation measures for an office building in hot and humid climate, choosing Dammam, Saudi Arabia as their location of study. Very recently, Al-ajmi and Hanby (2008) have reported their work on simulation of energy consumption on Kuwaiti domestic buildings while Radhi (2008) has proposed a systematic methodology for optimizing the energy performance of buildings in Bahrain. Al-Iriani (2005) proposed a climate related Demand Side Management (DSM) program with policy actions to include measures to reduce cooling degrees requirement using the case of UAE.

The need for research and documentation on automated lighting systems in the region has assumed much more significance now after His Highness Sheikh Mohammed Bin Rashid Al Maktoum, UAE Vice-president and Prime Minister and the ruler of Dubai issued a resolution on implementation of green building specifications. The objective described in this thesis was motivated by the author's observation that all the works mentioned above have concentrated on the energy-efficient air-conditioning systems of buildings in the region and that there is a need to identify how the lighting systems are performing presently which could serve as an indicator for future measures.

The emerging technologies in energy saving in lighting have been discussed in the literature. Geller (2003) talked about how growth in global use of Compact Fluorescent Lamps (CFL) has gone up from the year 1988 to 2000 and a work describing a Canadian research pilot project on achieving 40% reduction in energy costs in five houses clarifies that measures such as substituting of CFL for commonly used incandescent lamps is effective and simple (Fugler et al. 2005). Hadley et al. (2004) talked about future of solid state lighting. The potential and future of dimming (DiLouie 2006), fluorescent dimming (Chang-Hua 2005), load shedding control (Akashi and Neches 2005), Digital Addressable Lighting Interface (DALI) compatible ballast controller (Roisin et al. 2008), high frequency dimming controls (Li et al. 2006) and total energy impact of manual and automated lighting control (Bourgeois et al. 2006) are some relevant works in dimming.

How building automation helped acquire Leadership in Energy and Environmental Design (LEED) rating was explained by Herrmann (2005). Lane (2005) discussed about how to gain LEED point via lighting, namely using T5 high-output (HO) fluorescent lamp, DALI technology and digital dimmable ballasts operated locally or from a central location. Direct Digital Control (DDC) was discussed by McGoven (1995) stating that wireless communications, self-optimizing software and improved operator softwares would make the buildings self checking and in many cases they would be able to repair or modify themselves to meet any ongoing or new problems as they may arise.

As for the previous work in optimisation measures of intelligent buildings, Heating, Ventilation and Air-Conditioning (HVAC) set points were developed on top of DDC system and a method that combines Lagrangian relaxation, neural network, stochastic dynamic programming and heuristics was developed to predict the system dynamics and uncontrollable load and to optimize the set points (Xu et al. 2005). For multi building load management, a list of 11 tools such as load forecasting etc. was identified and proposed by Reddy and Norford (2004) and for the tool 9 namely communication between aggregator and customer, enhancing the capability of building automation systems through load management service and energy efficient monitoring were proposed (Norford and Reddy 2004). For short term load control measures to limit the lighting and chiller power to a specified fraction of the maximum, the authors suggested Genetic Algorithm (GA) search engines and reckoned that this single building optimisation control strategy produced best performance for lighting control as well. A parallel genetic algorithm for optimization of multi objective demand side management system in building automation was proposed and the architecture supporting the algorithm was outlined by Penya (2003). In a distributed building automation system, the Demand Side Management (DSM) process of communicating the prognosis of energy consumption of each device has to be done coordinately to achieve optimum solution and hence these models were recommended as scheduling problem for adaptation to buildings.

1.3.1 Need for Intelligent Simulation Model

The second and third objectives are concerned with the development of an intelligent simulation model that are impacted by non-linear, dynamic processes due to fluctuation of geographical, environmental and occupancy factors in the building. The use of intelligent techniques is advocated because the traditional systems do not function when the input data is incorrect or when the environment is dynamic. Hybrid intelligent systems also bring to the table the advantages of tackling uncertainty, vagueness and also catering to high-dimensionality.

The application of soft computing techniques such as fuzzy logic, neural networks and Genetic Algorithm (GA) for modeling and control of lighting subsystems in the built environment have been discussed in the literature as current trends of research. Kristl et al. (2008) reckoned that the field of application of artificial intelligence automation in the built environment is still in its early phases and the researchers have described a fuzzy control system for thermal and visual comfort in the building using experimentation. A fuzzy logic PID (Proportional-Integral-Derivative) controller implementation along with sensors, actuators and a smart card terminal on top of LonWorks (Local Operating Network) for global control of thermal comfort (Predicted Mean Vote-PMV), visual comfort (illuminance level) and indoor air quality (CO_2) in an existing building were discussed by Kolokotsa et al. (2001). Dounis et al. (1993) and Dounis et al. (1995) applied fuzzy set theory to visual comfort control while Bernard (1993) considered neural network as a potential area of application in building services. A lighting controller, which can integrate itself into an advanced building control system according to user wishes, was implemented using GA applications and the architecture was presented in Gullemin and Morel (2001).

Some work has been reported in the literature on the application of hybrid techniques (that combines two or more intelligent techniques or approaches) in the visual environment control domain. An approach to daylighting control based on methods from combining fuzzy and probabilistic methods, using wireless sensor (Smart Dust motes) was presented in Granderson et al. (2004). Using the exciting wireless sensing technology, the author discussed how through intelligent daylighting control, conflicting occupant preferences (sharing a common light source) and perceptions can be balanced, demand responsiveness can be implemented through load shedding during times of peak electricity pricing and sensed values of illuminance can be validated and fused. For sensor validation and fusion, an existing algorithm was enhanced and tested on a small network using MATLAB. The work assumed that the occupant's perception of lighting quality depended on task type and work surface illuminance only and there was no effect of electricity price on this perception while the price of electricity was the major preference of building manager.

Chang (2000) described the development of a hybrid construct out of both simulation and machine learning technique. The author argued that the computational model could support the control of a dynamic building process such as load side management and or visual environment and comfort in a building. A hybrid prototype control system Hybrid Intelligence for System State Transition Operation (HISSTO) was presented. The seamless control was tested and implemented with a view to minimize data dependency and sensor dependency using neural network implementation. To model daylighting and artificial lighting processes, a lighting simulation program called LUMINA was used. Kurian et al. (2008) discussed about a model based on ANFIS which was used for training and retraining of large amount of data on the visual task. From the literature review, it is clear that use of soft computing techniques can significantly improve the effectiveness of control process when used along with simulation.

1.3.2 Gap in Existing Research

A traditional PID control algorithm can not always yield satisfactory response due to the ill-defined and dynamic nature of parameters of the visual environment control domain. So an adaptive neuro-fuzzy controller is proposed in which the fuzzy technique takes care of tackling uncertainty such as environmental conditions while the neural network facilitates machine learning to tune the weight matrix for the desired output levels. Chang (2000) whose work was based on neural networks quoted the issue of improvement of the design and the training scheme for the machine learner to enhance its prediction capability as one of the future research areas. This aspect is taken up in the proposed hybrid scheme, by estimating the variation range of control parameter within a period of time. The thermal comfort is a subjective parameter that is complex to be validated due to its occupant-specific nature. The objective parameters such as illuminance and average illuminance as well as the subjective parameter such as heat gain are taken up in the validation of the model. Thus the three important components of lighting control namely, simulation, control mechanism and occupant preferences are addressed in the research. When simulation is combined with machine learning, the advantages result due to the improvement in simulator's prediction error and reduction in computational complexity and time. The simulation is done using MATLAB programming and the source of system knowledge is obtained by an advanced lighting simulation tool. Such a simulation-assisted model can have the prediction errors corrected by learning from the past inputs. Should an alternative and unexpected control scenario occur in future, the model can adapt itself better for unknown conditions when tuned online.

1.4 Scope and Limitation

The study component pertaining to the fulfillment of the first objective of the research is done with Dubai as the geographic location. This objective focuses on the available technology, infrastructure, knowledge and awareness in the existing energy-saving and control schemes of lighting in the region. The various factors originating from the overall perspective of owners, engineers, designers and suppliers involved with new projects are taken up for the study. From the analysis of these factors, some pointers such as governmental measures are presented which could serve as future measures which could, in turn make the lighting controls potentially a standard feature in each building. The study input has been carefully chosen to represent a wide and varied spectrum of projects, types of controls and suppliers so that it truly describes a realistic scenario. However, the application of the results to represent a wider geographic location is not attempted in the thesis, though the extent and sophistication of lighting control systems and BAS can be seen stretching to the neighbouring emirates and countries (Alnaser et al. 2008).

In the development of intelligent simulation model, the main focus is to accentuate the cooperation of simulation and machine learning for building control. Hence the proposed scheme has the illuminance values simulated unlike the commercially available sensor-based lighting controllers. The ANFIS scheme has been shown to improve the performance of simulation predictions. The model obtained is able to maintain an illuminance profile between the set value and its multiple as desired by the user at all time. This modelling and control approach is suitable for any plant which can not be described by a set of mathematical equations. This work, in particular, presents a model for the blind position controller applicable to daylighting schemes and the obtained model is adaptive and robust to the hot environment of Dubai. The objective parameters such as illuminance and average illuminance as well as the subjective parameter such as heat gain are taken up in the validation of the model. The thermal control loop is implemented in basic form and can be extended with more refinement in heat gain modelling studies. The controller is validated in a daylight-artificial light integrated scheme equipped with dimming controls.

The universal model approach for daylighting systems may not be desirable since the models for daylighting control are to contend with multi-variant, dynamic, non-linear components impacted by geographical, environmental and occupancy factors amongst many other things. Though the proposed model exhibits good adaptive and predictive capability to environmental and occupancy fluctuations, it may not be able to guarantee energy savings in buildings whose structures are not adequately planned at the design stage to support daylighting. The same is also true when poor daylighting conditions such as overcast sky and sandstorms are experienced.

1.5 Organisation of the Thesis

This thesis has seven chapters. Chapter 1 (this chapter) is an introduction to the problem with a discussion on the objectives, literature review, scope and limitation of the research topic. Chapter 2 reviews the lighting control types and technology, daylighting principles and design aspects from an overall perspective of users, designers and engineers. It also concentrates on the vital role played by BAS towards equipment control and energy management on a real time basis. Chapter 3 presents the research study conducted to analyse the various lighting control technologies that are available in Dubai. It also analyses and presents the results and discusses the pointers for future measures such as enforcement of energy code practices and standards. Chapter 4 explains the procedural steps for development of the model and the advanced lighting simulation tools are dealt with extensively in chapter 5, along with the various features of the chosen simulation software used for data collection. Chapter 6 presents and discusses the results obtained on the neuro-fuzzy model for blind position control. As a conclusion, Chapter 7 summarises the work and presents the specific contributions of this thesis. It also suggests ideas for future research in this field.

Chapter 2

Energy Saving and Integrated Lighting Control Systems in Buildings

2.1 Introduction

This chapter describes the existing energy saving and control schemes available in lighting subsystems under three major categories. Firstly, the lighting control systems are reviewed in terms of their types and control strategies adopted. The next section presents daylighting principles and design aspects along with the issues concerned. The integrated systems are discussed next which involves equipments controlled by Building Automation Systems (BAS), their protocols and Direct Digital Control (DDC) which is followed by a discussion on how BAS can help in making “green” buildings. Then the important topic of how lighting can be controlled by BAS follows and the chapter concludes with case studies done in Dubai along with its results for energy saving.

2.2 Energy Saving Lighting Systems

Energy saving in a building depends on economic background and lifetime costs of building fabric, of maintenance and of energy. Saving energy helps us maintain a healthy environment because the energy we use in lighting is usually derived from conventional power plants by burning the fossil fuels, which causes air pollution and contributes to acid rain, respiratory diseases, climate change and global warming. The higher saving of energy means the more pollution we prevent. Lighting controls makes buildings more comfortable, productive and energy efficient. Lighting control also helps utilities offset their peak loads and avoid the need to construct newer power plants, which indirectly tax the consumer. Apart from energy saving, controls are also of interest from the aspect of their influence or contribution to the introduction of harmonics into the power systems.

Illuminating Engineering Society of North America (IESNA) recommends the baseline conditions for the energy efficiencies for the interiors of buildings as T8 lamps and electronic ballasts for most commercial spaces and the use of lighting controls to shut off lighting automatically when not needed (Liebel and Brodrick 2005). American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) standard 90.1 requires that all lighting be controlled by an automatic shut-off control device for buildings more than 5000 ft^2 and each room has own lighting control for automatic turn off (Liebel and Brodrick 2005). Modern lighting control schemes offer not only convenience and also the ability to change light distribution to accommodate changes in workspace configuration, schedules and activities.

2.2.1 Types of Lighting

Table 2.1 classifies the types of lighting based on the purpose for which it serves or how the light emerges.

Table 2.1 Types of Lighting

Lighting	Main Function	Typical Use
General lighting or ambient lighting	gives a base amount of uniform light	ceiling, table, floor lights
Accent lighting	gives concentrated light to highlight an object	spot lights, flood lights
Task lighting	provides light on a specific area for a task	reading light, appliance light
Decorative lighting	adds aesthetics to the room	chandeliers, pendants, candles

A project work done for the U.S. department of energy recommends Solid-State Lighting (SSL) as one of the five promising technologies for long-term potential energy saving up to 33% by 2025 (Hadley et al. 2004). The report highlights SSL to be responsible for energy efficient, longer lasting and more versatile light sources (Hadley et al. 2004). The future research in SSL will focus around developing substrate materials, photo conversion materials, super luminescent diodes and light extraction techniques because of the high refractive index of Light Emitting Diode (LED), making white light by colour mixing and in minimizing the cost of LED technologies. In fixture design, to cater to the increased reflectivity, instead of raw aluminium, anodised aluminium and Miro are the current trends (Samuel 2003).

Table 2.2 lists the vital parameters of each kind of lighting. Here luminous efficacy is defined as the ratio between the light output and electrical input. Colour Rendering Index (CRI) is used to describe the effect of a light source on the colour appearance of objects with respect to a reference source (sunlight) of same colour temperature. Higher the CRI, higher will be the enhancement of visual environment. The maximum value is 100. Light sources should have a minimum CRI of 75 for most interior spaces. Retail spaces, art rooms, exhibition spaces are better served with a source of CRI of at least 80.

Table 2.2 Comparison of Vital Parameters of Different Types of Lighting

Lighting type	Light output (lm)	Electrical Input (w)	Luminous efficacy (lm/w)	Useful life (h)	Colour Rendering Index (CRI)
Incandescent	1360	100	13.6	2000	90
Fluorescent	5200	58	90	20000	70
Compact Fluorescent Lamps (CFL)	1600	20	80	8000	85
High pressure sodium	50000	400	125	12000	21
LED	550	13	42.3	35000	80

Small diameter T5 fluorescent fixture lamps are available as High Efficiency (HE)/ High Output (HO) where HE is optimised for maximum light output (up to 104 lm/w) and HO is optimised for maximum light current. These lamps work only with electronic ballasts which gives rise to flicker free, noiseless light output along with energy saving and increased lamp life. T5-HO also has a longer lamp life of about 20000 hours compared to 12000 hours of metal-halide lamps and they have a CRI of about 70 and do not have colour shift problems. Measures such as substituting of CFL for commonly used incandescent lamps are effective and simple (Fugler et al. 2005). Figure 2.1 depicts pictures of different lighting types.

Figure 2.1 Some Lighting Pictures; (from left to right), HID, Fluorescent, incandescent, LED and CFL

LED is a low-voltage light source that requires a constant DC (Direct Current) voltage or current for optimal operation. They are safe, adaptable and reliable and have long life and hold a lot of promise for the future as low energy alternatives. LED is rated for a current range and its light output is proportional to current. A fluctuating line voltage can produce a disproportionate change in current, which in turn can cause the light output to vary. The current if exceeds manufacturer's specification can cause excessive heat which would eventually shorten the useful life of LED over time.

So LED requires a device called driver whose function is to convert the incoming alternating power to the proper DC voltage and regulate the current that flows through the device during operation. LEDs can be dimmed from 0 to 100% over the full range, most often using Pulse Width Modulation (PWM) techniques. The result is high efficiency, flicker-free dimming with negligible colour shift. Some common mistakes that are repeatedly done in LED specification and installation are overloading the driver, using the wrong voltage driver and not paying attention to ambient temperatures at the application and environmental rating of the driver (DiLouie 2006). LEDs continue to break into new markets and whether they stay there will depend on how diligent installers are in applying the devices necessary to keep them working properly. (DiLouie 2006).

2.2.2 Control Strategies

The modern lighting control uses one or more of the following strategies: occupancy based, schedule based, light level based and load shedding. The kind of control strategy to be employed in a building depends on the type of visual tasks to be performed in the facility, the electricity rate at different times of the day and the control that are suitable for each room. Table 2.3 illustrates the main functions of different control strategies.

Table 2.3 Lighting Control Strategies

Control Strategy	Main Function
Occupancy sensors	switch light on/off depending on the presence of people in a particular space
Schedule based control	activates light at preset time intervals
Astronomical control	activates light at preset time according to daylight
Light level control	uses dimming as a percentage of full output
Lumen maintenance	allows an even level of illumination throughout the useful life of lamps, light level is increased incrementally when lumen output decreases over time
Load shedding control	enables reduction in lighting load to achieve reduction in power demand at the peak time
Architectural lighting control system (scene control)	allows any group of lighting fixtures and multiple luminaires powered from different phases of the power system to be activated at a user-programmed brightness level according to tasks or moods of the occupants

Occupancy based control

Occupancy sensors are the most effective way of control in spaces with constant presence of people for a good number of hours. (eg.) in schools, classrooms, conference rooms etc. Occupancy based control can employ three types of sensors namely Passive Infra Red (PIR), ultrasonic and dual technology sensors. The PIR sensors operate on a line of sight and hence detect occupant's heat emitted by the body to detect motion while ultrasonic sensors emit a humanly inaudible sound wave to differentiate it from a reflected sound wave. A built-in Circadian Calendar provides a four week learning period during which the sensor monitors occupancy to establish trends for automatic control. During peak occupancy, periods the sensor remains in high sensitivity mode and during low occupancy periods it switches to economy mode to maximise energy savings.

Ultrasonic sensors are more sensitive and far-reaching than PIR sensors but they can be triggered falsely by air currents generated by a person running near a door or moving curtains or the on-off cycling of a Heating Ventilation and Air-conditioning (HVAC) system. Ultrasonic sensors are most suitable for partitioned areas and areas with large objects which could have blocked PIR's line of sight.

Hybrid systems combine the advantages of PIR's resistance to false triggering and the higher sensitivity of ultrasonic sensors. An outdoor motion sensor with a PIR technology can be used for industrial applications such as parking areas, storage facilities, loading docks, and walkways. A temperature compensation feature ensures uniform performance in extreme hot or cold weather and during temperature fluctuations. Surge suppression minimizes the likelihood of damage due to electrical surges.

Schedule based control

Mechanical and electronic time switches activate lighting loads based on a specified interval. The time intervals typically range between ten minutes to twelve hours. These switches can replace conventional wall switches without the need for additional wiring. It is also compatible with central time clocks or building management systems. In high traffic areas, these types of switches can give rise to mechanical failures. Electronic time switches are like conventional toggle switches and hence are easy to operate and highly recommended for places such as retail outlets where a set time limit is the pattern of schedule. In locations where power failures are common, a battery backup is needed for mechanical time switches, which could triple the price of these packages ultimately. The latest innovations in these can receive time signals from the National Institute of Standards and Technology (NIST) to update the clock.

To quote a case study, Dynalite heavy-duty controllers which are concealed on the podium roof are installed at Grand Hyatt Hotel in Dubai. The exterior lighting is controlled by a time clock and creates a spectacular colour changing effect. Figure 2.2 shows the façade of the building when lit by white and blue light sequence. To switch on large lighting load, the controllers can be programmed to stagger the switch on, minimizing the peak demand current (Bhavani and Khan, 2007c).

Figure 2.2 A View of Grand Hyatt's Façade at Dubai, UAE

Light level control

Occupants can be given the capability of reducing the light level in their area to suit their personal choice which can aid in saving energy. The visual comfort is a very personal parameter and hence the controls loaded on an individual desktop computer give freedom to the employee while reducing energy consumption.

Step dimming typically offers one third, half or full lighting levels. It can also be used to save energy by dimming during non-critical hours and to shed peak demand in common areas such as corridors. It can be used with occupancy sensors so that the sensors can dim the lamp rather than turn them off which can reduce on-off cycling thus extending lamp life. High Intensity Discharge (HID) lamps normally need high starting times and hence can not be switched on or off frequently by occupancy sensors. Some types of HID lamps can be dimmed using specialized ballast and electronics. HID dimming suffers from reduced CRI, increased flicker, reduction in lamp life due to frequent shutdown and voltage fluctuations. New electronic dimming ballasts for metal lamps solve some of these problems.

Continuous dimming controls let users adjust the lighting levels over a wider range. Incandescent dimming causes the filament to run colour and render colour temperature. The power does not vary linearly with light output and the lamp efficacy is reduced during dimming. Some new models allow dimming from two or more locations, which previously required a remotely controlled dimmer module.

Architectural lighting systems need fluorescent lamps, which are capable of dimming to levels as low as 1%. Unlike incandescent dimming, fluorescent dimming does not improve light life and if they are operated at very low light levels, their life tend to reduce over time. They are particularly effective in medium to large day lit spaces, computer classrooms, audiovisual rooms and conference rooms. Dimmable CFL provides dimming to 10 to 20%.

Automatic fluorescent lamp dimming can be accomplished in three ways: 1) Use of a photo sensor that responds to change in luminance by varying the voltage over a range of 1V DC to 10V DC in a two-conductor control circuit. This type of control circuit can offer a dimming range from 1% to 100%; 2) Sending digitally encoded pulse signals over a two-conductor control circuit, from the photo sensor unit to a microchip within the ballast, instead of a variable control voltage. 3) Pulse code modulating the frequency of the control signal establishes the ballast's output and the light level. It is imperative that these dimming ballasts and photo sensors must come from the same manufacturer. For dimming the cold cathode fluorescent lamp (CCFL) high ignition voltage and ignition current spikes pose problems. New full bridge resonant inverter techniques boost the power efficiency to 85% while reducing ignition voltage by 30% without any current spikes (Chang-Hua 2005).

Load shedding control

The load shedding control permits a reduction in lighting load to achieve reduction in power demand at the peak time. For short term load control measures to limit the lighting and chiller power to a specified fraction of the maximum, artificial intelligence applications such as Genetic Algorithm (GA) search engines can be used and this single building optimisation control strategy produced best performance for lighting control as well (Reddy and Norford 2004). Smart lighting applications recognise utility power to be precious and hence use it to optimum levels. An experimental study conducted by Akashi and Neches (2005) revealed that an employer or a facility manager could reduce illuminance by 15% for paper tasks and 20% for computer tasks at a time of peak electricity demand without the reduction being noticed by half of the employee population. The authors observed that more load could be shed by lowering the illuminance by 30% for paper tasks and 40% for computer tasks; at those dimming levels, 80% of employees would still accept that amount of illuminance reduction. Another interesting suggestion was, if even more reduction in energy consumption were needed at a time of peak demand, illuminance could be reduced by 40% for paper tasks and 50% for computer tasks, provided the employees were educated about the importance of load shedding for the company, the community and the environment.

Sophisticated control

More advanced and sophisticated control circuits exist in the market and one such scheme is Digital Addressable Lighting Interface (DALI) (Figure 2.3). DALI is a non-proprietary protocol that offers both dimming and switching functions via digital signals over the two-conductor control circuit and this system provides digital communications between a controller and an individual lighting fixture, which could contain a linear fluorescent, a compact fluorescent, or even an incandescent lamp. Since each fixture, or ballast, has a microchip with its own address, it can be controlled individually by each occupant. The data sent to the microchip is held in memory and retained even if a power loss occurs. DALI control systems are more expensive than 1V DC to 10V DC analog control systems but less expensive than the more complex bus control used in BAS.

Figure 2.3 DALI Touch Panel and Symbol Options

Non-Addressable digital control (DSI) is another sophisticated method of control in which all luminaires connected to the system are controlled in the same way irrespective of the distance between the control unit and the luminaire. DSI luminaire or group can be controlled via a computer and its components in the system are not addressable. There is a constant supply to the luminaires, even when switched off. The minimum level is dependent on the type of light source and can vary between 1%, 3% or 10%. Being a digital control, DSI gives a more satisfactory control since the high frequency ballast can be regulated according to eye's sensitivity. Initial costs along with a user perception that advanced controls should be more complex to use are seen as the major barriers for adoption to lighting control systems (Winsor 2001).

Some unconventional functions of lighting control

Sometimes automated lighting can serve some unconventional purposes as well. The indoor and outdoor lighting installed at the cost of $ 18.5 million at Chicago's park district was designed to enhance park security and with improved activity lighting (Hislop 1997). When installed in bathrooms, the lamps can be made to shut off automatically after 30 minutes which can be used to signal the children and teens to leave the shower, thus conserving both energy and water! An illness called Seasonal Affective Disorder (SAD) is related to the amount of light entering the eye which modifies a certain hormone level in the brain, causing a mild depression in some people. Researchers are working on the therapeutic lighting systems to see whether creating high intensity light levels of 3000 to 10000 lux can provide a solution to the suffering patients. Aripin (2007) presented a study of hospital design to examine the physical conditions of healing environment such as appropriate daylighting design, access to outside view, window design, etc. and concluded by calling for a comprehensive critical review of the physical aspects, to create a healing environment that is physically and psychologically appropriate in hospital design.

LEED (Leadership in Energy and Environmental Design) points via lighting can be gained by using T5 HO fluorescent lamp, DALI technology and digital dimmable ballasts operated locally or from a central location (Lane 2005). The LEED rating system sets a series of goals that must be met to obtain certification points in sustainable design and operation. Lighting controls, as a minimum per local energy code compliance, is required on all LEED projects; in fact, it`s a prerequisite (Lane 2005). In addition, lighting controls can be a major contributing factor to the Energy and Atmosphere category, Credit 1, Maximizing Energy Performance and the Indoor Environmental Quality category, Credit 6, Controllability (Lane 2005). DALI can also be used to verify energy saving if integrated with Building Automation Systems (BAS). (Lane 2005). LEED, BAS and green building concepts are covered in detail in the subsequent sections.

The measurements of the energy consumption of the sensors and detectors also permit to conclude that systems with embedded DALI-compatible ballast controllers should be abandoned in favour of a centralized DALI-compatible ballast controller or embedded analogue systems (Roisin et al. 2008).

2.2.3 Criteria for Use of Various Control Strategies

The criteria for using a particular control strategy are often need based. The knowledge about the type of visual task that is going to be done in a given space and the electricity rates at various times of the day will help in deciding a particular control mechanism. In hotel rooms and restaurants, the priority could be scene control because of the need to provide aesthetics and ambiance with different mood settings. In a villa, the convenience factor and the ability to control any device from any interface could play a major role in going for occupancy sensors for hallways, toilets, garages etc. and time-based control for exterior lightings typically. Occupancy sensors may not be the ideal choice in open-plan offices and hospital wards where a few people may be always present. Simple time scheduling can be employed for large open office areas and schools while more sophisticated computer controls can come in handy for hotel exteriors. In a large factory, the need to monitor lighting energy usage and to collect statistical data for maintenance and replacement of lamps, fixtures etc. could be met by designing a specific control strategy.

Energy saving can be the objective of providing lighting control in a typical scenario. The emerging technologies in energy saving in lighting include replacing lamps and fixtures, relamping incandescent by fluorescent fixtures, by using occupancy sensors, light level sensors, dimming systems, energy efficient lamps, energy controllers, solar energy panels and power factor controllers (Samuel 2003). To address changing office space requirements, electronic ballasts can be a cost effective solution. The dimming mechanism can be chosen for a simple step-dimming or for continuous dimming of lamps in commercial buildings. The ability to shed lighting in response to a utility request and personal control accessible from laptops are some other preferred choices for specific clients. Daylighting controls (which are discussed in the following section) can be employed for corridors and open cubicles near windows, particularly those with task lighting. Private offices with windows can have significant energy savings and an improvement in employee productivity if these daylight sensors are calibrated and commissioned properly.

The combination of the above mentioned strategies provide the highest level of energy savings. To make the best choice, the control should be chosen based on the usage of space and the expected load profile and of course cost effectiveness. If the space use is unpredictable, occupancy sensors and timers could be used. For a space with a predictable work schedule, controls that reduce peak demand should be made use of. It is impossible to assume that there could be a single ideal set of criteria for good lighting (Tregenza 2003). The association between the nature of lighting and people's expectation and satisfaction is very complex and hence is very challenging and interesting.

2.3 Daylighting Control Systems

With the catastrophic effects of climate change and environmental impacts looming large for our next generation citizens, the research community is now looking up for solutions to creating zero energy buildings in every possible geographic location. Daylighting the building is one such solution wherein the abundant source of sun's energy when designed and utilised properly can not only save energy, but also create a general well being amongst its occupants. Studies indicate improvement in productivity and creativity of people exposed to good quality lighting (Veitch et al. 2008). Daylight as a primary light source can introduce occupants to a sense of inner harmony resulting from a state of spiritual transformation (Lau 2007). Daylight as a source is best known for its colour rendering and matching of human visual response. Daylighting is the ability to adapt electric light in the presence of daylight. There are three areas that are significant when it comes to daylighting the buildings: simulation, daylighting control and occupant behaviour and preferences (Maamari et al. 2006).

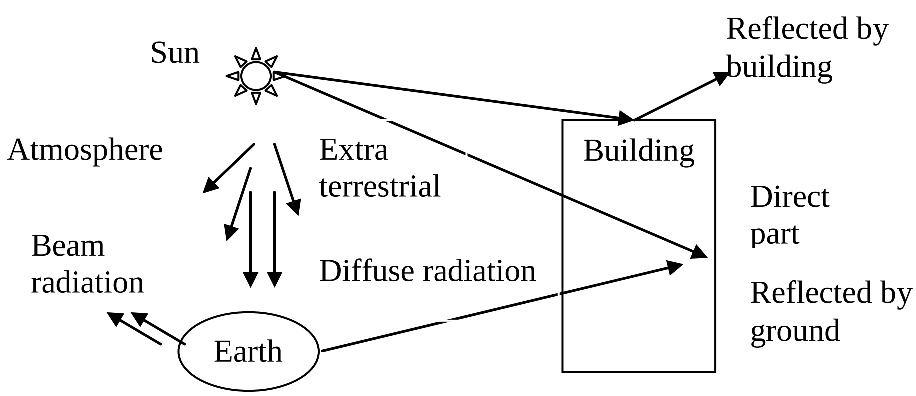


Figure 2.4 Daylight: Attenuation and Components

The sunlight is the most important source of renewable energy. Solar radiation attenuation is shown in Figure 2.4. A small part of sun's energy reaches the earth's surface as global radiation. The buildings, adjacent structures, ground etc. can reflect or diffuse the incoming sunlight before it gets introduced into the building interior. The particles in the atmosphere reflect or scatter light. Solar irradiance is the amount of energy coming from the sun and a small area around it and reaching a surface at right angles to the incident sunlight. Solar irradiance outside the atmosphere has only direct component with parallel radiations as direct, normal or beam irradiance. Diffuse irradiance is useful for daylighting systems. For daylight calculations, direct, beam, diffuse, reflected and transmitted components of sunlight are to be taken into account.

Horizontal illuminance represents the amount of light coming from the sky, excluding the sun and arriving at a horizontal surface. For daylighting design, global horizontal illuminance can be calculated for each hour during a given period from International Daylight Measurement Programme (IDMP) if such a data exists for the region. The amount of sunlight reaching a particular surface depends on factors such as angular relationship between the sun and target space, solar azimuth, solar altitude (which in turn depends on site location and time) and building orientation.

In locations which are inundated with high-rise structures, the indoor daylight availability is only due that coming from zenith part of the sky. Under such circumstances, light redirecting devices or skylights are employed. A new protocol to quantify solar access and daylight availability for dense urban environments is necessary for daylighting design and performance analysis (Chung 2003).

Daylight factor is another parameter that is to be taken care of when designing daylight controls. Although no empirical formula exists for this factor, the designers go by standard values, which take into account the blind position, the distance into a space from a window etc. Daylighting design and performance assessment methods such as the daylight factor method have to be tested for use in the high density and high-rise building configurations and different geographical conditions. Gaining insight into the relationship between building densities, building patterns, building types on the one hand and the main aspects of the physical urban climate such as penetration of daylight, solar irradiation of facades and outdoor spaces, wind, air temperature, air quality and (traffic) noise on the other hand is important in daylighting design (Esch et al. 2007). A new paradigm called Useful Daylight Illuminance (UDI) was developed to assess daylight in buildings instead of daylight factor (Nabil and Mardaljevic 2005).

Energy savings resulting from daylighting mean not only low electric lighting and reduced peak electrical demands, but also reduced cooling loads and potential for smaller Heating, Ventilation and Air-conditioning (HVAC) plants (Li et al. 2005). Some studies have attempted to evaluate the energy savings due to daylighting control strategies. Bodart and Herde (2002) have used an integrated approach combining the daylighting and the thermal aspects to evaluate the impact of lighting energy savings on global energy consumption in office buildings. Ihm et al. (2009) developed a simplified analysis method and validated it to estimate the potential reduction in annual electrical lighting energy use (50 to 80%) for office buildings and the simplified analysis accounted for the building geometry, the window size, and the type of glazing. A case study done at Malaysia reported 10% savings by daylight in passive solar design of buildings (Zain-Ahmed et al. 2002). A report on two field-monitored case studies in Canada indicated that the continuous dimming control systems provided 46% annual savings while the automatic on/off saved about 11 and 17% (Atif and Galasiu 2003). Behavioural models derived from on-going field studies can provide the basis for predicting personal action taken to adjust lighting levels, remedy direct glare, and save energy in response to physical conditions (Bourgeois et al. 2006). The absolute magnitude of savings depend on how the systems are used and accepted by the occupants and on baseline energy consumption of manual systems in buildings which remain largely unquantified and unpredictable.

2.3.1 Daylight Harvesting

Daylight harvesting means making use of daylight and reducing electric light intensity in the building. Without an integrated control, daylighting the building is simply a waste of energy and hence artificial lighting and daylighting systems should be designed so that they are complementary to each other. Energy savings from daylighting controls depend on building type, location, operation and local cost of energy. The primary factors are amount of daylight available and occupancy pattern and the control strategy. Since daylight is available during utility peak demand hours, daylight harvesting reduces demand charges also. Daylighting control achieves its maximum potential when the accompanying technology is designed perfectly and the initial cost is justified by payback calculations.

The basic components of a typical daylighting control system are smart ballasts and sensors including photocells, infra red receivers, occupancy sensors and wall station controls and finally the control device, which runs the algorithm. The main issues in these systems are that of heat gain, glare and reliability. An intelligent control system will take the input data from sensors, interpret them and transmit to the ballasts for either switching off or for dimming. Typical daylighting systems employ a photosensor technology coupled with a dimming fluorescent lighting system, which dims lights proportional to the daylight as seen by the sensor at a reference plane. The system can not guarantee satisfactory operation because daylight does not penetrate the building uniformly. Installing sky lights, light pipes, light shelves, controlling shades, blinds etc. can increase daylight penetration in the building’s interior. The designing of such systems has to be done considering the following parameters and criteria to justify the high initial costs of full dimming ballasts and other auxiliary systems.

2.3.2 Some Critical Design Aspects

Continuing refinements in the design and integration will change the way the daylighting is looked at by the building owners and occupants. As daylighting becomes a prominent part of lighting design work, specifying shading systems such as louvers will become standard practice for lighting designers and architects. When daylighting controls are integrated with blind control or other devices it results in maximum energy saving. The following are some well known facts about good design practices.

- Single story buildings can be easily upgraded for daylighting.
- Daylighting system should take care of desired reflectance values for good indoor effect.
- Optimum combination of shading devices along with daylighting control can reduce energy savings on lighting to as high as 80% while providing a high quality and pleasing visual environment.
- When light that falls near the windows is of much high intensity compared to deep areas, it creates an undesirable "cave effect". This has to be avoided by proper glazing of windows and overhangs.
- Skylighting is a solution for enclosed corridors and deep plan offices.
- Window-to-wall ratio is specified depending on the geographic location and the amount of daylight penetration all around the year. A glass area of one-sixteenth of the floor area of a room should be satisfactory for lighting purposes in a hot dry climate (Saini 1980).
- Clerestory windows, a row of small windows at the top of the wall, allow uniform glow and intensity forming a sky-like-effect on the ceiling.
- In sidelighting design with windows in one wall, the luminaires can be placed in rows parallel to the wall so that the row closest to the wall dim first or switch off followed by successive rows in response to sunlight.

When it comes to dimming, daylighting systems have to follow some specific design requirements. Each space must have a reasonable amount of horizontal illumination from daylight with effective shading systems, which can be achieved by overhangs, and window glazing (Horwitz 2002). Local utilities rate and photsensor placement, combined with its control algorithm are critical elements for a functional system (Horwitz 2002). Open loop and closed loop control strategy systems require different parameters for photo sensor placement (Horwitz 2002). Calibration and proper commissioning of photosensors are the other areas to be focused upon. Separately zoning and circuiting fluorescent fixtures parallel to windows and compatibility of lamps, ballasts, photo sensors and dimming controls are also of interest to the designer (Horwitz 2002). One of the design challenges is the placement of sensor as it has to not only measure the daylight on the task surface accurately, but also should be free from outside glare sources. Table 2.4 summarises the factors involved in the design of daylighting control systems for a building.

Table 2.4 Factors Impacting Design of Daylighting Control Systems

Factors	Details
Climate factors	sky condition, solar irradiation, dry bulb temperature, cloud condition, external illuminance
Building factors	building orientation, geometry, configuration, type of use, overhangs, shading systems, adjacent structures, landscaping, type of ceiling and facade, glazing and interior surface properties (such as transmittance, reflectance and area for both)
Occupancy factors	occupant schedule, type of activity, number of occupants and their position

Factors	Details
Photo sensor factors	placement, control strategy (open loop/closed loop), type of control (proportional, integral, derivative), calibration and commissioning, characteristics (spectral/spatial response, intensity range), presence of elements such as skylights
Programme factors	Set points (to define on-off limits), mimimum run-times (for HID lamp dimming), dead bands (to prevent on-off loops), reaction time delays (to compensate for suddenly changing weather pattern), fade or ramp rates (to maximise occupant comfort)
Manufacturer’s specification	compatibility of lamps, ballasts, photo sensor, dimming controls, dimming range, power factor, total harmonic distortion, ballast factor

2.3.3 The Glare and (heat) Gain Issues

Glare happens when too much direct sunlight enters a space. Glare is an interference with visual perception caused by an uncomfortably bright light source or reflection and it is considered as a form of visual noise. Direct Glare is the glare resulting from high luminances in the visual environment that is directly visible from a viewer’s position. Reflected Glare is a reflection of incident light that partially or totally obscures the details to be seen on a surface by reducing the contrast. Discomfort Glare interferes with the perception of visual information, but does not significantly reduce the ability to see information needed for activities. Disability Glare is glare which reduces the ability to perceive the visual information needed for a particular activity and caused by light scattered within the eye, causing a haze of veiling luminance that decreases contrast and reduces visibility. Blinding Glare is glare, which is so intense that for an appreciable length of time after it has been removed, no visual perception is possible.

Many works have been reported in the literature that identifies the difficulties associated with measurement and quantification of glare. Controlling glare is a non-trivial task because glare depends on such factors such as occupant's position and the mode of activities in a dynamic space (Chang 2000). The discomfort due to glare is caused by visual sensations that are due to occupant's position and light falling on the cornea, psychological factors, cultural factors and behavioural factors along with a lack of understanding of glare. Currently for the quantification of discomfort glare, DGI (Daylight Glare Index) for daylight and UGR (Unified Glare Rating) for artificial light are used.

Virtually all studies quantifying discomfort glare concentrate on the influence of environmental parameters, such as luminance, angular size, and glare angle on the discomfort rating (Johannes 2003). Very large sources could add to the problem of glare, producing too much illuminance for the space. Actually, in recent years, a new approach, in terms of disturbing glare in outdoor sports lighting has been introduced, which does not discriminate between discomfort and disability glare (Johannes 2003). An article by Werner (2005) concluded that the available assessment and prediction methods of discomfort glare are of limited practical use in daylit situations and currently have no provision for integrated systems that combine daylighting and electric lighting. Fisekis et al. (2003) reported on the valuation of several models for prediction of discomfort glare from daylighting using data collected over a ten month period.

A new index called Daylight Glare Probability (DGP) was developed by Wienold and Christoffersen (2006) in which DGP was the function of vertical eye luminance and glare source luminance, its solid angle and its position index. A new mathematical method was tested in a daylit office environment in Japan and a new Daylight Glare Index DGI_N was analysed together with the measured illuminance ratios to analyse discomfort glare in a quantitative manner (Ali and Masato 2007). The authors noted that the DGI_N method could serve architects and lighting designers in testing daylighting systems, and also guide the action of daylight responsive lighting controls (Ali and Masato 2007). Another parameter Visual Comfort Probability (VCP) is the percentage of people feeling comfortable at a given lighting environment.

A good daylighting control design will have to always guard against glare and the ongoing studies involving which will significantly affect the design of future daylighting systems (Bhavani and Khan 2007a). For example, adding external reflective light shelf in different slopes improves daylighting level and replacement of current transparent glazing in the skylights by a diffusing translucent glazing reduces glare in a third floor studio (Al-Sallal 2006).

Another factor to account for in daylighting calculations is heat gain. Solar radiation, along with light also brings in heat as well which might increase the cooling load on the HVAC systems. Hence daylighting systems should carefully take into account as to how much of light should be brought inside the building. Harmonization of thermal and illumination loop is a complex task, since the thermal part of solar radiation is not linearly proportional to daylight (Kladnik et al. 1997). For daylighting to become much popular and to reduce the total reliance of electric lighting, practical and effective methods and calculation tools are needed to assess the amount of daylight in relation with heat gain (Chirarattananon et al. 2003).

2.4 Building Automation Systems

Building Automation Systems (BAS) which is also referred to Building Management Systems (BMS) or Facility Management Systems support intelligent lighting. BAS aims at centralizing and simplifying the monitoring, operation and management of a building facility. Building automation is the process of integrating systems such as lighting control, air-conditioning control, elevator control, parking lot supervision, fire alarm monitoring, Closed Circuit TV

(CCTV) and other building systems into one network. Because of the integrated approach, the overall building efficiency is maximised. The major part of this section is published in Bhavani and Khan (2007b).

2.4.1 Applications and Benefits

BAS use computer-based monitoring to coordinate, organise and optimise building control sub-systems such as security, fire/life safety, elevators, etc. Table 2.5 lists the common applications of BAS. In addition to lighting, the most commonly controlled equipments are HVAC which includes Air Handling Units (AHU), Fan Coil Units (FCU), chillers, boilers, fans and pumps, fire safety systems, CCTV, elevators and escalators. The devices such as sensors, actuators and smart controllers can coordinate to perform distributed control application functionality such as temperate and climate control, access and security control, lighting and scenery control, blinds and shutter control along with load shedding and energy management.

With BAS, the economical and qualitative parameters of a facility increase as follows. Building automation and control can achieve Real Time Pricing (RTP) savings in a large commercial building (Norford and Reddy 2004). BAS add value to the operation of the buildings, since they help increase the efficiency and cost effectiveness of operating commercial buildings (Henze 2001). It can be used for comfort monitoring, service and space planning, predictive maintenance scheduling and supervisory control for load shedding from a central location for proactive load management (Norford and Reddy 2004). In a deregulated market, BAS will gather weather forecast and choose the utility service based on market rate. They also do utility enterprise resource planning by forecasting and reacting to dynamic utility rates (Norford and Reddy 2004). Building automation also helps protect environment by saving natural resources for the future by optimum use of energy. Building automation and control forms a part of the technical facility management and bridges the gap to commercial and infrastructure building management through digital communication and net capabilities. Figure 2.5 lists the equipments that are typically controlled by BAS for carrying out various functions.

Table 2.5 Applications of BAS

Applications	Details
Sensing and Control	HVAC system, lighting system, emergency shut down on security alert, water irrigation systems, electricity meters, variable frequency drives, variable and constant motor loads etc.
Equipment scheduling	turn an equipment on/off as required
Optimum start/stop	turn a heating / cooling equipment on in advance to ensure that the building is at the required temperature during occupancy
Operator adjustment	access operator set-points that tune the system to changing conditions
Monitoring	logg of temperature, energy use, equipment start times, operator log-on, and indoor air quality
Alarm reporting/ annunciation	notify the operator of failed equipment (like bulbs, fixtures, motor), out of limit temperature, pressure, humidity, conditions or equipment that are scheduled for maintenance
Gathering and storing of data	data collection and report generation of all connected systems and components, weather data over BAS internet connection for environmental condition monitoring or trending
Testing and commissioning	Upkeep of dynamic information and status report of all connected systems

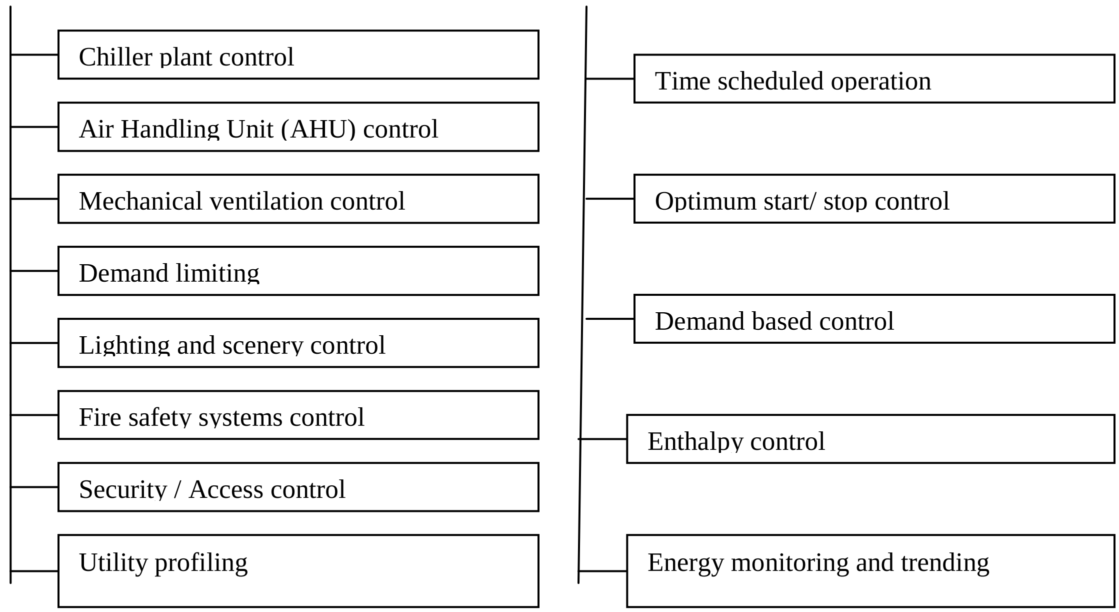


Figure 2.5 Equipments Controlled by BAS (left column) and Main Functions (right column)

Cost reduction through maintenance and training

Building automation results in increase in building's worth as real estate and decrease in maintenance cost. It is possible to immediately perform system service and prevent possible damages and hence service costs decrease. The operating costs decrease because it is possible to program and control building equipment remotely through telephone lines or internet from around the world (Quillinan 2005). Building automation provides a possibility to extend the system in the future in every forward configuration. It results in reduced operator training time via on-screen instructions and supporting graphic displays and faster and better responsiveness to occupants' needs and troubled conditions. It also enables flexibility of programming for facility needs, size, organization and expansion requirements.

By reduction in maintenance costs, it means that the faultfinding and repair is easier and much faster. The BAS system does its own faultfinding and gives an alarm if it finds a fault. The ability to use web servers to provide ready connection of BAS to subsystems and the use of networking and structured cabling enables reduced connection cost and ease of access.

Ease of monitoring or trending

BAS can be programmed to give out timely alarm and annunciation routines and hence makes the building service personnel more pro-active rather than reactive to system faults. The tenants can be charged for exactly the units they consumed in air-conditioning equipments since BAS keeps record of use of HVAC equipments. This results in more transparency between the owner and tenant and a better relationship. BAS can even monitor or control functions at the fuel refueling stations, building gas utility meters and variable frequency drives.

Increased occupant comfort

As explained earlier, the tenants are more convinced of and satisfied with the energy they use since BAS keeps record of these real time. BAS is able to monitor and control the following for increased occupant comfort:

- personal control of lighting and shading systems
- Monitor or trend air flow rates
- ventilation controlled in accordance with schedules and occupancy fluctuation
- monitor and trend corbon-di-oxide levels, increasing indoor air quality
- monitor user-preferred values of indoor temperature
- ensure adequate thermal comfort through monitoring/ control of humidity and air velocity

Remote monitoring

With the advent of internet, the complex building management and control systems have become flexible for the user. Remote monitoring of the subsystems such as lighting and security has guaranteed a level of comfort and control, which was unimaginable a few years ago. The capability to remotely monitor and operate facilities allows for decreased on-site operating costs and increased performance. In the case of building management, wireless communications offer benefits such as increased mobility and decreased cabling costs. The security of the building or apartment can be monitored from a centralized location that is not geographically limited. Thus an occupant of the building can activate the sprinklers in the garden for a specified duration even when he is vacationing in another part of the world or he can switch on the lights of his bedroom over the net so that the burglars are kept away. If conditions that are being monitored change, BAS attempts to bring the settings back to normal. Through the internet connectivity, weather data can be collected before hand and incorporated in the control algorithm, for the prediction of environmental condition.

2.4.2 Protocols

Protocols are a set of common language rules for the communication signals sent on a physical medium such as optical fiber, radio or wire. Each component in building system architecture is connected with each other via a communication system. The standard communication protocols widely used in BAS are BACnet (Building Automation and Control Network - an industrial protocol), EIB (European Installation Bus) and LonWorks (Local Opearting Networks). Some other popular ones are PROFIBUS (Process field bus), Modbus / JBus, S-bus and FND. The BACnet was described in ANSI/ ASHRAE 135-1995 and developed in the United States by ASHRAE, specifically for the manufacturers of direct digital control modules of HVAC system components so as to have compatibility across their products.

In Europe, CEN/ TC247 is involved in standardising protocols for communication in HVAC applications. Table 2.6 provides the list of protocols approved by CEN/ TC247 for the three level model of BAS.

Table 2.6 Protocols Approved by CEN/ TC247 for Three Levels of BAS

Levels in BAS	Function	Approved Protocols
Management level	workstation to workstation communication , monitoring of alarms	BACnet, FND
Automation level	Plant controllers and work station doing real time control	BACnet, FIP, PROFIBUS
Field level	Terminal unit controls, sensors, actuators	Lon, BATIBUS, EIB

The BACnet also supports transmission over the media-independent Transmission Control Protocol / Internet Protocol (TCP/ IP) enabling Internet access over cable, company networks, satellite, wireless systems (Wi-Fi) or telephone (Quillinan 2005). According to the author, TCP/IP is media-independent and hence the best communication path can be selected for every application. The TCP/ IP technology has the following plus points: The information transfers are standardized because all equipments use TCP/ IP. The distance is irrelevant because once the data enters the network the distance problems are solved by cable, satellite or wireless.

EIB proposes an open multi-vendor system for embedded home and building control networks. At the core of EIB, is its embedded control protocol. This protocol is the digital language by which any number of devices in the building may communicate with each other (Tweed and Quigley 2000). For example, the advantages of EIB based lighting control are its cost effectiveness and the communication is done electrically via telegrams instead of a rigid mechanical connection. It offers flexible solutions, fast expandability and easy adaptation to customer needs and supports intelligent microprocessor based devices. Further, no specific installation knowledge is required for the system.

Local Operating Network (LON) was developed by a company called Echelon in the United States and LonWorks is the general-purpose network based around a special neuron chip and LonWorks protocol. Lon technology was designed for connection of distributed control devices, sensors and actuators (Tweed and Quigley 2000). The Lon talk protocol may be applied over a wide variety of physical transport media including twisted pair and radio transmission.

Interoperability issues

With the number of suppliers of each subsystem increasing worldwide, the interoperability between the components of different suppliers at the system level had become one of the issues. The field of building automation was characterized by many incompatible standards resulting in little interoperability across systems or system components. Components developed for specific network would not work with other standards. So there was a strong move for standardized protocols to get compatibility for connecting different pieces of control equipment. Tweed and Quigley (2000) mentioned in their research project report that there were nearly fifty different sets of standards for home automation. The authors also listed the main choices for physical medium and summarized the advantages and disadvantages in the form of a table. The choice of which protocol to go for lighting control in an existing building depends on what control systems are already in place so that interoperability issues do not play up.

Because of the arrival of open system technology and availability of "gateways", today's BAS is able to talk to an application with a different protocol. This is driving the market highly competitive towards price and the initial and operating costs would continue to decrease in future. BACnet is one of the highest level protocols used in the industry today that can be used to integrate building automation and control products from different manufacturers into a single cohesive system (Newman 1996). The use of open systems such as BACnet, Lonworks and internet communications offer the ability to meet many of the goals of open systems (Ehrlich 2005). If a manufacturer of a direct digital component follows an open standard such as Lonworks, his product will be compatible with that of other systems following the same protocol. Thus a lighting component can talk to a HVAC component in the same language. Cost savings and integration are driving clients' decision-making processes. Innovation is occurring in integrating systems. Technology is now allowing software and building systems to interact and gather information from each other (Shachter 2000).

2.4.3 Direct Digital Control

The controllers used in BAS are mostly Programmable Logic Controller (PLC) and Direct Digital Controller (DDC). These are connected to the peripherals and to each other usually through an interface for exchange of information from one another. A DDC Controller is an intelligent microprocessor based controller that may incorporate Proportional (P), Proportional Integral (PI) or Proportional Integral Derivative (PID) control. A digital controller thus performs mathematical and logical functions on the incoming signal to arrive at the required control output signal.

Figure 2.6 illustrates the difference between a conventional building automation as against the one with DDC.

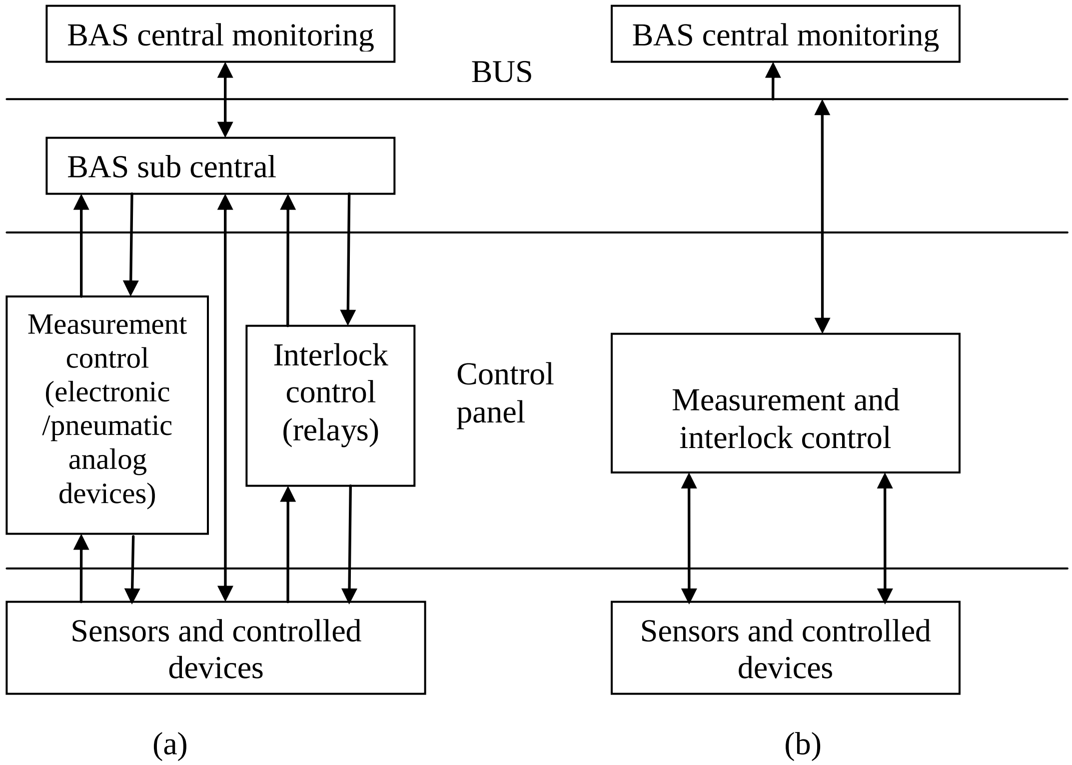


Figure 2.6 Schematic Diagram for (a) Conventional BAS (b) BAS with DDC

In a conventional automation system, electronic or pneumatic analog devices form measurement control technology which is logically connected to interlock technology by means of relays. Duplication of sensors and connections to the sub central of BAS are required for analog values and digital information whereas in DDC based BAS, the duplication is not necessary. If a fully integrated solution is implemented in a DDC, the measurement control and interlock control are both incorporated by a single controller in the control panel where all the functions are programmable. The information can be exchanged between the control panel and BAS central without any constraint. Since there is no logical connection between measurement control technology and interlock control technology and there is no duplication of sensor and connection, fully integrated solutions represent higher savings compared to the conventional automation systems. The users can change the control logic by software methods to apply complex strategies so that building energy optimization measures can be incorporated at no additional cost. By the same reason, controlling reset schedules and set points of HVAC systems is more effective through DDC.

Complex strategies and energy management functions are readily available at the lowest level of the system architecture. Since DDC systems integrate with other computer-controlled systems over a common network, the energy efficiency is maximised. If conflicting air conditioning requirements exist across zones, the integration helps resolve them. The overall demand to a facility can be monitored and controlled by resetting set points based on different demand levels. Since BAS can generate reports of energy consumption of clients, their consumption patterns can be monitored and equipments can also be centrally switched on or off during dynamic scheduling.

The DDC program can find the optimum time to start to warm up a building enabling system wide access and control from a single or remote computer. The energy management software when programmed in DDC can determine when to start a heating / cooling system in preparation for the day's occupancy by taking into account space temperature, outdoor air temperature, comfort range and unique characteristics of HVAC system. Similarly the optimum stop programme can shut off air circulating systems before the end of occupancy without compromising on the comfort limits. Figure 2.7 depicts the typical optimum start/ stop with cooling.

The optimum start/stop function is very effective when

- the building works with a known occupancy period, such as schools and sports complexes
- the depression period should be completely off rather than a reduction in the flow temperature
- a model room's temperature is used for optimisation

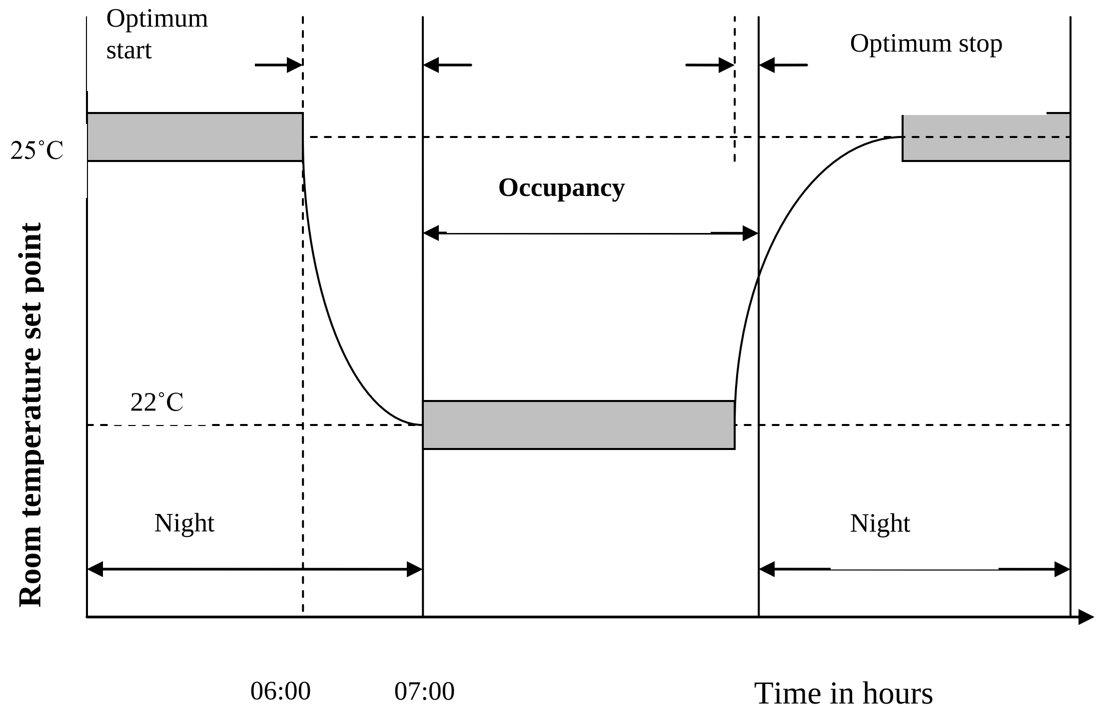


Figure 2.7 Optimum Start / stop Graphic with Cooling

A night cycle program can also implemented in DDC by providing the necessary input sensors and programming the input parameters. This program was implemented by a Honeywell controller for an office building in Dubai consisting of 30 single-zone HVAC units. Figure 2.8 depicts the typical night cycle graphic in which energy is saved by maintaining night space conditions outside the normal human comfort levels. During winter, the program maintains the space temperature at a level lower than that of occupancy by closing outdoor air dampers. In the summer, the vice versa happens. Operating a space at wider limits during unoccupied periods reduces energy consumption.

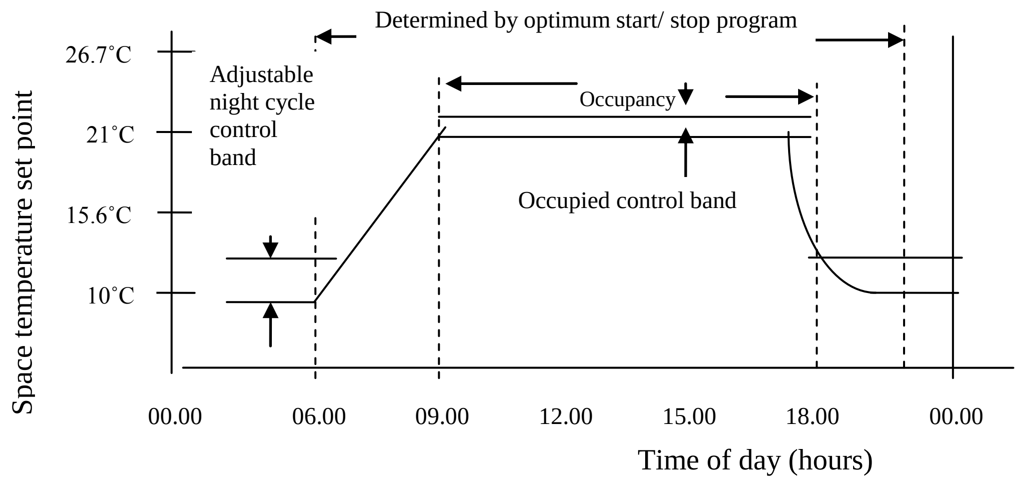


Figure 2.8 Night Cycle Graphic for Winter

The overall demand to a facility can be monitored and controlled by a DDC system and control can be done on a zone level as well. The recent advancement of DDC provides an architecture allowing high level control through setting temperature or other set points while letting DDC implement the low level control (Xu et al 2005). DDC was also discussed by McGoven (1995) stating that wireless communications, self-optimizing software and improved operator softwares would make the buildings self checking and in many cases they would be able to repair or modify them to meet any ongoing or new problems as they may arise.

2.4.4 Energy Management

In the field of whole building energy management, BAS, green concepts and LEED (Leadership in Energy and Environmental Design**)** ratings share a functional relationship which will be discussed in this section. Only optimal sized systems that are adapted to the building envelope can be operated in an ecologically sound manner. Oversizing can be avoided by BAS since it enables the correct interaction of artificial lighting and air conditioning. With the use of

BAS, the energy engineer gets an overall picture of the energy scenario of the building and hence can use the data effectively for load shedding or some other energy saving measure. Similarly a building owner can see his tenants' energy pattern through a broader outlook rather than an occupant of a single apartment. Thus the buildings are able to adapt quickly and easily to changing loads, and the efficiency is monitored to remain high under all load conditions. The important measured data that are systematically acquired and evaluated support intelligently planned automation systems in creating comfortable working conditions with minimum energy input.

A smart building can sense when staff have left and turn down the heating or air conditioning accordingly. Linking control systems as part of an energy management strategy can slash energy costs by as much as 30%, claimed John Geaney, Hewlett –Packard's business development manager for intelligent buildings (Quillinan 2005). Conventionally, energy management measures are designed and deployed in buildings, expecting and typically achieving energy savings from changes to the building envelope or energy systems such as lighting system retrofits. However, additional savings opportunities can be identified by analyzing interaction between building systems and the influence of building opponents.

Green buildings

Buildings that have the least impact on the environment, consume less energy, resources and have comfortable occupants are termed as green buildings. Green buildings are expected to provide 35% savings in energy compared to normal buildings (Gulf news 2005). Green buildings are a happening concept in today's scenario of global warming and air pollution. Green buildings highlight the use of renewable energy, maximum use of day lighting, energy efficient lighting, effective use of landscapes, better environments (because of improved indoor air quality for human health and comfort), effective use of water and reduced running costs because of all the factors mentioned above. The next chapter has some references to some green developments taking shape in the UAE. Table 2.7 enlists the credits given for various features of a building.

Table 2.7 Green Building Rating – Credits Given for Individual Features

Features	New Building	Existing Building
Energy and atmosphere	17	22
Indoor environmental quality	15	18
Water efficiency	5	5
Sustainable sites	14	16
Materials and resources	13	10
Innovation and accredited professional points	-	5
Total	64	76

LEED ratings

Implementation of a BAS is not required by LEED but it can be an effective tool in obtaining credit points and allowing the owner or operator to maintain the facility better. LEED was developed by U.S. Green Building Council (USGBC) and LEED allows the industry to be guided in the best practices in sustainable design and operation. LEED was created to define green buildings by establishing a common standard of measurement, promote integrated, whole building design practices, recognise environmental leadership in the building industry, stimulate green competition, raise consumer awareness of green building benefits and to transform the building market. LEED recognises achievements and promotes expertise through comprehensive system offering project certification, training and practical resources.

The LEED rating system sets a series of goals that must be met to obtain certification points. The rating and certification are linked to performance of the building. However, the rating system does not always set the methodology by which those goals should be met. Table 2.8 provides the details regarding LEED certification levels.

Table 2.8 LEED Rating – Certification Levels

Ratings	New Building	Existing Building
LEED certified	26-32	28-35
LEED certified Silver Level	33-38	36-42
LEED certified Gold Level	39-51	43-56
LEED certified Platinum Level	52-69	57+

The potential to save or reduce energy consumption is so high that the LEED rating system keeps provisions of energy reduction of up to 60% for new buildings and up to 50% for existing buildings. Since a green building encompasses certain criteria that required to be done at the design stage itself (such as the use of recycled material, effective landscaping etc.), some existing buildings cannot be made into green building. For design stage buildings, additional investments needed to achieve green status would pay back much faster as these would be offset by normal investments needed.

BAS and LEED credits

The three fundamental strategies to increase energy performance are: reduce demand, harvest site energy and maximize efficiency out of which BAS can help in the first and the third strategies. LEED points can be obtained for reducing energy use compared to baseline building performance rating per ANSI/

ASHRAE/IESNA Standard 90.1-2004, Energy standard for Buildings Except Low-Rise Residential Buildings. This standard establishes minimum requirements for the energy efficient design of buildings. Table 2.9 enlists the details about points.

Table 2.9 LEED Points for Energy Saving

Energy Cost Savings (Minimum) (%)	**Points**
10.5	1
14	2
17.5	3
21	4
24.5	5
28	6
31.5	7
35	8
38.5	9
42	10

According to Herrmann (2005) BAS technologies can be applied to approximately 40% of the criteria of the United States Green Building Council's (USGBC) LEED-NC, proposed version 2.2 green building rating system. Hernandes and Duarte (2007) presented the evolution of LEED-NC application in its native environment between 2000 and 2005, with an aim to support the critical analysis of the LEED system application outside the USA. Table 2.10 enlists the areas in which BAS can help buildings get LEED points. It can be observed that other than the materials and resources feature, BAS can assist in every other area.

Table 2.10 Role of BAS Strategies in Getting LEED Points

Areas	BAS Application
Energy and atmosphere	Building commissioning – proper operation of building systems, compliance with the intended design, verifying the operation of HVAC and other electric systems, trending and alarm of parameters, reporting of dynamic data and environmental conditions Minimum energy performance – lighting controls and other control applications
Indoor environmental quality	Minimum indoor air quality – monitoring and control of ventilation rates, CO_2 levels, temperature and humidity levels
Water efficiency	Landscaping – monitoring and control of high efficiency irrigation systems, water recycling systems and monitoring of storage tank levels Monitoring and trending of wastewater treatment systems
Sustainable sites	Monitoring and control of alternative fuel refueling stations
Innovation and design process	Any other sustainable practice and advancement that can be implemented in the control algorithm

Some vital guidelines for optimum functioning of BAS

In the past, there was a feeling that BAS are not being operated to its full potential. Some researchers tried to identify the reasons for this and found out that there was a resistance to accepting a new technology (Mason 1993). Commissioning (Levermore 1994) and complicated design (Butler 1998) were the major stumbling blocks. Over the years the teething problems associated with

BAS have been removed through research and innovation and the following emerged as guidelines for optimum functioning of BAS.

- The cost justification is very essential for people involved in decision making process to go in for the system.
- Operational staff of BAS has also to be convinced about the benefits and functioning of BAS.
- Preventive maintenance can not be replaced by BAS; it still has to be done by qualified technical staff.
- BAS is an energy optimization tool; the energy consumption data of all clients and the corresponding reports have to be properly interpreted by qualified engineers. Investigation of scope for further optimization rests with the people who handle it.
- A single integrator can be given responsibility of design, installation, commissioning and follow-up. This will alleviate problems due to interoperability.
- Changes in the building use have to be continuously adapted in the control algorithm.

The significant factors associated with the success of BMS installations are user involvement in specification, the user's perception of the performance of the vendor and satisfactory commissioning of the system (Lowry 2002). The effective working of BAS lies as much as with the people who procure, manufacture, design, install and commission the system as the inbuilt functions of the system itself.

2.4.5 Lighting Control by BAS

Unlike the dedicated lighting control systems which require their circuits to be wired to a single control panel, lighting control by BAS is done from a distributed network that controls other equipments such as HVAC, emergency lighting and fire alarm systems as well. The DDC modules when implemented with the lighting system components can help extend or modify the system easier than a conventional control since it is done by software means. Also the hardware implementation is done easily since the system is more distributed over the entire network. BAS can control lighting over a larger area because of these reasons. Lighting can be controlled based on the reports of occupancy, schedule and sensor information generated by BAS. BAS can help detect a malfunctioning fixture or a lamp and save energy by reducing peak demand if the electricity rate is so structured. The following are some of the methods in which BAS can control lighting.

Personal dimming control

Light switches and dimmers can be connected to DDC modules to have people control their lighting to suit their requirements. The lighting preference for individuals is as varied as any other personal choice. Personal control options are a much sought-after entity in lighting control where remote-control panels or liquid crystal display panels form user interfaces. Controls can be loaded onto the personal computers wherein the user settings can be stored to provide maximum visual comfort for computer-related activities. In its sophisticated form, voice messages can be used as control signals.

Figure 2.9 illustrates how different DDC modules can typically form a lighting control system in a building.

Control based on schedule, occupancy, daylight or its combination
Occupancy patterns can be learnt by BAS and lighting can be scheduled according to this. Time scheduling and daylight-responsive scheduling are other options. Lighting can be scheduled to be in accordance with the availability of daylight. In more advanced levels of programming, BAS can have in-built intelligent routines to adjust lighting based on schedule, occupancy and daylight.

BAS can turn off some lights when signals from a photo sensor inform them that a user-set illuminance level has been exceeded. Alternatively, it can dim the light gradually to allow more uniform light levels. Since BAS is an integrated system of lighting and HVAC subsystems, the occupancy pattern learnt can be made use of to turn off both lighting and HVAC systems when people leave the offices, thus maximising energy savings.

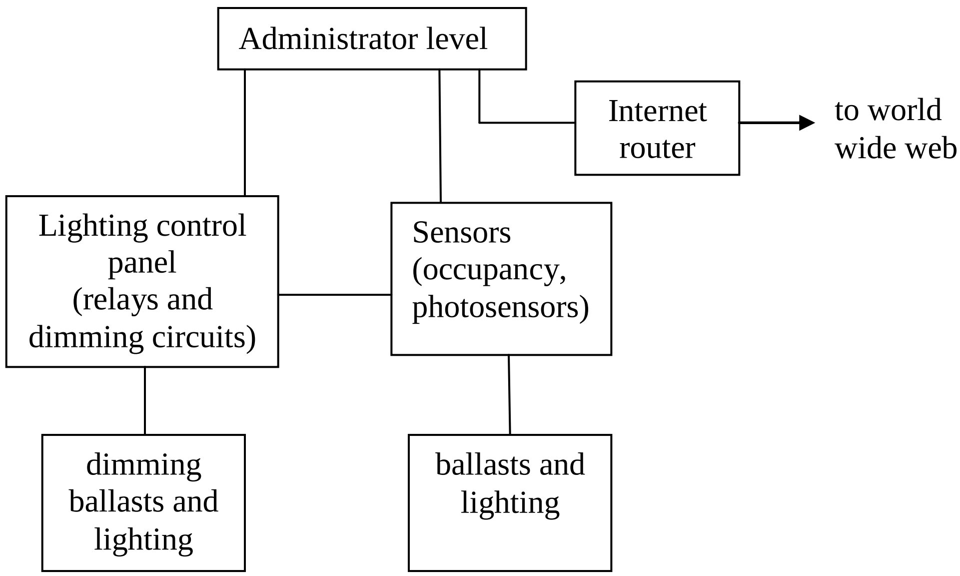


Figure 2.9 Scheme of DDC based Lighting Control System in a Building

2.4.6 Dubai Case Studies

The lighting in a villa was to be controlled by BAS with DDC components on EIB protocol. The villa consisted of ground and first floor with 50 devices arranged on a single line. The maximum number of devices that can be accommodated in a single line was 64. The living room had grouped lights with a common switch as shown in the Figure 2.10.

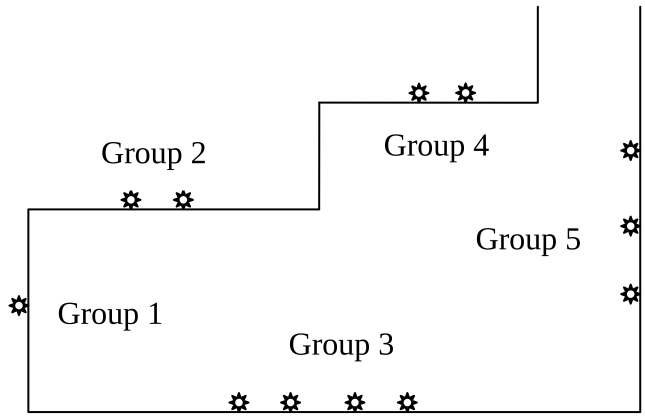


Figure 2.10 Grouping of Lights in the Living Room

Each lighting group was integrated with each other and to the NCRS system controller as shown in Figure 2.11. The system architecture and controller details are given in Appendix A.

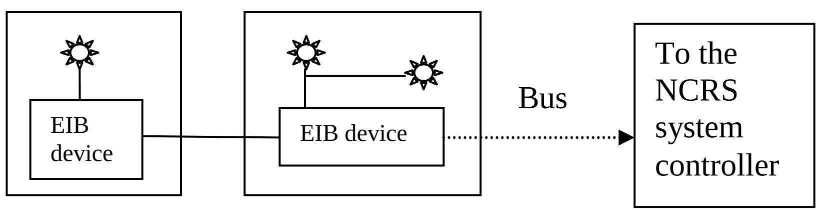


Figure 2.11 Connection of Grouped Lights to the System Controller

Occupancy sensors were used in the compound wall, near the entrance door, corridors, stairwells and garages. These sensors were connected between light and EIB devices.

Results and discussion

An energy saving of 36% in lighting was achieved by making use of occupancy sensors for areas in and around the house and time based switches for external lighting. Table 2.11 gives the control scheme for indoor and external lighting while Table 2.12 compares the obtained energy saving against conventional wiring.

Table 2.11 EIB Control Scheme in a Dubai Villa

Group	No. of devices	Load Details
Circuit 1	30 Nos.	200 W lights inside and in compound wall
Circuit 2	10 Nos.	150 W Garden Boland lights
Circuit 3	10 Nos.	150 W external lights in corridor and garage, external first floor and backyard

Table 2.12 Energy Saving in Dubai villa - EIB Control / Conventional Wiring

Control Method	Energy Consumption per Night
By conventional method assuming the lights are on from 7.00 p.m. to 6.00 a.m.	11x ((30*200)+(10*150)+(10*150)) = 99 kWhr
Circuit1 and 2 with occupancy sensors	57.5 kWhr
circuit3 using time-based control in which lights were on between 7.00 p.m. to 10.30 p.m.	3.5 x(10*150W) =5.25 kWhr
Total energy saving	99-(57.5+5.25)/99 =36.6%

With Dubai's light levels being consistent throughout the year, the energy saving remains reliable and predictable for the whole year in the above case. In another case study conducted in an office building in Dubai, the operation costs per year were found to be reduced by implementing EIB based intelligent lighting control as described by Figure 2.12.

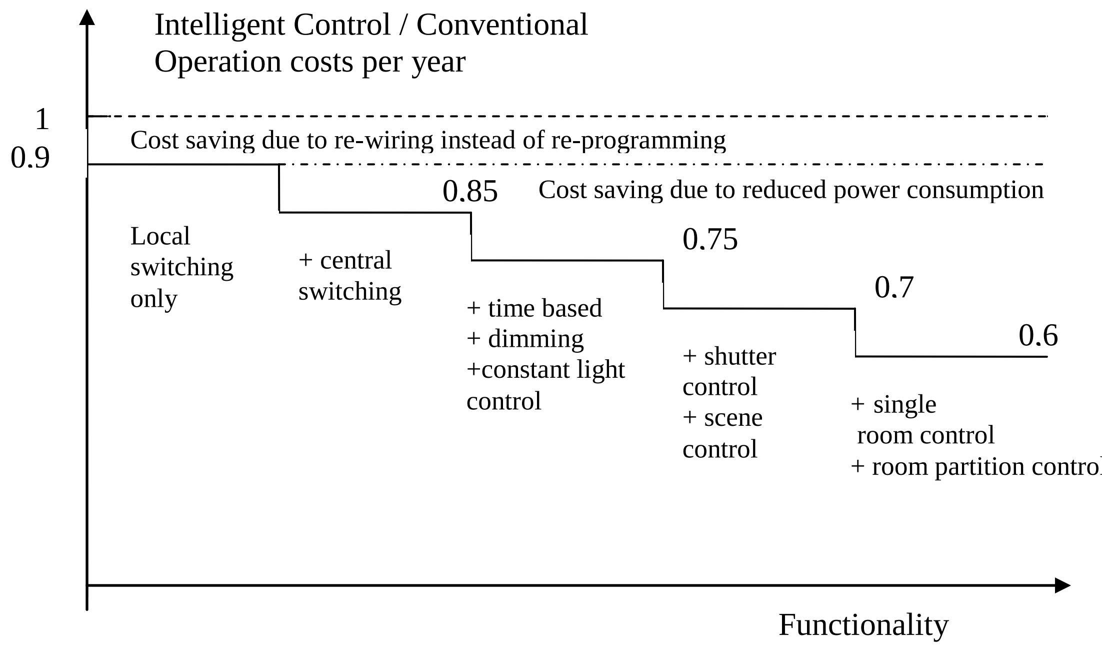


Figure 2.12 Operation Costs per year-Intelligent Lighting Control / Conventional Wiring (Adurkar 2003).

The cost saving was found to be maximum at 40% by implementing all types of control namely dimming, time based, shutter control etc. Rewiring for an existing building would involve additional costs. The absolute magnitude of energy saving due to EIB wiring for a new building and its control method depend on a particular application, the building operation and local cost of energy.

2.5 Concluding Remarks

The lighting control of today uses one or more of the following strategies: occupancy based, schedule based, light level based and load shedding. The criteria for using a particular control strategy are often need based. Lighting control strategies reach their potential when users are convinced about the energy saving and payback calculations and they are educated as to how to operate them. When advanced controls are transparent to the end user and when the users are made confident, the controls work to their satisfaction.

Proper commissioning of daylighting control systems should satisfy the design that they are intended for and they should be regularly maintained to achieve long-term success. Glare and heat gain are the issues associated with these systems.

BAS can help monitor or control systems such as lighting, HVAC, water meters, constant and variable motor loads etc. and equipments. BAS promote overall building energy efficiency since all the systems can be monitored over a common network. Furthermore, if measurement and control is done in a dynamic fashion it becomes possible to maintain efficiency over the long term. BAS can play many roles in the effective and efficient operation of a building. Creative applications and emerging technologies will make BAS here to stay as a valuable tool in achieving energy efficient and environmentally friendly society. In complex buildings, especially those with mixed-use, it is necessary to separate the different drivers for energy consumption where automation will play a major role in the future in energy management.

Chapter 3

Present Trends and Future Direction of Lighting Control Systems in Dubai

3.1 Introduction

The findings of a research study conducted to analyse the present trends and future direction of various lighting control systems in the new projects of Dubai is presented in this chapter. Firstly, to illustrate the current trends in lighting control technology in the region, the case studies of four major manufacturers in Dubai are highlighted. Then the research study follows in which a sample of 205 new projects in Dubai are classified into three categories namely residential, commercial and hotel projects and the five forms of lighting control technologies in these buildings are analysed. From the response of participants, the demand drivers and the factors for resistance to adoption of these systems are presented. Looking into the future scenarios, the study identifies the different factors that would make these controls more common in future. The chapter concludes with an analysis on industrial feasibility of lighting control in the residential sector of Middle Eastern countries and we estimate this industry to be fast growing in the region as a whole.

3.2 Background

The United Arab Emirates (UAE) government's clear vision of the future, its relaxed policies on trade and investment lead to the development of this country from the beginning of 1980s. The population spread of UAE is very different in the sense that expatriates from other countries outnumber the nationals by a huge margin. Expatriates make up the majority of population and are mainly drawn from the Indian subcontinent, Europe and neighbouring Arab countries (Al Tamimi, 2006). A Dubai policy in the summer of 2002 announced freehold property ownership for people of all nationalities (Al Tamimi 2006). Since then, buyers have been flocking to the various upscale developments and buying property in record times (Al Tamimi 2006). The overall strategy of adopting free market principles has brought about an increasing volume of investments in a large variety of projects and joint ventures, manufacturing and service industries; retail and tourism business have increased (Al Tamimi 2006).

The major boom in the building and construction industries has significantly enhanced the demand for lighting and electrical products. The many sophisticated developments taking shape across the UAE are wooing the customers using the dramatic effects that can be created through architectural lighting to enhance their properties and theatrical lighting, which uses intelligent lighting to improve the quality of the audience experience. Dubai, which is the commercial hub of the Middle East and melting pot of many nationalities, is concerned about its image and its international brand identity.

The need for research and documentation on automated lighting systems in the region has assumed much more significance now after His Highness Sheikh Mohammed Bin Rashid Al Maktoum, UAE Vice-president and Prime Minister and the ruler of Dubai issued a resolution on implementation of green building specifications. The research study described in this chapter was motivated by the author’s observation that the works pertaining to the Gulf States as mentioned in the literature (Omar and Al-Ragom 2002, Al-Iriani 2005, Iqbal and Al-Houmoud 2007, Radhi 2008, Al-ajmi and Hanby 2008) have concentrated on the energy-efficient air-conditioning systems of buildings in the region and that there is a need to identify how the lighting systems are performing presently which could serve as an indicator for future measures.

The objective of this chapter therefore is to present the results of the research study conducted to analyze five lighting control technologies employed in the new projects in Dubai and to analyze the extent and sophistication of lighting control on the present installations. From the study, the demand drivers and challenges faced by providers of lighting control business in the region are examined. The aggressive energy policies of the government may mandate lighting code regulations in future. So the difficulties and challenges associated with implementing such regulations in an expatriate-dominated society like Dubai are identified.

3.3 Specific Case Studies in Dubai Projects

Some key projects currently underway that would require lighting solutions and services are: Burj Dubai; the tallest building in the world, Business Bay; a multi billion dollar global commercial and business centre in the heart of Dubai, Dubai Autodrome and Business park; a state-of-the-art motor racing facility containing six different track configurations and motor industry companies, Dubailand; a US$ 7.5 billion mixed-use theme park consisting of stadiums, golf courses, academies and facilities, Dubai International City; 20 000 apartments in 350 buildings with townships based on China, England, Italy, France, Russia and Morocco, Dubai Metro and Railway projects; a US$ 4 billion project catering to 70 km length underground and elevated train systems etc.(Dubai Explorer 2007). Downtown Dubai; a working, living and entertainment neighbourhood, Dubai Sports City; a US$ 2 billion development for sports facilities, Aqua Dubai Water park; a US$ 200 million leisure, hotel and spa investment are also some of the landmark developments taking shape (Middle East electricity 2006).

The major manufacturers involved in some of the above mentioned projects include are Clipsal, Dynalite, Lutron and Poloron. Some new projects that use these company products are cited as illustrations for current trends in control technology in the region.

Clipsal, a leading international electrical and communications solutions company offers the latest range of products such as the Clipsal Premise Gateway and Colour Touch Screen integrated with C-Bus technology with which home owners can activate their home theatre and lighting, close their curtains and even control their air conditioning from a single control point (Gulf Industry Magazine 2006). The Clipsal C-Bus systems integrated with Building Management Systems (BMS) are installed in the Dubai International Financial Center (DIFC), (Figure 3.1) which houses two towers called "gate building" where the office of the crown prince of Dubai is located. The external fazzad lighting are scheduled to a 6 p.m. to 6 a.m. routine and the lighting in the common areas such as lift lobbies are controlled with 360˚ PIR (Passive InfraRed) sensors and 4 x 20A relays. The crown prince's office has C-Bus DALI gateways controlling dimming ballasts and C-Bus professional series dimmers controlling architectural light fittings. The input devices used for control are C-Touch and screw less faceplate (Figure 3.1).

Figure 3.1 Dubai International Financial Center (left); 4 key Screwless Flat Metal Key Inputs

Dynalite, specialising in lighting control and energy management systems offers seamless integration with BMS systems. The company has done landmark projects in Grand Hyatt hotel, which has more than 670 rooms as well as 186 luxury-serviced apartments. The exterior lighting creates white light ambience on most evenings and spectacular colour changing scenes for special events (Dynalite 2006). Dynalite 12 x 20A heavy-duty relay controllers switch the exterior fittings, which are concealed on the podium roof and are controlled via a time clock. These controllers can be programmed to stagger the switch on, minimizing peak demand current where it is beneficial to sequentially switch on large lighting loads (Dynalite 2006). Dynalite leading edge dimming is utilized in all of the restaurants, public areas, ballrooms and meeting rooms (Figure 3.2). 12 x 10A and 12 x 16A leading edge dimmers are used extensively, controlling a total of 2448 channels of lighting hotel-wide. The hotel's two pillarless ballrooms are provided with scene control options to suit the mood or occasion via DTK600 LCD touch screen. All Dynalite dimmers incorporate voltage regulation and soft start technologies, protecting lamps and dramatically increasing lamp life. This is particularly useful in a hotel situation, where changing lamps in public areas can be difficult and costly (Dynalite 2006).

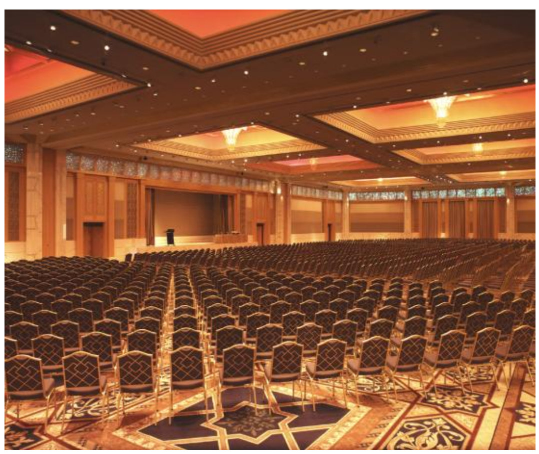


Figure 3.2 Colour Cathode Lighting at Grand Hyatt Dubai's Ballroom to Suit Different Moods

The BurJuman Centre in Dubai houses a corporate office tower, luxury residential apartments and a three-level 800 000 ft^2 shopping complex with over 300 stores. Dynalite dimmers control seven sections of three channel colour cold cathode (red, purple and blue) creating a sunrise to sunset simulation that radiates from the eastern most point of an observatory dome to the west at fifteen minute intervals (Architectural lighting control- case studies 2006). Dynalite dimming and lighting controls were also implemented in the public areas of both the residential and office towers, as well as the nine luxury penthouses.

Lutron Electronics Co. has implemented dimming in DEC Towers and Fairmont Hotel (Lutron 2006). In the one and only Royal Mirage Resort, GRAFIK 6000 lighting control system is installed for its flexibility for handling multiple set up requirements and functionality for controlling large ballrooms, meeting rooms, lobby and reception areas. It is sophisticated enough to interface to specialty lighting systems, emergency lighting and security and still simple to be operated by hotel staff. Lighting divided into many zones can be remotely adjusted to any desired levels for theatrical or special effects with a hand held programmer connected to a wall station or programmer jack. With the GRAFIK 6000 system, the room scenes can be preprogrammed and recalled and partitioned spaces can be automatically and dynamically combined or separated for different scene control functions.

The Poloron lighting control systems are implemented in two of the seven star hotels of the region. In Abu Dhabi, the neighbouring emirate of Dubai, the public areas and suites of Conference Palace Hotel are fitted with 2350 remote control plates and more than 16 000 dimmable lighting channels, as well as a central computer system and the project was worth approximately of £1 million (SourceWire 2004). The company had also done the complete lighting control system for the world famous Burj Al Arab in Dubai. The system made use of Polaron's latest Lightlink dimmer modules to control a wide range of light sources that can be interfaced directly with the BMS. Seamless integration and control as well as interoperability with wide range of other equipments from various suppliers are other features of the system (SourceWire 2004).

3.4 The Research Study

The study was conducted between April 2006 and October 2007 on a sample of 205 new projects in Dubai. By data collection through the web and interaction with the construction industry, the buildings were identified as to whether the projects use at least one form of lighting control. Appendix A provides the master list of projects through which this decision was made. The projects were classified as residential, commercial and hotel projects. It was found that out of 205 projects, 94 projects (45.9%) were using some form of lighting control out of which 53 were residential buildings, 25 were commercial and 16 were hotel projects. Table 3.1 summarises the detail.

Table 3.1 Details of New Projects

Categories of New Projects	No. of Projects Taken for the Study	No. of Projects that Use Lighting Control
Residential	129	53
Commercial	60	25
Hotels	16	16
Total	205	94

It was identified that the projects that use lighting control could be further classified into the categories as shown in Table 3.2 according to the building use. A total of 38 professionals involved in the lighting control business from among these 94 projects were chosen and interviews were held with them.

The professions of participants are indicated in Table 3.3. The participants were asked as to whether the project they represent indeed used any form of lighting control and what method of control was specified in the project. Depending on the answers provided on a particular category of lighting control systems, follow-up questions were asked. Appendix A contains the list and order of questions posed to a particular participant.

Table 3.2 Types of New Projects that use Lighting Control

Categories of New Projects	No. of Projects that use Lighting Control
Residential (53)	
Villas	9
Apartment Buildings	33
Staff accommodation	11
Commercial (25)	
Banks	4
Offices	8
Educational institutions	3
Recreational facilities and Shopping malls	8
Hospitals	2
Hotels (16)	
3 star hotels	4
4 star hotels	3
5 star hotels	5
Service apartments	4

A. Values given in the parentheses are total number of projects in the given category.

Table 3.3 Professions of Participants

Professions of participants	No. of participants interviewed
Lighting Designers	11
Engineers	14
Manufacturers	13
Total	38

A. Engineers' category also included four energy consultants.

3.5 Results

The results of the study are presented in this section. The various factors are analysed for the penetration of lighting control systems in Dubai.

3.5.1 Prevalence and Penetration

Given in Table 3.4 is the result of the research study conducted on the five different forms of lighting control used in each of the three categories of projects. During the follow-up phase of the study, the participants indicated the following as the most important reason for prevalence or acceptance of a particular system in a given category. The dimming is most popular in hotels (100%) mainly because of the prevalence of use of architectural control in conference rooms and ballrooms and stand-alone dimmers in hotel rooms. Commercial buildings widely adopt dimming (40%) and some of them for fluorescent lighting using electronic ballasts and DALI and non-addressable digital control, DSI technology.

Table 3.4 Prevalence of Lighting Control in New Projects in Dubai

Categories of New Projects	Dimming (%)	Lighting Control panels (%)	Occupancy Sensors (%)	Building Management Systems (%)	Daylighting Systems (%)
Residential (53)	18.9	75.5	28.3	37.7	0
Commercial (25)	40	80	20	80	12
Hotels (16)	100	62.5	0	100	0

A. Values given in the parentheses are total number of projects in the given category.

Lighting control panels are housed near the distribution boards and they control the lighting circuitries. All the relays and dimmers predominantly are controlled by a common protocol such as EIB (European Installation Bus), C-Bus, PROFIBUS (Process field bus) etc. and lighting control panels are widely employed in residential (75.5%) and commercial projects (80%) and could potentially become a standard feature in future, according to 21 participants.

Occupancy sensors are mostly used in corridors and lift lobbies in residential projects (28.3%) and in conference rooms, boardrooms, car parks and reception areas in commercial projects (20%). Twenty four participants felt that this simple technology has the reach to achieve significant energy savings in buildings in Dubai.

BMS has wide acceptability in most of the new projects and lighting control is generally interfaced with BMS thus offering flexible solutions, fast expandability and easy adaptation to customer needs, remote monitoring and greater energy efficiency. In some projects, lighting control panels are used as standalone as well.

Daylighting though highlighted by most of the manufacturers in promoting their systems, is being adopted in few projects (12%). This is likely due to heat gain problems associated with it in the desert climate of Dubai since it has a direct impact on the air-conditioning load. There is less work done to assess and evaluate the performance of daylighting systems in the buildings of Dubai. However Al- Sallal (2006) has done an experimental work recently in universal space studios in Al-Ain, UAE and the research done by Aboulnaga (2006) investigates the problems associated with misuse of glass, as a building element in UAE particularly in Dubai. Inadequate design with ill-selected glass/glazing type may lead not only to poor daylighting in building interiors but also contribute significantly to fatigue, insomnia, seasonal affective disorder (SAD) and above all increase CO_2 emission (Aboulnaga 2006). According to ten participants, with more such research and refinement coming into daylighting systems meant for hot regions, the adoption of these systems in Dubai would become more common in design practice. According to Yannas (2007), 1 to 2% of the outdoor illuminance in the UAE can be sufficient to provide the illumination levels of 300 to 500 lux required for typical indoor activities.

3.5.2 Demand Drivers

The participants were asked about what they considered as the demand drivers of automated lighting control business in Dubai. Options included meeting the requirements of the property developers, incorporating personal control for increased satisfaction, comfort and productivity, flexibility in controlling the floor area, willingness to embrace new technologies such as DALI and energy savings. Table 3.5 shows the participants' choices.

Table 3.5 Factors Driving the Demand of Lighting Control Systems in Dubai

Demand drivers	Percentage of Participants that Choose this Option
Meeting the requirements of the property developers	89
Incorporating personal control for increased satisfaction	63
Productivity and comfort	48
Flexibility in controlling the floor area	38
Willingness to embrace new technologies such as DALI	51
Energy savings	41

From the interaction with the participants, the following emerged as the reason for their choices. Major developers in Dubai see the automation in lighting as a selling feature to promote their properties. This is the biggest driving force (89%).They offer lighting control or create containment for future incorporation. Scene control, occupancy sensors and workstation lighting controls dominate the market due to user satisfaction and convenience factors. Open office spaces require modification and alteration depending on the client's requirement and adaptation of lighting control makes these tasks easier.

Though energy saving is the ultimate feature of automated control, it is still not a major driving force in decision making in Dubai (41%), due the fact there are no specific regulation or energy codes in place and also the cost of energy is less because UAE contains 98 billion barrels, or nearly 10 percent, of the world's proven oil reserves and 4.6% of world's total natural gas reserves and exports significant amounts of liquefied natural gas (EIA 2006). Considering the fact that UAE enjoys the highest per capita income, the consumers are still not feeling the pinch due to cost of energy when compared to their other expenditures.

3.5.3 Resistance to Adoption

The participants from the professional group responded as given in Table 3.6, when asked about the various factors that prevent a project from using lighting control technologies. Participants could choose more than one factor.

Table 3.6 Resistance to Adoption

Factors for Resistance	Percentage of Participants that Choose this Option (%)
Initial cost	78
Educating the user in operating the controls and making him feel comfortable	48
Operational issues	32
Perception of clients that system may not function as intended	36
Difficulty in specification	58

The main resistance to adoption comes due to the initial cost, which is the same reason that concerns the providers the world over. The specific reason of educating the user in operating the controls and making him feel comfortable with the expertise is particularly relevant in the case of BMS (48%). With a proper after-sales service network non-existent, the apprehension of clients is not completely unjustified. Operational issues or technical drawbacks (32%) are mainly due to the occupancy sensor category wherein countering the delays and false-offs continue to pose some problem, even though design refinements have injected some confidence with the users.

The designer group expressed that some clients perceive that these systems may not function as intended as they have experienced lights going off at wrong times (36%). They also face challenges while integrating an existing light system with new controls, looking for more creative solutions. The respondents also felt that they faced a unique and difficult situation to specify lighting control systems in a region where energy costs are minimal and value engineering is the norm considering the fact that labour costs form a substantial portion of the overall project costs. When it comes to cost cutting in a project, the lighting control becomes one of the first casualties. With the rental properties forming a major part in residential and commercial sectors in Dubai, some owners have hesitation in going for advanced controls. This explains why a high factor (58%) accounted for resistance due to specification.

3.5.4 Reason for Optimism

Overall, the participants agreed that lighting controls are becoming common in all commercial projects and the extent of advancement and sophistication is dependent on project type, scale, client criteria and cost. They also opined that if some new codes mandating lighting controls such as ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers)/ IESNA (Illuminating Engineering Society of North America) 90.1-1999 are mandated, the cost for these systems will eventually reduce because of increase in demand. Table 3.7 gives the details of responses when asked about what are the factors that would make these controls common in future. The awareness and willingness to experiment new ideas cause encouragement among the providers and this poses design challenges and search for innovative approach. Lighting controls work independently and yet still communicate with BMS. Integrating lighting control systems with the BMS is seen as a major trend and the issues concerning interoperability raises more scope for improvisation in design and programming.

Table 3.7 Factors that would Make the Controls More Common in Future

Reason for Becoming Common in Future	Percentage of Participants that Choose this Option (%)
Future implementation of codes and standards	81
Boom in construction	72
More user awareness and willingness to experiment	70
Integration with BMS and improvisation in design	51
Rise in inflation and energy costs	42

3.6 Discussion

Firstly, the challenges of suppliers and manufacturers of lighting control are discussed.

3.6.1 Challenges of Providers of Lighting Control in Dubai

From the interaction with the engineers and manufacturers, a definite picture emerged as to what they considered as the challenges of lighting control business in this region.

- The cost issues and justifying the payback dominate the concerns of the providers.
- The awareness and willingness to experiment new ideas cause encouragement among the providers and this poses design challenges and search for innovative approach.
- Integrating an existing light system with new controls poses challenges for the designers, for they have to look for more creative solutions.
- If there is a general perception among the end-users that the advanced systems must be complex to operate and maintain, educating and orienting the clients becomes vital and part of the job.

- In some situations where value engineering is the decisive factor, in addition to clients, the design team inclusive of construction managers and contractors also are to be convinced.
- BMS can offer minimal lighting control with incremental savings. In buildings where BMS is already installed, some owners question the need to have separate lighting control systems.

3.6.2 Governmental Measures

In this section, issues such as how Dubai buildings will accept and adapt themselves to automated lighting control in future are examined with particular focus on energy perspective. The study conducted indicates that energy saving is not the biggest demand driver for these controls and hence this area is identified as untapped and scrutinized for interpretation of future scenarios. The study also has two other important results that property developers require lighting controls to be installed in their buildings and that the willingness to experiment new ideas cause encouragement among the providers and designers. With these significant findings, the role of the government is examined in making the controls popular.

Presently Dubai Electricity and Water Authority (DEWA) have an energy conservation cell and it releases advertisements in the local newspapers to raise awareness among the public for efficient use of energy (Gulf News 2007). DEWA recently launched “your decision campaign” to raise awareness among the community to curb excessive consumption of electricity. It has introduced different slabs to charge tariff for residential, commercial and industrial consumers ranging from 20 fils per kWh to 33 fils per kWh. In an effort to utilise solar energy, Dubai Municipality erected solar-powered parking meters as well as some road signage in and around the city (Kazim 2007).

The government of Dubai recognizes and encourages people who have adopted energy efficient strategies in their buildings and is committed to achieving sustainable environment protection by encouraging more green buildings to be constructed and Leadership in Energy and Environmental Design (LEED) ratings to be achieved for new buildings. Though LEED points are obtained for areas such as sustainable site development, water efficiency, energy and atmosphere, indoor environmental quality, design innovation and materials and resources selection, energy efficiency is highlighted with more and more buildings going in for LEED certification in Dubai.

Since January 1, 2008 the villas, hotels, mosques and all kinds of buildings planned for future must conform to sustainable development criteria as announced by His Highness Sheikh Mohammed Bin Rashid Al Maktoum, UAE Vice-president and Prime Minister and the ruler of Dubai. There are 70 planned U.A.E. buildings now aiming for green status, according to Hilson Moran, which has a seat on the Emirates Green Building Council (Hughes 2008). The UAE is picking up on messages from around the world and one of those is sustainability and they have the ability to implement it, says Chris Johnson, a Gensler managing principal (Hughes 2008).

The company Pacific Control Systems specializing in automation solutions has achieved the platinum rating for the Green Building under the LEED Certification Programme of United States Green Building Council (USGBC) based at Washington (Salian 2006). With a built up area of over 120 000 ft^2, the 5-storey headquarters building at the Dubai Techno Park makes use of solar photovoltaic cells for the entire lighting needs (Salian 2006). Wafi City's District Cooling Plant was also awarded a silver LEED certification. Metito`s headquarters would have the number of installed lights reduced by maximizing the use of indirect sunlight, thus reducing costs while ensuring each person was receiving appropriate illumination for his job (Salian 2006). Tameer`s towers, a 72 storey building made of locally produced pre-cast-concrete panels are few of the many examples vying for green status. The developers are responding very positively to the Ruler`s new resolution. A regional English daily reported that the developers in the UAE are choosing to build the highest level of green buildings to the surprise of certifying body, Middle East Centre for Sustainable Development (Gulf News 2008a). The finding namely, meeting the requirements of the property developer as the primary demand driver underscores this aspect.

In line with the green building resolution, DEWA enforces regulations through various stages. As per this regulation, the control systems such as motion sensors, dimming systems and lighting with timers are required to be used in all buildings and are to be considered by all consultants, consumers, developers etc.

Such market pressures can simulate the need for lighting control technologies. To quote the U.S. example, Snoonian and Bowen (2005) expressed that the electricity prices would rise in the next five years, creating an incentive to owners and operators to adopt such measures to slash costs. Complying with California's mandatory energy code requirements not only saves money by reducing energy costs, but also qualify people for a cash rebate from the public utility company for implementing energy efficient lighting controls such as new or retrofit installations, ballasts, occupancy sensors and daylight sensors. Title 24 legislation in California requires automated shut-off controls, daylight responsive control, exterior and display lighting control for all new and remodeled residential and commercial buildings. Furthermore, the Energy Policy Act of 2005 (EPAct 2005) provides the building owners with up to a $1.80 per qualifying square foot tax deduction for beating the lighting portion of the code requirements (DiLouie 2005).

The population mix of Dubai is predominantly expatriate-oriented, thanks to its tax-free atmosphere and high level of living standards. This aspect poses unique issues concerning labour and expertise in implementing and pursuing energy standards and codes, if the government chooses to do so (Bhavani and Khan 2007c).

3.6.3 Challenges in Implementing Lighting Codes Regulations

Due to the climate change and global warming concerns all countries including the developing economies are under pressure to promote energy conservation among its citizens by devising strategies such as regulation, awareness campaigns, cash incentives and tax benefits. Dubai's geographic location as the commercial hub in the Middle East, bridging Asia and Europe, along with its expanding economy and aggressive intent on becoming one of the major players of trade and industry in the globe necessitate the implementation of energy policies. In this section, the challenges of implementing codes and standards are examined with particular focus on lighting and associated controls.

Design challenges

Building codes and standards have enormous effect on the type of controls designed and implemented into a lighting system. The codes if implemented will make the designers think innovatively to structure a lighting system into a building`s network. Devising of such control strategies to suit a particular requirement needs huge design expertise and all the more so in adoption of retrofit applications. These design criteria are to be reviewed and approved by the inspection team during development and testing phases. When these sustainable design requirements become code, the industry and its products should rise up to the challenge and expect to be refined for the better. The region should equip itself with the design skills to match these technical demands.

Challenges in training

The lighting codes if implemented will set maximum allowable energy consumption levels for various lighting systems and will have its statements of requirements and evaluation methodologies. The assessment of impacts of these codes, its economic analysis and training is a complex and technical task (Chan and Yeung 2005). The analysis of cost data for lighting products involves difficult calculations because products having variable costs and shapes can offer similar light at the same efficiency and efficacy. This poses challenge in cost analysis and hence requires training at this level too. The training of design professionals, contractors, lighting equipment suppliers, code officials or inspectors is critical for successful implementation of codes and hence the training will have to be implemented by way of seminars, presentations and software to demonstrate lighting design compliance.

Challenges in enforcement

Codes will not deliver the intended energy savings if not enforced properly and complied by the construction industry. Enforcing the codes requires high level of expertise and the government has to hire multiple code officials with specific areas of specialisation. Recruitment of skilled code officials and training them could put additional pressure on the government, which already relies on the expatriate community for most of its labour needs.

It is worthwhile looking back at the experience of California, which was the first state to develop mandatory energy standard in 1977. The local building departments suffering from heavy workloads created major enforcement loophole in the regulations (Wilms 1982). The author observed that the hard path regulatory policies, which were opposed by designers, builders and building officials could not be properly enforced and hence the state gradually substituted soft-path training and education for the people concerned on how to understand and comply with the standards. Building contractors and developers may tend to feel codes as an unnecessary regulation that increases costs by means of additional or expensive materials and may not like the construction delays happening due to learning and adhering to complex requirements. So alternative implementation strategies is suggested to ensure effective compliance to win sufficient public support to help government agencies avoid conflict between local and state jurisdictions (Wilms 1982).

Informing the consumers

If codes are mandated the government has to equip the residential consumers with the accurate and reliable information of products. The consumers have to be oriented towards financial incentives or cost benefits for them to employ energy saving schemes. For the expatriate community in Dubai, the short-term financial needs may be a higher priority than the long-term thinking about the future savings gained by energy efficiency policies. So the government has to invest in creating more awareness among the public before introducing the codes.

The government has to insist on printing lamp output in lumens, energy wattage and average lifetime on the packaging of lamps. This will enable the consumers to choose more energy efficient products and help avoid confusion. Mandatory labeling of energy efficient bulbs will create healthy competition among the manufacturers or dealers of lighting products. The successful inclusion of a community into environmental policy brings with it a need to develop both environmental awareness within the community and capacity building within a nation`s human resources. (O`Brien et al. 2007). When awareness and capacity building are attempted without policy participation the results have often been poor (O`Brien et al. 2007).

Other challenges

The implementation of code would require formation of extensive databases for adoption process, compliance methods, enforcement and residential and commercial construction data happening in the city. The procedures of documentation are often extensive and elaborate. Training and enforcement would involve additional manpower as well as initial and operational costs towards hardware and other resources. Much like the U.S. energy policy act of 1992, the government may have to regulate the manufacturing and import of lamps that do not meet specified energy performance. All these activities involve expenditures and additional manpower for performance verification and technical support.

Figure 3.3 summarises the entire framework of code implementation in the form of a flow diagram. The important factors and their inter-dependence are shown. For the successful implementation of codes and standards, it is very vital that the definition and relationships of these factors are clearly understood.

If codes become the norm and are well defined, the most popular control technology will evolve with time. From the study, the sheer amount of construction activities happening in Dubai can be seen as a tremendous opportunity for implementing energy codes and standards.

3.6.4 Industrial Feasibility for Residential Customers

In this section, the industrial feasibility of lighting control is examined with respect to residential sector of Middle Eastern countries. The UAE power demand is among the largest in the region due to financial and tourist projects as well as a growing population where the residential consumers constitute an important sector. An average household in the region dedicates about 5 to 10% of its energy budget to lighting (Radhi 2008). In the Middle East, the energy cost is not a major factor yet in general and so each home can start with energy-efficient devices and simple control mechanisms with short payback which can lead to a more focused approach.

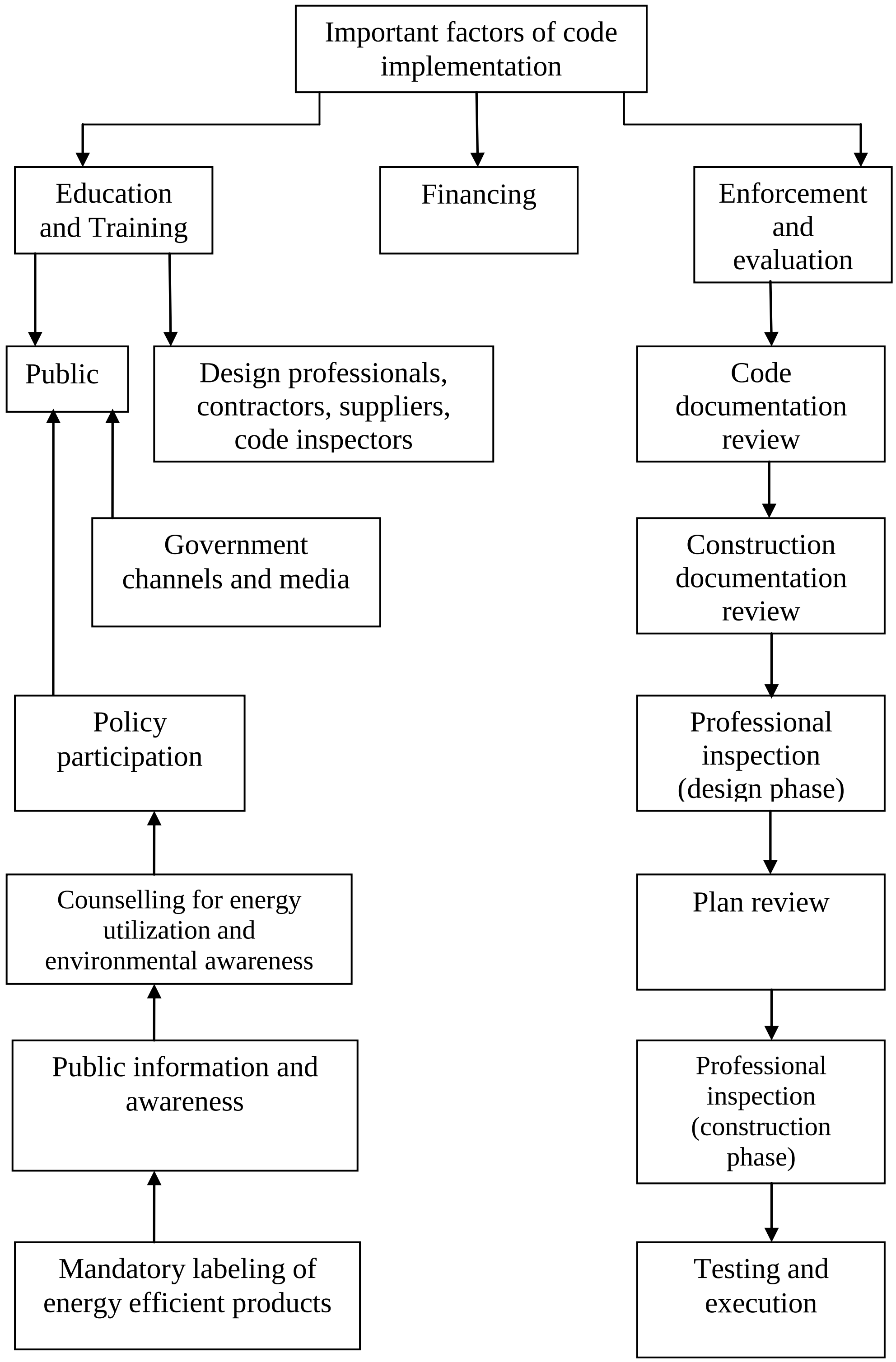


Figure 3.3 Framework of Code Implementation Strategies

For example, if a long corridor in a residential building is installed with nine fluorescent fixtures with four tubes per fixture (quad type) each of 18 W, the hourly energy consumed is 0.648 kWh only. Let us assume that this arrangement replaces an incandescent downlight set up of 32 numbers of 100 W each and the UAE electricity rate as 20 fils (US$ 0.054) per kWh (for under 2000 hours of operation for residential consumers). Annual energy cost is given by

$$C_{en} = \frac{(365 N_f N_t W_l P_e H_{op})}{1000} \tag{3.1}$$

where N_f is the number of fixtures, N_t is the number of tube per fixture, W_l is the wattage of the luminaires , P_e is the unit price of electricity and $H_{op}$is the average daily hours of operation. Table 3.8 provides the comparison for retrofitting.

Table 3.8 Incandescent and CFL Lamp Data

Type of Lamps	Light Output (lm)	Electrical Input (w)	Luminous Efficacy (lm/w)	Useful Life (h)	Cost per Fixture (AED)
Incandescent	1360	100	13.6	2000	4.00
CFL	1440	18	80	8000	100.00

If retrofit alone is considered, it will bring in savings due to high lumen per wattage of CFL. But, automatic shut-off control can result in still more savings. Occupancy sensors using infra scan, three in number are assumed to provide an 5- hour operation as against the conventional 12 hour operation in the enclosed corridor. This 5-hour operation is arrived at with a time-out setting of 15 minutes. This setting if too short may cause false cycling and long time-out setting fails to save considerable energy. For an efficient operation, this setting is reasonable. The payback period in its simplest of form is given by

$$T_{pb} = \frac{C_i}{C_{as}} \tag{3.2}$$

where C_i is the initial cost of lamp and fixtures plus the automatic shut off control and C_{as} is annual savings due to retrofit.

Table 3.9 summarises the retrofit as well as the combined arrangement of CFL and occupancy sensor. The figures have been rounded off to the nearest dirhams.

Table 3.9 Cost Details of Retrofit and Automatic Shut-off

Lighting	**Annual Energy Cost (AED) C_{en}**	**Initial Cost (AED) C_i**	**Annual Savings (AED) C_{as}**	**Payback Period (years) T_{pb}**
Incandescent downlight	2804.00*	128.00	-	-
CFL fixture retrofit	568.00*	900.00	2236.00	0.4 (4.83 months)
CFL with occupancy sensor	237.00	2400.00**	2567.00	0.93 (11.21 months)

* Assuming a 12-hour operation in the corridor; ** Occupancy sensor cost is assumed to be 500.00 AED each.

The payback period of CFL retrofit is less compared to the life time of the lamp (4.3 years assuming a 5-hour operation every night). Even though the payback period of CFL plus occupancy sensor arrangement is more than the mere retrofit, the net annual energy saving is more. Hence after the initial investment is paid back (after one year approximately) the arrangement gives more return due to decreased energy bills. The sensor arrangement also extends the life of the lamp since it switches the lamp only during occupancy and hence the maintenance cost is also much less. This method is the most economical and viable of all the three.

The number of housing units in the UAE is 863,860 according to 2006 official statistics of the country. Even if we assume 500,000 units are utilising CFL with occupancy sensor control, the net annual savings will be to the tune of

1283.5 million! With the increase in energy costs and number of households, this simple scheme can cut back a lot of spending on power generation for the government and also ease consumer spending. The sensitivity of annual energy savings (in AED) has been studied for an increase in hours of use and unit electricity prices (Figures 3.4 to 3.7).

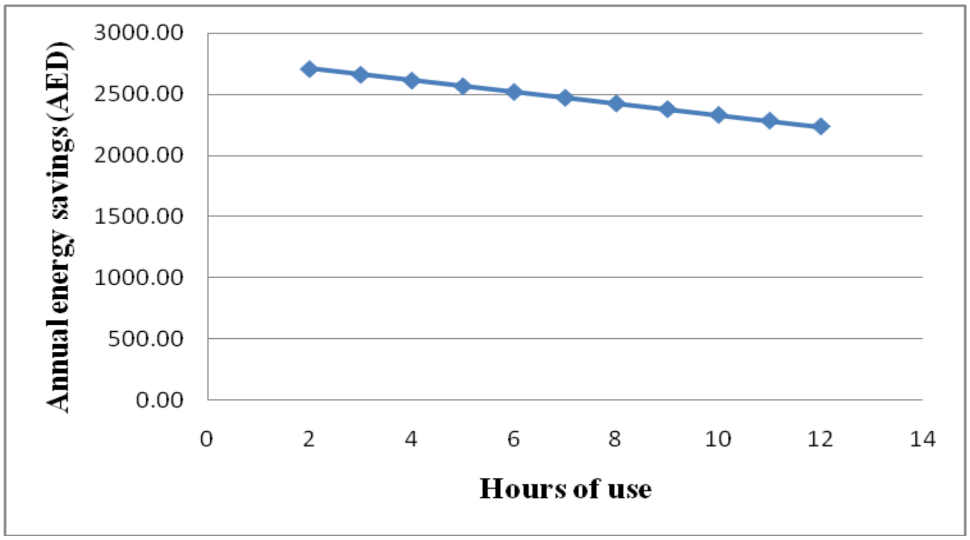


Figure 3.4 Variation of Annual Energy Savings on Hours of Use

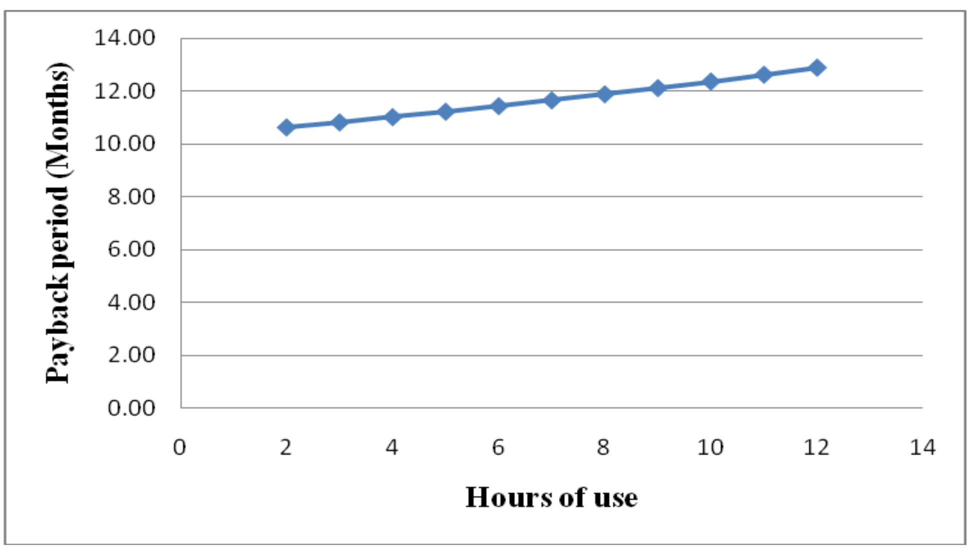


Figure 3.5 Variation of Simple Payback Period on Hours of Use

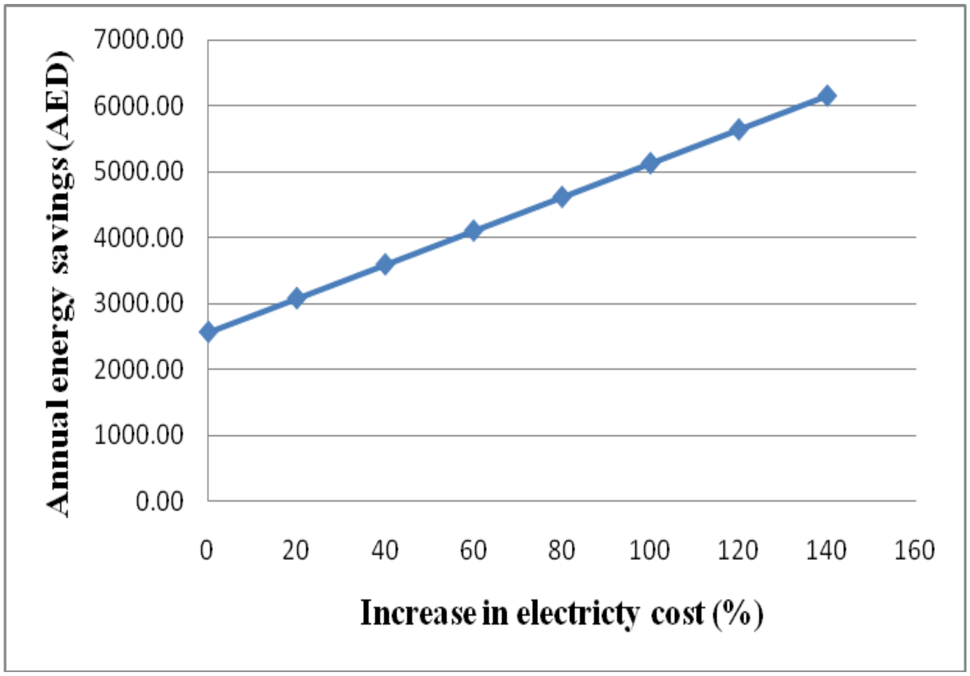


Figure 3.6 Variation of Annual Energy Savings on Increase in Electricity Price

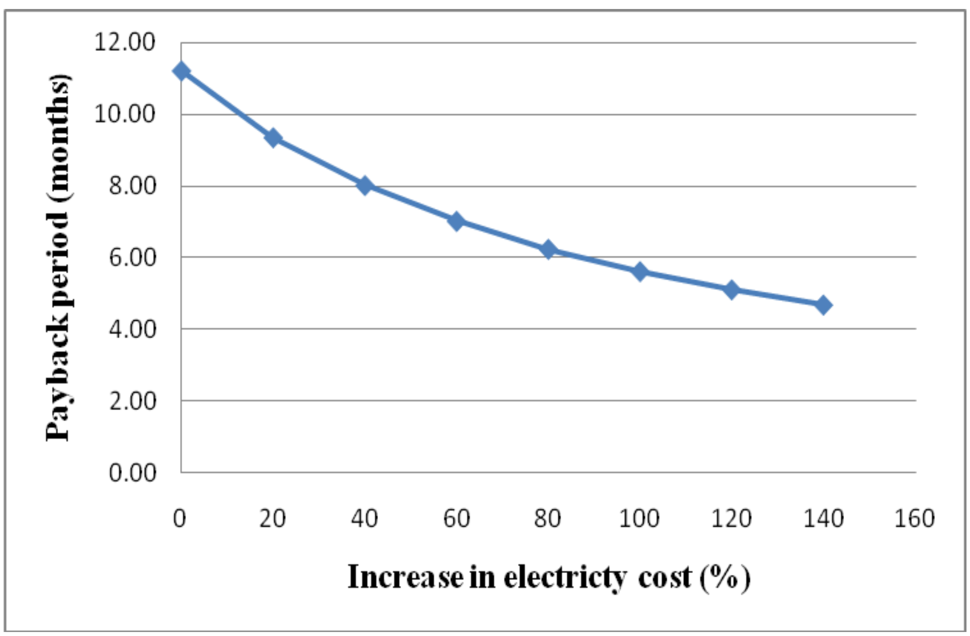


Figure 3.7 Variation of Simple Payback Period on Increase in Electricity Price

By employing simple measures such as replacing common 40 W and 70 W lamps with energy saving lamps of 34 to 60 W respectively and by using improved electromagnetic and electronic ballasts, the operating, maintenance and energy costs come down with a marginal increase in first cost. Hence the life cycle cost also becomes less for these devices. By definition, life cycle cost is the sum of first cost, maintenance cost, disposal cost, finance cost, productivity cost, risk cost and energy cost. It is estimated that the average light settings optimal for most of the visual tasks is 70% of the full output of the lamps and hence the energy consumption also reduces to 70% of the pre-retrofit baseline levels, if proper dimmers are used. An added benefit of dimming is the extension of lamp life. The residential units can employ local switching, central switching and time-based dimming with which a short payback of 1 to 3 years is expected because of the reduction in energy cost as well as operating cost due to increase in lamp life and fixtures.

3.6.5 The Ever-increasing Energy Demand

As Figure 3.8 indicates, UAE enjoys the highest per capita electricity consumption among the Middle Eastern countries, considerably higher than the world average. There are three major parameters that could significantly influence the UAE’s energy consumption namely population growth, high urbanization and economic growth (Kazim 2007). Figure 3.9 depicts this scenario clearly. With high economic and population growth rates and a fairly low energy cost, the country`s energy consumption has risen tremendously in the past decades (Kazim, 2007).

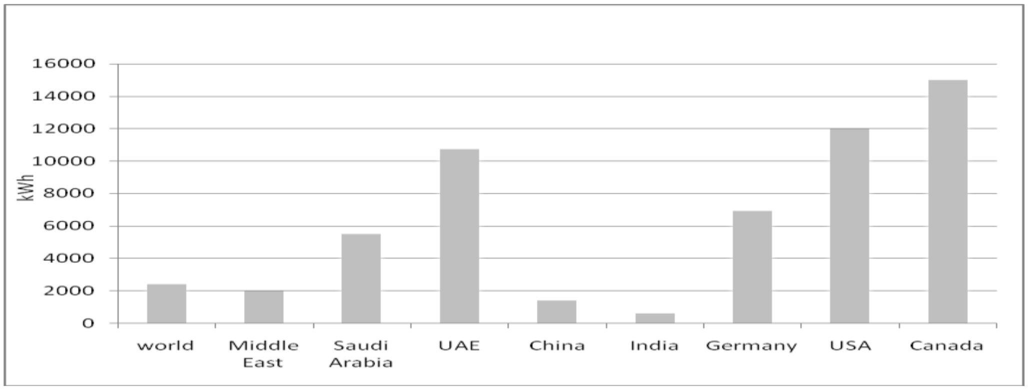


Figure 3.8 Per capita Electricity Consumption of UAE and Selected Countries (WCD 2005)

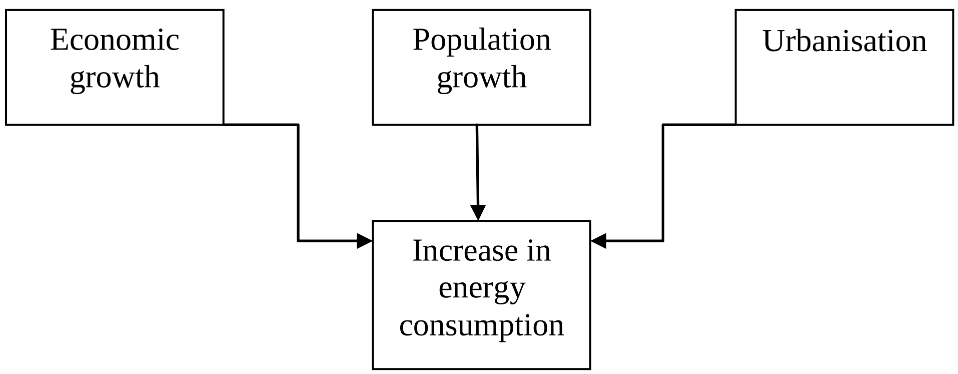


Figure 3.9 Factors Contributing to Increase in Energy Consumption in the UAE.

Figure 3.10 shows the UAE's sectoral energy consumption (EIA 2006). The residential and commercial sectors represent 16.2% and 15.1% of the total primary energy consumption respectively. The industrial sector constitutes mainly electricity generation and water desalination plants, building materials, aluminium and other small industries and consumes the highest share namely 58.4% of the total energy. The transportation sector right now consumes the lowest share (10.3%) of the overall energy consumption, but the Metro rail projects and other measures of promoting public transport services would significantly increase this figure in the future. This percentage is anticipated to double in the next decade due to predicted increase in the population (Kazim 2003).

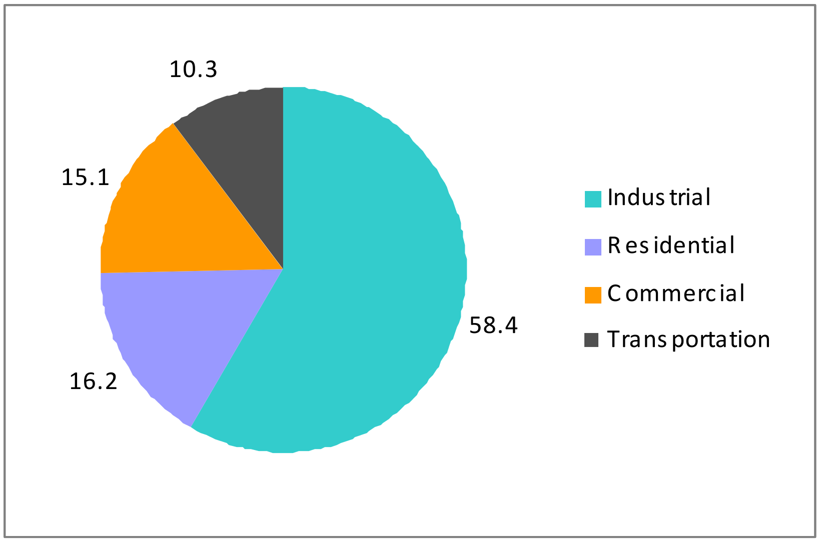


Figure 3.10 UAE's Energy Consumption – sector wise (EIA 2006); The figures shown are percentages

A recent report prepared by Department of Planning and Economy estimates that during the first three months of 2008, the UAE's inflation index for rent, electricity and water was up 18.21 % from 2007 (Gulf News, 2008b). With the cost of energy going up, the government may mandate more energy code practices in future.

Table 3.10 summarises the power capacity and expansion requirements of the other Middle Eastern countries along with that of Dubai (APICORP 2007). The domestic power tariffs vary little across the Middle East and customers in the countries examined by Middle East Economic Digest (MEED) are charged an average \$0.029 a kWh, indicating heavily subsidized services (Oliver 2003). DEWA cannot only charge a relatively high tariff, but also rely on a healthy revenue stream (Oliver 2003). Saudi Arabia has also set power tariffs to encourage non-peak power use by commercial users, even though these account for only half of overall national demand (MEES 2007).

Table 3.10 Power Capacity and Tariff Comparison of Middle Eastern Countries

Country	2006 Capacity* (GW)	Capacity Expansion* 2007-11 (GW)	Resulting Investment* 2007-11 (US$ billion)	Domestic Power Tariff per kWh** (US$)
Iran	41.5	12.0	13.2	0 to 0.141
Saudi Arabia	35.6	11.5	11.0	0.032
Egypt	24.2	7.0	7.4	0.008 to 0.041
UAE	14.8	8.7	8.3	Dubai - 0.054
				Abudhabi - 0.041
				Sharjah - 0.046
				Other Emirates – 0.041
Kuwait	11.7	4.6	4.4	0.044 to 0.114
Qatar	3.6	2.1	2.1	0.030

(*-Source:ARICORP 2007; **- Source: MEED 2007)

The region comprising of UAE, Saudi Arabia, Kuwait and Qatar will require an additional 26.9 GW of power capacity in 2007-11 and the expansion in demand is being driven by broad-based social and economic development, with rising salaries driving the take-up of domestic power use (MEES 2007). UAE, Saudi Arabia, Kuwait and Qatar are identically positioned in the power arena in the sense that expatriates accounting for a major percentage of its customer base and these countries are driven by a booming economy because of soaring oil prices. So all these economies are keen to promote energy efficient measures and lighting control is here to stay and grow in this region as a whole. Considering the future expansion requirements, UAE has to increase its capacity by more than

50% in the next 4 years and if investments are made in energy efficient schemes, it would lessen the burden on the capacity expansion.

3.7 Conclusions

This research study highlighted the prevalence and penetration of lighting control systems in Dubai with an aim of providing some insight as to how these systems will evolve in future in the region.

The following is the summary of findings from the study:

- The case studies highlight the extent and sophistication of lighting control systems.
- This research study identified that intelligent and automated lighting finds its place in almost all landmark developments in commercial and hotel projects in Dubai mainly for scene control and due to the ability to employ multiple control strategies simultaneously with a centralized intelligence. This is mainly because building owners and property developers see them as a way to promote the image of buildings or properties. The study also highlighted that the feasibility of these systems in all types of buildings and their demand will rise in future.
- The study identified that meeting the requirements of property developers –not energy saving- is the biggest demand driver of lighting control business in Dubai.
- The study observed that the objective of lighting control as an energy conservation scheme can be achieved if the government imposes tougher standards on commercial building energy usage. The adoption of these systems is already on the rise due to the recent requirements enforced by DEWA and sustainable development resolution announced by the Ruler. The increase of and curiosity towards green buildings also bear a testimony to the fact that these systems are going to be much sought after in future. The paper also has identified that the sheer amount of buzz and

activity in the construction industry is seen as an opportunity to enforce lighting power budget requirements though it will have its share of challenges that are specific to the region. Building owners will then highlight their buildings as energy efficient and justify the initial cost to their customers and lighting control can then become a standard feature in each building. The work identified that Dubai has the technology, infrastructure and most importantly, the government with a readiness and vision in place, for the automated lighting control to develop and establish as a must-have feature in each building.

- Some retrofit installations in residential buildings can give a high return on investment due to short payback period and increased energy savings. One such case study has been demonstrated for a long corridor. The government can cut back on spending on power infrastructure and the customers can pay reduced bills in addition to the hidden benefits of sustainable technology. The ever increasing energy demands of Middle Eastern countries necessitate such policies in every building. As regards to the industrial feasibility of lighting control in the residential sector of Middle Eastern countries, we estimate this industry to be fast growing in the region as a whole.
- Daylighting systems, though highlighted by most of the manufacturers in the region are adopted in few projects and there is a need for more holistic performance indicators and design procedures in daylighting systems that can be developed specific to the (hot) region, taking into account the heat gain factor.

Chapter 4

Intelligent Control Systems for Integrated Lighting Schemes

4.1 Introduction

This chapter presents the methodology regarding the design and implementation associated with the proposed scheme. The discussion starts off with the model based controller approach and the relevance to the same in the present day building scenarios. Then the general requirements of adaptive, predictive control are given which is followed by a discussion on suitable intelligent control techniques. The proposed scheme consists of and explained in two parts, the first one being the simulation model while the other is machine learner model. The final section of this chapter presents the details of hybridisation of both these models.

4.2 Control Problem in Integrated Lighting Environments

An adaptive control system is defined as the one that is capable of changing or modifying the behavior and response of an unknown plant to meet certain performance requirements. The plant in question is an interior space with Venetian blinds, light redirection louvers, blind systems, skylights, sensors, dimming ballasts, luminaires, and lamps along with corresponding actuators. The test space for the daylight-artificial light integrated scheme is very dynamic due to the environmental factors such as sky conditions, solar radiation, moving cloud cover etc., building factors such as type, window orientation, presence or absence of neighbouring buildings etc., room layout factors such as partition, irregular floor plan, configuration change, presence of furniture etc. The time-variant properties of the transparent elements in the facade also pose significant changes to the amount of daylight entering the building interior. The input-output parameters of such an environment could be exterior illuminance, daylight on window, interior illuminance, heat gain, various glare indices, indoor temperature, blind angles, artificial light settings etc.

Designing an adaptive controller for such a scheme is a complex and challenging problem. This becomes more compounded with the rapid changes of occupancy patterns and subjective nature of user wishes. Therefore, it is of paramount importance to pay attention to occupant preferences and situations in which occupant conflict can arise. Realistic modelling of human behavior is a major area of research in building systems. Occupant control actions in a building (i.e. user interactions with environmental systems for heating, cooling, ventilation, lighting, etc.) can significantly affect both indoor climate and the environmental performance of buildings (Chien and Mahdavi 2009). Nonetheless, relatively few systematic (long-term and high-resolution) efforts have been made to observe and analyse the means and patterns of such user-system interactions with building systems (Chien and Mahdavi 2009). Since daylight entering a building also brings heat along with it, the thermal comfort of the occupants can not be compromised. The visual comfort parameters such as illuminance, uniformity and glare should be synergized with the thermal comfort parameters such as Solar Heat Gain Coefficient (SHGC), Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) etc. PPD is a quantitative measure of the thermal comfort of a group of people at a particular thermal environment. The energy consumption of the overall building must be designed in such a way that the daylight penetration does not increase the cooling load of the Heating, Ventilation and Air-Conditioning (HVAC) systems during summer months and the heating load in the winter months. So the constraints for the controller are that it should contain a feedback mechanism and is intelligent enough to adjust its parameters so as to operate in an optimal manner according to the environmental and user preferences.

Such a controller design and optimisation is a complex one but the availability of abundant computing power and application of intelligent techniques have made it possible for us to realise such a system. We are interested in developing and optimising an intelligent model for controller specifically suited to the integrated lighting scheme. The next subsection reviews some of the relevant concepts associated with model based adaptive controller design and its characteristics.

4.2.1 Adaptive, Predictive Controller

The integrated lighting schemes have to contend with multi-variant, dynamic and non-linear processes impacted by geographical, environmental and occupancy factors amongst many other things. Traditional control methods such as PID do not offer satisfactory results in dealing with these processes. The manual tuning of process loops would result in issues related to productivity, safety, quality and energy in these schemes. For us to design an adaptive control scheme, the process dynamics are to be understood. For this, some form of system identification is essential.

The unknown parameters in a process model can be determined by numerically manipulating the existing mathematical model and studying the effects. Sometimes it is suitable to employ a regression method for hypothesized entities. Otherwise, if many options are available for different model forms, a best-choice method can be obtained by arriving at a cross-correlation function from input-output data. In the dayligting control scenario, we may have some uncertain process knowledge but we can not clearly identify the outcome of this knowledge with respect to the control process. Hence we assume that the process is unknown and treat it as a grey-box problem.

This particular control problem is also treated as a predictive process model that is capable of predicting the future output, based on historical information of the process as well as future input. The future system behavior is thus shown by the model so that different control scenarios can be tested to verify the corresponding output. The optimisation of such a control is to be done within a certain time frame and updated continuously online.

4.3 Simulation Model for Building Control

Simulation, over the years has become an integral part of analysis and control in the domain of building systems. The high cost of real life testing and low accuracy of empirical methods necessitate simulation in the building domain. A simulation model is used to pre-assess the performance and efficiency of the building and its components (its occupants included) in a variety of ways by analysing the individual components and processes and their interaction between them. Simulation facilitates to see what effect a parameter has in the overall target system being designed when an actual system is not available, or under construction. It can serve as a tool during the building life cycle at different stages: schematic design, final drawing, construction, commissioning, operation, control and maintenance. For an existing building, some of these stages would make use of simulation, if not all. Simulation can be employed in the following areas in analysis and design:

- Performance of energy consuming systems such as HVAC systems, alternative energy systems such as solar and daylighting systems, district heating or cooling systems etc.
- Mathematical modelling of building products, heat and mass transfer, air movement, lighting, lighting control, emergency lighting, fire alarm, acoustics, sprinkler systems etc.

- Optimisation methods, fault detection, inverse models, validation and calibration methods

- Analysis of synergistic effects between building's subsystems (such as lighting and thermal) in terms of characteristics and extent of interoperability

- Sustainable building practices and design tools and testing for implementation of codes and standards, green building requirements etc.

- Most importantly, the occupants' behavioural patterns, comfort, productivity, health, sickness and syndromes

The validation for a simulation model can be done in a variety of ways. For example, assuming a particular blind angle (control action), the average illuminance (corresponding outcome) can be verified and the assumption for input validated. A sensitivity analysis can be performed to see what all parameters (daylight illuminance, artificial light illuminance, dimmer settings, blind angle etc.) influence control outcome by keeping one parameter varying at a time while the rest are held constant. Another technique for validation is to pre-define an outcome to see what all possible control actions can result that. Figure 4.1 illustrates the flow diagram of such a simulation based lighting control approach. Though there are many ways to arrive at particular control options, two are primarily used as shown in Figure 4.2 (Mahdavi 1997).

While the Bi-directional Inference Method (BDI) involves the explicit definition of control variables (such as dimmer setting) and performance indicators (such as average illuminance, discomfort glare index), the Generate-and-Test Method (GAT) involves the rule-based generation of distinct, multiple control options. For example, BDI mechanism facilitates the derivation of required changes in the dimmer settings based on the desired illuminance level whereas GAT results are often multiple criteria evaluation on preferences.

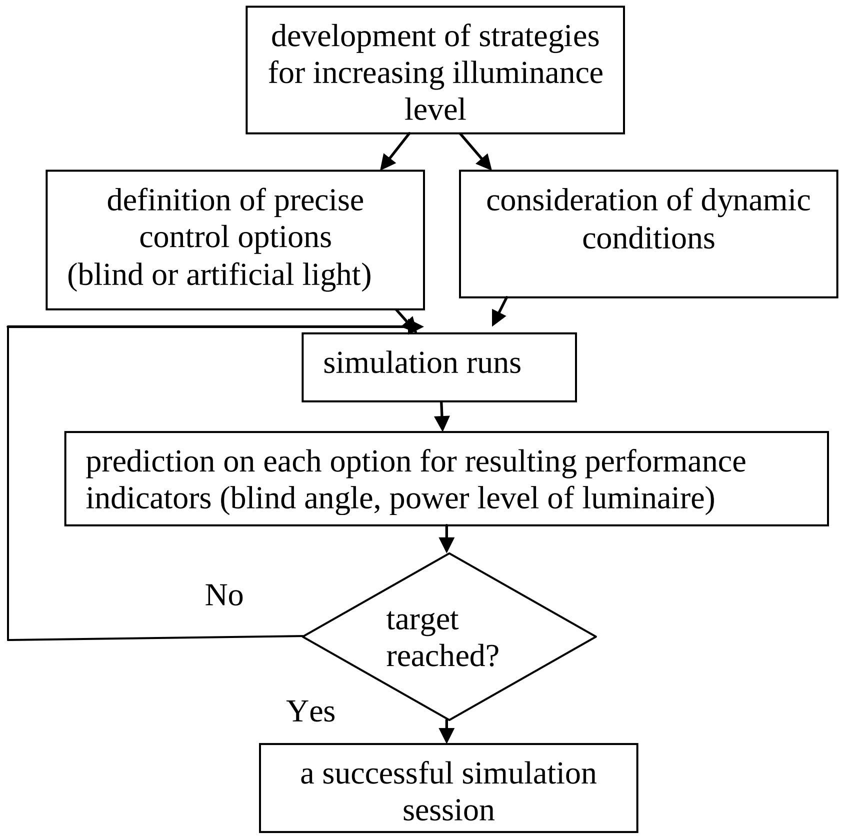


Figure 4.1 Flow Diagram of Simulation Based Lighting Control Approach

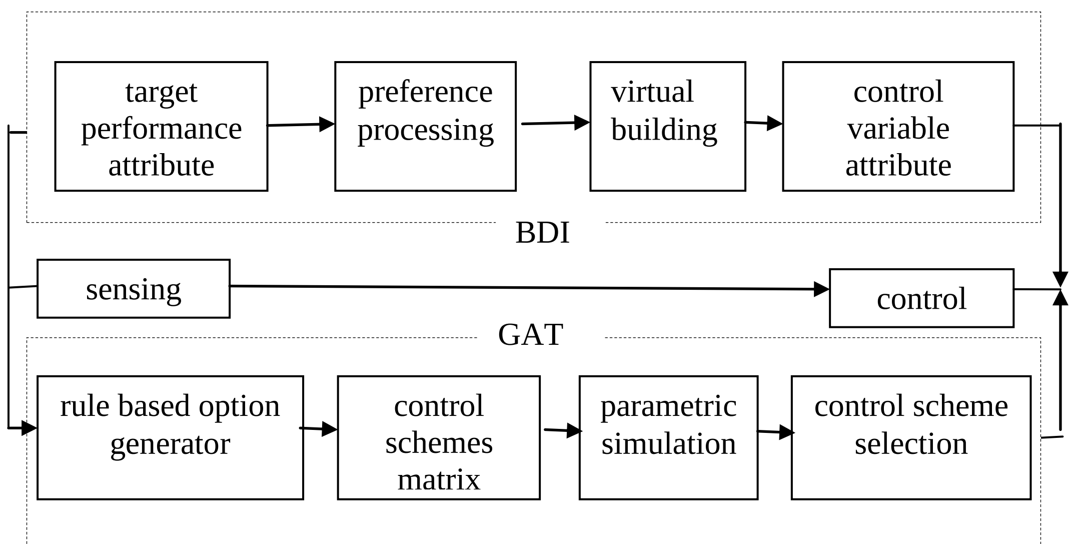


Figure 4.2 Two Approaches to Arrive at a Structured Set of Control Options

(Mahdavi 1997)

While the real building can react only to conditions such as occupancy and environmental conditions to build candidate control actions, the simulation can have an enhanced accuracy in prediction and hence better reaction to unknown and sudden conditions. The simulation model can look at the past behavior and learn to predict better and look through to the future to adapt to a variety of control options based on a predefined user preference.

4.4 Intelligent Simulation Model for Daylighting Control

The ultimate priority and challenge in a daylighting control scenario is to create a system that consumes minimum energy while providing maximum comfort to the occupant. Given restrictions that comfort conditions in the interior of the building are satisfied, it becomes obvious that the problem of energy consumption is a multidimensional one (Dounis and Caraiscos 2009). Scientists from a variety of fields have been working on this problem for a few decades now; however, essentially it remains an open issue (Dounis and Caraiscos 2009). Advances in the field of artificial intelligence have shown that the use of “intelligent techniques” for the automation of building envelope can lower energy consumption and also can keep internal living conditions in optimal range (Kristl et al. 2008).

The building domain being non-linear and complex as it is, the system model has to adapt itself to the environmental as well as user controlled variables. To ensure maximum occupant comfort, a human override option is inevitable. The model should be able to learn from its past experiences for adaption and react according to prediction. This requirement has necessitated the use of artificial intelligence techniques for thermal and visual domains. These advanced computational models can supplement or substitute actual modelling systems or procedures.

4.4.1 Limited Capabilities of Lighting Simulator

Typical drawbacks of the lighting simulation tools are a high level of complexity and long computation times, both of which have inhibited the deployment of lighting simulation in the building simulation process. If each time-step requires a computation time of many minutes, then the simulations needed for the entire season will take far too long to be practicable. Different approaches have been proposed by previous researchers to reduce the number of daylight conditions to be simulated. Daylight factor method (Tregenza 1980), interpolating between two extreme sky luminance distributions (Winkelmann and Selkowitz 1985), grouping all daylight conditions (Herkel and Pasquay 1997) and deriving all daylight coefficients from the simulation of an entire homogeneous sky (Geebelen et al. 2005) are some of the approaches that attempted solving issues associated with the computationally intensive process of lighting simulation. Normally, model predictions and the control decisions based on them should be done within a certain time frame (Chang 2000). Those simulation programs demanding heavy computation are not suitable for the control purpose unless the control state search space is dramatically reduced to limit the number of simulation sessions necessary for testing different control options (Chang 2000). The biggest computational challenge lies in time varying geometry, such as adjustable blinds and in realistic modelling of human behaviour and system control regimes.

4.4.2 Limitations of Learning Approaches

Soft computing consists of several learning paradigms such as neural networks, fuzzy set theory, genetic algorithm etc. In building control applications, soft computing applications have been proved useful as found in the literature. Table 4.1 summarises the strengths and weaknesses of each of these methodologies.

Table 4.1 Comparison between the Methodologies of Soft Computing

Methodology	Strengths	Weaknesses
Neural network	learning and adaptation	low-level computational structures, requirements of sensory data
Fuzzy set theory	applied at higher level of hierarchical control systems, reasoning and decision making through fuzzy if-then rules	not much learning capability, difficult to tune the fuzzy rules and membership functions from the training data set
Genetic algorithm	systematic random search	increased complexity due to reinforcement learning
Support vector machines	higher learning ability	model complexity should match data complexity, long learning time

Fuzzy systems can be used in control applications if sufficient knowledge about the solution is available, typically, in the form of linguistic if-then rules. But, in the case of daylighting environment, knowledge becomes very subjective due to the changing nature of geographical, environmental and occupancy patterns. The experts have concerns about structuring this knowledge. The block diagram shown in Figure 4.3 emphasises this overdependence of fuzzy controller on the knowledge base which ultimately impacts all the other basic steps of fuzzy inference process.

Neural learning, on the other hand, requires large amount of data and hence suffers from long computation times. When the system undergoes configuration changes, the neural learning requires retraining and hence becomes slow to respond and adapt. This problem necessitates an addition or supplementation of an algorithm so that the retraining occurs needing lesser memory.

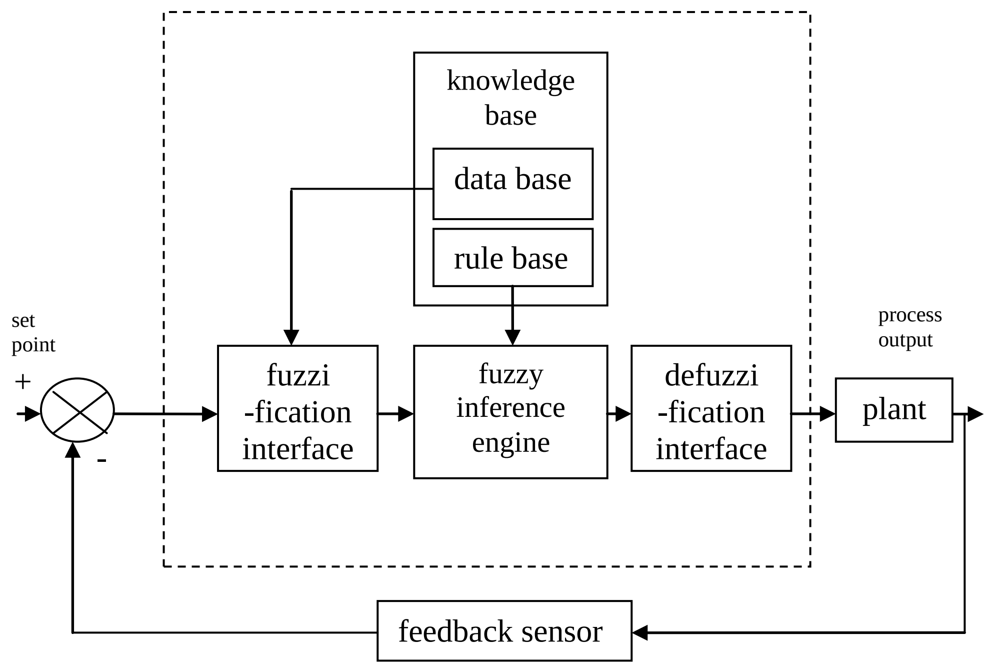


Figure 4.3 Block Diagram of a Fuzzy Logic Controller

4.5 Combining Simulation Model with Learning Techniques

In the daylighting control scenario, the complexity of the controller is a major challenge due to the non-linear and ill-defined nature of the system. Added to this is the fluctuation in occupancy and subjective nature of user preferences. If a large number of performance indicators such as average illuminance, uniformity, heat gain, glare indices, electrical power consumption etc. are to be considered for evaluation purposes, the control system has to deal with increased complexity. Combining simulation with learning can ease the burden of complex control process. Table 4.2 summarises the benefits of combining the simulation model with learning techniques.

Table 4.2 Co-operation between Simulation and Learner

Simulation	Learning
Provides prior knowledge to the learner	improves the simulator's prediction by tuning
Assists the learner in system identification of control sensitive variables	learning from the simulator's knowledge, it reduces computational complexity and time of the building control process
Reduces the large data and sensory information requirements of learner	can contribute to control search space reduction and accelerated computation, by some techniques

While the simulator acts as a source of system knowledge, the machine learner learns from the simulated data. The cooperation between the simulator model and the learner is a two way process which works to the advantage of building systems control. The prediction by the simulator is improved by learning from the past inputs and should an alternative and unexpected control scenario occur in future, the model can adapt itself better for unknown conditions when tuned online. When simulation is combined with machine learning, simulator also acts as a validation tool for the machine learning model in addition to providing the data for training. As given in Figures 4.1 and 4.2, the most reliable control option can be identified by generating and investigating the predicted outputs.

4.5.1 Suitability of ANFIS Learning for Daylighting Control

ANFIS is a hybrid approach used for the design of intelligent systems in which fuzzy logic and neural networks complement each other. The use of hybrid intelligent techniques brings to the table the advantages of tackling uncertainty, vagueness and also catering to high-dimensionality. Typically, the neural network is mixed with fuzzy inference systems (FIS) in three ways, namely cooperative, concurrent and fused. The most common architecture is the fused neuro fuzzy system (NFS) that uses neural networks ideas just to learn some internal parameters of a fixed structure (Nauck et al. 1997). The ANFIS belongs to fused NFS and it was introduced by Jang (1992) and is able to approach any linear or non linear function (universal approximator) (Jang 1993). ANFIS can represent structured knowledge and the model structure need not be known prior (Jang 1993). The synergism in ANFIS allows to incorporate human knowledge effectively, deal with imprecision and uncertainty and learn to adapt to unknown or changing environment for better performance (Jang et al. 1997).

Data emulation

The attractive features of ANFIS include: easy to implement, fast and accurate learning, strong generalization abilities, excellent explanation facilities through fuzzy rules, and easy to incorporate both linguistic and numeric knowledge for problem solving (Jang et al. 1997). ANFIS is used in this work to capture the non-linear, time varying behaviour of blind position dynamics in daylighting schemes. It is used to establish the relationship between daylight illuminance and blind control signals. The main focus is to develop a model for the design of a daylighting controller which is adaptive and robust to the hot environment. The fuzzy technique takes care of tackling uncertainty such as environmental conditions while the neural network facilitates machine learning to tune the weight matrix for the resulting blind position levels. The data based approach of ANFIS wherein the knowledge is contained within and extracted from data itself is very much applicable for illuminance level and blind position coordination because of the nonlinearity and ill-defined nature of the system due to environmental and occupancy factors.

Fine tuning of membership functions

Due to the lack of human expertise in the given problem, initial membership functions (MFs) are set up by intuition and the learning process is initiated so that a set of fuzzy if-then rules that approximate the data set can be generated. Computations in ANFIS effectively tune the membership functions so that output error is minimised. The membership functions take their final forms after training. This automatic generation of data-driven rules and parameter adjustment makes ANFIS superior to fuzzy logic. At the same time, ANFIS requires smaller number of parameters and hence converges to a control decision faster than neural networks.

Reduction of control state search space

In a building zone where there are multiple shading systems such as blinds, louvers etc., the control application has to consider numerous options for candidate control state space. From the computational point of view, an exhaustive coverage of such large search spaces may easily become infeasible for realistic applications (Mahdavi 2008). A number of approaches toward efficient operation of model-based control strategies involve search space reduction and accelerated computation via substitution of simulation engines with neural networks (Mahdavi 2004). The proposed ANFIS for blind position control has the search space dimensions significantly reduced rather than a pure back propagation method since it employs a combination of least squares method and gradient descent for updating the consequent parameters and premise parameters respectively. To achieve a desired input-output mapping, these parameters are updated according to the given training data (daylight illuminance). This kind of supervised learning employed in ANFIS is referred to as hybrid learning. Each epoch of this hybrid learning procedure has two passes, forward and backward. Updating of parameters in each pass continues till the error criterion is satisfied. The hybrid learning also cuts down the convergence time substantially (Jang 1993) and hence the control decision is arrived at faster for the resulting blind signal. A detailed discussion on hybrid learning is given in Chapter 6.

4.6 The Proposed Scheme

Conventional techniques for system analysis are not suitable for dealing with blind control systems whose positions are strongly influenced by occupant’s mood, emotions and perception. The illuminance level and blind position are typical parameters determined by human options and preferences and hence the chosen intelligent technique can model these ill-defined dynamics much better, when combined with simulation.

The block diagram representation of the proposed scheme is shown in Figure 4.4. The collection of data for the scheme is obtained from simulator because of the need to do away with the sensor dependency. By relying on sensors, the periphery of the adoptable performance criteria by which a desired control option is selected can be restricted. Also, placing sensors is not always easy and maintaining sensors could become a costly option under some situations. In a daylighting environment, the subjective parameters such as glare (which depends on occupant’s location and view angle) and heat gain (which depends on occupant’s clothing and perception, efficiency of HVAC system, amount of solar radiation etc.) can not easily be measured by sensors. The next chapter deals with simulator details and description in an elaborate manner.

The simulated data is trained by ANFIS learner which also serves as predictor. If there is any change in room configuration, environment or building systems, the error between the system output and learner’s predicted output increases and the learner is updated by retraining. The controller blocks shown in the ANFIS control scheme (Figure 4.4) are exact duplicates of each other. After the desired signal is obtained from the simulator- learner combination, the overall control options are analysed in connection with that of artificial light control.

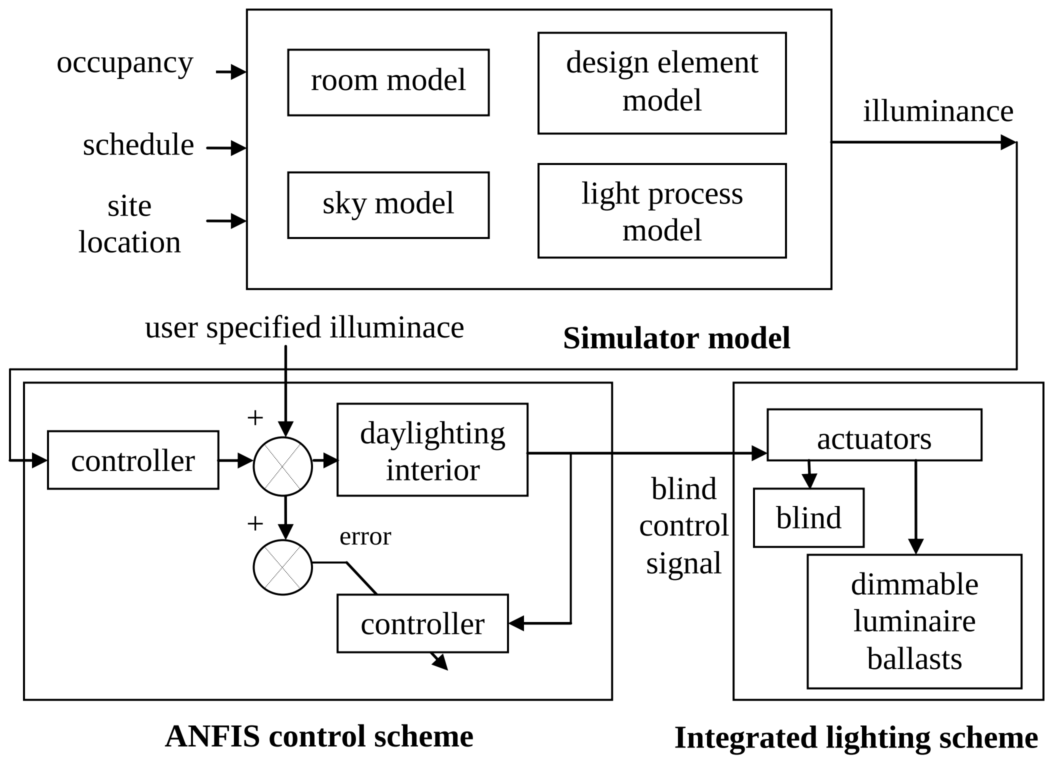


Figure 4.4 Block Diagram Representation of the Overall Scheme

The controller validation is done with two types of scenarios. The first scenario uses an algorithm that maintains optimum illuminance levels while ensuring thermal comfort of the occupants, with due consideration to the hot climate of Dubai. The second scenario combines the daylight control with artificial light settings with a strategy to reduce the dimension of control state search space when multiple luminaire and blinds are involved. Dealing the control options of artificial light separately reduces the dimension of control state search space. As stated earlier, the hybrid learning of ANFIS in itself reduces the convergence time substantially and hence such a strategy will be an effective one from the computational point of view. The actuators provide interfaces to blind controller and dimmable luminaire ballasts as shown in Figure 4.4.

The ANFIS modelling approach described in this thesis has two objectives: It provides a model that depicts the behaviour of the underlying system and the model is then used for controller design and validation. This approach is applicable to any plant for which the model structure is not known prior.

4.7 Conclusions

The daylighting schemes have to contend with multi-variant, dynamic, non-linear processes impacted by geographical, environmental and occupancy factors amongst many other things. Traditional control methods such as PID do not offer satisfactory results in dealing with these processes. The model based controller approach is proposed in which simulation is combined with machine learning to ease the burden of complex control process. The hybrid learning of ANFIS is best suited to provide intelligence to the controller so that its parameters can be adjusted for the system to operate in an optimal manner according to the environmental and user preferences.

Chapter 5

Advanced Lighting Simulation Tools

5.1 Introduction

The training data for the research work has been collected by simulation of daylight inside a building interior. This chapter introduces the requirements and issues concerned with lighting simulation tools. The two major processes of lighting simulation tools are then explained. A detailed literature on the tools available in the market is then presented. The final section demonstrates the systematic procedures of simulation with the corresponding values and parameters, adopted in the work.

Advanced lighting simulation tools are used to see how light will behave in a building. The energy consultants, engineers, lighting designers, architects and researchers form the core of the group who use these tools. There were some problems associated with these tools such as complexity and insufficient program documentation earlier. The persistent research in daylighting and energy friendly lighting systems have paved the way for sophisticated lighting tools, which predict the indoor lighting levels accurately. For designing effective lighting control systems, which responds to user inputs and environmental conditions, the advanced computer simulation softwares need to be carefully chosen. The designers constantly look for solutions to reduce the degree of complexity in the algorithms.

5.2 Requirements of Simulator

Typically a simulator in a daylight or integrated lighting scheme will have the following models in built in it. Table 5.1. summarises the details.

Table 5.1 Simulator's Internal Models

Models	Details
Sky model	for daylighting scheme only; Different CIE sky conditions such as overcast, clear etc. are accommodated
Process model	for light process; radiosity and ray tracing methods used
Room model	for incorporating different room configurations and geometry
Design element model	for specifying shading devices such as window blinds, louvers, luminaries, furniture objects, door, pillar, sensors etc.
Occupancy model	to define lunch breaks for people and to create, record, interpret and analyse occupancy pattern of the given space

Emergency lighting, outdoor lighting are some optional features available with simulators. Some simulator programmes will have additional module for energy calculations and validation. The challenges associated with energy simulation are dealt with in the subsequent section. Other optional features of simulator are solar diagrams, insolation, solar altitude graph etc. which give a better perspective of how daylight behaves within the room. Some simulators will also have a indoor temperature model which can help determine whether daylight availability within the room is in agreement with the thermal comfort of the occupants or not. Models for incorporating weather data, solar radiation, wind speed, external illuminance etc. can be a part of some simulation programmes by which the users can analyse the thermal comfort bands on a zonal level along with the daylight process model.

5.2.1 Sky Model

In designing daylit buildings, the daylight predictions and calculations are the basic prerequisites to predetermine design consequences or to create desired ergonomic conditions in interiors. For this, equivalent exterior conditions are to be assumed or standardized. Thus the standard sky conditions such as clear (CIE

1973) and overcast (CIE 1990) were created and defined by Commission Internationale de L′Eclairage using empirical formulae. Though these sky standards do not have components for meteorological data of sunlight or cloud cover, they provide a sufficient reference for sky luminance distribution. Dubai being predominantly lit with a clear sky for most part of the year, these models are relevant to this work.

Since the external illuminance available and daylight on window are directly dependent on these assumed sky standards, they impact not only simple luminance calculation but also the following mechanisms: (i) Evaluation of visual comfort parameters such as glare (ii) Design of objects such as windows and skylights taking heat gain calculations into account (iii) Assessment and comparison of energy performance of buildings located in different climatic regions and (iv) Measurement of daylight illuminance in real buildings when they are up. During different times of the day within the same location, as well as at different climatic regions, the insolation conditions, cloud cover, turbidity and sky luminance vary in dynamic patterns. The basic sky standards attempt to characterize this widely varying sky pattern for the purpose of evaluation towards creating energy-friendly and visually comfortable building interiors.

5.2.2 Room Model

The room model consists of information about room geometry, pillar, partition, door, furniture, the placement and size of windows as well as the physical properties of room components such as reflectance and transmittance. In a daylighting scheme, it can also have provision for sensors and in an integrated scheme, for luminaires. The luminaire library of various manufacturers that comes along with the simulation software can help choose the wattage and number of devices needed for a given room for an adequate and glare-free illumination. The complex room geometry and configuration can be created by means of surfaces and blocks and multi room capability entails a designer to handle many such rooms in a single project. Typically a three dimensional room is built in a Computer Aided Design (CAD) package and exported into lighting software for lighting-related calculations. This room serves as a platform for system's internal representation and hence sometimes simply referred to as 'model'. The designer can then input surface, geometrical, date and time and various sky conditions.

5.2.3 Design Element Model

The room elements such as window, door, skylight and picture form part of this model. If we want to position the window, we have to choose the wall on which it is likely to appear and for the skylight, the ceiling should be chosen. Basic objects such as cube, pillar, partitioning wall and a working surface such as a desk or a drawing board can also be specified and defined using design element model. Furniture objects can be placed into the room interior by importing from the standard library. Highly intricate and detailed furniture are made up of large amounts of individual elements. If the room consists of a lot of such elements, the computing time can become very high and hence the hidden or unseen portions of such type of furniture can be removed after creation. The three dimensional (3D) objects such as trees or plants can also be included in the room model. The types, properties and placement of these 3D objects can be custom-designed. In some lighting simulation tools, there is provision for adding sensors and motion detectors to the model. The lamp and luminaire type can be chosen from a standard library and imported into the project. Some light simulation tools support large volume of manufacturer's information on luminaire using which the colour impact of lamps can even be visualised. We can see the effect of colour temperatures of lamp and colour filters in a given room's interior. The alignment and arrangement of luminaire can be done according to user's wish. Even escape route for emergency lighting can also be included in a project.

Light process model

There is a separate section devoted to light process models in which the major challenge is the trade-off between computational storage and computational time.

5.3 Various Issues in Lighting Simulation

This section focuses on various issues connected with lighting simulation. The next subsection is applicable only to daylighting simulation.

5.3.1 Issues in Modeling Sky

When modeling sky, the variability of daylight presents a challenge along with the calculation of interior light, solar gain and glare. As explained in chapter 2, a part of the sky component of light reaching a given space can be diffused or reflected by neighbouring buildings or some other objects before coming indoors.

The standard sky models such as clear and overcast alone can not describe sky luminance conditions for all locations. To accommodate the worldwide sky conditions, for the prediction of daylight in buildings, models which can be universally applied are being developed. The International Daylight Measurement Programme (IDMP) has stimulated wide research activities in daylighting measurement analysis and modelling. The data from luminance measurements from the IDMP are used to develop modelling strategies which have been applied and tested in a proven internationally used computer program. These research activities contribute towards the development of sky modelling strategies for the whole sky spectrum under real conditions and their universal applicability by providing a process in which local sky models can be created in computerised terms.

Figure 5.1 illustrates the various phases of these research efforts. BRE average sky (Littlefair 1981), mean sky (Nakamura and Oki 1986), intermediate sky (Nakamura et al. 1987) and Harrison model (Harrison 1991) were developed which became useful for some locations in the world.

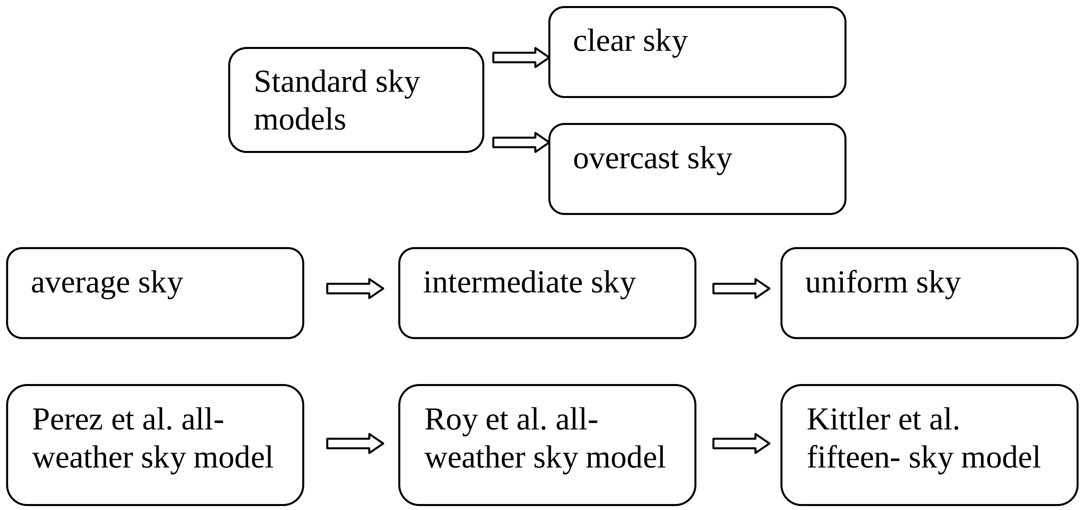


Figure 5.1 Evolution of Sky Models

Perez et al. (1993) proposed an all-weather sky model that was derived from CIE clear sky and Perez model required hourly time series of direct and diffuse irradiance values as inputs. Julian and Hayman (1995) have presented a study on the reliability of existing CIE sky models. A new approach to modeling sky luminance was defined by Roy et al. (1995) and the authors claimed this approach could be used to accurately represent sky luminance characteristics under all sky conditions. The development of these methodologies are for the inclusion of efficient representational formats for use with existing computer software or software packages and for the comparison and validation of existing analytical sky models using measured data and the representational formats (Roy et al. 1995). Kittler et al. (1997) have defined a new range of sky luminance distributions for overcast, partly cloudy and clear sky types of each five amounting to a total of fifteen sky types. Their main aim was to develop a world-wide comparability and mutual proportion of sunlight and skylight under the same turbidity conditions and to find out the significance or importance of different sky types, their range and frequency of occurrence in relation to insolation conditions, seasonal and weather changes.

Because actual sky-luminance distribution data are available only for a handful of locations (Muneer et al. 2003) the reliability and accuracy in estimation of luminances is a major area of research activity happening in daylighting systems. Hayman (2003) discussed errors associated with techniques of data gathering and measurement accuracy with examples and remarked that the extension of daylight measurement in tropical regions will not be immune from these potential sources of error even with superficially static daylight climates. Also the author noted that some variables such as cloud cover and distribution have been difficult to measure and hence have largely been ignored in sky model calculations. Furthermore, data that has been collected has limitations on its accuracy (Hayman 2003).

Chirarattananon et al. (2003) developed an illuminance and irradiance models for tropical region from the measurement records at a station in Thailand and argued that the tropical sky's dynamics pose unique challenges some of which are to still to be accommodated in modelling. For example, even a completely overcast sky in the tropics will have variable patch clouds whose daylight information will be different for a window located at a particular orientation. To facilitate the creation of sky luminance distributions of real occurring skies, Mardaljevic (1995) has advocated the use of sky scanners. Sky scanners are not affordable at all locations. Sky scanner data are rare and generally not publicly available (Reinhart and Anderson 2006). This scarcity of sky scanner data forces most daylight simulators to use a sky model as a starting point of their simulations (Reinhart and Anderson 2006). Spasojevic and Mahdavi (2007) have demonstrated that sky luminance mapping with digital photography can provide an alternative to sky scanners in these locations. However this approach requires calibration since the camera is not a photometric device.

Mahdavi (2008) demonstrated the use of digital camera with a fish-eye converter for obtaining sky luminance distribution maps of various real occouring skies.

Modeling the effect of cloud conditions that are not uniform and adjacent structures are issues to be resolved as well. The adjoining structures and objects such as trees reflect light and hence can affect the amount of daylight entering a space and accommodating these objects in the model is a significant step towards refinement of daylighting design of buildings.

5.3.2 Issues Related to Simulation Software

As will be explained at length in section 5.5, the space and time complexities associated with light processes namely radiosity and ray tracing also pose some issues related to simulation. For example, ray tracing softwares takes too long a time since the law of physics demand complex calculations for precision. Typically, predictions by the model and the control decision based on them should be done within a reasonable time limit since the entire control process is very dynamic. Hence those simulation softwares that take too much time for each simulation run are too impractical for control purposes unless the control state search space is reduced. Combining simulation with machine learning in this research work is a solution to tackle this issue as demonstrated in the next chapter. Today's computers have very large computing power and this aspect also alleviates this particular issue.

Rendering is another important feature that is to be done properly when modeling daylight. Rendering is the process of generating an image from a model described in three-dimensional objects. Sunlight and skylight are rarely rendered correctly in computer graphics because of high computational expense and because precise atmospheric data is rarely available as explained earlier.

5.3.3 Issues in Validation

The lighting simulation softwares require large amount of empirical data for validation. This is a very inconvenient, cumbersome, costly and complex process. Lighting simulation is normally done to arrive at the most favourable control scenario in terms of optimum energy usage with lighting and thermal comfort. The control action taken (such as change of a blind angle) and the corresponding output (such as indoor illuminance value) can be verified only if the actual scenario is available in a real building under operation. So a complete perspective on building usage and the corresponding data of real buildings are prerequisites for simulation validation.

5.3.4 Issues in Energy Simulation

With the advent of Building Management Systems (BMS), the issues related to energy simulation are somewhat resolved. But when it comes to dedicated lighting control systems, energy simulation is still a complex process in which organisation, management, analysis and validation of lighting energy data sets are concerns to be addressed. The maintenance and calibration of energy equipments remain an issue as always.

The complexity of knowledge awareness of lighting levels at different points in a given space and the varying degree of perception of light by occupants and design of a controller makes it very challenging for subjecting to advanced computer applications. The ongoing research in simulation tools attempt to solve these issues, at the same time optimising the power of software tools for simulation.

5.4 Lighting Simulation Softwares

There are several softwares that are available in the market for lighting simulation. Built by companies promoting daylighting and integrated lighting, each of these softwares cater to a particular application and hence has its own benefits. A summary of the list of softwares that are currently available is given in Table 5.2 and by no means, this list is complete.

Table 5.2 List of Lighting Simulation Softwares

Name of software	Light Process	Details/ Salient Features
RADIANCE	Ray tracing	global illumination using Monte Carlo method
Relux	RADIANCE engine supplemented with radiosity techniques	in built with ReluxCAD, Energy calculation by EN15193 and DIN18599 standards
ADELINE	radiosity	ADELINE contains SCRIBE-MODELLER as CAD interface, the lighting tools SUPERLITE and RADIANCE
DIAlux	Integrated ray tracing	emergency lighting according to EN1838, Energy evaluation according to DIN V18599 and EN15899
Lightscape	radiosity	made by Autodesk, possible to change viewpoints without recalculating the scene
Inspirer	bi-directional Monte Carlo ray tracing method	appearance of aerospace objects and automobiles in outdoor spaces under clear or cloudy sky can be simulated
Rayfront	ray tracing	makes use of radiance engine and has interfaces for enhancement of geometry and complexity issues

Name of software	Light Process	Details/ Salient Features
3D studioMAX	ray tracing	improved rendering and integration with other toolkits for enhancements
Lumen-Micro	Ray tracing	product library of over 70 manufacturers' luminaire data
Superlite	radiosity	quick on numerical feedback on a given design on aperture, reflectance and glazing
Specter	bi-directional Monte Carlo ray tracing method	accurate simulation results for models involving arbitrary long sequences of specular and diffuse inter-reflections
ESP vision	Ray tracing	simulated camera and rendering features
Light works	Ray tracing	progressive rendering gives immediate feedback of the final image with a fast preview of the lighting and materials within the scene
DAYSIM	Ray tracing	precise sky modeling taking into account the sun position and real sky distribution

5.5 Light Processes in Simulation Softwares

There are two methods namely radiosity and ray tracing, that are widely used for predicting internal luminance calculation for both artificial and daylighting conditions.

The major drawbacks of these techniques are having to compromise between computational storage and computational time. The designers believe that the radiosity method is suitable for diffuse surfaces while ray tracing is preferred to specular surfaces for accurate illuminance calculation. The computational storage is a concern in the case of radiosity and the computation time is critical in ray tracing. However, the classical algorithms in both these cases have given way to improved simulation tools and hence both these methods are now being used effectively. In fact, they are complementary methods. Relux uses ray tracing engine combined with radiosity features for photo-realistic images. The following section deals with the physics behind each of these two methods.

5.5.1 Ray Tracing Method

The ray tracing method is a popular rendering method in which images are produced with photo realistic quality. It is based on Monte Carlo method to calculate the illuminance distribution in 3D models. It is particularly useful where complex and accurate rendering of shadows, refraction or reflection are main requirements. The angle of incidence equals angle of reflection; this law of optics is used in final rendering of ray traced work in which multiple rays are generally shot for each pixel and traced not just to the first object of intersection, but rather through a number of sequential bounces. Once the ray encounters a light source, or once a set limiting number of bounces have been evaluated, the surface illumination at that final point is evaluated and also the changes along the way through the various bounces evaluated to estimate a value observed at that point of view. The process is repeated for each sample and each pixel. In some cases, at each point of intersection, multiple rays can be spawned.

Ray tracing produces some of the most realistic images. The specular surfaces, transparent and translucent surfaces can be effectively modeled. As a brute-force method, ray tracing may be too slow to consider real time modeling but it has powerful special effect sequences and photo realistic footages. If the number of calculations needed is reduced, the ray tracing features become more effective.

On the flip side, realistic shadows are difficult to image in ray tracing method. The reflection models used in ray tracing are usually empirical and approximate. They are often chosen based on subjective results rather than physics laws of energy equilibrium unlike radiosity method. The computationally intensive process of recursively tracing rays for each pixel on a screen with reasonable resolution can make the method very slow. This is because each change in the viewing transformation requires that the entire ray tracing process be repeated to render the new view.

5.5.2 Radiosity Method

The classic radiosity algorithm sees all surfaces as Lambertian diffuse surfaces and hence radiosity is readily made for diffuse surfaces. As explained in chapter 4, the long term seasonal or annual prediction of daylight availability would need several thousand separate luminous sky conditions assuming each time-step of daylight simulation takes several minutes. For these long time simulations, Geebelen et al. (2005) have presented two computation techniques that could be incorporated into any radiosity algorithm resulting in reduction of computation times to the order of seconds.

The radiosity method is based on global illumination method in which the light that reaches an object by reflection from or transmission through other objects in the scene is also considered. That is directly illuminated surfaces act as indirect light sources for other surfaces, thus producing an ambience-enhanced simulation. The radiosity model is based on laws of conservation of energy. The core of the radiosity algorithm is the form factor. The radiosity simulation is run in three steps: computing the form factors, inverting the form factor and reflectance based coefficient matrix and multiplying the inverse matrix with the emittance matrix. In advanced simulations, recursive, finite element algorithms bounce the light back and forth between surfaces in the model, until some recursion counter reaches a value. Thus the colouring of one surface impacts the adjacent surface and vice versa.

The complex objects are slow to be simulated because of the presence of recursive techniques and they may be replaced by identical simpler objects. Radiosity can also be used where the contribution from complex objects has to be negligible in a scene. Illuminance modeling is decoupled from scan conversion and rendering in the radiosity method. The radiosity method offers powerful rendering features that can be produced real time.

The next section looks at some of the popular work done in the field of lighting simulation tools and their major contributions.

5.6 Previous Work in Lighting Simulation Softwares

RADIANCE is a stochastic, deterministic backward ray tracing simulation engine developed by Ward, at Lawrence Berkeley National Laboratory (Ward and Shakespeare 1998). The RADIANCE software is immensely popular among the lighting experts for estimating indoor luminance for designing and analysing the efficiency of daylighting systems and lighting technologies. RADIANCE was originally written by Greg Ward in C and it runs on UNIX, Linux and Windows platforms. It also implements global illumination using Monte Carlo method to a sample light falling on a point, combining the powerful features for simulation. Invoked globally, the light that reaches an object by reflection from or transmission through other objects in the scene environmental is also considered. The result is a photo realistic picture with computationally intensive algorithm. The theory that the interactivity is sacrificed for photorealism holds good only for classical ray tracing techniques.

After the creation of a three dimensional model in AUTOCAD version 14 (computer aided design software), the same is imported into lighting software for daylighting calculation. The designer can also then input surface, geometrical, date and time and various sky conditions. Some versions take the input of user defined materials, glazings, luminaries and furnishings. We can also create an abstract human figure or position windows at a wall. Once the model is complete, the analysis parameters such as camera views or reference point calculations, building orientation and zone of interest are defined. Then the image can be rendered using the simulation menu commands that initiate the export of geometry and analysis parameters. In addition to luminance calculations, glare calculations can also be performed to analyse the occupant comfort. The RADIANCE software also has powerful graphic editors, image analysers and library wizards for clear and interactive simulation.

Mardaljevic (1999) in his Ph.D. thesis concluded that RADIANCE was able to predict internal illuminances to a high degree of accuracy for a wide range of actual sky conditions. Mardaljevic (2000) implemented the concept of daylight coefficients into the RADIANCE simulation environment and concluded that future research should concentrate on interpreting and applying the annual daylighting profiles effectively. Reinhart and Herkel (2000) carried out a performance evaluation concerning accuracy and simulation times for six RADIANCE -based simulation algorithms namely, ADELINE, ESP-R, a daylight coefficient approach, a brute-force approach, classified weather data and DAYSIM and concluded that daylight factor method outperformed all other daylight simulation methods. RADIANCE and Lightscape simulation engines were tested by Ng et al. (2001) for CIE overcast sky conditions in an urban setting in Hong Kong.

An article by Mardaljevic (2004) on the assumptions commonly made in validation studies of lighting simulation programs concluded that one has to carefully watch the external overcast sky conditions while making measurements using CIE overcast sky for program validation. The article also discussed simulation errors arising from choosing incorrect reflectance values for obstructing facades. Development and validation of a RADIANCE model for translucent panels was described in Reinhart and Anderson (2006). If multiple sky conditions are to be considered, RADIANCE can be combined with a daylight coefficient approach to speed up the calculation without any significant penalty in the accuracy of simulation (Reinhart and Anderson 2006). The authors measured over 120,000 desktop and ceiling illuminances under 24,000 different sky conditions and compared to the simulation results using Perez sky model and a RADIANCE based daylight coefficient approach. ADELINE and RADIANCE were tested by Galasiu and Atif (2002). With reference to Dubai as a geographic location, the RADIANCE program was used to evaluate the lighting performance of the three daylighting systems under clear sky conditions and on-site measurements were also conducted to validate the simulations (Al Nuaimi and Beltran 2007).

Improvements and refinements in RADIANCE happened due to the researchers wanting to achieve photo-realistic images with ray tracers. DAYSIM is another RADIANCE based algorithm which uses hourly climatic data files to calculate illuminance according to a precise sky modeling taking into account the sun position and real sky distribution (Reinhart and Walkenhorst 2001). DAYSIM would require several thousand simulations if annual data is to be collected. Hence for a practical solution, DAYSIM uses RADIANCE engine with a daylight co-efficient approach. DAYSIM has a user behavior control model called Lightswitch which can be used to estimate energy saving potential of an occupancy sensor when compared to normal wall switch (Reinhart 2004). This model has occupancy profiles based on behavioral studies conducted in the western world and annual luminance profiles, inbuilt into it.

Roisin et al. (2008), in their article have reported the use of DAYSIM for calculating daylight illuminance for each daylight sensor location in the room and DIAlux software for artificial light simulation for four luminaires in two rows. The daylight simulations were done for every five minutes, over the whole year. Doulos et al. (2008) have used DAYSIM to test the measured data for electronic dimming ballasts to quantify energy savings and the subsequent payback period.

Superlite was used by Gugliermetti and Bisegna (2003) to develop and compare simple calculation procedures to be used in building energy analysis for a quick assessment of minimum illuminance on the working plane, in office spaces equipped with natural and artificial light control systems and external shading devices. A comparison between ray tracing software (RADIANCE) and radioisty (Lightscape) was done by Tsangrassoulis and Bourdakis (2003) for the prediction of daylight levels in atria. Huang et al. (2008) have formulated a scalable lighting simulation tool for integrated building design in which Radiance, Lightscape and EnergyPlus softwares were analysed. Reinhart and Fitz (2006) have conducted a survey on the current use of daylight simulations in building design in which it was found that the participants named 42 simulation programs that they routinely used out of which over 50% programme selections were for tools that use the RADIANCE simulation engine, revealing the programme's predominance within the daylight simulation community.

5.6.1 Previous Work with Relux and Its Features

This work uses Relux Professional 2004 (Relux Pro 2004) software for calculating internal illuminance values at the task surface. This section looks at the works that have used Relux and see what they have commented about the software. Relux, according to its manufacturer, has its calculation engine based on RADIANCE software which uses ray tracing for producing images of photo-realistic quality. It also combines radiosity techniques. Relux has an extensive luminaire library which houses plenty of manufacturers' luminaire data and details.

Maamari et al. (2006) have done an extensive application of CIE test cases to assess the accuracy of two lighting simulation softwares, Lightscape and Relux Pro 2004 and the authors declared that Relux professional (pro) is capable of modeling indoor illuminances with a high accuracy when tested for 32 different scenarios covering direct daylighting, direct artificial lighting, diffuse reflections and inter reflections. Some of their results are presented here for emphasising Relux's ability of accurate simulation. Maamari et al. (2006) report strongly in favour of Relux Pro 2004 in the following areas:

1) Daylight luminous flux conservation in a daylight simulation between an external luminance field and the internal space through an unglazed aperture; The simulation results show good flux conservation.

2) Directional transmittance of clear glass; Relux accounts for angular transmission effect but underestimation is observed when compared with analytical solution.

3) Direct daylighting – glazed and unglazed opening; Relux results show a good agreement with analytical reference for the floor points.

4) Direct daylighting with external mask; This has a considerable influence on the indoor illuminance distribution of the building. Relux was able to simulate the influence of the 6 m external vertical mask under the CIE clear sky with an acceptable accuracy.

5) Computing the light reflection over diffuse surfaces; Relux results show a good agreement with analytical reference for the 50 cm x 50 cm diffusing surface.

6) To simulate the influence of an obstruction to a diffuse reflection; Relux predicted this accurately.

7) Handling diffuse inter-reflections; Relux slightly underestimated inter-reflections for reflectance values above 0.7, however, it should be noted that such high reflectance values are rarely present in real world scenarios.

When compared with three other daylighting softwares Desktop Radiance, Rayfront and Lightscape, Relux is the most adequate for architect's use (Christakou and David 2005). It has all the conditions and capacity to support the diverse phases of the architecture project (Christakou and David 2005). Bragança and Almeida (2004) have used Relux for the natural lighting evaluation for their project and reported its merits. Using Relux vision software, Linhart and Scartezzini (2007) presented a computer model of a Singapore office room equipped with an anidolic integrated ceiling and calculated daylight autonomies. Doulos et al. (2005) have compared Relux, SPOT and DAYSIM softwares and reported that Relux calculations are extremely fast while SPOT and DAYSIM calculations are computationally expensive. Because of all the above-mentioned powerful features, Relux simulation was used to obtain the training data in this work.

5.7 Data Collection from Simulation

Relux Pro 2004 is a light calculation program based on the solid angle projection procedure for the calculation of the following:

- Artificial light according to the standard DIN 5035 > EN 12264
- Daylight as per DIN 5034 (DIN 1983) to diffused or clear sky
- Artificial and daylight combined
- Insolation
- Luminaire efficiency
- Energy saving potential of artificial light by the use of daylight
- Calculation of the external illumination
- Street lighting as per DIN 5044 > EN 13201)

Relux Pro can display output in anyone of the following forms: Illuminance on the reference plane in the form of a table, room's floor plan, 3D luminance distribution, isoline representation on the reference plane, pseudo colour diagrams or isolux on the reference plane, 3D representation of the light distribution and 3D view.

The test space for daylighting is very dynamic because of the environmental factors such as sky conditions, cloud cover and solar radiation, building factors such as type, window orientation, neighbouring buildings etc., room layout factors such as partition, irregular floor plan, configuration change, presence of furniture etc. along with occupancy fluctuation. To create a model for daylighting calculations, first we have to specify the project location by entering the geographical longitude and latitude along with the corresponding time zone. It is also possible to make allowance for daylight saving time and the start and end of daylight saving time. The simulation site information pertaining to our work is shown in Table 5.3.

Table 5.3 Location and Daylighting Data of the Project

Latitude	25.16° N
Longitude	55.15° E
Elevation	5 m, 16'
Time	GMT +4.00 hours
Sky Luminance (Yannas 2007)	
Annual Mean	25,000 lux
December to March (mild)	Cloudy to clear sky – up to 80 000 lux
November and April (warm)	Clear sky – up to 80 000 lux
May to October (hot)	Clear sky – up to 107 500 lux

The ground floor wing-A block of BITS, Pilani Dubai situated at Dubai International Academic City was taken as test space and the floor plan of the same was generated in ReluxCAD software (Refer to Figure 5.2). An L-shaped geometry of the office block at the university was considered for room model and the location for Dubai was specified with longitude 55.15° E and latitude 25.16° N and the time zone was entered. The multi room feature allows us to administer all relevant scenes in a single project. The north angle shows the orientation of the room compared with geographic north corresponding to the project and this alignment is important for daylighting calculations. The north angle is shown in the floor plan, Figure 5.2.

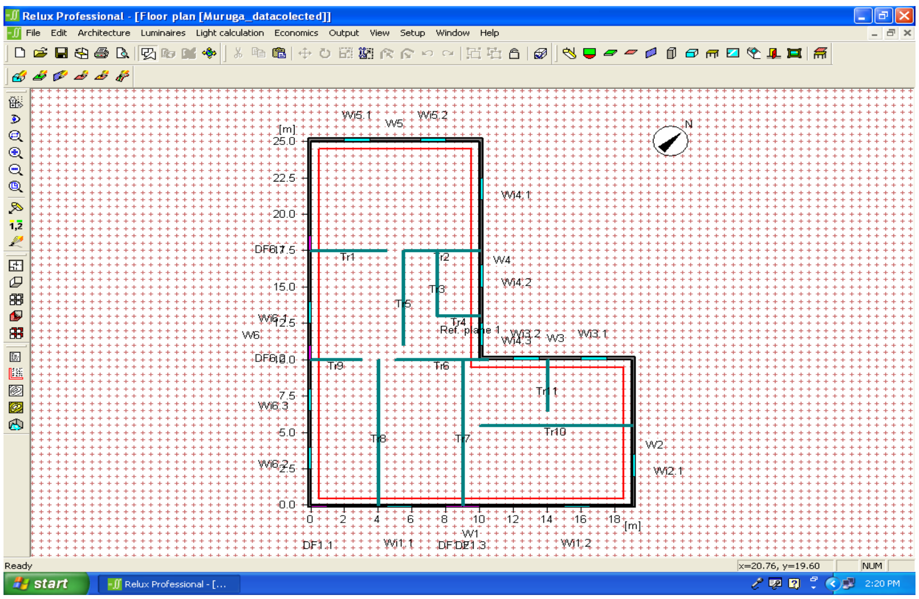


Figure 5.2 Floor Plan of the Building Zone Simulated

We can also specify the height of the reference plane and the offset (i.e.) the distance between the reference plane and the wall. The height of the reference plane was kept at the default value of 0.75 m. In the case of windows, transmittance is specified. The dirtying of the window is accounted by pollution factor and the value 1 corresponds to no pollution and 0.9 is the default value. For highly industrialized areas, a value of 0.7 is recommended for pollution factor. For partitioning of the window, 1 corresponds to no partitioning and 0.9 is the standard value. A partition wall is defined with a default thickness of 10 cm. For doors, pictures and windows, the option multiple placement in a row can be used sometimes. For all the basic objects such as cube, working surface, pillar and partition wall, if the element is ‘locked’, the same can not be edited or moved and a ‘hidden’ element can not be seen in floor plan but accounted for calculations, if any. It is possible to include the surface for calculation by means of programming using ‘extended tab’ option.

For the floor, ceiling, wall, door and windows, the surface properties were specified as given in Table 5.4. The colours (reflectances) and textures of surfaces of each object impacts the lighting quality and hence these material properties have to be chosen realistically. The texture properties can be varied by means of colour, contrast, saturation and brightness. The height to width ratio of the texture should correspond with the height to width ratio of the surface to which it belongs, failing which the texture would look distorted.

Table 5.4 Design Parameters Considered for the Test Space

Structural Properties	Specification
Reference plane	0.75 m
Offset to wall	0.5 m
Floor height	3.5 m
Optical Properties	
Ceiling	80% diffuse reflectance
Walls	65% diffuse reflectance
Floor	20% diffuse reflectance
Door	40% diffuse reflectance
Window frame & door frame	80% diffuse reflectance
Window	75% reflectance
Glazing	40% visible transmittance, double glazed

We define task area by compiling a measuring surface and allocating to individual workplaces. The working surface has two active sides which are seen as surfaces in the 3D view. Both isolines and illuminance outputs can be shown on each of these sides. A typical working surface is a desk and the default value for the height of the working surface is 0.02 m. The 3D room view can be seen in Figure 5.3.

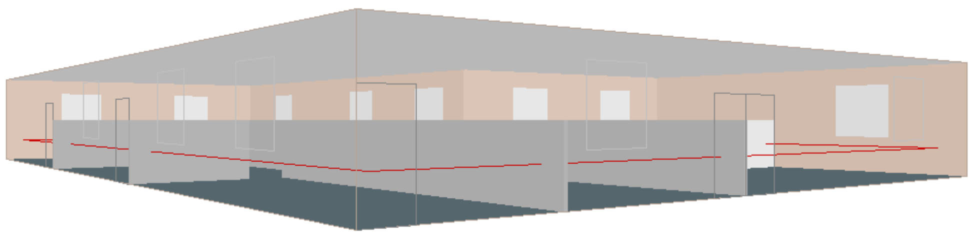


Figure 5.3 3D Representation of the Model (variable view)

5.7.1 Daylight Calculations

Relux uses DIN 5043 standard for calculating daylight factors, given in percentages as shown below.

$$D = \frac{E_i}{E_a} * 100 \tag{5.1}$$

where E_i is the horizontal illuminance (in lux) at the point of interest in the given interior while E_a is the horizontal outdoor illuminance with a uniformly overcast sky. Relux also calculates the resultant luminance for the uniformly overcast sky to DIN 5043. Typically, daylight calculations can yield outputs such as interior illuminance, interior luminance, daylight factor, 3D room view, electric lighting use, glare indices, daylight autonomy etc. Daylight calculations are specified in three steps as shown in Table 5.5.

Table 5.5 Daylight Calculation Steps in Relux

Step	Processes	Sub-processes	Options
1	Daylight calculation	precision	only direct fraction, low indirect fraction, average indirect fraction, high indirect fraction
		raster	standard, extended
		sky	overcast sky and clear sky according to CIE
		miscellaneous	consider luminous shadows, save results after calculation
2	Measuring areas/ glare rating	grid interval	reference plane, environment
		glare rating observer	position, direction, angle of picture, step size
3	Schedule	date, time	

Precision is a measure of the number of inter-reflected components defined in image generation. In Relux, we can choose any one of the four settings namely, only-direct-fraction, low indirect fraction, average indirect fraction and high indirect fraction. When the option of higher indirect fraction is chosen, the number of inter-reflections required for the calculation also increases, thereby lengthening the computing time. But a higher indirect fraction would also give the most accurate results. The software tool recommends a particular setting depending on the chosen room model and luminaire combinations involved in a scene. The only-direct-fraction can be selected for exterior projects such as pitches at the playing fields. The low indirect fraction is used when the number of inter-reflected components does not have much influence on the task illuminance levels, such as when performing calculations for a big hall with little wall surface and for rooms with large window spaces. The high indirect fraction is necessary for luminaires involving a high indirect component and for diffuse reflection tests.

The standard mode of precision for daylighting calculation is done by average indirect fraction and the same has been specified in our project. This mode of calculation with an average number of inter-reflections is sufficiently accurate for control applications and suitable for the same due to the reasonable amount of computing time involved.

Raster intervals on the room surfaces and surfaces for structural elements are then specified. The raster spacing for the measuring areas is set on the measuring areas/glare assessment index card (as given in step 2 in Table 5.5). The dynamic raster option improves the results by working out the luminous fluxes and illuminance gradients when the calculation is under progress. Then the program calculates the areas requiring additional raster points. However, this option increases the computing time required for calculation. The date and time field is to be entered so that the solar altitude for a particular location can be input from which the resultant luminance in the sky can be specified. The raster points thus generated for our model is shown in Figure 5.4.

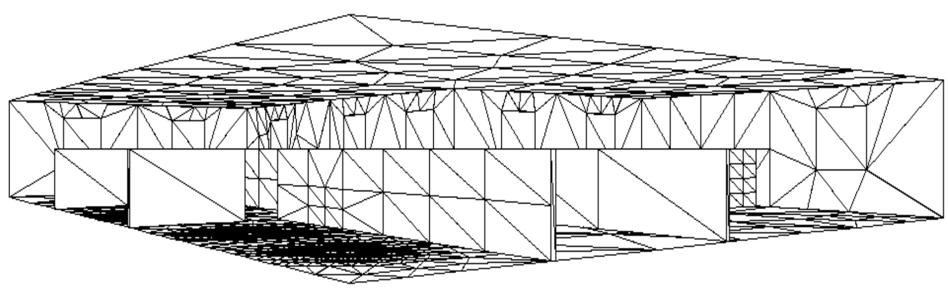


Figure 5.4 3D Raster Spacing of the Model (variable view)

The impact of daylight and insolation are reduced by external obstructions, if present. The basic object of cube is used to represent external obstruction. Relux Pro also provides results for daylight efficiency for a daylight based control system. The program calculates the monthly or annual percentage of time with which the space can be lit with a given illuminance with a predefined daylight factor as given by Equation 5.1. The results obtained for such a calculation with Dubai as a location are presented in Figures 5.5 to 5.7. The isolux curves for a clear and overcast sky are depicted in Figure 5.5 and 5.6 respectively. It can be seen that the test space can be illuminated by pure daylight for most part of the year due to higher sunshine probability. Figure 5.7 illustrates that for 96.8% of the working time, the space receives sufficient illuminance from daylight as an annual average.

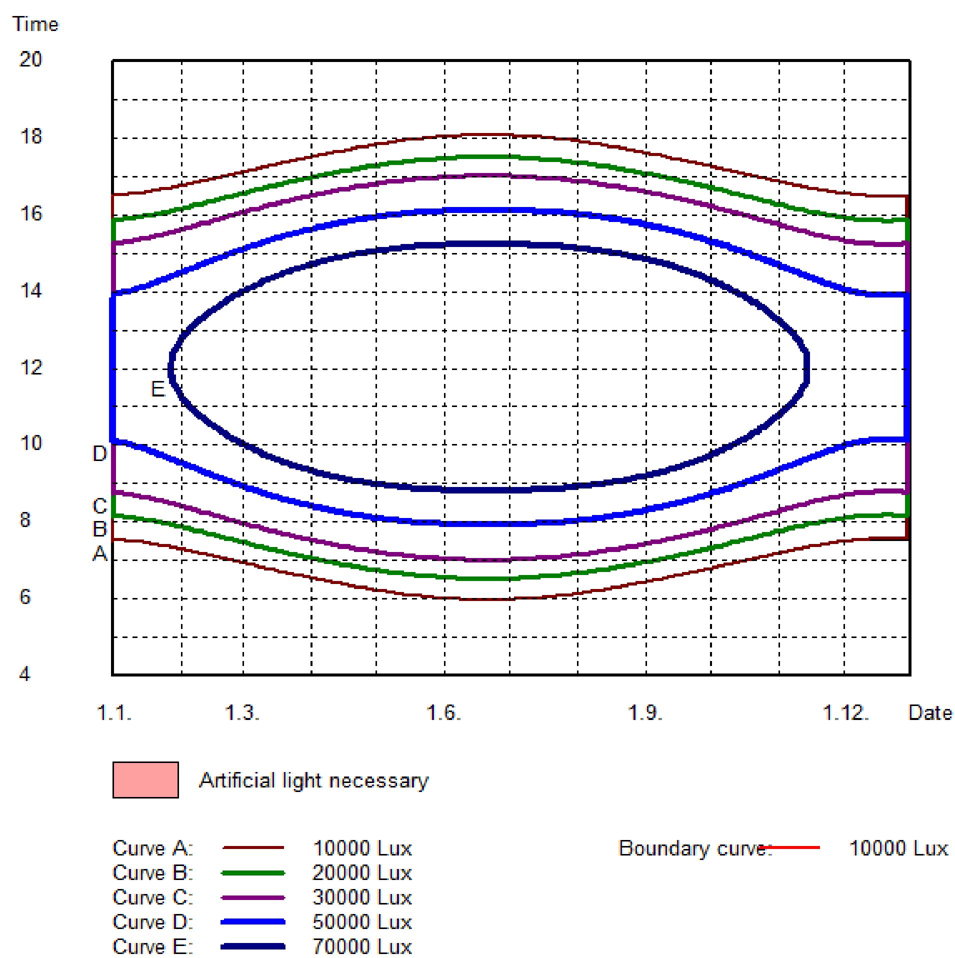


Figure 5.5 Isolux Curves for Clear Sky for the Test Space

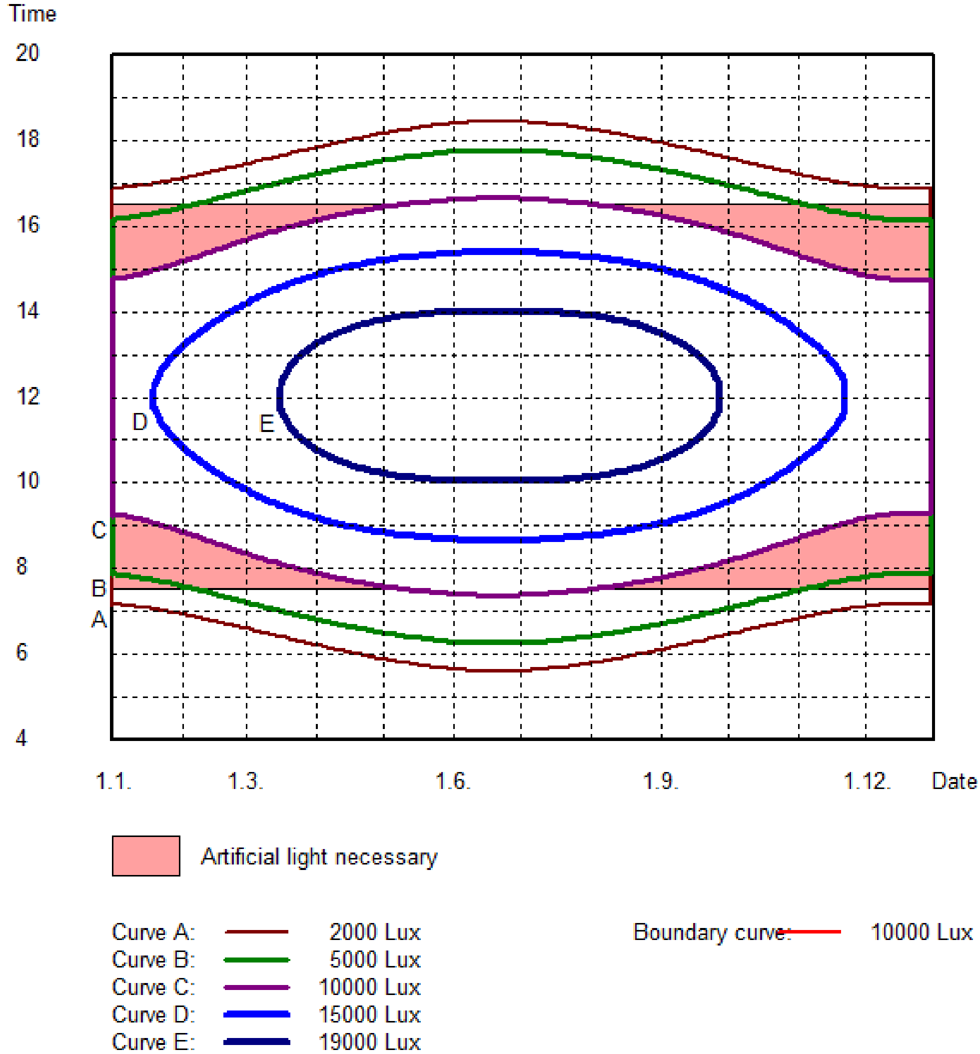


Figure 5.6 Isolux Curves for Overcast Sky for the Test Space

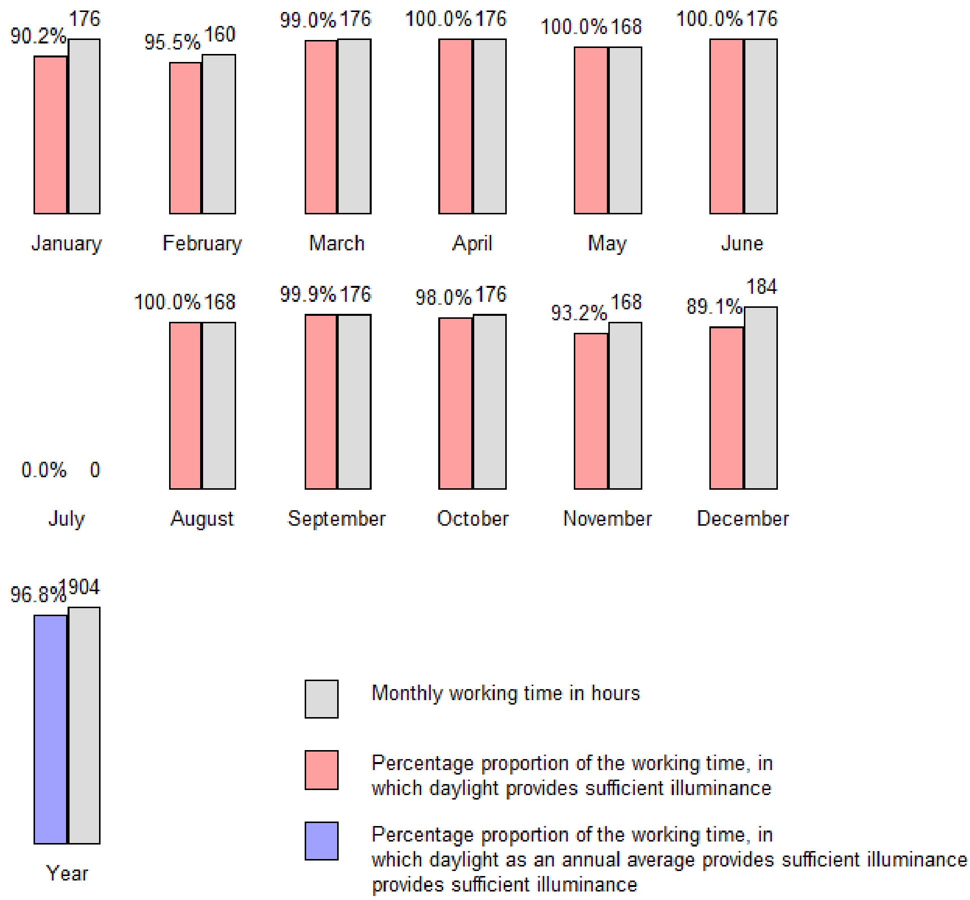


Figure 5.7 Evaluation of Isolux Curves for the Test Space; July defined as holiday period

Typically daylighting simulations require a time step of one minute (Walkenhorst et al. 2002). Lindsay and Littlefair (1992) observe a typical behaviour in people operating the blinds; short periods of sunshine had little effect on blind movement; however, long periods of sunshine of over one hour generally triggered blinds to be lowered. Considering the above points, the simulation for daylight scenes was done for every 30 minutes interval. The daylight illuminance data was collected at the task surface adjacent to blinds for different CIE sky conditions for twenty days starting from 1st March. Figures 5.8 to 5.10 show the simulated scenes of room interior at 7.30 am on 1st March.

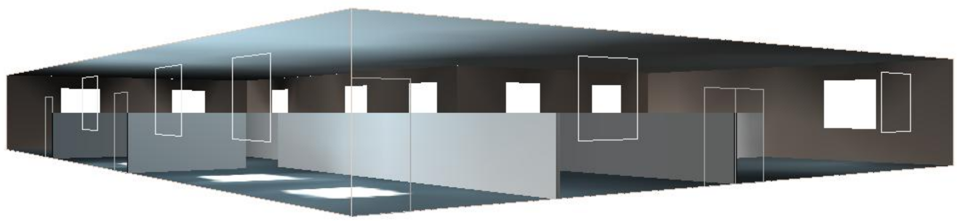


Figure 5.8 3D Luminance Distribution at 7.30 am on 1st March (variable view)

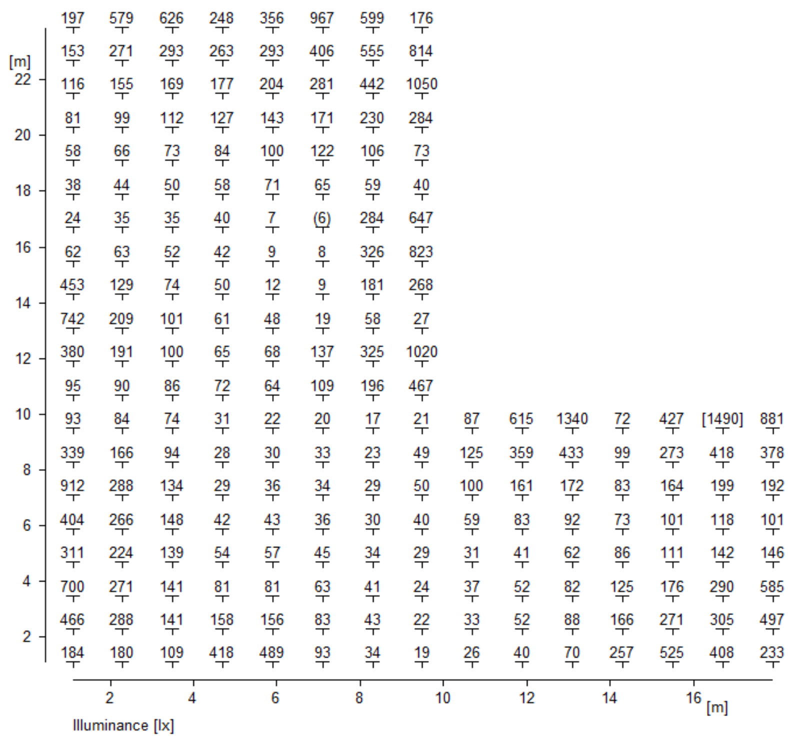


Figure 5.9 Table Output (reference plane) at 7.30 am on 1st March

Dubai has a mixed weather pattern of clear days with some precipitation, sandstorms and fog in March. March is therefore often a very changeable month when Dubai can experience a wide range of weather phenomena (Dubai

Meteorological Services 2005) and hence the duration chosen was such that it can adequately characterize the real system.

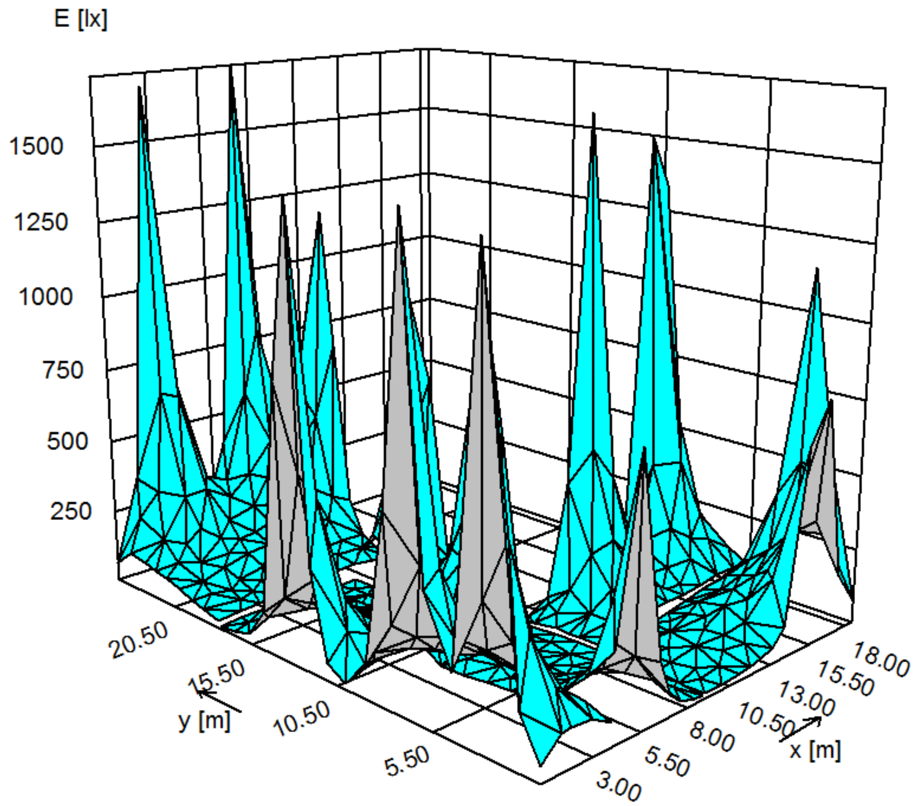


Figure 5.10 3D Mountain Plot of Illuminance at Different Points on the Reference Plane at 7.30 am on 1st March

The simulation runs that are needed for real time control purposes have to be practically less and the time taken by each run has to be small. Relux calculations are remarkably fast and hence it becomes an attractive proposition to combine simulator with ANFIS learning so as to enhance the effectiveness of control process. Relux, in our typical case, took about 17 seconds to complete a single daylight simulation session with average indirect fraction method. In comparison, Chang (2000) remarked that running LUMINA took about a minute for a normal sized room. Relux calculations are extremely fast while SPOT and DAYSIM are computationally expensive (Doulos et al. 2005).

5.8 Conclusions

The test space for daylighting is very dynamic because of the environmental factors such as sky conditions, cloud cover and solar radiation; building factors such as type, window orientation, neighbouring buildings etc.; room layout factors such as partition, irregular floor plan, configuration change, presence of furniture etc. along with occupancy fluctuation. The model accommodating all these features was built by having illuminance data simulated using a lighting simulation software Relux pro 2004. A detailed literature review on the available lighting simulation tools was presented along with discussions on their issues.

There are two major light processes employed in advanced lighting simulation tools, namely radiosity and ray tracing. While classical tools made use of either one of these processes, most of today’s tools model lighting combining both these techniques. Relux combines backward ray tracing with radiosity for producing photo-realistic images. It is found that Relux was able to model indoor daylight illuminances accurately for CIE sky conditions, L-type geometry and room configuration. The wide range of reflectances and transmittances are also supported by Relux for mimicking real world glazing surfaces and materials. Daylight illuminance values were collected at the task surface as training data for the machine learning model.

Even though Relux simulations are comparatively fast, the real time control applications necessitate that the control state search space be dramatically reduced, especially in the case of time varying geometry, such as automated blinds. Under these circumstances, combining simulation with ANFIS learning is a promising strategy and this aspect is explained in the next chapter.

Chapter 6

ANFIS Controller Design and Validation

6.1 Introduction

In this chapter, the controller design and validation procedures are described. Firstly, the steps involved in fuzzy inference process and a simple fuzzy blind controller are explained. The chapter then gives the procedure for creating an intelligent model based on ANFIS, which is capable of maintaining a user-specified illuminance profile. This is followed by the demonstration of simulation results and controller validation. The controller validation is done by means of an algorithm that maintains optimum illuminance levels while ensuring thermal comfort of the occupants, with due consideration to the hot climate of Dubai. Ultimately, the controller is validated with respect to the effectiveness of the control process that ANFIS brings to the table.

6.2 Fuzzy Logic Controllers

For complex and ill-defined systems that have troubles being subject to conventional automatic control methods, fuzzy logic controllers provide a very good alternative since they capture vague, qualitative aspects of human reasoning and decision making processes. Neural network and fuzzy systems based adaptive control methodologies are receiving considerable attention, emerging as promising approaches for controlling highly uncertain and nonlinear dynamical systems (Moustakidis et al. 2008). This is because the uncertainty and disturbances can be dealt with, increasing the robustness of the control process.

6.2.1 Fuzzy Inference Systems

Fuzzy Inference System (FIS) is a system created by the process of mapping from a given input to an output using fuzzy logic. The basic functional blocks of an FIS are shown in Figure 6.1. The rule base contains if-then rules, the numbers of which are determined from the knowledge about the target system to be modelled. The database defines the membership functions of fuzzy sets used in the rules and together the rule base and database are known as knowledge base. The decision making unit performs inference procedures on these rules. While the fuzzification interface transforms the crisp inputs into degrees of match with linguistic values, the defuzzification interface transforms the fuzzy results into crisp output. The antecedent of a rule defines the fuzzy region in the input space and the consequent specifies the output in the fuzzy region.

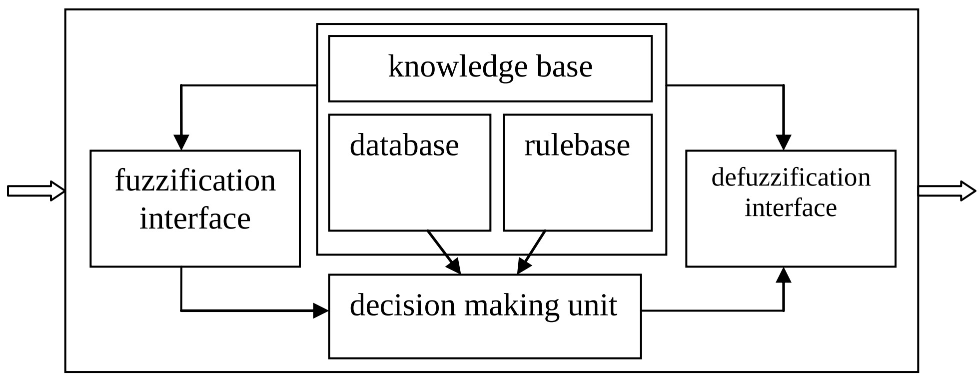


Figure 6.1 Functional Blocks of Fuzzy Inference System

Based on the past known behaviour of the target system, the FIS is designed so as to represent the target system very closely. In the case of automatic blind operation, the target system is occupants with varied human perceptions, emotion and mood and the FIS becomes a Fuzzy Logic Controller (FLC). Such a controller has to respond quickly and behave reliably to replace the humanistic process.

6.2.2 Fuzzy Logic Controller for Blind Systems

Blind as a device used in daylighting schemes is a common element in building envelope but the study of how the blinds are being manipulated by the occupants is a complex one since it impacts human perception such as glare and heat gain in addition to task illuminance and daylight on window. Various studies have reported the behavioural patterns of humans operating the blinds with an aim of automating them. Human control of blind is normally inefficient and unreliable (Vine et al. 1998; Foster and Oreszczyn 2001). Sutter et al. (2001) developed a predictive model to determine the recommended blind positions to achieve visual comfort as defined in previous works. Reinhart and Voss (2003) observed that the automatic blind system prompted the users to manipulate the blinds, but they could not conclude if the same users would have manipulated their blinds with the same frequency if the blinds had been only manual. Nicol et al. (2006) presented the results of a Europe-wide survey that explored how occupants use lights and blinds to modify light levels at their desks.

Towards analysing the correlation between sunlight and the heat gain associated with the use of blinds, some research efforts have been reported in the literature. Rea (1984) concluded that blind positions change irregularly and that an occupant most likely changes the position of the blind when direct sunlight reaches the work area. Inoue et al. (1988) reported in his study conducted at Japan that 70% of the occupants responded that they usually liked to keep the blind open for as long as possible unless it was too bright or too hot, suggesting that glare and heat were the main reasons for blind manipulation. In agreement with previous works, Lindsay and Littlefair (1992) found a strong correlation between the amount of sunshine, the sun position and the blind use. Reinhart and Voss (2003) found that the occupants mostly accepted the automatic lowering of the blinds only when the illuminance on the facade of the building was above 50 klux (~450 W/m^2). Newsham (1994) and Inoue et al. (1988) assumed that the occupants would close their blinds if solar radiation is greater than 233 W/m^2

depending on their seating position. Further, the blinds were assumed to be closed until the following morning. Lah et al. (2006), Gullemin and Molteni (2002) and Kristl et al. (2008) have applied fuzzy logic to manage roller blind control.

To illustrate a simple FLC for blind control, two types of FLCs have been constructed in this thesis by the following steps:

1. Decide on the input, output variables.
2. Choose a specific type of FIS, namely Sugeno or Mamdani.
3. Determine the number of linguistic terms to describe each input and output variable.
4. Obtain a set of fuzzy if-then rules.

The above steps to construct the surface structure are guided by common sense and the literature mentioned above about human behaviour on blind operation.

Fuzzy controller 1

The first type uses daylight on window (in klux) and solar altitude (in degrees) as inputs and the output is blind control signal. According to Perez model (Perez et al. 1990), the daylight on window can be calculated from direct normal solar radiation and diffuse horizontal radiation. The solar altitude can be determined from longitude, latitude, local time and date. The rules and structure of the model are shown in Figures 6.2 (a) and (b) respectively.

Fuzzy controller 2

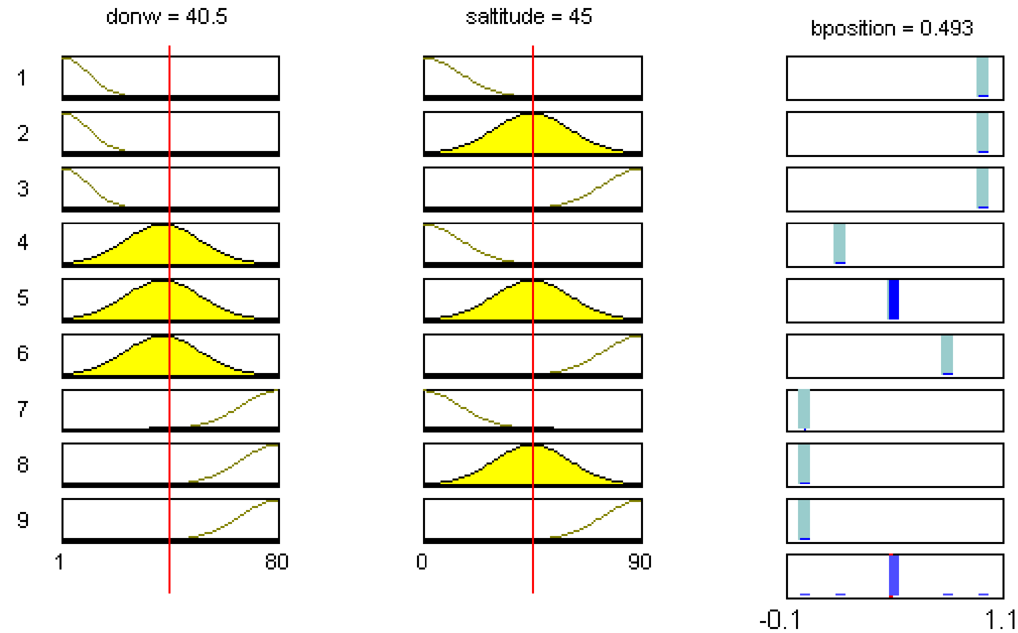
For the blind controllers to work to occupant's satisfaction, the thermal comfort of the occupants must be assessed carefully, because light also brings in heat. This means that the difference between the day lit room's temperature and the set point temperature (T_{diff}) should be within the tolerance level accepted by the users. The second fuzzy controller has illuminance data and T_{diff} as inputs. Figure 6.3 (a) shows the rules of this fuzzy controller and its (b) part illustrates the complexity of the surface. The set of rules are shown in Appendix C.

The surface structures of both controllers are designed with nine rules with each input described by three generalised bell (g-bell) membership functions. Since the identification of deep structure requires more expert knowledge and refining of parameters using regression and optimisation techniques, the simple fuzzy controllers are seldom optimal to describe the complex control process.

The shown fuzzy logic controllers depend on the availability of human expertise and hence on the knowledge acquisition techniques to convert the knowledge into appropriate fuzzy if-then rules. If design approaches from neural control can be directly brought to fuzzy logic controllers, the resulting neuro-fuzzy control can have excellent learning ability which is a plus from neural control as well as the advantage of fuzzy inference system, namely, structured knowledge representation. Such neuro fuzzy controllers are employed in expert control, specialised learning, inverse learning etc.

ANFIS is a form of fuzzy inference system wherein the fuzzy logic and neural network approaches are fused together and ANFIS controllers exhibit the following advantages, specifically suited to nonlinear and time varying applications:

- Directly applicable to adaptive control because of adaptive capability
- Learning ability
- Structured knowledge representation
- Better integration with other control design approaches
- Flexibility of parallel operation



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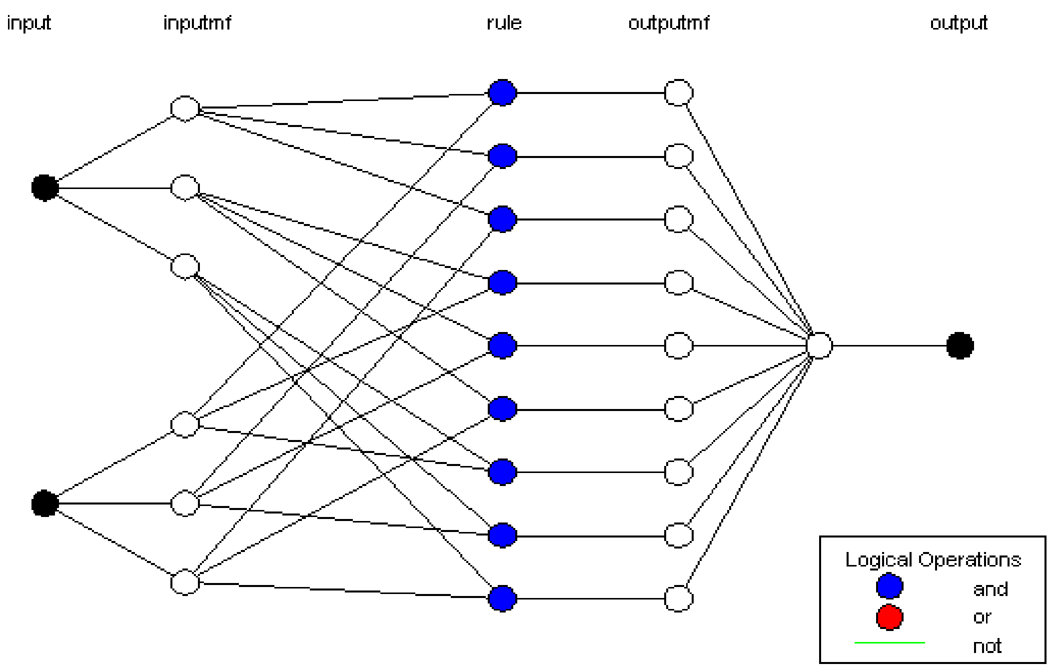
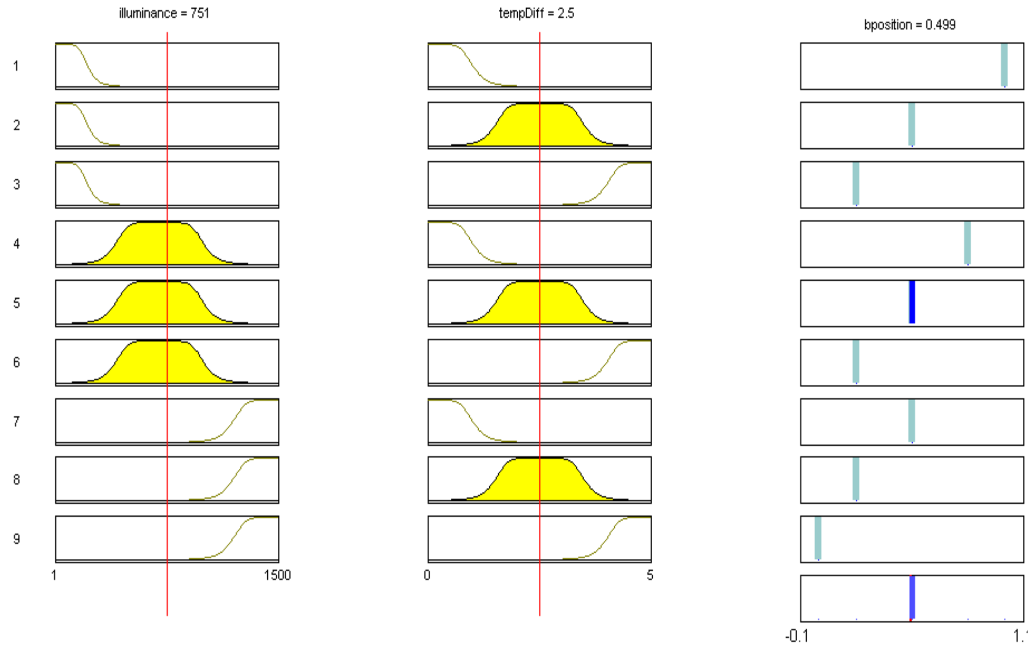
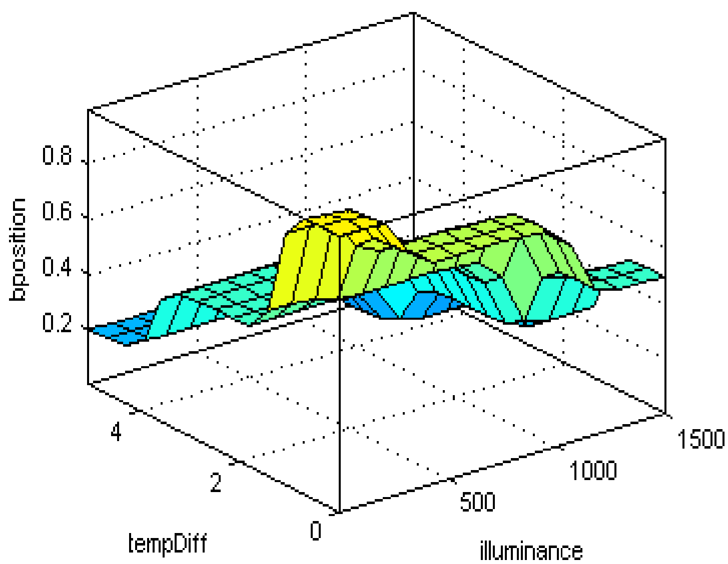


(b)

Figure 6.2 (a) The Rules of the Fuzzy Controller1: *donw*-daylight on window (klux), *saltitude*-solar altitude (degrees), *bposition*–blind position**; (b) Its Corresponding Structure**



(a)



(b)

Figure 6.3 (a) The Rules of the Fuzzy Controller 2; (b) Its Corresponding Surface

A pure neural control is considered as a black box method and hence does not represent structured knowledge and also integrating neural networks with other control design methods is more complex and in this way, ANFIS is considered to be superior to both fuzzy logic and neural network methods.

6.3 Model Design

ANFIS based modelling combines the transparent linguistic representation of fuzzy systems with the learning ability of neural networks so that they can be trained to perform an input/output mapping. In situations such as illuminance conditions, we can not decide what the membership function must be, just by merely looking at the data. ANFIS permits the parameters to be automatically adjusted so that the membership functions capture the dynamics of data. The set of rules ANFIS provides is indicative of the underlying system and hence is valuable information to gain further insight into the process model.

When a FIS is launched as a controller, the special requirement is that the refining of parameters of membership functions should be done in such a way that the best performance of the plant is guaranteed. ANFIS is a specific network structure that facilitates searching and refining of parameters of membership functions using either a back propagation gradient descent (GD) method alone or in combination with Least Squares Estimates (LSE).

6.3.1 ANFIS Architecture

ANFIS structure allows the rules to be constructed using a decompositional strategy. ANFIS represents a multi-layer feed-forward network in which each node (neuron) performs a specific function on the incoming signals and there are two types of nodes: adaptive and fixed. The rules are first extracted at individual node levels within the neural network and then aggregated to capture the global dynamics of the system (Jang 1993). The fuzzy if-then rules with appropriate membership functions generate the preliminary stipulated input-output pairs and these membership functions take their final forms during training due to regression and optimisation procedures.

The gradient vector provides a measure of how well the system is emulating the given training data set for a given set of parameters. Once the gradient vector is got, the optimisation routines are applied to adjust the parameters in such a way as to reduce a chosen error criterion. The system converges when the training and checking errors are within an acceptable limit.

The blind control system here is considered as a first order system and hence will be described by first order Sugeno fuzzy model. We shall utilise the first order Sugeno fuzzy model for the dynamic application due to its transparency and efficiency (Zilouchian and Howard 2001). Higher order Sugeno models introduce more complexity into the system without significant benefit. Hence the blind control system is implemented as a first order system.

As described in Figure 6.4 (a) in the following page, each rule has crisp output and the overall output is obtained through weighted average because it facilitates time reduction for computation due to the absence of mathematically intractable defuzzification operation. The crisp output is also a requirement when the fuzzy system is to be launched as controller. These properties of Sugeno system makes it as the most popular choice for sample-based fuzzy modelling such as in our work.

A two input first order sugeno fuzzy model with two rules is shown in Figure 6.4 (a). The rule base for a two rule fuzzy set is given by

If x is A_1 and y is B_1 then $Z_1 = p_1 * x + q_1 * y + r_1$

If x is A_2 and y is B_2 then $Z_2 = p_2 * x + q_2 * y + r_2$

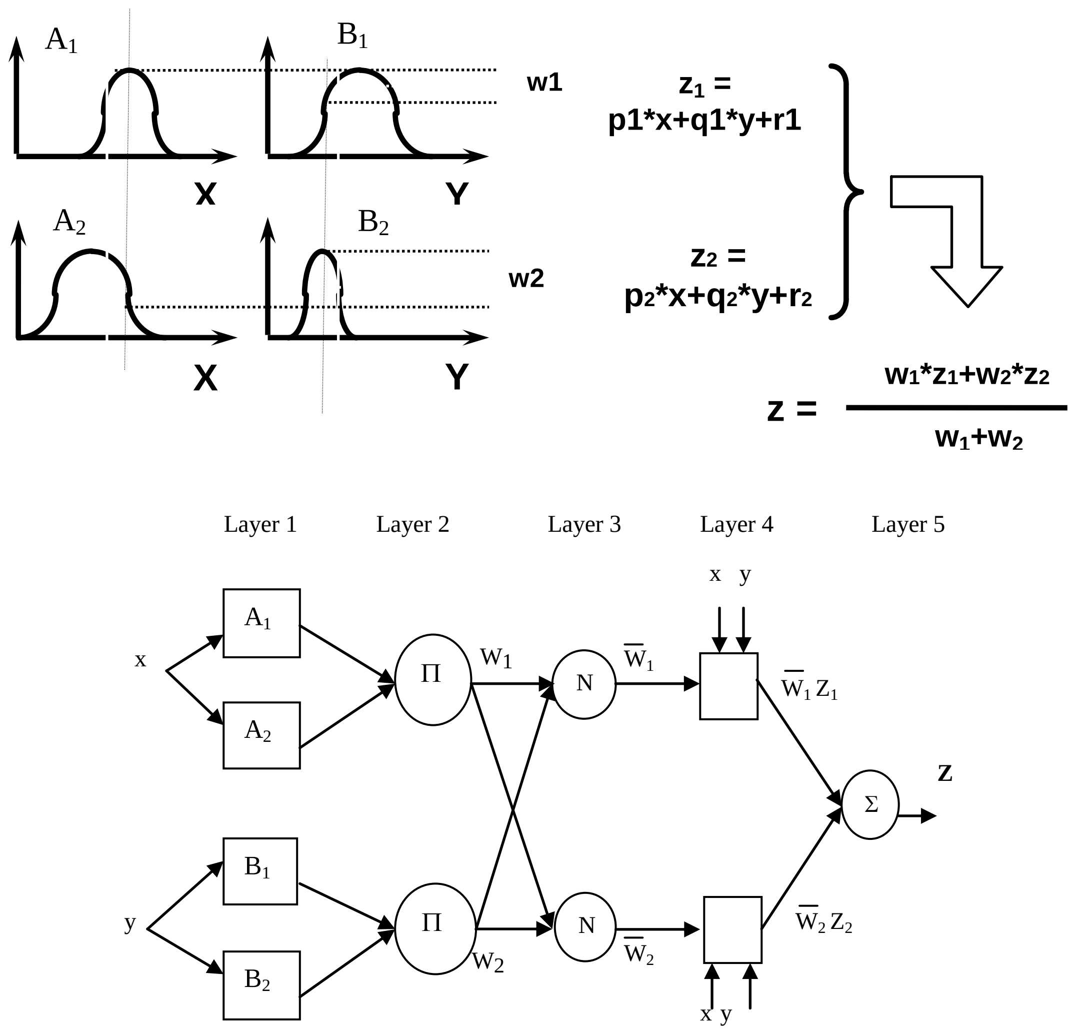


Figure 6.4 (a) Two Input Fuzzy Reasoning for a Sugeno System; (b) Equivalent ANFIS Architecture (Jang et al. 1997)

The ANFIS network shown in Figure 6.4 (b) is composed of five layers. Each square node in the first layer is an adaptive node with a node function computed as follows (Jang et al. 1997):

$$O_i^1 = \mu_{Ai}(x) \tag{6.1}$$

where x is the first input vector and μ is the membership function for that particular input. Parameters in this layer are called premise (or nonlinear) parameters. Layer two consists of only fixed (circle) nodes. The output of each node is the product of the two membership functions as shown below:

$$O_i^2 = W_1 = \mu_{Ai}(x)\mu_{Bi}(y) \tag{6.2}$$

Layer three also contains fixed nodes only with their normalized firing strengths in the following form:

$$O_3^i = \overline{W_i} = \frac{W_1}{W_1 + W_2} \quad i = 1,2 \tag{6.3}$$

The fourth layer is an adaptive layer and the output is computed from the product of consequent parameter set and the third layer's normalised firing strength as:

$$O_4^i = \overline{W_i}(p_i x + q_i y + r_i) \tag{6.4}$$

Parameters in this layer are known as consequent (or linear) parameters. The layer five output, consisting of fixed nodes is the sum of all incoming signals.

$$O_{5,1} = \sum_i \overline{W_i} Z_i \tag{6.5}$$

In our model, the blinds are assumed to be in any one of possible discrete states and controlled at the same time. Since the system is used as a controller, a crisp output is obtained by defuzzification and the system implements non linear mapping from the illuminance input space to blind position output space by means of fuzzy if-then rules.

6.3.2 Hybrid Learning

From Fig. 6.4 (b), the overall output

$$\begin{aligned} z &= \frac{w_1}{w_1 + w_2} z_1 + \frac{w_2}{w_1 + w_2} z_2 \\ &= \overline{w_1}(p_1 x + q_1 y + r_1) + \overline{w_2}(p_2 x = q_2 y + r_2) \\ &= (\overline{w_1} x) p_1 + (\overline{w_1} y) q_1 + (\overline{w_1}) r_1 + (\overline{w_2} x) p_2 + (\overline{w_2} y) q_2 + (\overline{w_2}) r_2 \end{aligned} \tag{6.6}$$

When the values of premise parameters at layer two are fixed, the overall output z can be expressed in terms of linear combination of the consequent parameters p_1, q_1, r_1, p_2, q_2 *and* r_2 which is of the form

$$S = S_1 \oplus S_2 \tag{6.7}$$

The above equation signifies that the set of total parameters (S) can be divided into a set of premise parameters (S_1) and consequent parameters (S_2) where $\oplus$ represents direct sum. The adaptive network's output can be written as

$$o = F(i, S) \tag{6.8}$$

where i is the vector of input variables and F is the function of the fuzzy inference system. The total parameter set S is divided such that $H \ o \ F$ is linear in the elements of S_2 where H is the identity function.

The hybrid learning algorithm of applying back propagation to find premise parameters S_1 and Least Squares Estimates (LSE) to determine consequent parameters S_2 is made use of in this offline learning. Each learning step consists of two passes namely, forward and backward. In the forward pass, node outputs are propagated and the optimal consequent parameters are estimated by LSE while the premise parameters are assumed to be fixed for the current cycle. In the backward pass, back propagation modifies the premise parameters by gradient descent and the consequent parameters remain fixed. This iterative procedure is carried on till the error criterion is satisfied. Typically, this error criterion is the sum of the squared difference between the actual and desired outputs or in some situations, a user defined performance measure. Table 6.1 summarises these activities in each pass. The mathematical description of hybrid learning algorithm employed in ANFIS is given in Appendix C. This hybrid approach converges much faster since it reduces the search space dimensions of the original pure back propagation algorithm (Jang et al. 1997). This is because of the optimal estimation of consequent parameters while assuming premise parameters as fixed. As explained in chapter 4, the control state search space is an important parameter for building systems control applications involving several numbers of devices such as luminaries, blinds and louvers and is an exponential function of the number of devices. The search space reduction is a very important advantage ANFIS brings to the table making the control process more effective.

Table 6.1 Two Passes in the Hybrid Learning Procedure for ANFIS (Jang et al. 1997)

Parameters/Pass-→	Forward pass	Backward pass
Premise parameters	fixed	gradient descent
Consequent parameters	least-squares estimator	fixed
signals	node outputs	error signals

6.3.3 Prediction of Light Levels

For developing automated lighting control systems with occupant- friendly and energy saving strategies, the knowledge awareness of lighting levels at different points in space and their distribution are some of the most important and fundamental requirements. For the model to become adaptive to occupancy and environmental conditions, it should be able to predict the interior illuminance levels.

Various methods are employed to predict the lighting levels for daylighting applications. Daylight coefficient (Tregenza and Waters 1983) is an approach in which the sky is treated as an array of point sources and is efficient in calculating the light reflected through different optical systems. If the shading systems are considered dynamic such as in our thesis, the calculation of interreflected light involves the time consuming part of finding new set of coefficients for each position of blind. As explained by Equation 5.1, daylight factor is E_i / E_a in percentage where E_i is the horizontal illuminance (in lux) at the point of interest in the given interior while E_a is the horizontal outdoor illuminance with a uniformly overcast sky. Li et al. (2003) have suggested an approach based on daylight factor to predict daylight illuminance but this is not flexible enough to predict dynamic variations in illuminance due to the prevailing sky conditions. Useful daylight illuminace (UDI) (Nabil and Mardaljevic 2005) is a new paradigm that calculates illuminance from absolute values of annual daylight illuminance which in turn depend on average hourly irradiance and Test Reference Year (TRY) data sets. Due to the dynamic nature of cloud cover and sky luminance patterns, UDI is not suitable for blind systems control due to increased complexity. Computer simulation tools alone can not accurately predict illuminance suitable for real time control as discussed in chapter 5. One of the objectives of employing a learner is to enhance the prediction capability of simulator. Here, ANFIS is used to predict the future illuminance values by using the illuminance obtained from simulator as training data. ANFIS treats data adaptively in a time series sense and can predict future values ahead of time as demonstrated in Jang (1993).

The values of daylight illuminance up to time t are used to predict the future value at a point P later. A mapping from D points of the time series spaced Δ apart is created to a predicted value $x(t+P)$. For example, if we map 5 points $x(t\text{-}32)$, $x(t\text{-}24)$, $x(t\text{-}16)$, $x(t\text{-}8)$ and $x(t)$ to the future value at $x(t+8)$, D =5 and Δ =P =8. Such a mapping would involve five inputs and one output. In this work, the first 500 data pairs were used as training data and the remaining 500 pairs were used as checking data to validate the prediction capability. The iterative process of presenting the entire data set to validate the prediction is defined as an epoch. MATLAB's fuzzy logic toolbox was used for training and checking purposes.

The various options for choosing the number of membership functions (MF) assigned to each input, mapping of points, number of steps and epochs were done by trial and error and the results are presented in Table 6.2. The type of membership functions used was generalized bell (g-bell) and they are specified by three parameters {a, b, c} as:

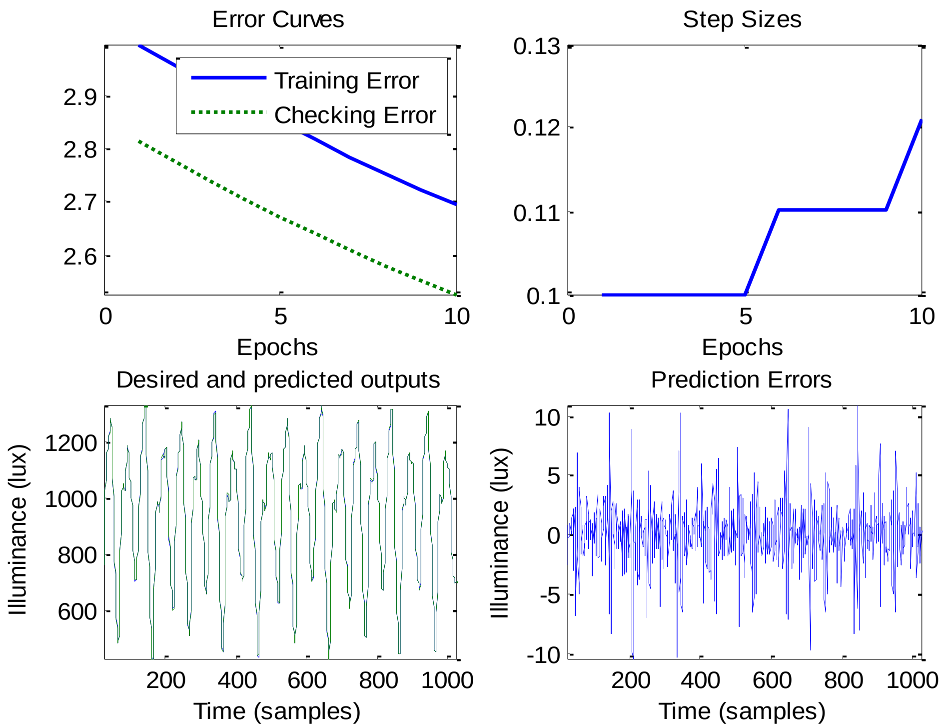
$$bell(x; a, b, c) = \frac{1}{1 + \left| \frac{x - c}{a} \right|^{2b}} \tag{6.9}$$

where *b* is usually positive for an upright function. The g-bell MFs were chosen because of their smoothness and concise notation as described by Equation 6.9 and its flexibility of adjusting steepness at crossover points and ability to describe a complex linguistic profile.

Table 6.2 Comparison of Prediction of Illuminance

Epoch No.	No. of MF	Mapping	Step	No. of Nodes	No. of Linear Parameters	No. of Nonlinear Parameters	Elapsed Time (sec)	No. of rules
10	2	4	6	55	80	24	1.287	16
100	2	4	6	55	80	24	12.872	16
10	3	4	6	193	405	36	34.991	81
10	3	3	6	78	108	27	2.2449	27
10	2	4	8	55	80	24	1.4667	16
10	2	3	8	34	32	18	0.3163	8
25	2	4	6	55	80	24	1.3936	16
50	2	4	6	55	80	24	3.1895	16

Figure 6.5 shows the illuminance prediction with 2 membership functions on the inputs and 10 epochs. As can be seen from Figure 6.6 (a), ANFIS is able to predict the illuminance values accurately within 2 lux and this illuminance change is hardly noticeable by human eye. Figure 6.6 (b) depicts the non linear surface of the scheme. Figure 6.7 indicates the final membership functions on the four inputs after training.



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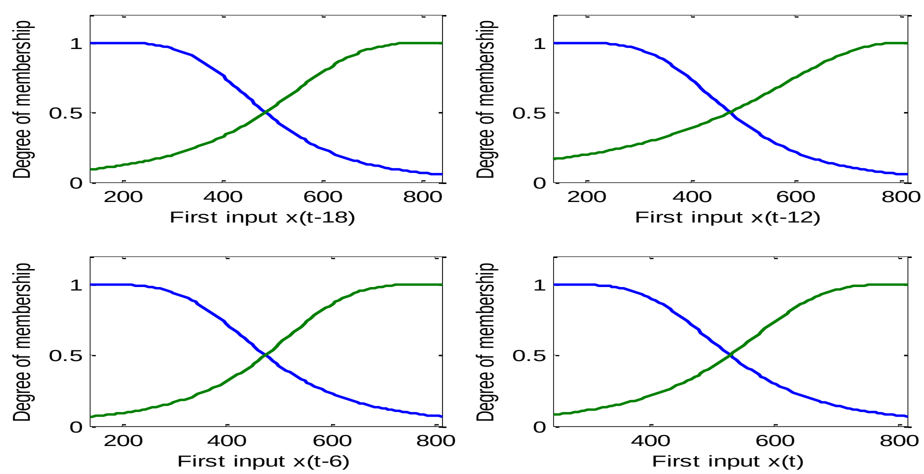
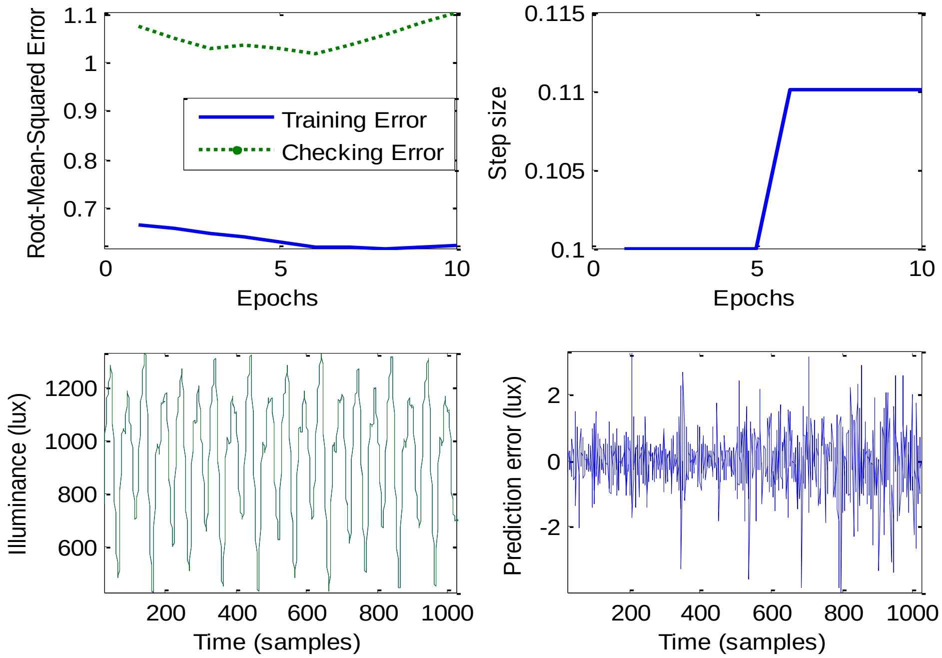


(b)

Figure 6.5 Illuminance Prediction for the Case, 2 Membership Functions on the Inputs and 10 Training Epochs: (a) (clockwise from top left) Error Curves, Step Size, Prediction Error Plots and Desired (vs) ANFIS Outputs; (b) Final Membership Functions on the Inputs



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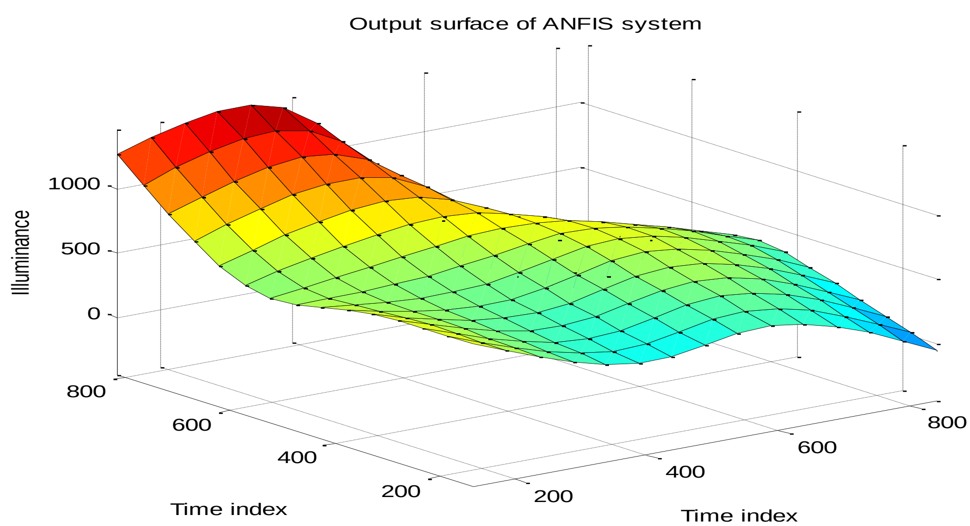
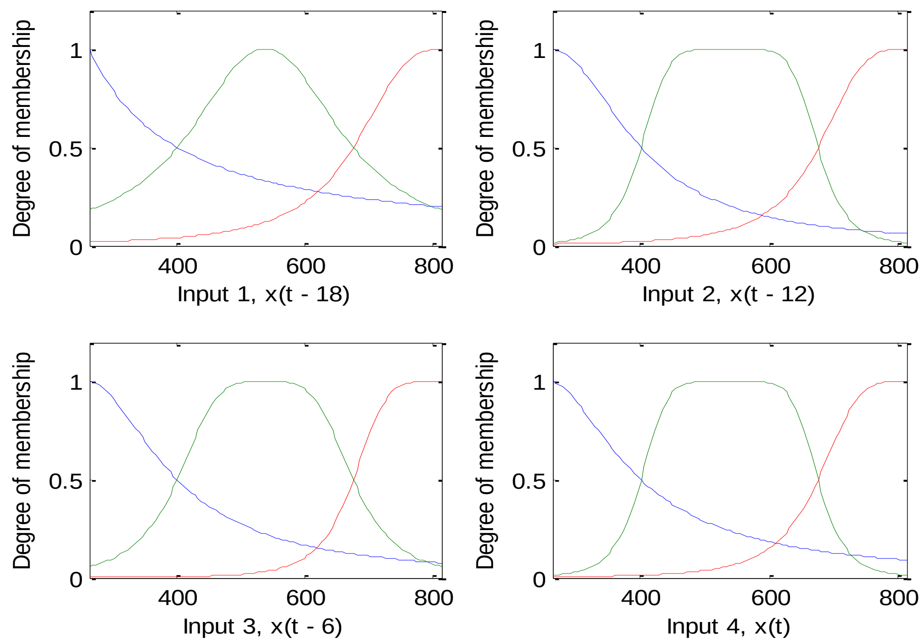


(b)

Figure 6.6 Illuminance Prediction for the Case, 3 Membership Functions on the Inputs and 10 Epochs: (a) The Bottom Left Graph Shows that the Desired and Predicted Illuminance being Indistinguishable from One Another; (b) Output Surface



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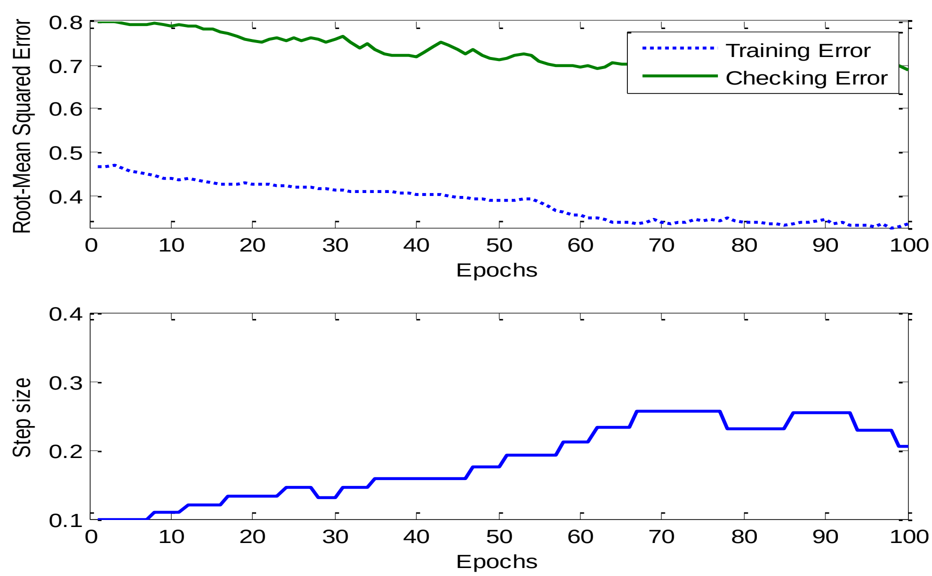


(b)

Figure 6.7 Illuminance Prediction for the Case, 3 Membership Functions on the Inputs and 100 Epochs: (a) Final Membership Functions on the Inputs; (b) RMSE Curves and Step Size Plots

It can be observed from Figure 6.7 that the training and checking errors reduced considerably when the number of epochs is increased to 100 while this case also involves a higher elapsed time of prediction. The small value of Root Mean Squared Error (RMSE) of both training and checking data indicates that ANFIS was able to capture the nonlinear dynamics of illuminance data and predict the same after six time steps. The structure of the 3 MFs model is shown in Figure 6.8. The structure has 3^4 =81 rules for describing four inputs with three membership functions each. Most of the data emulation is done by linear parameters and the nonlinear parameters are used for further fine tuning.

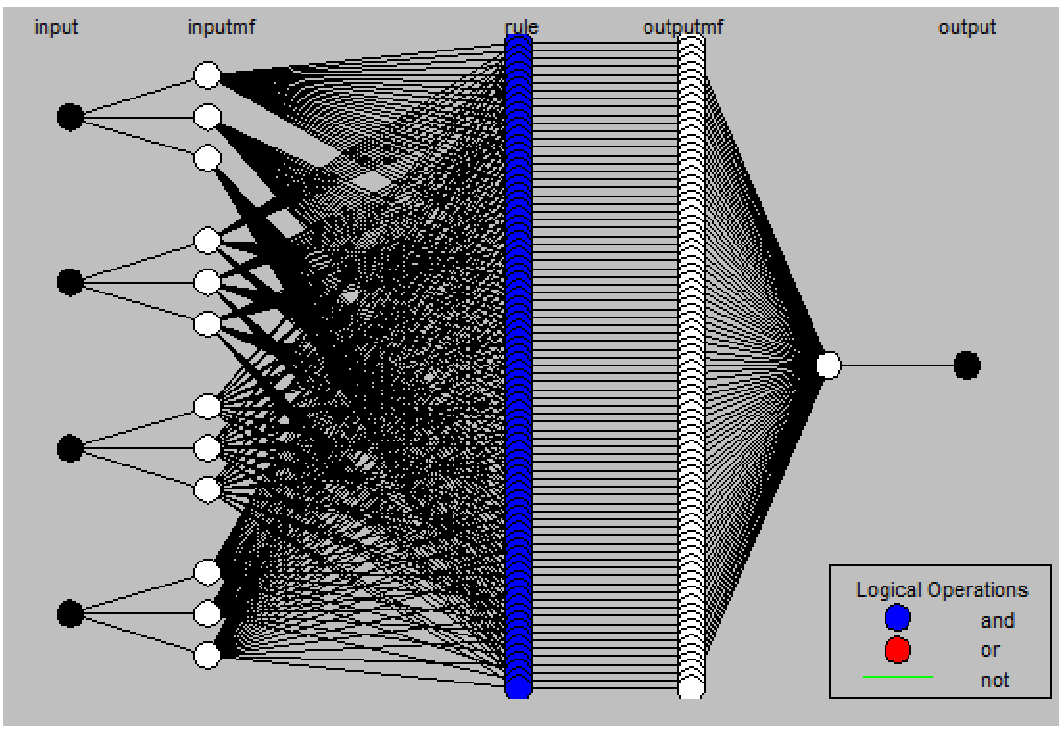


Figure 6.8 ANFIS Structure for the Case, 3 Membership Functions on the Four Inputs (connections from inputs to layer 4 not shown)

6.3.4 Inverse Control Method

Conventional techniques for system analysis are not suitable for dealing with blind control systems whose positions are strongly influenced by occupant's mood, emotions and perception. In this work, ANFIS is used to model the non-linear blind position dynamics from simulated illuminance data. The model is built using inverse learning, considering the geographical, environmental and occupancy factors. The model is also used as a controller for blind positions and to predict the non linear behaviour of the underlying system. The implementation is done using MATLAB's Fuzzy logic toolbox. The ANFIS modeling approach described in this thesis has two objectives: It provides a model that depicts the behaviour of the underlying system and the model is then used for controller validation (Bhavani and Khan 2009). This approach is applicable to any plant for which the model structure is not known prior.

The simplest approach for controller design is a completely open-loop control strategy, in which the controller is the inverse of the process (Denai et al. 2007). This method seems straightforward and only one learning task is needed to find the inverse model of the plant (Denai et al. 2007). In direct inverse control method, the inverse model is connected in series with the plant. The process of inverse learning (Widrow and Stearns 1985) proceeds in two phases. The first phase of inverse learning is called as learning phase during which the inverse model is obtained from input-output data generated from the former ANFIS model of the system (Figure 6.9 (a)). The second phase is known as application phase and in this phase, the inverse model is used to generate control actions (Figure 6.9 (b)). The two phases can proceed simultaneously, much in line with the classical adaptive control schemes.

Feedback control systems and ANFIS control

The relevant concepts of discrete-time feedback control system towards ANFIS control is presented here. The assumption behind the hypothesis is given in Table 6.3. The system is described as a first-order plant for the reasons explained in section 6.3.1. The existence of inverse dynamics of the plant does not pose a problem because of the lower order plant dynamics.

Table 6.3 Assumptions for Inverse Control

No.	Assumptions
1	The order of the plant is one, that is the number of state variable is one, namely illuminance output
2	The state variable is measurable
3	The system has a unique inverse

With the assumption that that the state variables are measurable and are known in number,

$$y(k+1) = f\left(y(k), u(k)\right) \tag{6.10}$$

for a first order plant. Here *y(k+1)* is the state variable at time *k+1*, *y(k)* is the state at time *k* and *u(k)* is the control signal generated at *k*. This equation denotes that with the control signal *u* given as input, the state of the first order plant in question will move from *y(k)* to *y(k+1)* in one time step. For obtaining inverse model, the inverse dynamics of the plant is assumed to exist, and hence *U* can be described as an explicit function of *y(k)* and *y(k+1)* as

$$U = G\left(y(k), y(k+1)\right) \tag{6.11}$$

where *G* describes the inverse mapping. The assumption of existence of inverse dynamics essentially mean that there is a unique control sequence *U* as specified by the inverse mapping *G* that can drive the plant from *y(k)* to *y(k+1)* exactly in one time step. The ANFIS with two inputs and one output is used to approximate the inverse mapping *G* according to the following generic training data pairs:

$$[y(k)^T, y(k+1)^T; U^T] \tag{6.12}$$

This first phase of inverse learning phase is called as training phase and is illustrated in the block diagram of Figure 6.9 (a).

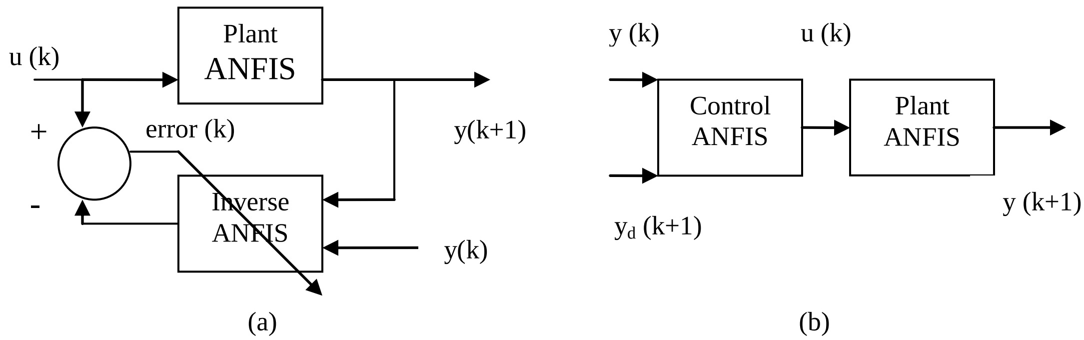


Figure 6.9 Block Diagram for Inverse Control Method: (a) Training Phase (b) Application Phase

Here, the plant output *y(k+1)* is a function of previous state *y(k)* and control signal *u(k)* in accordance with Equation 6.10. With the ANFIS model being able to capture the input-output mapping of the inverse dynamics *G*, an estimated control sequence is generated as follows:

$$\hat{U} = \hat{G}(y(k), y_d(k+1)) \tag{6.13}$$

This phase is known as application phase whose block diagram is shown in Figure 6.9 (b). During this application phase, the network generates an estimated control sequence which is a function of previous state *y(k)* and the future desired state $y_d(k+1)$. This control sequence would bring *y(k)* to $y_d(k+1)$ after one step, if the adaptive network function $\hat{G}$ is exactly the same as the inverse mapping *G*. As the training progresses, the parameters of ANFIS get refined and the adaptive network function $\hat{G}$ becomes closer to the inverse mapping *G*, making the control process more adaptive.

User specified illuminance profile

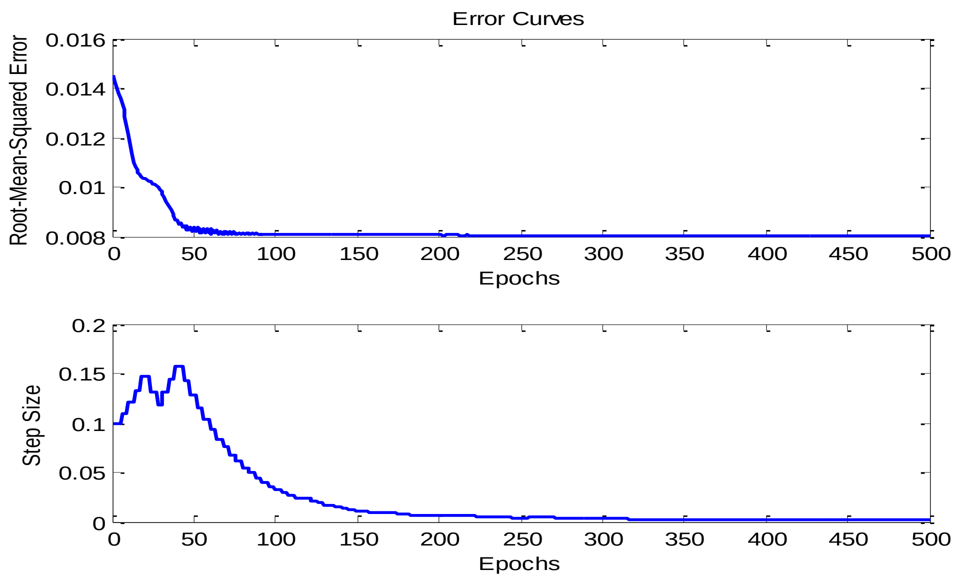
For finding the inverse mapping *G*, the illuminance data collected from simulation is defined as *y(k)* and the control signals for the blind as *u(k)*. To establish a non linear relationship between the collected illuminance data with the control signals, the following control scenario is hypothesised. If the available daylight illuminance (E_a) goes above pE_s, the blinds will be fully closed; the corresponding control signal will be 0. Here p can be a real number and E_s is the set illuminance level as desired by the user. If E_a becomes less than E_s, the blinds are fully open with a control signal of 1. In between this boundary, the control signal is generated by the formula $p\text{-}E_a/E_s$, enabling the entire space to have an illuminance profile of E_s to pE_s as specified by the user at any time k. The inverse model has two inputs $y(k)$ and $y(k+1)$ and the output is the control action for the blind, $u(k)$ which is given by Equation 6.11.

6.4 Simulation Results

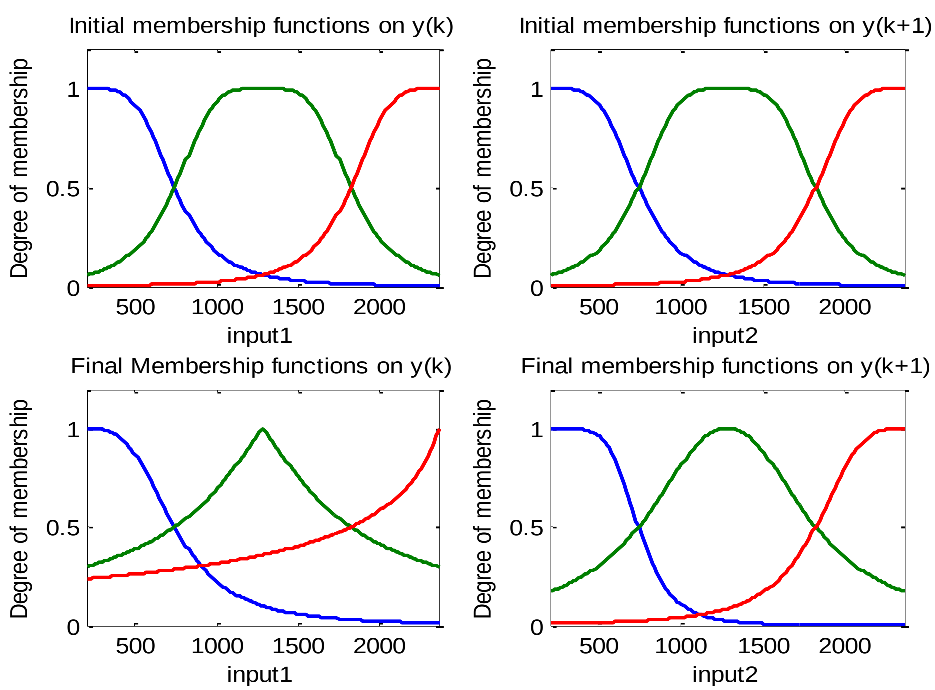
The results of simulation are presented next.

6.4.1 Structure and Parameter Identification

In a conventional fuzzy inference system, the number of rules is determined by an expert having knowledge about the target system. In the present scenario, since the training data was collected so as to be covering the entire input space and since its database is large enough, the learning mechanisms were applied to determine the membership functions. Since the model is launched as a controller, the fine tuning of membership functions should be done so that the best performance of the plant is guaranteed. In this situation, human-determined membership functions can not always generate the desired outputs optimally. Describing the system with more rules would result in better generalization capability although too many rules would make the system ineffective as a controller. Hence, the number of membership functions was chosen by trial and error and the results obtained with three and five MFs on the inputs are shown in Figures 6.10 and 6.11 respectively. The type of membership function chosen was generalized bell (g-bell) due to its flexibility and ease of describing a complex linguistic profile.

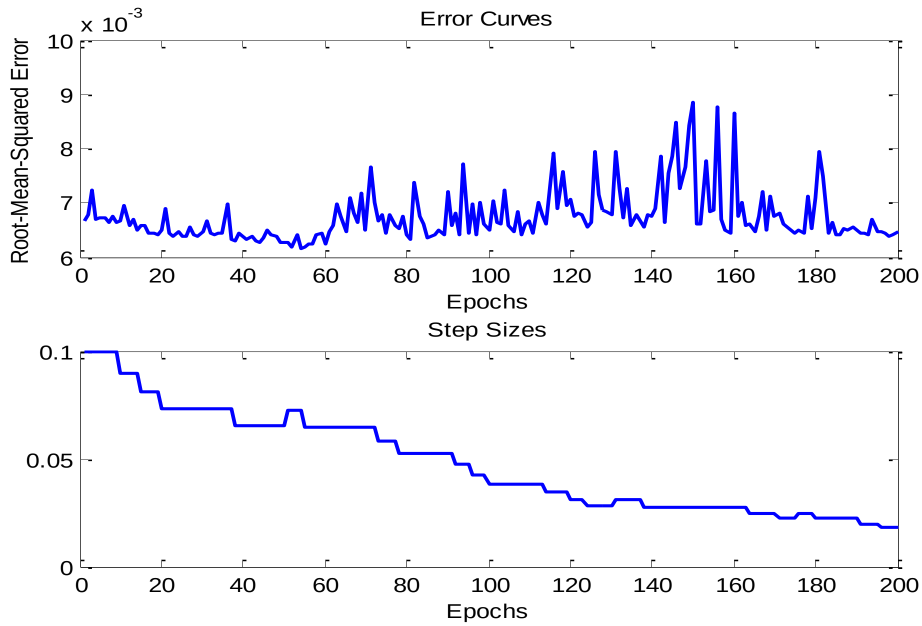


(a)

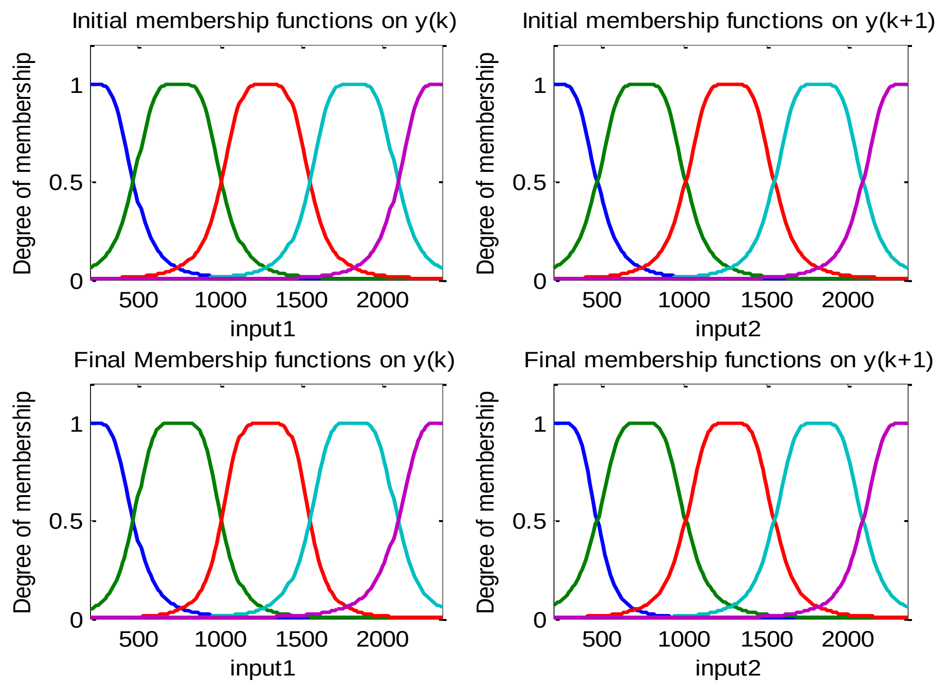


(b)

Figure 6.10 Model Results with Three MFs, 500 Epochs (a) Error Curves and Step Size Plots ; (b) Initial and Final Membership Functions on the Inputs



(a)



(b)

Figure 6. 11 Model Results with Five MFs, 200 Epochs (a) Error Curves and Step Size Plots; (b) Initial and Final Membership Functions on the Inputs

It can be observed from Figure 6.10 that the RMS error at the end of 500 epochs is 0.008 and that of Figure 6.11 is 0.0065. It is obvious here that ANFIS offers good modelling even when as few as three MFs are used. But with nine rules, ANFIS will be pressured to sacrifice its semantics in terms of its local description nature. Though describing the system with more rules would result in better generalization capability, too many rules would result in high computation time which is not suitable for real time control applications as explained earlier. So, describing each of the inputs with more than five MFs is not acceptable for an effective control process of the blind. So, the number of membership functions on the inputs was fixed at four because this option gave the least RMS Error (0.00209) (see Figure 6.16) out of the three cases. The system was built with sixteen rules (see Appendix C) with each input having four membership functions. The input space is therefore partitioned into sixteen fuzzy subspaces with each rule governing a subspace.

The scatter plot of the data collected from simulation is shown in Figure 6.12. The data was divided into training and test sets for the purpose of model validation. The training data set (the first 200 pairs) and the test set (the remaining 200 pairs) thus plotted are shown in Figure 6.13. The input vectors from the test set are presented to the trained ANFIS model to see how well the model responds to the test set and then predicts the corresponding output values. In addition to validating the obtained model, the test set is also used to test the generalization capability of ANFIS system at each epoch.

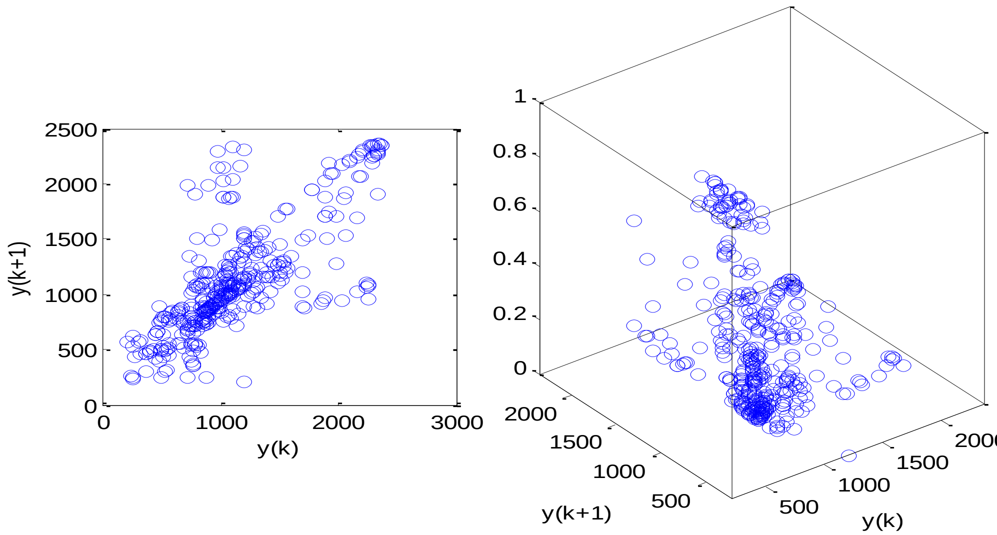


Figure 6.12 Scatter Plot of Collected Data

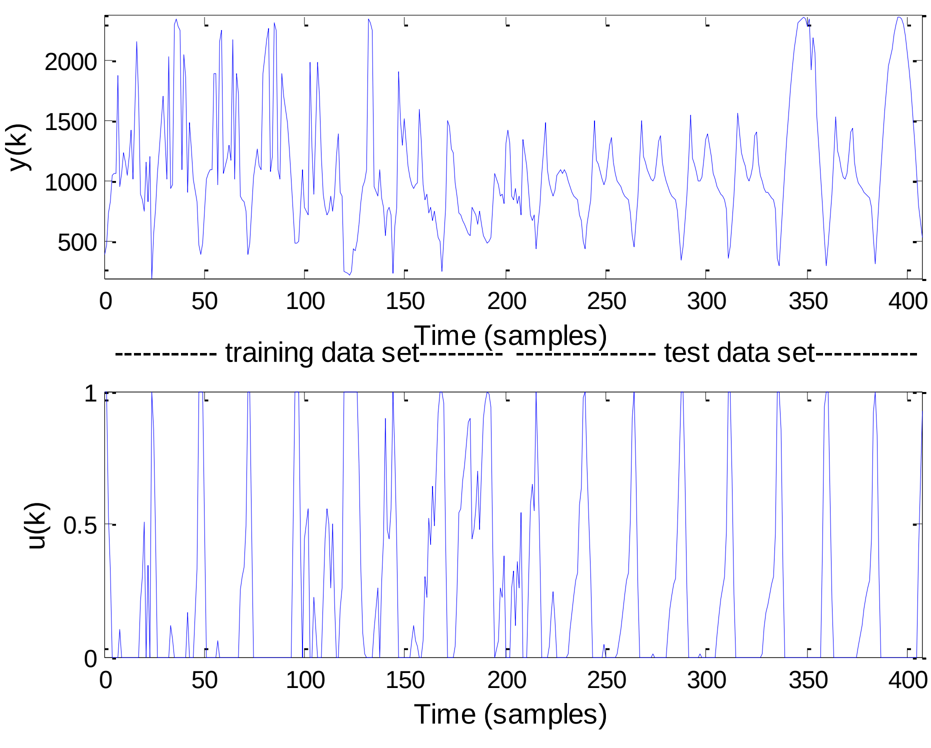


Figure 6.13 Training and Test Data Sets: *y(k)* - Simulated Illuminance in lux and *u(k)* -Blind Control Signals

6.4.2 Model Validation

The control surface of the two input model obtained after 200 training epochs has shown satisfactory results and is shown in Figure 6.14. The structure of the model is illustrated by the Figure 6.15. The total number of nodes is 53 with 24 premise parameters and 48 consequent parameters. The RMS error and step size graph of the model are displayed in Figure 6.16. It can be observed that at the end of 200 epochs, the RMSE of the training set is 0.00209 and that of the test set is 0.00219. The RMS errors are negligibly small, and hence the ANFIS captured the essential dynamics of underlying system. The RMSE of the test set being very close to that of training set indicates that the model exhibits a good generalization capability. It can also be noted from Figure 6.16 that most of the learning is done in the initial 130 epochs and hence we stopped training the model at 200 epochs. It was observed that the step size reduces to 0.0021 after epoch number 198.

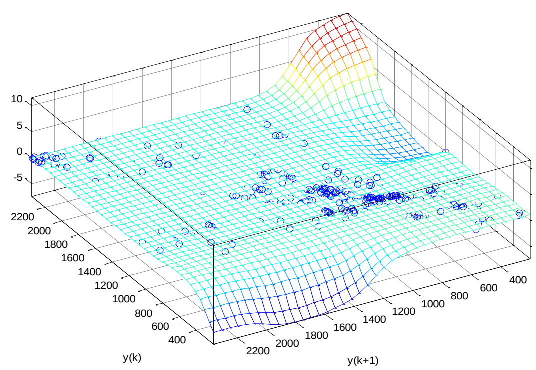


Figure 6.14 ANFIS Control Surface

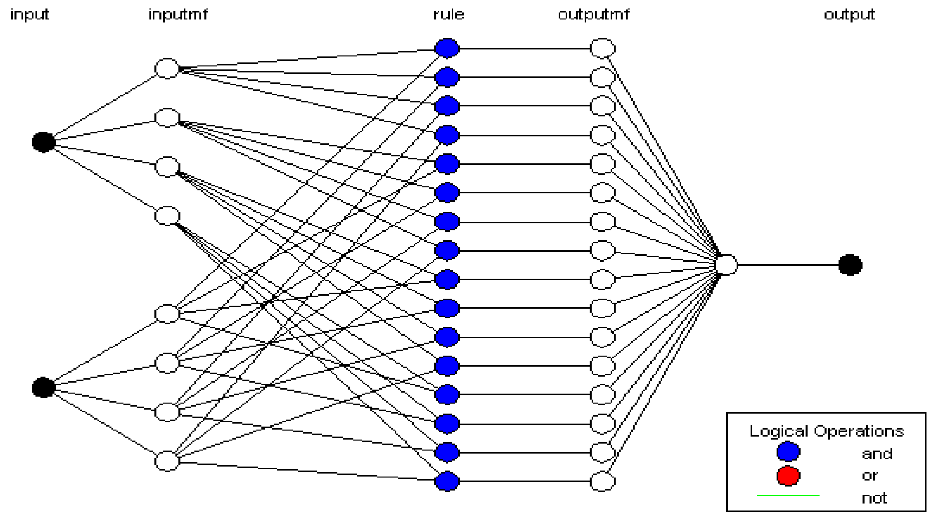


Figure 6.15 Structure of the ANFIS Model (connections from inputs to layer 4 are not shown)

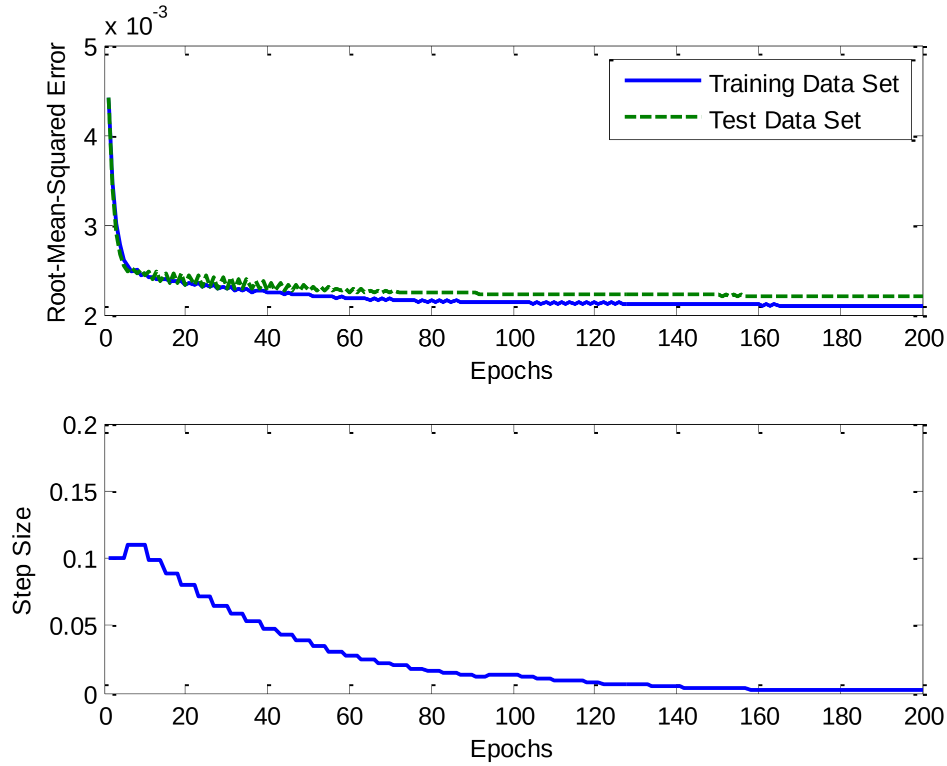


Figure 6.16 Error Curves and Step Sizes of the Obtained Model

Since the size of input-output data is large enough and is of good quality, fine-tuning of membership functions were done. The initial membership functions and the final membership functions obtained after training can be seen in Figure 6.17 and Figure 6.18 respectively. The four curves shown in different colours in both these figures represent the four g-bell membership functions of *y(k)* and *y(k+1)*, the inputs used for inverse learning. These membership functions describe the inputs with a varying degree of membership of low, medium, high and very high illuminance levels. For the design of fuzzy controllers, the best suited method of grid partitioning is made use of. This kind of partitioning involves many state variables as inputs to the controllers and requires only small number of MFs for each input as the number of inputs (*n*) and the number of membership functions on each input (*m*) would give rise to m^n rules.

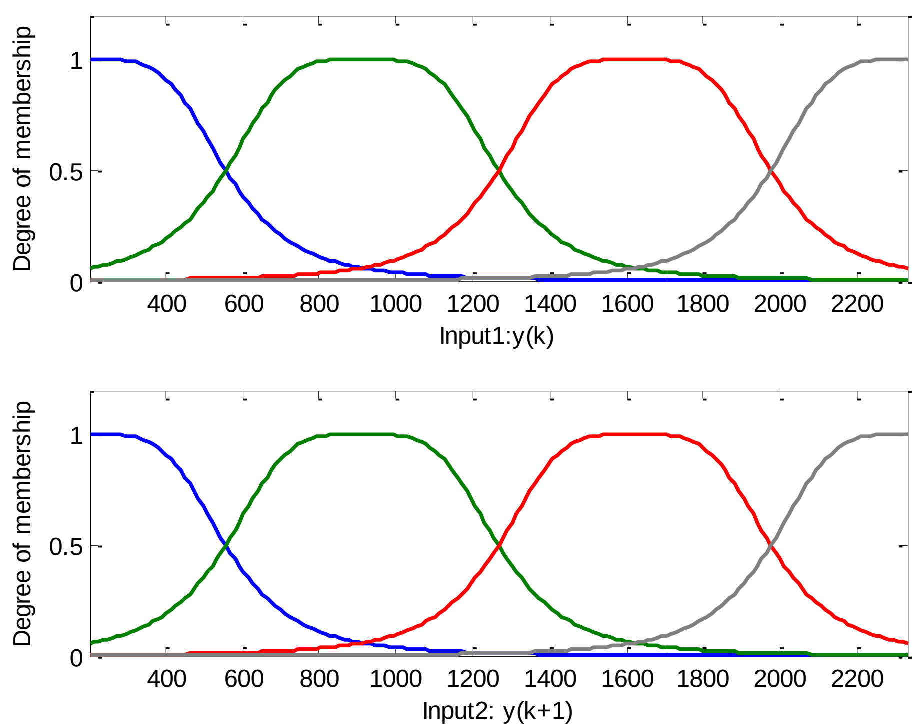


Figure 6.17 Initial Membership Functions: the four curves represent the four g-bell membership functions of the inputs *y(k)* and *y(k+1)*, before training.

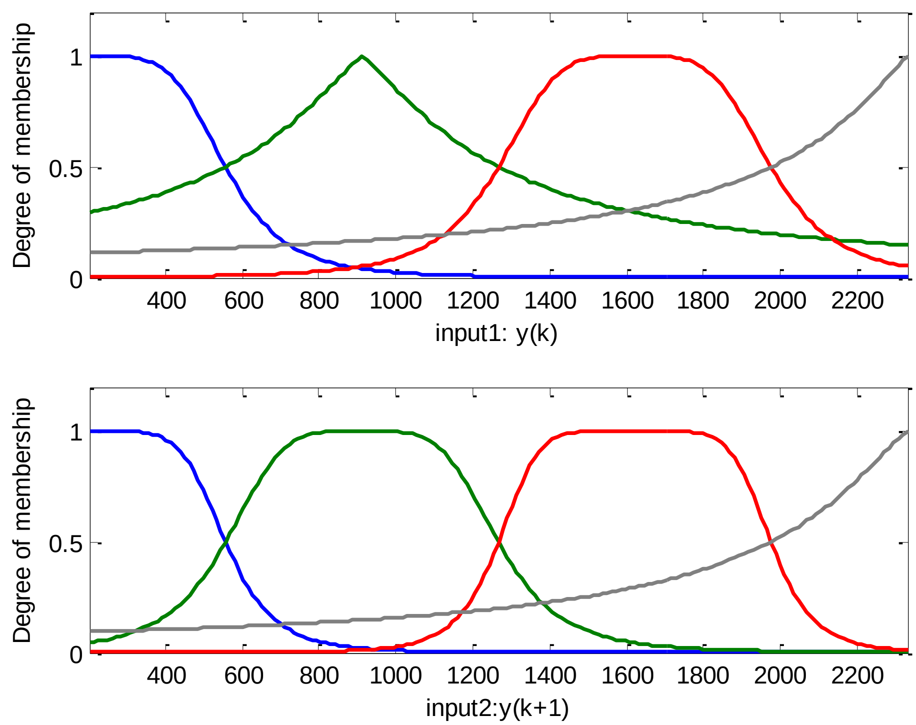


Figure 6.18 Final Membership Functions on the Inputs: the four membership functions take their final shape after training.

6.4.3 Inference Options

The functionality of five basic steps in the fuzzy inference process can be changed using the programming options of fuzzy logic tool box. The first two steps are fuzzifying the inputs to a degree of membership between 0 and 1 and applying the fuzzy operator. This is followed by applying the implication method to modify the output fuzzy set and to do truncation or scaling. The output fuzzy sets of each rule are then aggregated into a single output fuzzy set. Finally, this obtained fuzzy set is defuzzified into a single crisp number. These five basic steps are specified by the parameters and Method, or Method, implication method, aggregation method and defuzzification method in the fuzzy logic tool box for which the built-in methods available in the tool box are made use of. The chosen options for the obtained ANFIS structure in the proposed model are shown in Table 6.4. For constructing ANFIS structure, due to the higher complexity involved, we can specify only single output, obtained through weighted average defuzzification method. For Sugeno-type systems, the output membership functions are either linear or constant and the different rules cannot share the same output membership function. Also, unity weight for each rule is specified.

Table 6.4 Inference Options for the Obtained Structure

Parameters	Options Chosen
Type	Sugeno first order
And method	prod
Or method	max
Implication method	prod
Aggregation method	max
Defuzzification method	weighted average

Table 6.5 presents the complexity of the model obtained in summary.

Table 6.5 Complexity of the Model

Number of nodes	53
Number of linear parameters	48
Number of nonlinear parameters	24
Total number of parameters	72
Number of training data pairs	200
Number of test data pairs	200
Number of fuzzy rules	16
Number of epochs for training	200

6.5 Controller Validation

The controller validation is done with two types of scenarios. The first scenario uses an algorithm that maintains optimum illuminance levels while ensuring thermal comfort of the occupants, with due consideration to the hot climate of Dubai. The second scenario combines the daylight control with artificial lighting scheme with a strategy to reduce the dimension of control state search space when multiple luminaire and blinds are involved.

6.5.1 Visual and Thermal Comfort

The controller validation is done by developing a control algorithm that maintains optimum illuminance levels in the interior and testing the obtained controller. In a control cycle, this algorithm regulates the subsequent illuminance value if high levels of illuminance are observed at the task surface for a long time with the underlying assumption that such a condition would trigger heat gain for the occupants. The control algorithm has been developed to be requiring less computation, so that they are suitable for real time control, at the same time, effective enough to make control decisions according to the user-specified illuminance profile.

The control algorithm was developed and the obtained model was tested for the implemented routine. For ensuring both occupant comfort as well as optimum penetration of daylight into the interior, blind controllers have to work along with temperature controllers. The basic goal of the temperature controller is to keep the indoor temperature as close to the set-point temperature profile. The fuzzy logic controllers in their basic architecture consist of two control loops, one regulating the illuminance and the other, the thermal aspects (Kristl et al. 2008).

Heat gain due to lighting

Daylighting and the issues related to its associated heat gain in Dubai have been taken up by some researchers. Yannas (2007) mentioned that the daily values of global solar radiation on the horizontal are in the range of 3.7 to 7 kWh/m^2. There is a need for more holistic performance indicators and design procedures in daylighting systems that can be developed specific to the (hot) region, taking into account the heat gain factor (Bhavani and Khan 2008). Dubai receives high solar intensity in the summer period (May to August) at an average of 875 W/m^2 and this is above the American Society of Heating, Refrigeration and Air-conditioning Engineers' (ASHRAE) summer time (788 W/m^2) by 11% (Aboulnaga 2006).

Aboulnaga (2006) had done an investigation study on fifteen buildings of Dubai, in which a parametric analysis was conducted to compare different criteria such as thickness, shading coefficient, light transmission, reflection and relative heat gain. Out of the fifteen buildings taken up for that study, seven buildings exhibited almost a linear pattern between light transmittance and relative heat gain. Due to the misuse of glass, this pattern is observed (Aboulnaga 2006). Table 6.6 indicates the summary of this information. In keeping with this trend, the relative heat gain for the entire zone varies linearly with the percentage of visible light that is transmitted through the glazing. This means that the high illuminance levels on the task surface would translate into significant heat gain for the occupants while lower illuminance levels would lead to less heat gain.

Table 6.6 Relationship between Light Transmission and Relative Heat Gain in Dubai Buildings (Aboulnaga 2006)

Name of the Building	**Light Transmittance (%)**	**Relative Heat Gain (W/m^2)**
Mankhool tower	09	107
Emirates tower office	07	85
The tower	28	200
21st century tower	08	102
Dusit tower	07	86
Emaar residence tower	34	290
DICC	33	240

Since a user-specified illuminance profile of E_s to pE_s was defined, this illuminance range is considered to be corresponding to optimum conditions in which the heat gain is within the acceptable range. Optimal blind angles can simultaneously provide good daylighting and minimum heat gain in spaces (Hussain 2009). Having flexible range of illuminance level gives a high margin of choosing a good blind angle for minimum heat gain (Hussain 2009). In this work, illuminance levels above the threshold value of illuminance profile, pE_s are considered high enough to trigger significant heat gain for the occupants. Reinhart and Voss (2003) reported a similar observation that the occupants mostly accepted the automatic lowering of the blinds only when the illuminance on the facade of the building was above 50klux (~450 W/m^2), indicating that the occupants perceive heat gain only at high illuminance levels. Lindsay and Littlefair (1992) observed that short periods of sunshine had little effect on blind movement and that long periods of sunshine of over one hour generally triggered blinds to be lowered. Considering that the control cycle is repeated for every 30 minutes, it is assumed that the occupants would experience significant heat gain if high illuminance levels are maintained at the task surface for three consecutive control cycles. The thermal control loop is implemented in its basic form to indicate this condition to the blind control algorithm. The thermal control loop consists of a variable, *hgl* (heat gain due to lighting) which is set to 1, if high levels of illuminance are observed for three consecutive control cycles.

The scheme for controller validation that is implemented for this scenario is as follows: At time step k, the future desired state $y_d(k+1)$ is assumed to be available. This $y_d(k+1)$ is fed as one of the inputs to the controller during the application phase as shown in Figure 6.9 (b). To generate the sequence of values for $y_d(k+1)$, the control algorithm was built into a function. The function iteratively checks the following conditions at each time step k and assigns a value to $y_d(k+1)$ as given by the following control sequence:

(1) When the blinds are fully closed (u=0) due to the available illuminance being above pE_s, $y_d(k)$ is reduced by a fraction $r*p$ where p is the real number defined in the illuminance profile and r is the tolerance range for the occupant. This value is assigned to $y_d(k+1)$. This action slightly reduces the illuminance from that of defined value, but within the admissible tolerance. This tolerance range for the occupants was set at 3 to 5% in the control algorithm. (2) The thermal control loop iteratively sets the variable *hgl*, if the present and previous two time-step illuminance values of y_d are greater than pE_s. If *hgl is* set, y_d corresponding to the least u is assigned to $y_d(k+1)$. (3) If both the above conditions are not encountered, this means that a favourable $y(k)$ is maintained and the same has been assigned to $y_d(k+1)$.

The algorithm has been developed in such a way that it is not computationally too intensive for the control process to be effective. Establishment of optimum illuminance conditions at the task surface has been given a high priority in the control algorithm. Figure 6.19 shows the generated sequence of y_d and the variable *hgl*. The estimated control signals are plotted alongside the actual control signals and are presented in the top plot of Figure

6.20. The bottom graph shows the difference between the two that is seen as a negligibly small error signal which validates the controller for precision and flexibility.

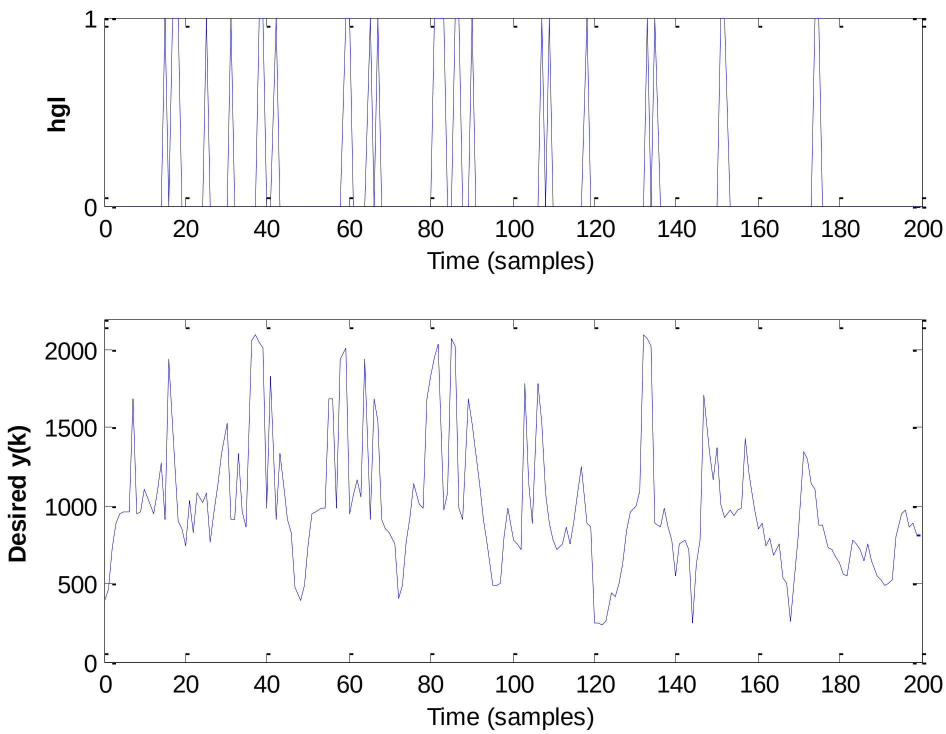


Figure 6.19 Signals Generated for the Controller: *hgl*-the Heat Gain Variable and $y_d(k)$-Desired Illuminance (lux)

When resulting illuminances are evaluated, the following information emerged. The user-specific illuminance profile is split into three groups for the sake of analysis and a preference function is defined as shown in the Figure 6.21. A wider illuminance range is assumed so that both the average illuminance and heat gain factors are kept within the acceptable range specified by the user.

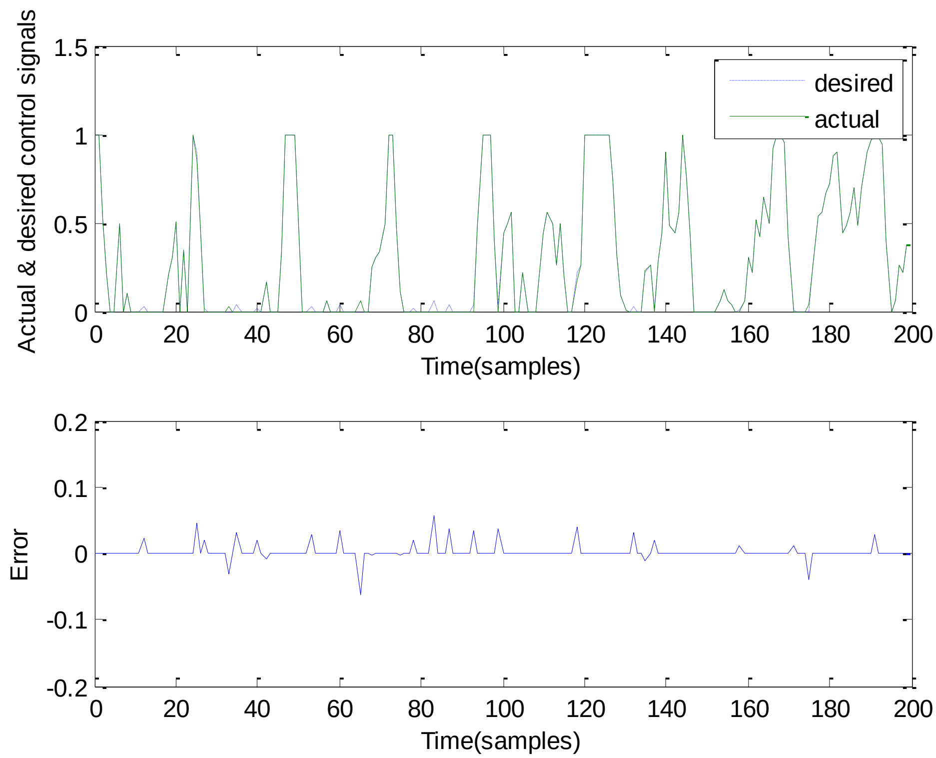


Figure 6.20 Controller Validation for Visual and Thermal Comfort

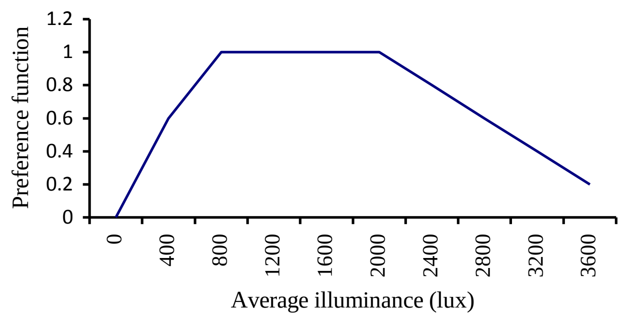


Figure 6.21 Preference Function for Average Illuminance

The percentage of total instances in which each group's specific illuminances would fall within this function is illustrated in Table 6.7. It can be observed that group 3 has a total instance of 53 % fall within its range.

Table 6.7 User Profile Group and Preference Function

User Profile Group	Time (samples)	Percentage of Total Instances within the Function
1	26	13
2	68	34
3	106	53

6.5.2 Integrated Lighting Scheme

When artificial light schemes are to be integrated with daylighting control, separately dealing the artificial light control options reduces the dimension of control state search space and cuts down the computing time. If various combinations of both daylight and electric light control options are to be assessed altogether, the possible number of states would become unmanageably large. For a four-luminaire, each capable of 3-step dimming, the electric lighting combinations will be 3^4, that is 81 alternatives are to be assessed in addition to the states of blind devices.

The integrated lighting scheme is validated by treating the artificial lighting options separately after the optimal position of blind is identified by the ANFIS controller. The following steps are done in sequence to identify the best control option for artificial light settings:

1) First, a blind position is identified as the initial state of the device. This is typically a u value at any given time k, derived from the controller. 2) The chosen blind position is combined with various combinations of luminaire and corresponding step dimming values. Here four luminaires each capable of maintaining three discrete power levels are assumed typically for 3 lamp T8 32 W set up. It is assumed that each luminaire has 33, 66 and 100 % power capability. The possible 81 alternatives are searched out to identify the best dimming options after evaluating all the candidate luminaire states. It can be observed from Table

6.8 is that the electric power saved because of the integrated scheme is between 59 to 67 % for the given control options.

Table 6.8 Best Dimming Options Suggested for *k*= 25

Dimming Level of Luminaire 1 (%)	Dimming Level of Luminaire 2 (%)	Dimming Level of Luminaire 3 (%)	Dimming Level of Luminaire 4 (%)	Power Consumed by Luminaires (W)	Power saved (%)
33	33	33	33	42.24	67.00
33	33	33	66	52.80	58.75
33	33	66	33	52.80	58.75
33	66	33	33	52.80	58.75
66	33	33	33	52.80	58.75

6.5.3 Reduction of Control State Search Space

In this thesis, since the inference system is used as a controller, it is imperative that it generates output pertaining to the best performance of the plant. In such a scenario, parameter identification is required and the same has been done by applying hybrid learning mechanism. As such, the ANFIS controller attains faster convergence to a control decision than the original pure back propagation method due to the presence of least squares algorithm that estimates optimal consequent parameters while keeping the premise parameters fixed. In such a situation, the consequent parameters are guaranteed to be the global optimum point in its parameter space because of the selection of squared error measure. The control state search space is an important parameter in building systems control applications involving several numbers of devices such as luminaries and blinds as illustrated in the previous section. The control state search space is an exponential function of the number of devices and hence the search space reduction is a very important advantage ANFIS offers to ease the burden of control process.

Also, the dimming options of artificial lighting have been dealt separately from that of daylighting control options. This approach reduces the possibility of having to deal with explosive number of luminaire and blind states all at once. Another advantage of this approach is that the luminaire information can be modified accordingly for any future change in their type, location, grouping and numbers. The typical time interval between the change in blind position and the corresponding change of dimming level of a luminaire in a real world situation is high enough to consider this approach as highly efficient from the view point of computational time and quick convergence.

In this work, the Relux Pro software took about 17 seconds to complete a simulation run with average indirect fraction while the time taken by ANFIS to validate the model and controller was found to be 8.5 seconds for 200 epochs and four MFs with step size equal to 0.1. This clearly highlights the advantage of combining simulator with ANFIS learner because it shows that the complex control process is eased by learning. Since system identification is embedded in ANFIS controller, the corresponding time is not separately considered. The average time for assessing the 81 dimming options is estimated to be 30 sec. Table 6.9 summarises the quick convergence of the combined approach of simulation and learning. The total number of simulation runs was made for 400 samples.

Table 6.9 Convergence to Control Decision

Method	Time Required (sec)
Simulation	6800
ANFIS training and validation	8.5
Average time for assessment of dimming control options	30

The speed of convergence of simulation is decided by many factors such as the precision needed in daylight calculations, presence of luminaires and furniture involving a high indirect component, the complexity of room configuration, multi room feature etc. In ANFIS learning, the step size chosen, number of membership functions, sample size, style of input space partitioning along with the type of hybrid learning rule that combines steepest descent with least squares estimation influence the convergence time. In each of these methods and while combining both the methods, the available computing power is also a major factor to be considered. Given these parameters remain the same, it is safe to say that ANFIS learning converges faster than the typical feed forward neural network. Table 6.10 provides the summary of the controller features.

Table 6.10 Summary of Controller Features

Features	Description/ Assessment
Sensor independent	the training data is obtained from simulation and thus is sensor-independent, the adoptable performance criteria for control option selection is not restricted
Data driven	capturing the non linear dynamics of source knowledge (Figures 6.11, 6.16)
Adaptability	due to the excellent learning ability of neural network back propagation
Compactness	due to smaller number of rules rather than using labels, desirable property of real time control
Smoothness	due to inference mechanism's ability to interpolate among rules
Generalisation capability	model response to the test set for prediction of output (Figure 6.16)
Flexibility	future changes of system, luminaires, room configuration and occupancy pattern can be accommodated (bottom plot of Figure 6.20)

Features	Description/ Assessment
Quick convergence	due to control state search space reduction and combining simulator with learner (Table 6.9)
Validation for occupant comfort	maintains an illuminance profile as desired by the user, visual and thermal comfort (Figure 6.20)

6.6 Further Discussion

ANFIS is used to achieve non linear mapping for capturing blind position dynamics, impacted by geographical, environmental and occupancy factors. In this work, the training was done offline in which the parameter updation takes place only after the entire training data has been presented whereas in an adaptive control scheme, the model could be further tuned online for time-varying dynamics. In such a case, the on-line learning and generation of the control sequence is done at every time step. This means that parameters are updated immediately after each input output pair has been presented and the control operation is enabled soon after. Figure 4.4 contains the ANFIS control scheme where on-line learning is made possible. As demonstrated earlier, the hybrid learning of ANFIS in itself reduces the convergence time substantially. Added to this, the dimming options of artificial lighting have been dealt separately from that of daylighting control options for control state search space reduction. This makes the model a very good candidate for real-time control purpose where the model predictions and control decisions happen within a very reasonable time frame.

Fuzzy rules of ANFIS are local mappings which facilitate minimal disturbance principle which is important in online learning. The adaptive capability reduces the output error for the currently trained pattern, at the same time, minimising the disturbance to the already learnt responses.

As can be seen in Figure 6.12, the training data is not very uniformly distributed across the input space of the controller due to the nature of plant dynamics. In spite of this, the model is able to emulate the complex pattern seen in the data. Parameter identification is done by applying hybrid learning rule so that the controller outputs result in best performance of the plant. To make the design more effective, structure identification is also obtained via the trial and error procedure of finding the number of membership functions on each input. Clustering is not attempted in this work because only two inputs are employed and hence the model does not suffer from "the curse of dimensionality" described in Brown and Harris (1994).

6.7 Conclusions

The data driven approach of ANFIS was used in this chapter to model the non-linear relationship by which a desired control option is chosen for the blind systems in a daylighting environment. The model obtained is able to maintain an illuminance profile between the set value and its multiple as desired by the user at all time. This modeling and control approach is suitable for any plant which can not be described by a set of mathematical equations.

The lighting simulation models that need to be controlled have to be computationally feasible to be considered for practical purposes. At the same time, they can not be too simple to model the complex control scenario. Hence hybrid learning of ANFIS has been used for parameter optimisation of consequent part which helps reduce control state search space. It is illustrated that the combination of simulation and supervised learning enhances the effectiveness of the control process. In this thesis, the existence of inverse dynamics of the plant is assumed. This means that the control signals to the blind can be described as an explicit function of current and next-step illuminance values. This assumption is completely true in the case of blind control systems of the real world. The controller is validated with an objective of providing occupant comfort in a hot region like Dubai where the issue of heat gain could easily overwhelm the benefit of daylighting.

The application of soft computing techniques in the built environment is a very promising field of research and would further pave way for more occupant friendly, energy-saving schemes in model-based adaptive control methods.

Chapter 7

Conclusion

With the catastrophic effects of climate change and environmental impacts looming large for our next generation citizens, the research community is now looking up for solutions to creating zero energy buildings in every possible geographic location. Automated and intelligent lighting control systems have emerged as a promising field of research since these systems when designed properly can not only create excellent occupant comfort but also decrease energy consumption in a building.

In the research study, which is done with respect to Dubai as the geographic location, it was found that the existing energy saving and control schemes vary in their types, mechanisms and patterns of use. These systems find their place in almost all landmark developments in commercial and hotel projects mainly for scene control and due to the ability to employ multiple control strategies simultaneously with a centralised intelligence. The study identified that meeting the requirements of property developers –not energy saving- is the biggest demand driver of lighting control business in Dubai. The objective of lighting control as an energy conservation scheme can be achieved if the government imposes tougher standards on commercial building energy usage. Further, the study observed that enforcing lighting power budget requirements in the region will have its share of challenges connected with manpower in areas such as training, enforcement, creating awareness and documentation. More buildings in the region are going for green status and LEED ratings which mean that the demand for these lighting control systems is on the rise. Daylighting the building is one such solution wherein the abundantly available sun's energy supplements or replaces the lighting energy, providing energy saving and comfort to the occupants. Daylighting systems, though highlighted by most of the manufacturers in the region are adopted in few projects.

Another way to create the dual goal of reduced energy consumption and increased occupant comfort is through the concept of intelligent buildings that have the ability to adapt themselves to changing environment and occupancy conditions. The lighting simulation models that need to be controlled have to be computationally feasible to be considered for practical purposes. At the same time, they can not be too simple to model the complex control scenario. In this thesis, simulation is combined with machine learning of ANFIS to model complex control process.

The cooperation between the simulation model and the learner is a two way process which works to the advantage of building systems control. The prediction by the simulator is improved by learning from the past inputs and should an alternative and unexpected control scenario occur in future, the model can adapt itself better for unknown conditions when tuned online. When simulation is combined with machine learning, simulator also acts as a validation tool for the machine learning model in addition to providing data for training.

The training data has been obtained from simulation and thus is sensor-independent. The data driven approach of ANFIS was used in this thesis to model the non-linear relationship by which a desired control option is chosen for the blind systems in a daylighting environment. The controller obtained is able to maintain an illuminance profile between the set value and its multiple as desired by the user at all time. The modelling and control approach mentioned in this thesis is suitable for any plant which can not be described by a set of mathematical equations. ANFIS being a hybrid (neuro fuzzy) system offers advantages such as tackling uncertainty, vagueness and also catering to high-dimensionality. Since ANFIS is used as a controller in our work, it is imperative that it generates output pertaining to the best performance of the plant. To achieve this, parameter identification is done by applying hybrid learning rule so that the controller outputs result in best performance of the plant. To make the design more effective, structure identification is also obtained via the trial and error procedure of finding the number of membership functions on each input. The controller validation is done by means of an algorithm that maintains optimum illuminance levels while ensuring thermal comfort of the occupants, with due consideration to the hot climate of Dubai. The energy saving, daylight-artificial light integrated control has been tested with the purpose of demonstrating its quick convergence when launched in a scenario of multiple luminaires and blinds and the results are encouraging.

The results show that the ANFIS controller attains faster convergence to a control decision when compared with pure simulator. This is due to the presence of least squares algorithm that estimates optimal consequent parameters while keeping the premise parameters fixed. The hybrid learning of ANFIS also helps reduce control state search space which is important in integrated lighting schemes that contains multiple luminaires and blinds. It is observed from the above points that the combination of simulation and ANFIS learning enhances the effectiveness of the control process. In addition to its prime feature of adaptation to occupancy and environment, the model exhibits excellent prediction capability, flexibility, generalisation capability, compactness and smoothness.

This specific model-based approach is promising because of its capacity to do away with the sensor dependency and the resulting model is more compact (due to smaller number of rules than labels), smooth (due to the inference mechanism's ability to interpolate among the rules) and adaptive (due to the neural network's back propagation).

7.1 Contributions

This work contributes in many ways to the field of building simulation with particular reference to automation in lighting control systems. The main contribution of this research is summarised as follows:

1) An exhaustive literature review of the energy saving and integrated lighting control system installations has been conducted and the gap in the existing research identified. Some of the case studies of present installations in Dubai have been presented.
2) A research study to analyse the present trends and future direction of various lighting control systems in the new projects of Dubai has been done. The study observed that the objective of lighting control as an energy conservation scheme can be achieved if the government imposes tougher standards on commercial building energy usage and identified the challenges associated with developing and enforcing such standards. The study also explored the industrial feasibility of residential consumers to opt for lighting controls.
3) A new technique of using ANFIS for blind position control has been proposed and implemented in this work. The model is built with user specific illuminance criteria and launched as a controller which is capable of dealing with the dynamic, non linear conditions.
4) The effectiveness of combining simulation and ANFIS learning has been accentuated. The simulator provides prior knowledge to the learner which effectively tunes the system towards adapting to the non-linear characteristics of occupancy and environment conditions. The resulting system is thus senor-independent, at the same time, capable of handling complex control parameters. ANFIS learning exhibits definite advantages over pure fuzzy logic methods or neural network learning when implemented in a controller. The integrated scheme is very effective for

buildings involving multiple luminaires and blinds because of control state search space reduction and quick convergence.

5) The main objective of the controller was to create optimal conditions for the occupants and the validation has been done with visual and thermal comforts of the occupants as its major priorities. In this work, attention has been paid to providing occupant comfort in a hot region like Dubai where the issue of heat gain could easily overwhelm the benefit of daylighting.

7.2 Future Scope of Research

The following are suggested as the extension of this work for future research.

Promotion of daylighting systems in the region

With respect to the study regarding the potential and gap of lighting control systems in Dubai, there is a lot of scope for future work as given under:

1) A complete study on knowledge and awareness among the public about building energy efficiency as a whole and lighting efficiency in particular is not well documented in the region and hence this can be taken up as a pilot study.
2) The significant data on energy audit on major landmark projects and subsequent feedback on actual installations can be collected and presented.
3) The satisfaction and comfort index analysis done on the general public who has been given the personal control option can throw light on the need to develop and bench mark the design criteria, which could potentially develop into region-specific information.
4) Ultimately, an energy efficient model encompassing the standards and best practices appropriate for the environment of Dubai can be built which could serve as an indicator for the entire region to follow in the future.

5) There is a need for more holistic performance indicators and design procedures in daylighting systems that can be developed specific to the (hot) region, taking into account the heat gain factor. Large scale field experiments and measurements need to be conducted to investigate the specific issues related to the modelling of heat gain and solar radiation in this region and their relationship with light transmission.

Improvisation in model design

The following are some suggestions for model design that can be attempted to see the effectiveness of the control process.

1) The computational complexity of ANFIS can be decreased by a variety of methods to accommodate scenarios requiring larger number of inputs. These include using "don't care" values in rules or using heterogeneous partitioning for state variables.
2) In addition to using least-squares method, the step size also controls the convergence time to a control decision and hence the same can be attempted.
3) Using GA schemes, the control actions of the system can be customised to individual occupant's requirements. Interpreting and analysing the user interactions can act as a guide to designing this learning approach.
4) The thermal control loop can be implemented in a more elaborate way, if the thermal behaviour of the system can be made known. For this, the heat gain modelling studies are of prime importance as mentioned earlier.