Occupancy Driven Supervisory Control of Indoor Environment Systems to Minimise Energy Consumption of Airport Terminal Building

by

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A Doctoral Thesis

Submitted in partial fulfilment of the award of Doctor of Philosophy of Loughborough University

(20th May, 2013)

ABSTRACT

A very economical way of reducing the operational energy consumed by large commercial buildings such as an airport terminal is the automatic control of its active energy systems. Such control can adjust the indoor environment systems' setpoints to satisfy comfort during occupancy or when unoccupied, initiate energy conservation setpoints and if necessary, shut down part of the building systems. Adjusting energy control setpoints manually in large commercial buildings can be a nightmare for facility managers. Incidentally for such buildings, occupancy based control strategies are not achieved through the use of conventional controllers alone. This research, therefore, investigated the potential of using a high-level control system in airport terminal building. The study presents the evolution of a novel fuzzy rule-based supervisory controller, which intelligently establishes comfort setpoints based on flow of passenger through the airport as well as variable external environmental conditions. The inputs to the supervisory controller include: the time schedule of the arriving and departing passenger planes; the expected number of passengers; zone daylight illuminance levels; and external temperature. The outputs from the supervisory controller are the low-level controllers' internal setpoint profile for thermal comfort, visual comfort and indoor air quality. Specifically, this thesis makes contribution to knowledge in the following ways:

- It utilised artificial intelligence to develop a novel fuzzy rule-based, energy-saving supervisory controller that is able to establish acceptable indoor environmental quality for airport terminals based on occupancy schedules and ambient conditions.
- It presents a unique methodology of designing a supervisory controller using expert knowledge of an airport's indoor environment systems through MATLAB/Simulink platform with the controller's performance evaluated in both MATLAB and EnergyPlus simulation engine.
- Using energy conservation strategies (setbacks and switch-offs), the proposed supervisory control system was shown to be capable of reducing the energy consumed in the Manchester Airport terminal building by up to 40-50% in winter and by 21-27% in summer.
- It demonstrates that if a 45 minutes passenger processing time is aimed for instead of the 60 minutes standard time suggested by ICAO, energy consumption is significantly reduced (with less carbon emission) in winter particularly.

The potential of the fuzzy rule-based supervisory controller to optimise comfort with minimal energy based on variation in occupancy and external conditions was demonstrated through this research. The systematic approach adopted, including the use of artificial intelligence to design supervisory controllers, can be extended to other large buildings which have variable but predictable occupancy patterns.

ACKNOWLEDGEMENTS

بسم الله الرحمن الرحيم

All praises is due to Allah; the lord of the worlds.

I am very grateful to my supervisors; Dr Mahroo Eftekhari and Dr Thomas Steffen for their professional guidance, unwavering supports, stimulating suggestions, comments and patience in reading through numerous papers and multiple drafts of this thesis. Particularly, I want to thank Dr Mahroo for inspiring me to do a PhD in the first place and her sincere show of concern for my numerous personal issues throughout the course of this study.

I also want to extend my warm regards to my colleagues in Loughborough University; Dr Saleh Altwaijri, Dr Zulfikar Aliyu, Muhammad Waseem, Faisal Durami, Dr Abdullahi Aliyu, Dr Ayodeji Akiwowo, and Ahmed Muhammed, in De-Montfort University; Dr James Parker and Tawfeeq Ibn Muh'd, in University of Sheffield, Dr Musa Abdulkareem, in Kent University, Kotopouleas Alkis, in Brunel University, Baboo Gowreesunker, in London South University, Misibahu Muhammad and Muhammad Nasidi in University of Abertay Dundee, who supported this journey one way or the other. Also my gratitude goes to other staffs of School of Civil and Building Engineering, Loughborough University and to Environment Staffs, Manchester Airport for facilitating data collection.

I give special thanks to my darling wife Ruqqayah, my beautiful kids, Ahmad and Maryam for their patience and supports and to my family and friends in Nigeria for their supports and prayers.

My gratitude also goes to my sponsors ESPRC and PTDF and my employer, FUT Minna for providing me with the necessary financial backing for this degree.

I am sure there are many others too numerous to mention here. Thank you all.

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CHAPTER 1: INTRODUCTION & GENERAL BACKGROUND

1.1 INTRODUCTION

This chapter provides a general overview of the research problem. It states the nature of research collaboration with other UK universities and explained what aspect of the research theme is the main concern of this study. The overall goal, aim, objectives, methodology and scope of this work will be defined, followed by the listing of the thesis organisation.

1.2 RESEARCH COLLABORATIONS

This research was funded by the Engineering and Physical Sciences Research Council (ESPRC), United Kingdom in its 'SANDPIT-Integration of Active and Passive Indoor Thermal Environment Control Systems to Minimise the Carbon Footprint of Airport Terminal Buildings'. This project brings together research teams from five UK universities; Kent, Brunel, City, Loughborough and De Montfort to investigate and develop active and passive technologies and real time integration and control methodologies for the management of the thermal environment of airport facilities.

The research component being undertaken by Kent University focuses on investigating and quantifying airport passenger's comfort requirements through measuring of the physical environmental conditions and recording passenger perceptions of the terminals microclimate with a view of providing environmental systems' setpoints for improving passengers comfort while at the same time saving energy.

Brunel University is undertaking the identification and characterisation of suitable materials for passive thermal control based on phase change materials and slurries (PCM and PCS) by developing small-scale experimental test facilities, establishing performance characteristics for different system arrangements and considering system integration and performance.

City University is concerned with investigation of Phase Change Materials (PCMs) using the T-history method by selecting sensor technologies to determine in real-time thermal energy stored in PCM and PCS materials.

De Montfort University in Leicester is concerned with how UK airports can reduce the carbon footprint of their buildings by using East Midlands, Birmingham and Manchester airport case studies to analyse carbon emission saving refurbishment options.

Loughborough University develops a Model Predictive Controller (MPC) of integrated energy systems for airport terminals on one hand and on the other hand, this project develops an occupancy-driven fuzzy supervisory controller to minimise energy use in airport terminal. Therefore, this research topic is a small part of the larger research theme, with other collaborative parts being undertaking by other researchers across the five UK universities (see Figure 1-1). Further details about the research collaboration can be found in the *appendix 1*.

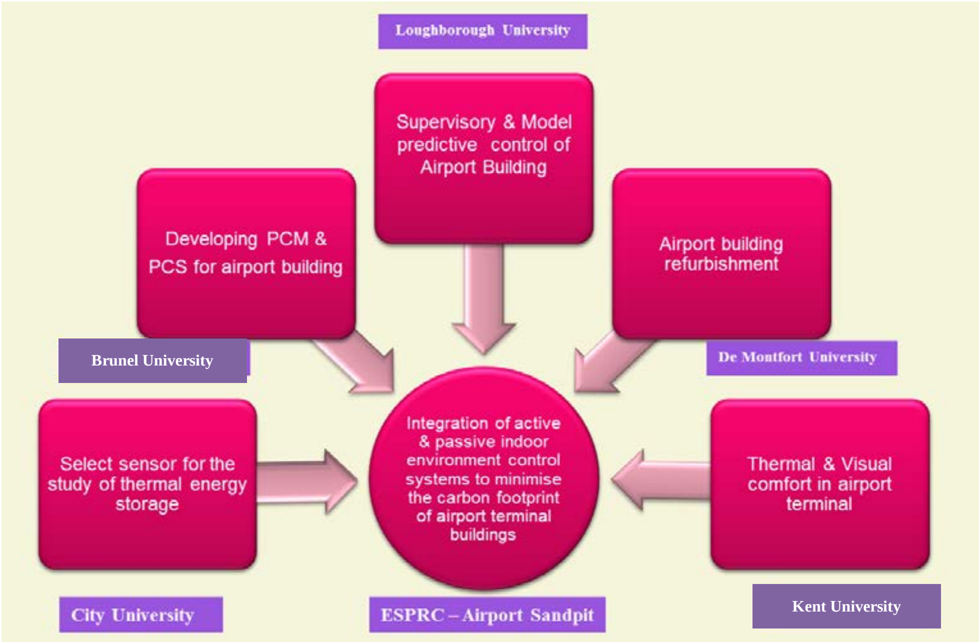


FIGURE 1-1: Research Collaboration

1.3 Background to the Research Project

The idea of sustainability in the built environment seeks to reduce the negative impact of buildings on the environment by enhancing efficiency not just in the use of construction materials but of increasing importance, the use of energy in operating buildings.

The issues surrounding the need to reduce energy use in buildings include climate change, increasing energy cost (Figure 1-2) and instability in major world supply sources of fossil fuels and the need to ensure energy security and create more employment.

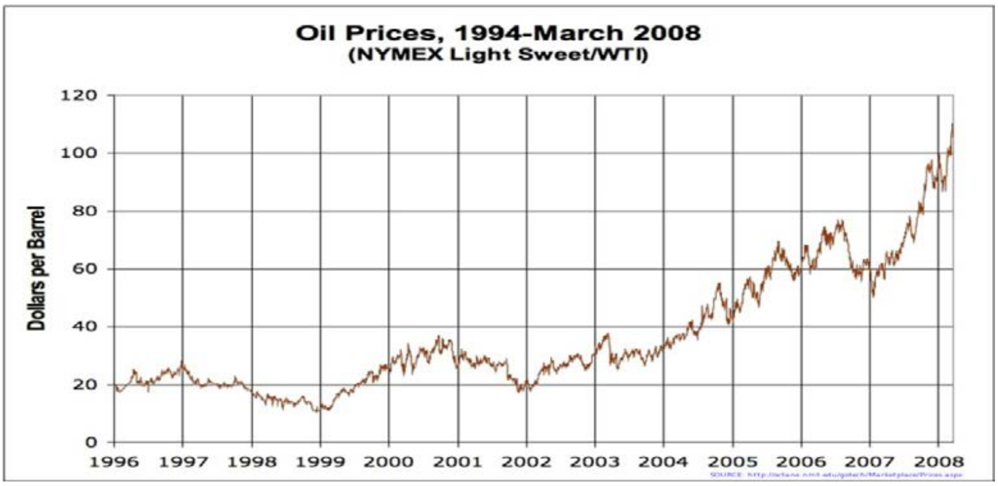


FIGURE 1-2: Soaring Oil Price (http://priceofoil.org/content/uploads/2008/06/oil_prices.png)

A conservative estimate puts the world's total carbon dioxide emission between 6.2 – 6.9 billion tons of carbon per annum. Provisional results showed that UK emissions of greenhouse gases stood at 544 million tonnes of carbon dioxide equivalent thereby contributing about 2% of the global carbon emission in 2008 (DEFRA 2008).

UK sets an ambitious target for overall CO_2 reductions of 80% by 2050 relative to 1990 level as her contribution in the global effort at combating global warming and climate change.

Aviation contributes only about 6.3% of UK's carbon emission (Pejovic, Noland et al. 2008). It may be argued that this impact is low but the projected growth in aviation is of growing concern; UK's aviation is growing at approximately 8% per annum and as highlighted by the Tyndall integrated scenarios project, under some growth projections, the lion's share of the UK's allowable CO_2 emissions will be derived from aviation by 2050 (Anderson 2005). In addition, building energy consumption has already reached over 40% of the total global energy consumption and has since surpassed other economic sectors (Perez-Lombard, Ortiz et al. 2008). So, while building engineers may not influence fuel or engine technology, they can help to significantly reduce or eliminate carbon emissions associated with designing and adapting airport infrastructure. Therefore, to achieve any meaningful emission savings in UK airports, terminal buildings' energy use must be given adequate attention.

The good news is that on the overall scale, buildings offer greatest cost effective and fastest means of carbon emission mitigation compare to other sector of the economy as illustrated in Figure 1-3. *This figure provides estimated sectorial economic potential for global mitigation for different regions as a function of carbon price in 2030 from bottom-up studies, compared to the respective baselines assumed in the sector assessments* (IPCC 2007).

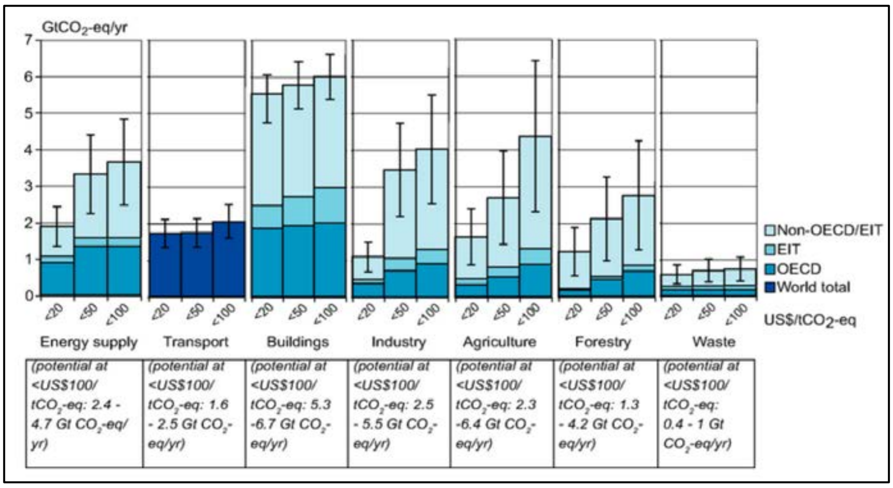


FIGURE 1-3: Estimated Economic Potential for Carbon Emission Reduction by Sector Based on Projected Available Technology Potential In 2030 (IPCC 2007)

The problem of energy consumption to provide thermal and visual comfort in work and living spaces has attracted much attention in recent years spurred initially by the incessant increase in the cost of fossil fuel and recently by the accruing evidence of environmental degradation resulting from the use of energy. This has resulted in renewed economic and political pressures, which has forced the aviation industries and its infrastructures to be reset within the concept of reducing the effect of global warming and to reduce maintenance and operating cost. The architectural and engineering responses to these concerns include developing renewable energy alternatives to fossil fuels and reducing the need for expending energy through optimal use of sustainable technologies such as passive designs and regulating the active building components (Szokolay 1998) to come on or off only according to their demand in the buildings.

While adopting sustainable construction and retrofit materials and method (initial and recurring embodied energy) is important in carbon emission mitigation, it is the building's operational energy that offers greater potential in gaining substantial reduction. This is because while embodied energy remains fairly stable throughout the life of a building, operational energy is always on the increase. A study by Cole and Kernan, 1996 (Figure 1-4), shows over a 50 years life cycle of a building, operational energy constitute 85.5% of its entire energy use (Cole, Kernan 1996).

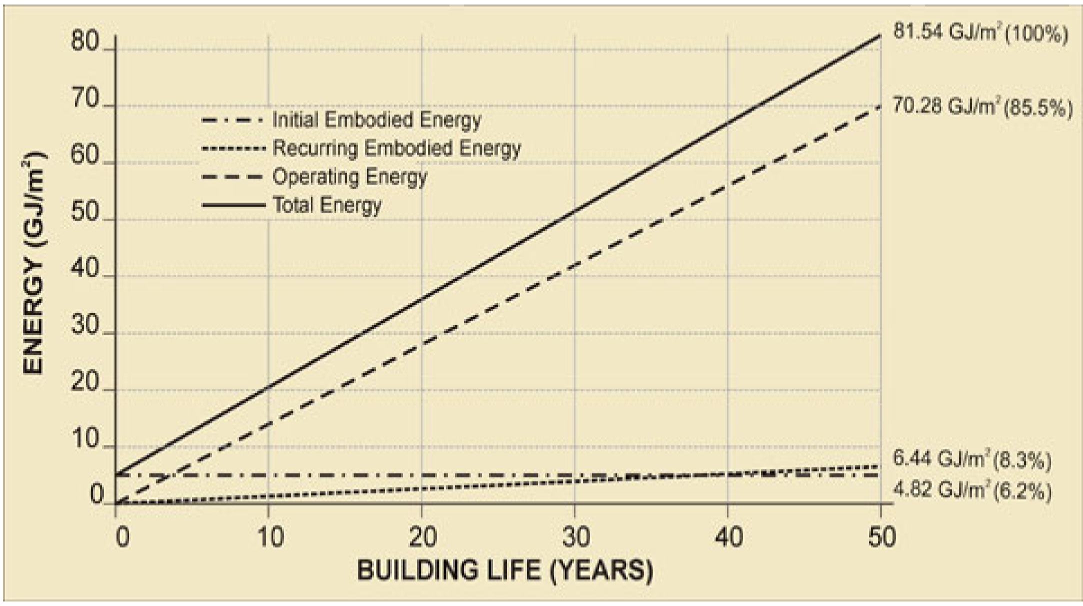


FIGURE 1-4: Energy Use During 50-Year Lifecycle of Typical Office Building (Cole, Kernan 1996)

HVAC and lighting of enclosed spaces are regulated to ensure: health and comfort for human occupants, proper storage conditions, proper functioning of sensitive electronic equipment and machines or to support some processes that will only do well within a prescribed range of temperatures and relative humidity, and importantly, to do all these at optimal energy consumption. Therefore, the drive for energy efficiency must be balanced with the need to provide adequate comfort to ensure that the occupied space is made conducive for its intended function. To achieve this objective of HVAC it follows therefore, that the degree of conditioning of a space depends among other things on the nature of the occupants and use of the space (Nikolopoulou, Baker et al. 2001a).Therefore, overall building energy efficiency will depend strongly on the space comfort requirements and the appropriate selection of the climate control system (Piechowski, Rowe 2007). From the preceding scholarly opinions, it is therefore necessary to consider airport terminal building separately because of its unique; indoor characteristic, use of space and occupancy.

The most cost-effective way to improve the energy efficiency of any building is often achieved through the application of an efficient control strategy for the indoor environment systems. Such strategies may include shutting down plant or setting back/up setpoints of indoor environment systems as the case may be during the period that the building is not occupied and providing optimal setpoints for comfort during occupancy. In most cases, airport terminal indoor environment systems run on designed conditions and do not have fine control based on detailed passenger flow information. While opportunities for complete shut-down of HVAC and lighting systems are limited in busy airport terminals due to round-the-clock operations opportunities exists to save energy by applying appropriate setpoints during occupancy conditions and set-back operation during unoccupancy conditions as an energy saving strategy for the indoor spaces of airport terminal.

Although building control systems are already being used in many airports building control application in the developed world, reports of unsatisfactory energy performance and the need for a more competent control system and strategies are common. The reason for this sub-optimal performance are many but chief among them is that the conventional control systems are designed for linear and constant operation but airport terminal building control operations are complex, highly non-linear, time invariant and multivariable.

Fuzzy logic as a branch of engineering has evolved as a way of representing imprecise human knowledge. For complex systems like buildings, it is difficult to describe its behaviour in a transparent and precise manner entirely through mathematical modelling. In this information age, human knowledge or expertise has become important in this regard. Fuzzy logic theory allows this expertise or knowledge to be combined with mathematical model and sensory measurements in a form suitable for digital computer processing through the use of fuzzy sets (Wang 1997).

1.4 Overall Research Goal

The overall goal of this research is to develop a rule-based fuzzy supervisory controller to regulate the conventional controllers in providing and varying comfort setpoints within indoor space in accordance to passenger flow and external conditions in order to maintain acceptable comfort conditions at reduced energy. The reason behind this approach is that rule-based controller is especially suitable for complex systems that are difficult to model from first principle but can be described using expert rules from operator's experience such as the airport terminal buildings.

1.5 Aim of the Research

This study will investigate and develop an indoor environment energy management system that will provide acceptable indoor environment and also guarantee further reductions in the carbon footprint of airport terminal buildings compare to existing building control systems in use.

1.6 OBJECTIVES OF THE RESEARCH

The objectives of this project are:

1. To undertake a literature review on existing indoor climate control systems in airport terminal buildings
2. To provide an integrated and intelligent real-time control of passive and active building environment components taking control of:

   i. indoor visual comfort levels,
   ii. thermal comfort levels and
   iii. indoor air quality

   in response to changes in:

   i. external conditions,
   ii. occupancy levels and
   iii. Passenger flows.

3. To analyse this controller and quantify its performance compare to a baseline control solutions.

1.7 METHODOLOGY OF THE RESEARCH

Indoor environment characteristic of airport terminals is analysed to gain sufficient understanding that will help in the formulation of necessary control strategy and the definition of adequate environmental setpoints.

Climate control systems currently used in buildings will be reviewed to establish their performance characteristics, their limitations and energy consumption especially as it relates to airport building. This is to generate design requirements and benchmarks for alternative systems or for an improvement over the existing ones.

A multi-variable controller will be developed using MATLAB/Simulink simulation packages. The model of the building will be implemented in DesignBuilder based on EnergyPlus simulation engine and the controller will be implemented offline through computer simulation in the MATLAB-Simulink environment. The output setpoints of the controller will be converted to HVAC and lighting schedules and used as input in the DesignBuilder airport building model. Results of improvement in energy consumption, carbon emission and comfort will be documented and analysed. This section's framework is provided in Figure 1-5.

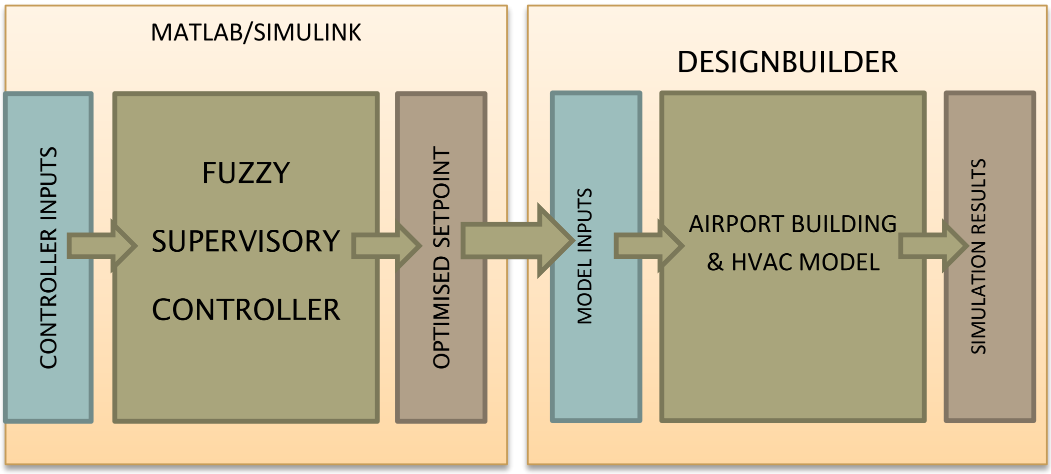


FIGURE 1-5: Framework of Research Methodology

1.8 ORGANISATION OF THESIS

This rest of the thesis is organised as follows:

CHAPTER TWO: This chapter review energy issues, occupancy flow, and environmental characteristics of airport buildings. Lastly, it will review building occupant's comfort in general and airport terminal indoor comfort in particular.

CHAPTER THREE: This chapter introduces building control systems. It also provides a general overview of systems and levels in building control. It reviews the literature on the general application of various control systems types in building and fuzzy logic in particular.

CHAPTER FOUR: This chapter presents the methodology, justification and limitation of the approach used. It ends with the description of the base case airport building model.

CHAPTER FIVE: This chapter discusses the current airport indoor environmental systems' comfort performance and compare it with the standard comfort requirement for such places while also exploring the opportunities for implementing energy conservation based on variation in passenger flow and external conditions.

CHAPTER SIX: This chapter detail discussions on fuzzy logic control modelling and elucidates on the theory of fuzzy sets and its basic operations. It also discusses fuzzy logic control theory in general and the design and validation of supervisory controller for airport building in particular.

CHAPTER SEVEN: This provides the general summary, conclusions and recommendation for future works.

CHAPTER 2: LITERATURE REVIEW ON COMFORT IN AIRPORT TERMINALS

2.1 INTRODUCTION

This chapter reviews energy issues, nature of occupancy, and environmental characteristics of airport buildings. It will also describe the building and HVAC system characteristics together with building occupant's comfort in general and airport terminal indoor comfort in particular. The major aim is to identify and define major comfort parameters and their relations with the building in providing occupant's comfort. This will form the basis of developing the fuzzy supervisory control strategies to provide comfort while at the same time reducing energy consumption of the terminal building. The other purpose of the chapter is to present a general overview of all airport issues relevant to this research.

2.2 ENERGY ISSUES IN AIRPORT TERMINAL BUILDINGS

Air transport is a novel concept that brings rapid economic and social transformation and it connects people, countries and cultures. It promotes trade and tourism and grant access to the global markets. Therefore, airports are major magnets of economic growth and development and because only about 5% of the population of the world have ever flown (Worldwatch Institute 2007), it is an area with huge capacity for further growth. However, like all human activities, airports have great impact on the environment. These impacts includes water and air pollution, waste generation, noise pollution, extensive use of land resources and the use of fossil energy which has been identified as a major culprit for climate change (Turnbull, Bevan 1995, Moussiopoulos, Sahm et al. 1997, Unal, Hu et al. 2005).

An air transport infrastructure is made up of three components; the airspace, airfield and the passenger terminal (Jim, Chang 1998). The airspace is occupied by aircraft in flight. The airfield on the other hand is made up of the airside and the landside. The airside is used by aircraft on the ground (stationary and in motion) and include infrastructures such as airport runways, taxiways, ramps, aircraft hangers, and control towers. The landside comprised supporting infrastructures (not used by aircrafts) such as the parking lots, bus and train stations and access road that are used to ferry goods and people to and from the airport (Jim, Chang 1998).

The airport passenger terminals are buildings in airports where passengers transfer from other ground mode of transportation to the facility that allows them to embark or disembark from an aircraft. It separates the airside from the landside and provides facilities that make this transition possible. Passenger terminal is an essential unit of the airport estate.

According to classification by (Horonjeff, McKelvey et al. 1975); the passenger terminal comprised three components:

- The *access interface*: this is where the passenger transfers from the land access mode of transportation to the passenger processing component. The activities that are carried out here include: Circulation, parking, and curb side loading and unloading of passengers.

- The *processing* area: this is where passengers are processed for beginning, ending, or continuation of an air journey. The basic tasks here are: ticketing, baggage check-in, baggage claim, seat assignment, federal inspection services, and security.

- The *flight interface*: Is where the passengers move from the processing section to the aircraft. The activities carried out here are assembly, conveyance to and from the aircraft, and aircraft loading and unloading.

Aviation industries do not only have to cope with growth and expansion issues, they also have to cope with some changes in politics and society. For example the introduction of European free trade zone, the Schengen zone, the new flight pattern to curtail noise and pollution and of recent, international terrorism all have huge impact on the way air transport industry are organised and operated (Gatersleben, Van der Weij 1999). So, although the air transport industry is constantly changing, the passenger terminal is one of its permanent features. The average life of the airport terminal is about 50 years. This is often more than the life of the airline company and about two to three times the life of an aircraft (Edwards 2005).

The reputation of an airport depends to a great extent on the quality of its terminal building. According to Brink and Madison (1975) passenger's perception of the quality of air terminal is predicated on the following factors (Brink, Maddison 1975):

a) Time necessary to be processed through the landside,

b) Reliability or predictability of processing time,

c) Reaction to overall landside environment,

d) Physical comfort and convenience,

e) Treatment by airline, concessionaire, security and other airport personnel,

f) Cost of air fare and airport services,

g) Type of passenger and purpose of trip,

h) Frequency of air travel, and

i) Expectation of level of service

Also, in Airport Development Reference Manual (IATA 1995), for an airport passenger terminal to score A, in the International Air Transport Association (IATA) A-F scale, it has to fulfil; excellent level of service, satisfy condition of free flow and provides excellent level of comfort. It is clear from the forgoing criteria that physical comfort is important in the quality of airport terminal building.

Depending on its capacity, the airport terminal, process millions of passengers per year. Within the airport terminals, passengers purchase tickets, move luggage and go through security checks. In addition, in order to maximise marketing and rental opportunities, modern airport terminals are known to contain several commercial enclaves. Airport own, manage and lease large pieces of the enclosed spaces within the terminals. They have extensive restaurants, retail shops and leisure facilities. These have led to increase in the demand for higher thermal and visual comfort conditions; so although compare to the aircraft and surface transport within the airport, passenger terminal building consumes less energy, it has a higher energy consumption rate compare to other commercial buildings (Babu 2008); in fact, airport terminals are among the greatest energy consuming centres per kilometres on our planet (Edwards 2005).

Every year about 200 million people transit through UK's airport (Aviation Foundation 2013) which has resulted in demands for huge amount of energy and created an equally huge amount of carbon emission. A large airport can consume more energy than a city of 50,000 households; for example, in 2008 UK's largest airport, Heathrow Airport, consumed over 1000 GWh of energy (Heathrow 2010) compared to an average of about 20 MWh (OFGEM 2011) for UK's dwellings. Therefore, any little energy saving effort in the way airports terminals are built and operated can result in huge energy savings.

United State Department of Energy (USDE) report that based upon the comparison of energy use in 200 US airports, building and systems design seems to exert greater influence on energy consumption than the climate or geographical location of the airport terminals (US Department of Energy 2003). This means that improving airport building and system efficiency is a sure way to make huge savings in energy.

Figure 2-1 shows the breakdown of CO_2 emission from Manchester airport, which was used as the case study of this research. It is worth noting that up to 18% of the total CO_2 emission comes from energy use to run the terminal buildings.

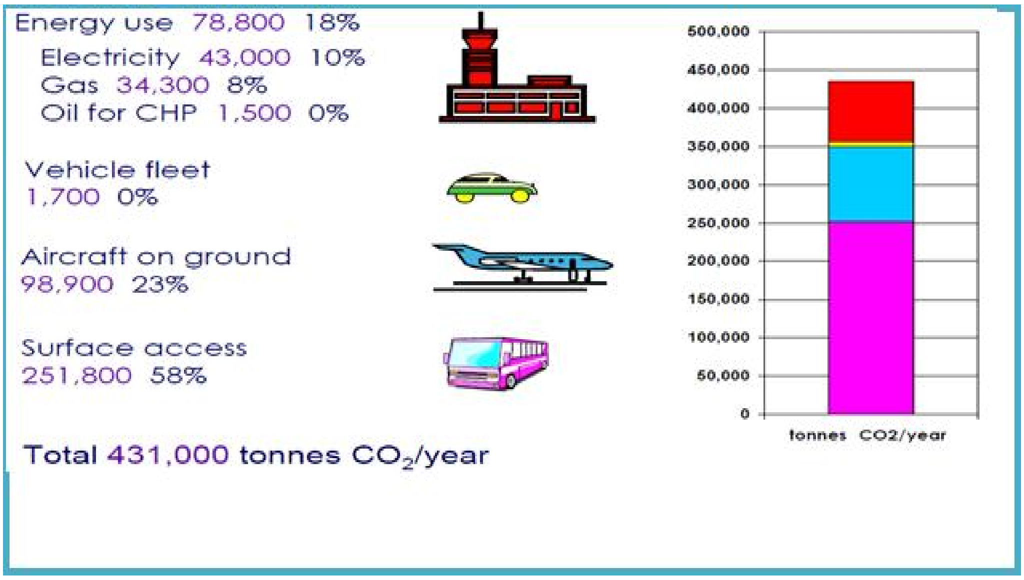


FIGURE 2-1: CARBON EMISSION BASELINES FOR MANCHESTER AIRPORT (KNOWLES 2006)

A further breakdown of this energy use in Manchester Airport shows that 45% of the energy is used by the 'service partners' onsite and of the remaining 55%, HVAC consumes 40%, lighting 35%, and conveyor systems 10% (Knowles 2006).

2.3 Occupancy of Airport Terminal Buildings

At peak occupancy, the people at the airport terminal are mostly the passengers and their escorts, then the airport and airline workers, the security (customs, immigration and police officials), fire and ambulance staff and the shop attendants.

Airport terminal operation is highly dynamic and the interplay between the passengers and the airport terminal processes; check-in, customs, shopping, eating and drinking, waiting, baggage reclaim, is difficult to control and predict because the passengers have freewill and so behave sometimes contrary to expectation (Yücesan, Chen et al. 2007).

Passengers in an airport are departing, arriving or transferring. The departing passengers enter the departure hall, proceeds to the check-in counters, pass through the emigration and security, walk through lounges and piers to arrive at the gate leading to the aircraft. The arriving process on the other hand starts from disembarkation from aircraft, walking through piers and lounges to arrive at immigration then unto the baggage collection area, the customs, arrival hall and exit. The transfer process is partly arrival and partly departure process. It is similar to arrival up to walking through piers and lounges and afterwards it is a departure process (Gatersleben, Van der Weij 1999).

Occupancy in airport terminals is mostly transient and concentric. That is, the passengers occupy the same area for short periods. There is a surge in activity and occupancy shortly before the departure or after the arrival of a passenger aircraft. The passengers are mostly engaged in standing on queues, brisk walking, strolling or even occasionally running in the transitional spaces. In the departure lounge there may be some sitting by passengers since most international airlines allows up to three hours check-in times and commuters might also be waiting to get inter connected with their next flight. Sitting is less at the arrival lounge as passengers are mostly interested in getting to their destination quickly. Both the outbound and the inbound passengers are often dressed or have within reach dress to suite the prevailing outside temperature while passing through the processes at the airport terminal buildings (Cassidy, Navarrete et al. 2009) (see Figure 2-2).

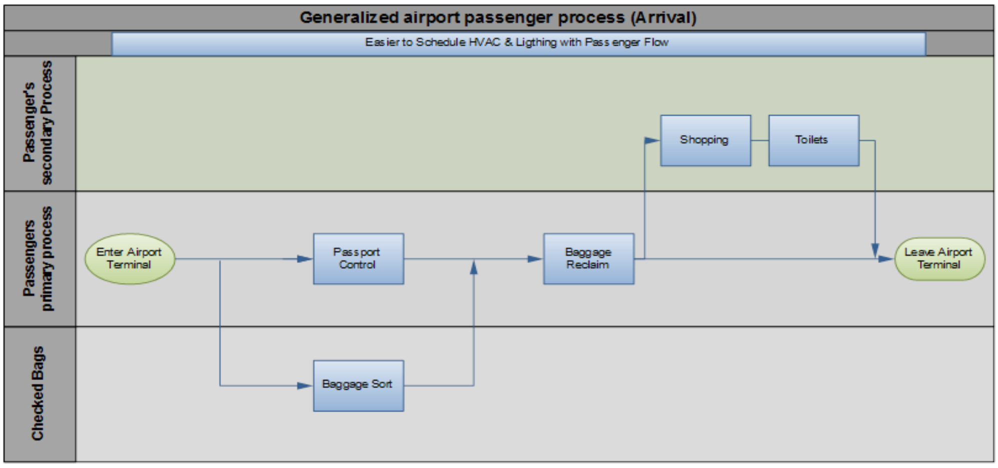


FIGURE 2-2: A Generalised Airport Passengers' Arrival Process (Cassidy, Navarrete et al. 2009)

The departing process takes longer time since passengers spend time waiting for departure at airport terminal. A typical passenger flow for departure (Cassidy, Navarrete et al. 2009) is shown in Figure 2-3 below.

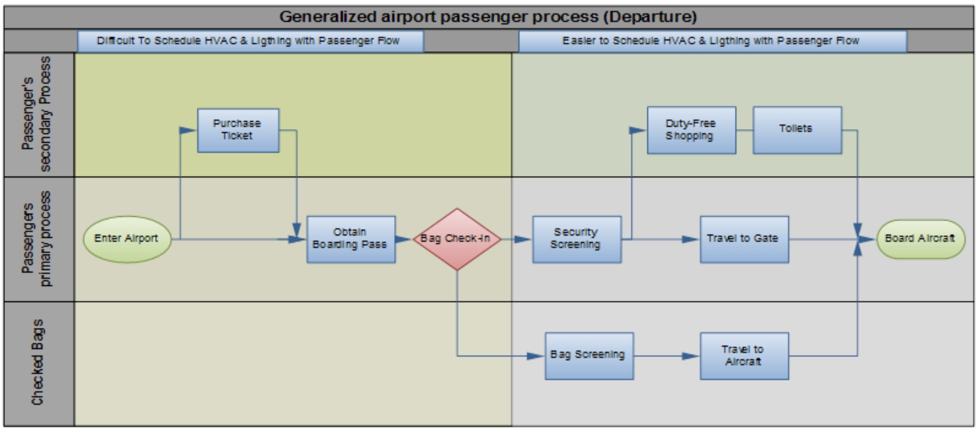


FIGURE 2-3: A Generalised Airport Passenger's Departure Process (Cassidy, Navarrete et al. 2009)

International Civil Aviation Organisation (ICAO) recommends forty-five minutes for international arrival passenger processing from disembarkation to completion of the last clearance process and one hour for the departing passenger from clearance to embarkation (ICAO 2005). A recent survey (DfT 2010) conducted in seven major UK airports (Manchester, Heathrow, Stansted, Gatwick, Luton, Edinburgh, Inverness) by Civil Aviation Authority (CAA) in 2009 shows that processing time for most passengers in these airports is even less than the provisions in the standard. The following tables and charts show the final results from the survey module conducted during 2009. The results are based on the responses received from the subsample of passengers interviewed by the CAA at the selected seven airports (DfT 2010). The report covers passengers' attitudes and experiences in relation to: check-in, flight information, airport facilities, public transport links, security screening. For example, the average queuing time at security screening in all the airports surveyed as shown in Figure 2-4 is just about 6.4 minutes. And overall, 87% of the passengers queued for less than 10 minutes here as shown in Figure 2-5. Similarly, overall, 71% queued at check-in for 5 minutes or less and 86% for 10 minutes or less (DfT 2010) as shown in Figure 2-6 and Figure 2-7.

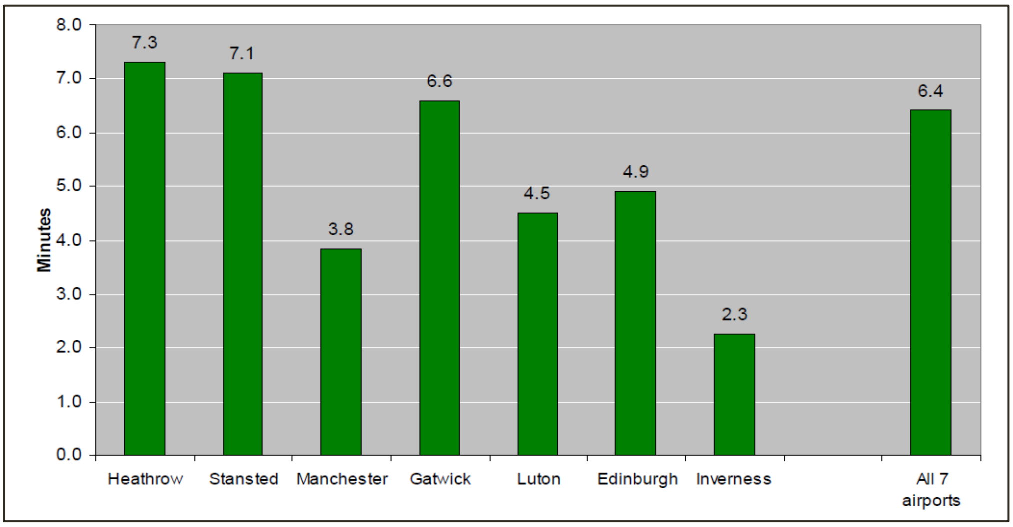


FIGURE 2-4: Average Time Queued at Security Screening (DfT 2010)

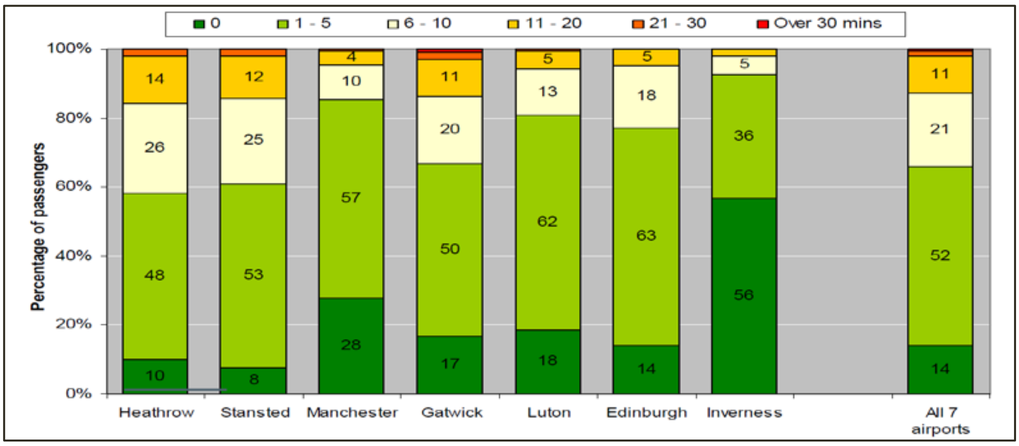


FIGURE 2-5: Time Band of Security Screening Queue Time (DfT 2010)

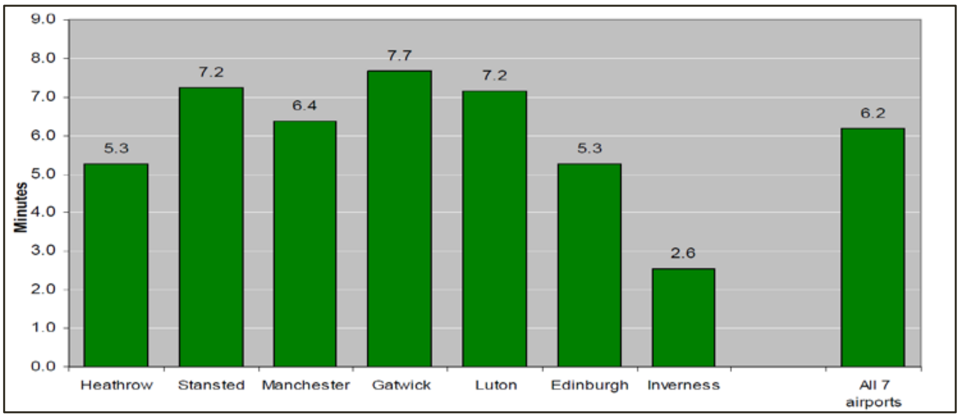


FIGURE 2-6: Average Time Queued at Check-In (DfT 2010)

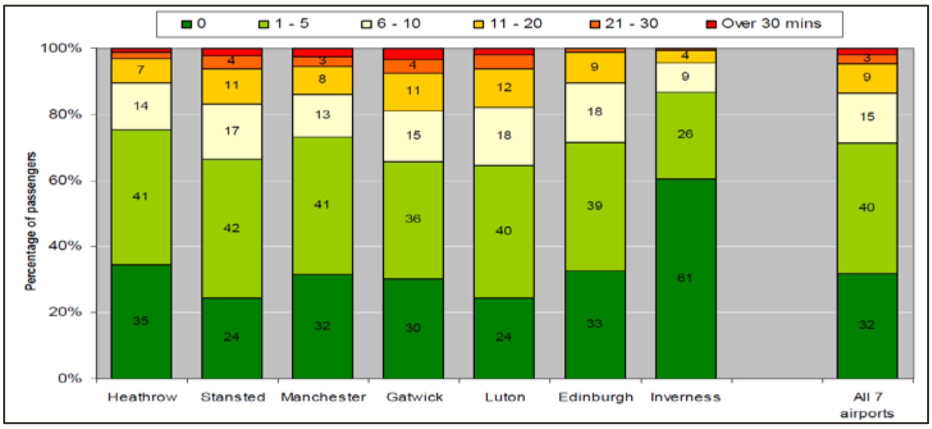


FIGURE 2-7: Time Band of Check-In Queue Time (DfT 2010)

Based on this survey's findings, total departing and arriving passenger processing times is less than 45 minutes for more than 90% of the time.

2.4 Environmental Characteristic of the Airport Terminals

Airports terminals are characterised for their large open spaces and high ceilings with not only diverse transient population but the space occupied by people in relation to the total volume of the enclosure is small (Piechowski, Rowe 2007, Murakami 1992). The high ceilings result in large vertical temperature distribution and stratification. Also as in most large enclosures such as the airport terminals, it is difficult to arrange exhaust and inlet openings in a suitable place. Furthermore, the interior heat sources are often distributed very unevenly causing large distribution in temperature and air velocity in both vertical and horizontal direction (Murakami 1992). The office and shopping spaces are often open to large-scale indoor spaces. All these make the control of indoor climate more difficult (Murakami 1992). Also, for aesthetic considerations, glass panels and transparent walls are used extensively to form the walls and roof facade. Thermal environments like this experience rapid deterioration due to radiant heat and the outer thermal conditions (Kim, Kang et al. 2001). These factors severely subject the indoor enclosures to the vagaries of the outdoor conditions and make fine control of the indoor climate difficult (Murakami 1992). Most airport terminals are detached buildings set in open landscapes and with the extensive glass facade earlier mentioned, this present armful opportunity to exploit daylight control more than other types of buildings (Edwards 2005).

When discussing the suitability of the indoor environment of airport terminal, comfort, health, and energy is very important. For example, there are indoor environment set-points that may be healthy but not comfortable. In addition, the nature of occupancy is a major factor in comfort definition within airport. Airport passengers occupy spaces for a short time and so little drift in temperature may not have any noticeable effect but some staff stays for longer period in the indoor spaces and long exposure to these uncomfortable but healthy setpoints could over time result in stress, which could lower productivity and even result in absenteeism from work (Kumar, Fisk 2002). Glare is especially important in places where occupancy is of long duration and so will have little effect on the transiting passengers but the staff who are likely to stay longer in a place must be protected from its effect. For example, results of occupant comfort survey conducted in 3 Hellenic airports shown in Figure 2-8 (Balaras, Dascalaki et al. 2003) clearly demonstrate these peculiarities. While passenger votes for all the airports averaged at about 80% satisfaction that of the staff is a lot less (about 45%) (Balaras, Dascalaki et al. 2003).

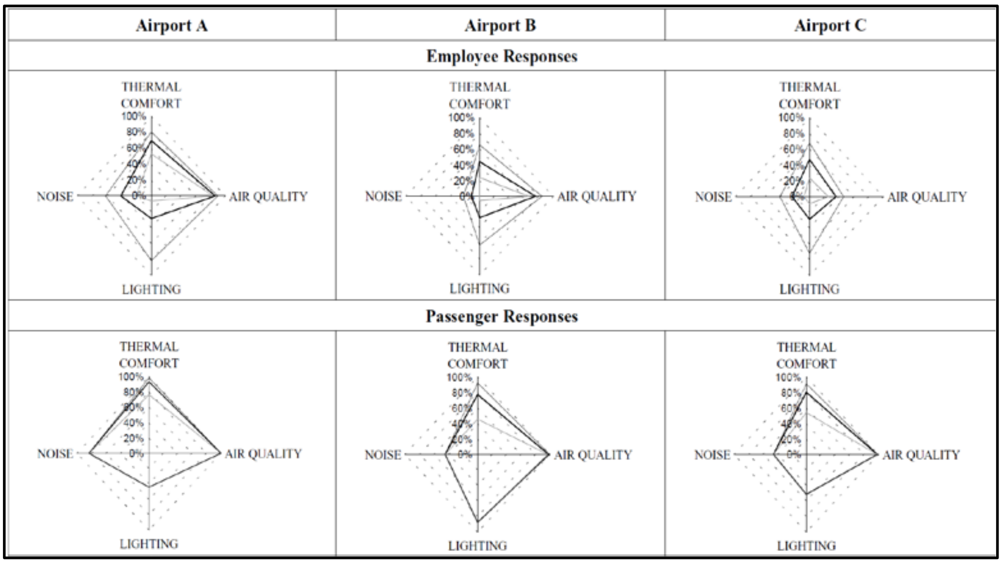


FIGURE 2-8: % Of People Satisfied with the Indoor Quality of Hellenic Airports (Balaras, Dascalaki et al. 2003)

This position was further corroborated by an unpublished early outcome from the thermal comfort studies being undertaken in our collaborating institution, Kent University by Alkis Kotopouleas (Kotopouleas 2012). In this study as shown in Figure 2-9, while over 80% of passengers (Arriving and departing) were satisfied with the indoor space, a significant 40% of the working personnel were dissatisfied.

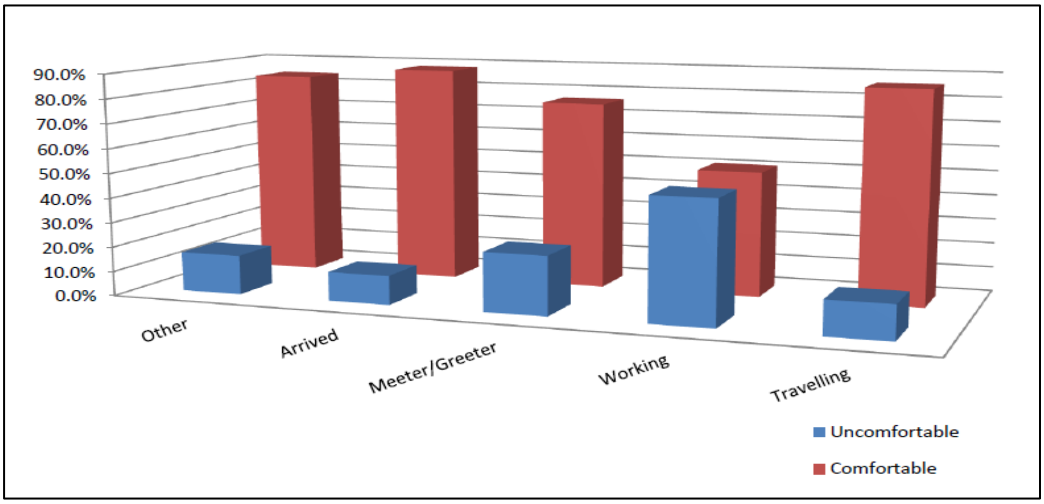


FIGURE 2-9: Variation of Comfort Votes among Groups in Manchester Airport T2 (Kotopouleas 2012)

Generally, comfort and wellbeing in the indoor spaces is predicated on the followings as shown in Figure 2-10 and presented in the list below (Shepherd, Batty 2003):

FIGURE 2-10: Factors Affecting Comfort and Health in the Indoor Environment (Shepherd, Batty 2003)

1. Low level of Indoor pollutants concentration: This means the availability of sufficient fresh air and absence of odour and other indoor air contaminants at harmful levels.

2. Building Services: this includes all HVAC systems that ensure the existence of thermal balance between the occupants and the indoor environment, adequate lighting and absence of discomforting noise.

3. Personal factors and preferences of the occupants such as level of metabolic activities, amount of clothing insulation, past experiences and expectation and having control to make choices as to how one wished to live.

4. Building's Physical Conditions: Poor building design and construction could lead to building related illnesses. So, building location, orientation, organisation of space and nature of use all have huge bearing on how comfortable and healthy it is.

5. Indoor Microclimate has to do with level of air purity, comfortable temperature, adequate humidity, sufficient lighting levels and absence of noise in a particular indoor space. More will be said on these factors latter in greater details.

6. External weather conditions affect indoor microclimate and occupants expectations.

Therefore, the next section of the chapter will be devoted to describing comfort parameters including method of analysing comfort (thermal comfort, visual comfort and indoor air quality) within building and concluded by selecting environmental parameters of interest for developing fuzzy control strategies. It also provides information on the research findings on airport terminal comfort studies.

2.5 Thermal Comfort Variables

Thermal comfort affects health and productivity of occupants as well as satisfaction with the indoor environment (Kumar, Fisk 2002, HSE 1999). It is very subjective and so difficult to define but according to ASHRAE Standard 55-56, Thermal comfort is 'that state of mind which expresses satisfaction with the thermal environment' (ASHRAE 2007). Although it may be influenced to some extent by contextual and cultural factors as will be shown latter, it is primarily of strong relationship to the heat balance of the body with the environment.

The human body produces heat relative to the level of activity and heat is transferred to the environment relative to the degree of clothing insulation and prevailing thermo-environment condition. Heat is lost from the body in four ways: convection, conduction, radiation, and evaporation. Heat generated by the body must balance heat transferred to the environment to ensure comfort and health. If the heat generated is greater than the corresponding heat lost, the body temperature will rise, this could trigger some involuntary thermo-physiological mechanism into action such as dilation of the blood vessels, sweating, and in the extreme, could lead to *hyperthermia*. On the other hand, if the rate of heat generation is less than the heat lost from the body, body temperature will fall and could lead to reaction such as constriction of the blood vessels, shivering, and in the extreme, result in *hypothermia* (Oughton, Hodkinson 2008).

Two approaches have emerged over time on the discus of thermal comfort; the static approach and the adaptive approach.

2.5.1 Static Approach

Static Model of thermal comfort proposed that it is the combined thermal effect of all the physical factors which is of importance for man's thermal state and comfort (Fanger 1972). This suggests that man is a passive recipient of his thermal environment. Fanger is the most influential figure in this study area. He enumerated three conditions for thermal comfort in humans:

- That the body must be in thermal equilibrium with the environment

- That the mean skin temperature (33-34^{0}C) is within comfort range, that is, sweating (or shivering) does not occur at sedentary activity
- And that at higher level of activity sweat rate is within comfort limit.

The principal environmental parameters that affect comforts are air temperature, mean radiant temperature, relative air velocity and vapour pressure in the ambient air while human parameters are activity level (metabolic rates) and thermal resistance of clothing (clothing insulations).

Air temperature: is a direct environmental index otherwise known as the dry bulb temperature of the surrounding air usually given in Degree Celsius or Fahrenheit. Temperature is an important indicator of human comfort (Parsons 2003) and will be given more attention in the subsequent paragraphs.

The Mean Radiant Temperature: is a derived environmental index defined as the uniform black-body temperature that would result in the same radiant energy exchange as in the actual environment.

Other temperature indices include;

Operative temperature- the uniform temperature of an imaginary enclosure in which man exchange the same dry heat by radiation and convection as the actual environment (Butera 1998) .

Wet Bulb temperature- is the temperature a parcel of air will have when it is cooled to saturation level (100% relative Humidity) by the evaporation of water into it (CIBSE 2006a).

Effective temperature- the uniform temperature of an imaginary enclosure at 50% relative humidity in which a person exchange the same heat as in actual environment (Butera 1998).

Resultant temperature- the temperature recorded by a thermometer at the centre of a black globe 100mm in diameter.

Air Velocity- Air velocity improves comfort by changing convective and evaporative heat loss. When air is completely still, the environment becomes stale and stuffy. Cooling breeze in winter can cause draught but will be pleasant in summer. Meaning that if the air temperature is warm, higher air velocity is acceptable but if reverse is the case then a low speed is preferred. Generally acceptable level of air velocity in indoor spaces is in the range of 0.1-0.3 m/s (CIBSE 2006a).

Relative Humidity – is the ratio of the prevailing partial pressure of water to that of saturated vapour pressure. In other words, it is a measure of the moisture in the air, compared to the potential saturation level. It is the percentage of water vapour held by air relative to the saturation level; the warmer the air the higher its capacity to hold more moisture. Higher relative humidity encourages the growth of mould within in-door spaces and could encourage the thriving of fungi and bacteria. Lower relative humidity on the other hand could results in irritation and stuffy nose (Fang, Clausen et al. 2004). A study of the health implications of relative humidity in indoor environ-ments suggests that it can induce the incidence of respiratory infections and allergies in its low or high level (Arundel, Sterling et al. 1986). Relative humidity in the range of 40 – 70% is generally acceptable for comfort in indoor spaces (CIBSE 2006a).

Clothing Insulation- also known as the clo value. Occupants improve their thermal conditions by changing the amount of clothing they have on them. Each layer of cloth type is assigned a clo value (1 clo value = $0.155m^2K/W$). McCullough and Jones, 1985, described how the clo value is calculated (McCullough, Jones et al. 1985). For example, a nude body has a clo value of 0, a casual summer clothe is 0.5, an office suit or a typical winter ensemble has a clo value of 1 and a typical heavy European business suit ensemble has a clo value of 1.5 (Butera 1998, Fanger 1986).

Metabolic rates – is the rate at which energy is produced in the body relative to the activity level of the individual. It is often measured in met (1 met = 50 kcal $h^{-1}m^{-2}$). The body uses oxygen and food ingested to produce heat and energy. When energy is used in the human body, heat is produced which is used to maintain the internal body temperature. Therefore, the higher the metabolic rate, the higher the heat produced (Havenith, Holmér et al. 2002). Although there is quite a list of activities (Butera 1998), the list here will be limited to major activity levels that could be found within the airport (Table 2-1) (ISO Standard 2005)(ASHRAE Standard 55-2004 2004b).

TABLE 2-1: Metabolic Rates for Typical Airport Activity Levels (ISO Standard 2005)

Activity	Met Value	W/m2
Reclining	0.8	46.6
Seated and quite	1.0	58.2
Sedentary activity	1.2	69.8
Standing, Relax	1.2	69.8
Standing, Light activity	1.6	93.1
Walking, 2 km/h	1.9	110
Walking, 3 km/h	2.4	140
Walking, 4 km/h	2.8	165

The summary of how these environmental variables interact to create comfortable environments can be demonstrated using the Psychometric chart. The chart as shown in Figure 2-11 (MIT OpenCourseWare) shows that most human will be comfortable within the range of temperature of 22-27 Degree Celsius and a relative humidity of 20 and 80%. Low temperature and Low RH (Bottom left of the comfort zone) will results in cold and dry environment, Low temperature and high RH will be cold and humid, high indoor temperature with low RH will be hot and dry and lastly high temperature and high RH will be hot and humid. Once two air variable is known, the other properties can be obtained from the psychometric chart.

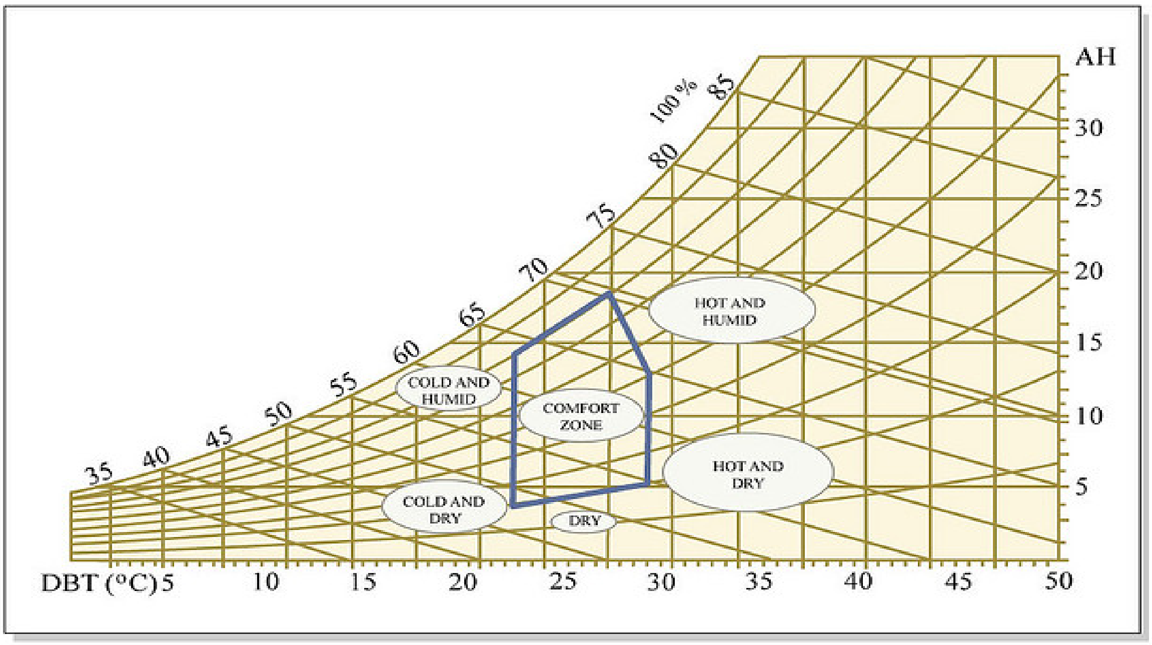


FIGURE 2-11: Simplified Psychometric Chart Depicting the Comfort Range (MIT OpenCourseWare)

Fanger also muted the idea of measuring thermal sensation for any combination of activity level, clo-value and the four other environmental parameters using the 7-point psycho-physical scale (Table 2-2) to obtain the Predictive Mean Vote (PMV) index.

This index is an average rating of a group of people exposed to a particular thermal condition of interest on the following scale (ISO Standard 2005, ISO Standard 2005):

TABLE 2-2: The PMV Scale (ISO Standard 2005)

Thermal Sensation	PMV
Hot	+3
Warm	+2
Slightly Warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

Using the result derived from thermal experiment on human subjects the Percentage of People Dissatisfied (PPD) can be calculated.

The PPD is a quantitative measure of the thermal comfort of a group of people at a particular thermal environment.

The PPD tells us whether an environment is acceptable while the PMV tell us why it is acceptable. For an average PMV vote of between -1 to +1, the PPD will be about 25%. About 5% of people will always be dissatisfied with any given optimal thermal environment (figure 2-12) (ISO Standard 2005). An indoor thermal environment that has a PPD of less than 10% corresponding to a PMV of about ± 0.50 is considered acceptable (Oughton, Hodkinson 2008). In a recent revision to ASHRAE Standard 55, satisfactory indoor spaces have thermal acceptability of 80% (PMV of ± 0.73) or more (Olesen, Brager 2004, ASHRAE Standard 55-2004 2004a).

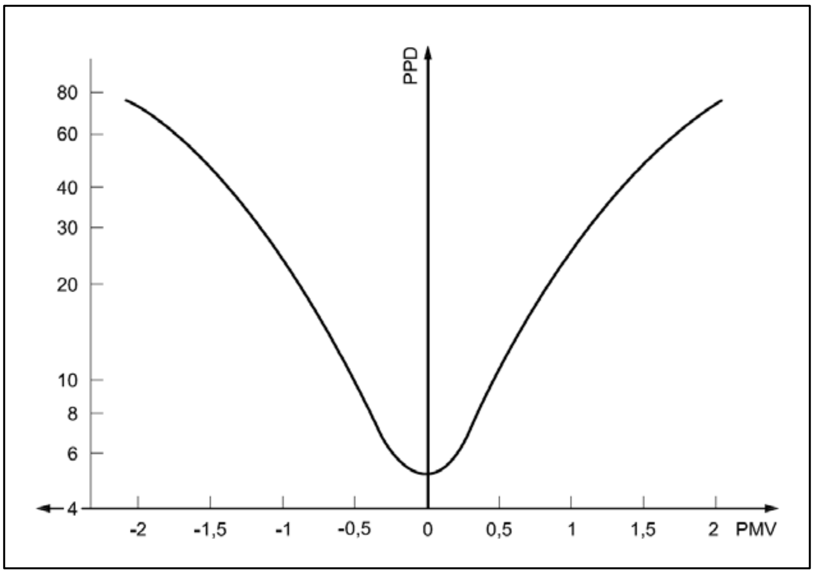


FIGURE 2-12: PMV VS PPD Graph (ISO STANDARD 2005)

Studies (Nakano, Tanabe et al. 2002, Mayer, Höppe 1987, Wong, Khoo 2003, Nikolopoulou, Baker et al. 2001b) have shown that age effects, nationality, sex and time of the day effect have no major significance to the perception of comfort in indoor spaces. This is important because in airports you find all kinds of people.

2.5.2 ADAPTIVE APPROACH

It has been argued (De Dear, Schiller Brager 2001) that these physiologically steady state indices (PMV and PPD indices) now accepted as ISO standard 7730 and ASHRAE 55 imposes a relatively tight limits on the indoor thermal environment which excludes the psychological dimension to the paradigm of comfort in the indoor thermal environment. Experts with these viewpoints propose the adaptive model of thermal comfort. The underlying premise of the adaptive model is that man is not a passive recipient of a given thermal environment. That it is not just the physics and physiology of heat transfer that controls how man perceived his thermal environment but also his psychology. Adaptation to the built environment could be physiological, behavioural and psychological (De Dear, Schiller Brager 2001).

Physiological adjustment includes all changes in physiology made in reaction to changes in the thermal environment such as acclimatisation and genetic adaptation.

Behavioural adaptation includes all conscious and unconscious adjustment made by the individual to contain thermal discomfort. Such adjustment may be changing posture, clothing or positions, opening and closing of windows, and observing siesta etc.

Physiological adjustment refers to altered perceptions and reaction to the thermal environment; Varying individual thermal 'setpoints' across time and space due to experience and expectations (De Dear, Schiller Brager 2001).

Therefore thermal discomfort as a sensation gives man an early and anticipatory drive for conscious action that may affects changes in the bodies microclimate rather than having him depends on the natural but transient means of thermal protection such as sweating, vasodilation, vasoconstriction and shivering (Gagge, Stolwijk et al. 1967). Brager (1996) argues that improved understanding of the influence of adaptation to thermal comfort in the built environment has the potential of helping to develop more sophisticated and responsive control algorithm.

From the forgoing analysis of the static and adaptive approach, it is clear that the sensation of thermal comfort is a complex function of both environmental variables and adaptation to the indoor environment (De Dear, Schiller Brager 2001, Brager, de Dear 1998).

This argument is beyond the scope of this study. We will be using the static analysis for this study since it is the more generally accepted approach.

2.6 INDOOR AIR QUALITY

Indoor air quality is used to refer to the quality of air within and around buildings with particular reference to how such quality affect the comfort and health of occupants. In specific terms; an indoor air quality is dependent on the presence of negligible health risk in breathing and the perception of such air as fresh and pleasant by the building occupants.

The possible sources of indoor air contaminations in airport buildings are many, some from within the building and others from without as shown in (Table 2-3)

TABLE 2-3: Indoor Air Contaminants, Sources and Effects

EXTERNAL		
CONTAMINANTS	SOURCES	EFFECTS
Oxides of sulphur	Sulphur impurities in fuel, jet, diesel engines and power generation	Odour, irritation, acidic behaviour and damage to respiratory tract
Oxides of nitrogen	Jet diesel engines and power generation	Smog/haze formation, acidic behaviour and lung irritation
Hydrocarbons	Fuel	Odour, smog, eye irritation, respiratory tract problems, headaches, and dizziness.
Aldehydes	Diesel fuel	Odour, eye irritation and respiratory tract issues
Ozone	Not directly emitted but formed from other contaminants	Impairment of lung function
Carbon monoxide	Jet, diesel engines and power generation	Headaches and dizziness
INTERNAL		
Hydrocarbons	Painting, cleaning agent, floor covering and floor polish	Soiling, decolouration deposits and can form acids
Formaldehyde	Carpets, wooden floors and furniture	Can be oxidized to form acids
Odours	Human, food facilities, cigarette smoke, equipment.	Unpleasant feelings

Ventilation is the magnitude of outdoor air flow to a room or building either through the ventilation system or infiltration through building envelope (EN15251 2007). Ventilation affects the health and comfort of occupants in buildings. Introducing outdoor air to neutralised contaminated indoor air is the common way of ensuring improved indoor air quality and control of condensation but this strategy comes with energy burden (Janssen, Hill et al. 1982). Air is needed indoor to support human existence and to disperse odours, fumes, unwanted heat, moisture and other contaminants. The approximate amount of fresh air required for these purposes are:

— 0.2 litre/s per person to provide Oxygen

— 1.0 litre/s per person to dilute CO_2

— 5 litre/s per person to dilute occupation contaminants

— 10 litre/s per person to give a feeling of freshness

Therefore we require around 50 times more fresh air to both dilute odours and create an acceptable fresh feeling than we do to provide oxygen (CIBSE 2006a).

Air enters into building through infiltration and ventilation. Infiltration usually due to defects in construction and detailing; It is not intentional and cannot be controlled but ventilation is ideally controlled by natural or mechanical means. Operable windows and doors, fans and dampers are the means by which ventilation is controlled.

Ventilation can be achieved in buildings through mechanical means or by natural means or by a combination of both but in airport buildings, it is achieved mainly by mechanical means. The need for security, noise and pollution control and deep plan nature of airport terminal buildings restrict the use of natural ventilation.

HVAC systems are used to provide air for ventilation at comfortable temperatures in airport terminal buildings. As such, mechanical ventilation consumes energy because the outdoor air is often conditioned (cleaned, heated, cooled, humidified or dehumidified) before being introduced indoor and energy is needed to drive fans and modulate dampers. Increase in mechanical ventilation rates will result in energy waste and increase carbon dioxide emissions. Reduction in ventilation rates will save energy but indoor air quality will deteriorate. Demand control ventilation (DCV) provides the balance between energy use and indoor air quality.

DCV is the method used to reduce heating and cooling needs by adjusting ventilation rates in response to occupancy (Lawrence, Braun 2007). DCV is mostly used in buildings with highly variable and sometimes dense occupancy such as airport terminal buildings. Seppanen (2008) stated that between 20-60% energy could be saved when DCV is deployed in airport buildings (Seppänen 2008). Although there are many indoor contaminants, carbon dioxide as a useful but not perfect indicator for ventilation need stands out because it also serves as a proxy for human occupancy since humans are the main sources of indoor carbon dioxide. As a result, CO_2 concentration is used as a measure of indoor air quality indoors (ASHRAE 2007, Seppänen, Fisk et al. 2004). Elevated indoor CO_2 concentration could also indicates elevation of other indoor contaminants. Although accepted maximum concentration of carbon dioxide in indoor spaces is 5000 part per million for about 8 hours exposure (Oughton, Hodkinson 2008), ANSI/ASHRAE Standard 62-2007 specified that an indoor concentration of no more than 700 ppm above the outdoor concentration will satisfy majority (80%) of building occupants. But CO_2 concentration of 700 ppm is far from its harmful threshold of 5000 ppm and 8 hours exposure level (other standards like the HSE as will be seen latter quoted even higher concentration tolerance) and as such CO_2 concentration is not a good measure of indoor air quality. The literatures are not clear about the amount of CO_2 concentration threshold for transient environment like airport buildings.

For buildings such as the airport where the emission from passengers is the major source of pollution within the indoor space, the number of people is the limiting factor for air ventilation. When such buildings are not used at full capacity, the ventilation and by implication the energy consumption, becomes very high. So, where the number of people within a space is known or can be predicted accurately, the minimum fresh airflow into that given space could be varied in response to occupancy by providing 10 litres per second persons in the occupied space (CIBSE 2006b). This is the option explored in this work because it has the advantage of providing the required outdoor air supply immediately, without waiting for CO2 levels to build up (Levermore 2000).

2.7 Visual Comfort Conditions

Visual comfort is feeling of ease or wellbeing within a visual environment. In other words it is the absence of visual discomfort. It is a common knowledge that visual performance depends on the adequacy of lighting. The primary purpose of lighting is to provide acceptable level of illumination for occupants to carry out the building's intended functions. Discomfort could be caused by over-illuminance, abstruse lighting, glare and poor colour rendering. Researches (Burks 1994, Knez, Hygge 2002) have shown that lighting discomfort could result in fatigue, stress, decrease in libido and increase in anxiety.

Additionally, artificial lighting is responsible for up to 19% of total electricity produced in the UK (Boyce, Raynham 2009), 30% of electricity use in commercial buildings (35% for Manchester airport) and offices (Oakley, Riffat et al. 2000) and up to 40% of energy bill for retail outlets (BRE 2004). Figure 2-13 (Pascall+Watson Architects 2011) shows the example of lighting use for retail activities in Manchester Airport.

FIGURE 2-13: Lighting Retail Shops in Manchester Airport (Pascall+Watson Architects 2011)

Sufficient light is usually described in terms of the illuminance or the amount of light on the task, measured in lumens/m2 or lux. For example bright moonlight has an illuminance of 0.5 lux, a typical brightly lit office could be 500 lux and sunlight outside has an illuminance of 100,000 lux (CIBSE 2006a). In the light of these limitations of artificial lighting, Ghisi (2002) argues that artificial lighting (Ghisi, Tinker 2006) should be used as a supplement rather than a replacement for day lighting.

Bordat (2001) reported energy savings from electricity of between 50 – 80% due to integrating day lighting with artificial lighting (Bodart, De Herde 2002). Other gains of day lighting in indoor spaces could be to provide; outside view, enough light to work with, enhanced colour rendering and enhanced appearance of place. These improvements have been shown capable of increasing retail sales (Heschong, Wright et al. 2002).

Effective integration of artificial lighting and day lighting is achieved when artificial lighting can be switch on, off or dimmed as a function of day lighting levels reaching the work surface to provide adequate light needed to perform a certain task comfortably and without wastage. Through the use of sensors and controllers, day lighting can reduce or even eliminate the use of artificial lighting.

Because lighting generates internal heat loads that affect cooling and heating energy use in buildings, energy can be saved through better coordination between lighting and HVAC systems (Salsbury 2005).

2.8 Defining the Comfort Setpoints

The choice of operating thermal setpoints such as relative humidity, air and radiant temperatures and air velocity affects occupant's comforts and building energy consumptions (Simmonds 1993, Olsen, Chen 2003).

It was surprising that; given the stated importance and uniqueness of the airport terminal buildings, published studies on thermal and visual comfort of airport terminals are quite few.

Babu (2008) used an existing design proposal for Ahmedabad International airport as a base case to proffer design alternatives. The alternatives are based on varying the building fabric and active thermal conditioning systems in order to save energy and at same time satisfy passenger comfort in the airport terminal. The paper identifies various building fabric design options to achieve stepped temperature transition for the identified zones. A survey involving 128 respondents was carried out to gauge passenger comfort preferences at the terminal. This survey shows that comfort votes ranged from temperatures 24-32^{o}C for the air-conditioned environment of the terminal building. It also shows that passengers expressed a higher thermal tolerance when transiting from a natural environment to a conditioned environment, and a higher comfort expectation when transiting from a conditioned space to another. This gives an obvious indication of the interplay between adaptive and static thermal behaviour (Babu 2008).

Liu *et al* (2009) used CFD thermal simulations, indoor environment monitoring and thermal comfort surveys based on the PMV at Chengdu Shuangliu International Airport. The result of the study shows that 95.8% of the passengers were satisfied with their thermal environment. The neutral operative temperatures and the comfort zone range in winter and summer for the passengers is 21.4℃, 19.2℃ to 23.1℃ and 25.6℃, 23.9 to 27.3℃ respectively (Liu, Yu et al. 2009).

Balaras *et al* (2003) analysed in detail using thermal simulations and collected site data, some specific measures aimed at reducing energy use without compromising comfort in Hellenic airports. The paper identified various design routes to provide satisfactory indoor environment. 285 questionnaires form was completed and respondents include both staff and passengers at the airport. The paper found that there is lack of proper regulations, adverse thermal conditions, RH remains outside comfort zone for long periods, excessive daylight levels and discomfort glare and that potential energy savings of 15-35% exist (Balaras, Dascalaki et al. 2003).

Kim et al (2001) described, using numerical simulations, the effect of vertical air circulation on the thermal environment in an airport passenger terminal with induced flow by jet fans. They submitted that comfort in the terminal investigated improves from “slightly warm” to “neutral” due to vertical air circulation (Kim, Kang et al. 2001).

Galliers and Booth in a publication by BSRIA carried out a physical and a public's perception survey of some 6 public transport buildings including an airport terminal. Comparison was made between the physical data, the questionnaire data and relevant standards and guide (Galliers, Booth 1996). The conclusion was that, among other things, *public transport buildings have a fair way to go in order to provide the ideal environment for the travelling public.* Table 2-4 summarised the result in their work as it relate to the some physical parameters of interest for the airport terminal.

TABLE 2-4: Physical and Environmental Parameters (Galliers, Booth 1996)

Parameters	**Standards**	**Standard level**	**Measured level**
Air Velocity	CIBSE Guide A, 2006		0.1 – 0.5 $m.s^{-1}$
Relative Humidity	CIBSE Guide A, 2006	40% - 70%	30 – 50%
Air temperature	CIBSE Guide A, 2006	Departure lounge Winter: 19 – 21^0C Summer: 22 – 24^0C	Departure lounge Winter: 13 – 27^0C Summer:18 – 27^0C
Carbon dioxide	HSE EH40/2000	Average time:15 minutes Concentration: 15000ppm Average time:8 hours Concentration: 5000ppm	400 – 1200 ppm
Light level	BS 8206 PT 1: 1985	200 – 500 Lux	190 – 520 lux

According to Yik et al (1994), it is reasonable to expend huge amount on energy to provide comfort for office buildings and shopping malls, similar expenditure is not justifiable for queuing enclosures in the terminus (Yik, Yiu et al. 1995). The criteria to be adopted for design should be established on the basis of tolerable limits for passengers rather than thermal comfort consideration (ISO Standard 2005). Achieving a PPD of 15 % (CIBSE 2006b) for baggage-reclaim area, concourses and check-in should be acceptable. *Table 2-5* shows the comfort setpoints for personal and environmental parameters of the airport terminal as in CIBSE Guide A.

These studies suggest that the airport terminal environment is indeed a lot different from other indoor spaces and as such does not require the mechanistic and often uniform application of the analytical comfort indices as that obtained in other indoor spaces. This claim was further reinforced by the variable nature of standard comfort setpoints in CIBSE Guide A for the various indoor spaces of the airport terminal as shown in Table 2-5 *below*.

TABLE 2-5: Airport Terminal Building's Environmental Parameters (CIBSE Guide A)

Area	AT [1] (°C)		RH[1] (%)	AV[1] (m/s)	CO_2L[2] (ppm)	LL[1] (lux)	ASR[1] (m/s/p)	CI[1] (clo)		MR[1] (met)
	W	S						W	S	
Baggage claim	12-19	21-25	40-70	0.1-0.3	5000	200	10	1.15	0.65	1.8
Check in	18-20	21-23	40-70	0.1-0.3	5000	500	10	1.15	0.65	1.4
Concourses	19-24	21-25	40-70	0.1-0.3	5000	200	10	1.15	0.65	1.8
Custom	18-20	21-23	40-70	0.1-0.3	5000	500	10	1.15	0.65	1.4
Departure lounge	19-21	22-24	40-70	0.1-0.3	5000	200	10	1.15	0.65	1.3
Shops	19-21	21-23	40-70	0.1-0.3	5000	500	10	1.15	0.65	1.4
Offices	21-23	22-24	40-70	0.1-0.3	5000	300-500	10	1.15	0.65	1.2

KEY: AT= AIR TEMPERATURE, RH = RELATIVE HUMIDITY, AV= AIR VELOCITY, CO_2L= CO_2 LEVELS, LL= LIGHTING LEVELS, ASR= AIR SUPPLY RATES, CI= CLOTHING INSULATION, MR= METABOLIC RATES, S = SUMMER, W= WINTER, 1 = CIBSE GUIDE 2006 A, 2 = HSE

Finally, Alkis, 2012, working within the umbrella of this ESPRC project, carried out a thermal comfort survey in three UK airports terminals; London City airport terminal, Manchester terminal 1 and Manchester terminal 2. The results for neutral temperature, 80% and 90% acceptability is presented in the Table 2-6 below:

TABLE 2-6: Recent Thermal Comfort Survey in Three UK Terminals (Kotopouleas 2012)

Airport Terminals	Neutral Temp (℃)	80% Acceptability	90% Acceptability
London City	21.4	18.1 – 24.8	19.5 – 23.4
Manchester T1	20.5	17.3 – 23.6	18.6 – 22.3
Manchester T2	21.1	18.2 – 24.1	19.4 – 22.9

2.9 Conclusions

It can be inferred from these studies that comfort is subjective since it depends on factors that are both empirical and adaptive. This also explained the reasons for the differential preference by the subjects for a particular range of comfort variables. Also, from the limited researches quoted above and the variable range in the indices for thermo-visual comfort and indoor air quality, it is clear that factors affecting indoor comfort do not have crisp limit, are imprecise, uncertain, time varying and nonlinear. This study will adopt the CIBSE range of neutral temperatures for airport spaces. These neutral temperatures are similar to the once provided by the umbrella project (Kotopouleas 2012) in the thermal comfort study conducted in Manchester airport, our case study. Relative humidity was not considered as a variable to be controlled in this study because its control is difficult and costly to implement and it is not a major influencing parameter in transient environment like the airport terminal. This study will adopt an artificial lighting setpoints of 200 lux for all the passenger area in accordance to CIBSE Guide A. It is assumed that staff function within passenger area will be illuminated from task light. Lastly, demand controlled ventilation based on providing 10 litres per second per person of fresh air is adopted for the ventilation flow rates in compliance to CIBSE Guide.

The next chapter will review building control system used in energy management.

CHAPTER 3: A REVIEW OF CONTROL SYSTEMS IN BUILDING ENERGY MANAGEMENT

3.1 INTRODUCTION

The main purpose of building's indoor environmental systems is to provide better indoor environment for occupants of buildings. Since the demands for heating, ventilation, humidification, cooling and artificial lighting varies both annually, diurnally and sometimes many times within the same day and as these systems have great influence on energy consumption, they must be controlled to respond to the prevailing load or demand at any given time. In any case, energy efficiency should not override indoor comfort for building occupants as indoor comfort can affect the productivity and health of the occupants.

Building control conjure a picture of a building machine which takes up inputs from sensors (light, temperature, CO_2, infra-red, PMV etc.) and uses these signals and other information to automatically trigger actuators (effectors) to control heating, cooling, ventilation, lighting, energy use etc. (Sharples, Callaghan et al. 1999).

Building control is becoming increasingly popular mainly due to new legislations, increasing energy cost and improvement in infrastructure technology such as increase network reliability, decreasing cost of installation and maintenance, and standardization of protocols which helps integrate different controllers (Salsbury 2005). It can help save more than 20% energy use, that is, more than 8% of total energy use in the EU (Alcalá, Alcalá-Fdez et al. 2009). It has also increased building's capacity for self-diagnosis and remote monitoring possibilities of its component systems from a central supervisor (Levermore 2000). Moreover, it can also help in increasing the life span of equipment and lower energy and operating costs leading to an advantageous return on investment (Vermesan 2012).

This review focuses on control of building's indoor environment systems in general but is more specific on expert control based on fuzzy logic. The objective is to present various applications of fuzzy logic control used in BEMS generally and especially at the supervisory level. The topics will be arranged thematically but the review of fuzzy logic control application at local and supervisory level will be set chronologically.

The review begins with a general discussion on building control types, fuzzy logic control application in close loop local control. It continues with the appraisal of expert control in building with greater emphasis on fuzzy logic supervisory control application in buildings. The review concludes with a summary table outlining the strength and weakness of various control system types that has been implemented in buildings. The concluding remarks justify the reason for the choice of applying fuzzy logic supervisory control for airport terminal building's indoor environment systems control.

Figure 3-1 provides the framework for the review. The control classification or grouping is not perfect since there are mostly no clear cut boundaries among many control systems types; that is, a control system can belong to one or more group. However, the grouping provides the basis to compare and contrast the strength and weaknesses of the various methods and their possible application in airport building. It also helps to lead the topic from general knowledge on BEMS to our specific focus on fuzzy supervisory control for airport building.

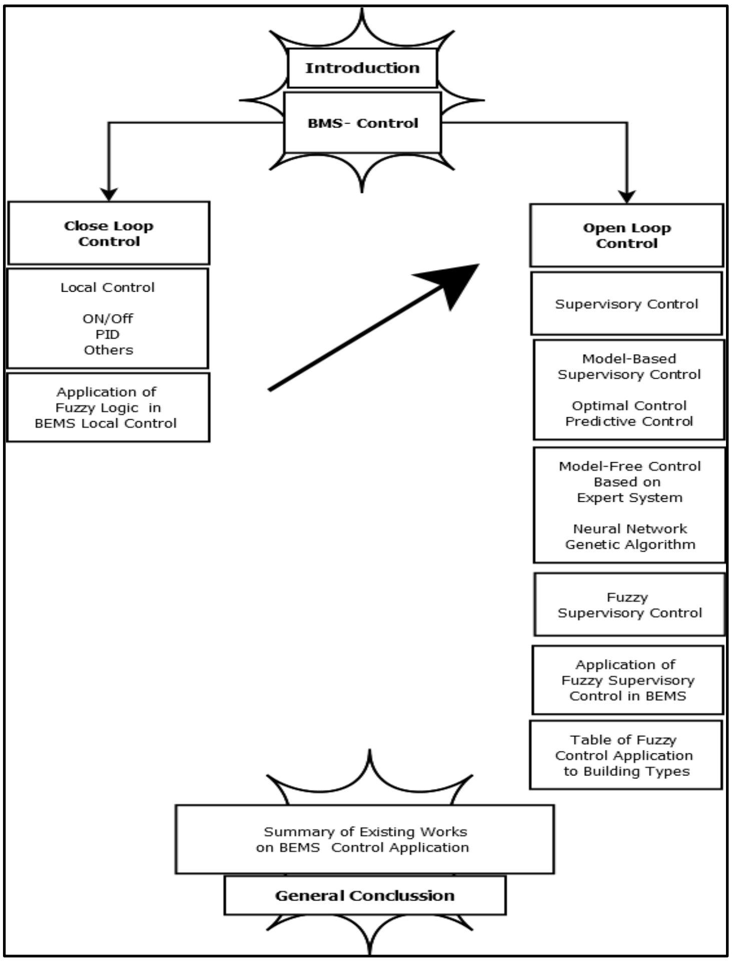


FIGURE 3-1: FRAMEWORK FOR THE REVIEW

3.2 TYPES OF CONTROL SYSTEMS USED IN BUILDING

There are generally two types of control system; open and closed loop control. Closed loop control is mostly deployed in local control and open loop control in supervisory control application. For simplicity, our discussion will retain this grouping even though overlaps exist.

3.2.1 Closed Loop Control

This is also known as feedback control. In this control action there is a direct link between the controller and the input variable(s) (see Figure 3-2). The controller compares the input to a desired setpoints value and generates an error value which was used to compute output signal. Depending on the magnitude of this error, this controller output signal is used to trigger the control device to effect the desired change in output that will maintain or correct conditions (Hordeski 2001).

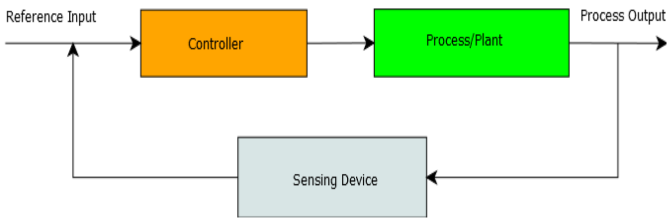


FIGURE 3-2: Closed Loop Control Action

Although this configuration has lower sensitivity to error/disturbances, its major setback occurs in the control of complex systems and so it is mostly deployed for local control.

3.2.2 Local Control Loop

A local closed loop control system comprises the plant (control process), the reference inputs or setpoints *r(t)*, controller inputs or error *u(t)* and controller outputs *y(t)*. According to Wang (2008), local control functions are the basic control and automation that allows building services to operate properly and to provide adequate services (Wang, Ma 2008). Local control loop is concerned with upholding a single variable to a setpoints by manipulating a single device (Hordeski 2001). As such they are mainly single input single output (SISO). A good example in *Figure 3-3* shows a basic heating control mainly concerned with upholding the indoor temperature at a set-points value.

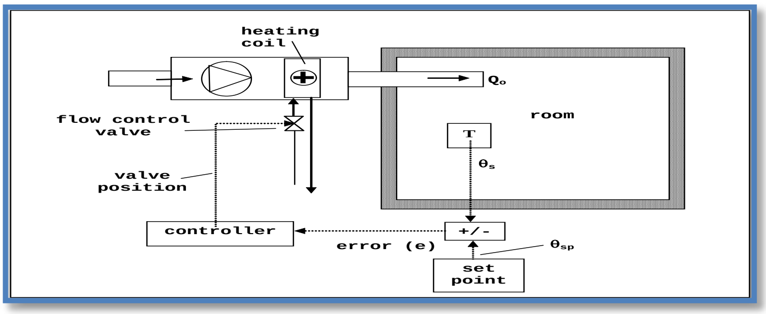


FIGURE 3-3: A Room Temperature Control System

Local control can be used for sequencing and process control in buildings. While sequencing control defines the order and conditions which bring equipment online or offline, process control adjusts the control variable to achieve the control objective in spite of disturbances. This type of control is used to sequence and control the actuation schemes of, pumps, chillers, fans, cooling towers etc.

The simplest form of local control used in building services is the On-Off controller, also referred to as the bang-bang controller. This is because the controller is designed to switch abruptly between two states of ON and OFF. Although this control system is very cheap to implement, is robust and can be used to control simple systems that changes very slowly, its oscillatory behaviour causes actuators to wear off easily and so it not used in many process control in buildings. An example of ON-OFF controller is the thermostat used for the control of temperature in building (Levermore 2000). Latter, to prevent controller swinging continuously in that bang-bang fashion, the dead zone was added. However, overshoot from the resulting controllers lead to increase energy consumption.

The Proportional, Integral and Derivative (PID) controllers were next adopted by designers (Dounis, Caraiscos 2009). The big problem with using PID controllers only in building as explained earlier is that most building systems are multivariable, time invariant and non-linear; a characteristic that causes control performance to change in response to changing condition and so loops becomes sluggish and oscillatory at a given times (Salsbury 2005).

The PID controllers used for indoor comfort calculate the controlled variable, at each time step from the prevailing values of air temperature and relative humidity while pinning down mean radiant temperature, room air velocity, activity and clothing levels as constants and external temperature, solar radiation and casual heat gains are treated as disturbances (Gouda, Danaher et al. 2001); this leads to inefficient operation. As much as three-fourths of annual energy consumption in some building systems is connected directly to PID-control losses. Also, PID control is labour intensive and can be costly to implement and support. Moreover, PID loops operate independently from each other and so cannot guarantee that all load demands can be met at any given time (Bhatia 2012).

There was also the problem of selecting appropriate gains for the controller which is a difficult and time consuming task if done manually especially for building systems where it may even be difficult to detect a de-tuned loop among hundreds of others. This has lead designers to device all sort of auto-tuning schemes (Salsbury 2005).

Auto-tuning is targeted at achieving; closed-loop stability, rapid and smooth response, elimination of offsets, reduction in overshoot, rise time and excessive control actions. These schemes are based on analytical, heuristic, frequency response, optimal and adaptive methods as can be found in the following works (Skogestad 2003, Tavakoli, Tavakoli 2003, Visioli 2001, Kim, Cho 2005, Cominos, Munro 2002). The big problem with these auto-tuning systems is that it often leads to disruption of the plant operations which may cause discomfort to occupants (Salsbury 2005). Also, auto-tuning requires experience, additional investment on tuning software and extensive training.

As a result of these difficulties some designers have attempted to provide alternatives to the PID control system by using predictive feedback (Xu, Li 2007, Oldewurtel, Parisio et al. 2010), neural networks (Kalogirou, Bojic 2000, Hepworth, Dexter et al. 1994, Han, Xiu et al. 1997), genetic algorithm (Wang, Jin 2000, Alcalá, Benítez et al. 2003a) and fuzzy logic (the theory of fuzzy logic will be treated latter).

3.2.3 Fuzzy Logic in Local Control of Building Systems

Dounis et al (1993) developed a control scheme for visual comfort in home or office building based on fuzzy logic. Mathematical model of the lighting plant was used to estimate lighting and glare levels. The fuzzy logic controller aimed to maintain lighting levels and acceptable glare as set by the building user by modulating window shading and lighting switches. The main advantage offered by this configuration is that with the use of heuristic rules based on fuzzy logic, the precise mathematical model of the plant was not compulsory for the attainment of desired control objective (Dounis, Santamouris et al. 1993).

Dounis et al (1995) presented the design of fuzzy control system for the achievement of thermal comfort in buildings (Dounis, Santamouris et al. 1995). The system was to decide the actuator(s) to trigger due to environmental measurement made in real time. This system comprise of a building simulator integrated with a fuzzy logic controller. Although the paper stated that the controller input variables includes PMV, Illuminance Level (IL) and the Direct Glare Index (DGI) which were used to process the actuator(s) action, the architecture of the fuzzy control rules and the results of the simulations presented do not show that visual comfort was considered in this study. However, the results for ‘two extreme climatological seasons shows that the fuzzy control system was able to keep the indoor environmental variables (Temperature and relative humidity) within the comfort zone of $-0.5<PMV<0.5$ for both seasons.

Hamdi & Lachiver (1998) proposed a fuzzy logic system for the control of HVAC based on human sensation of thermal comfort. The fuzzy system evaluates the indoor thermal comfort level based on inputs of the personal and environmental parameters it received. If discomfort is sensed, the control algorithm supplies the HVAC system with the required air temperature and velocity to correct the variance; otherwise the previous level is maintained. Figure 3-4 shows the architecture of the control algorithm (Hamdi, Lachiver 1998).

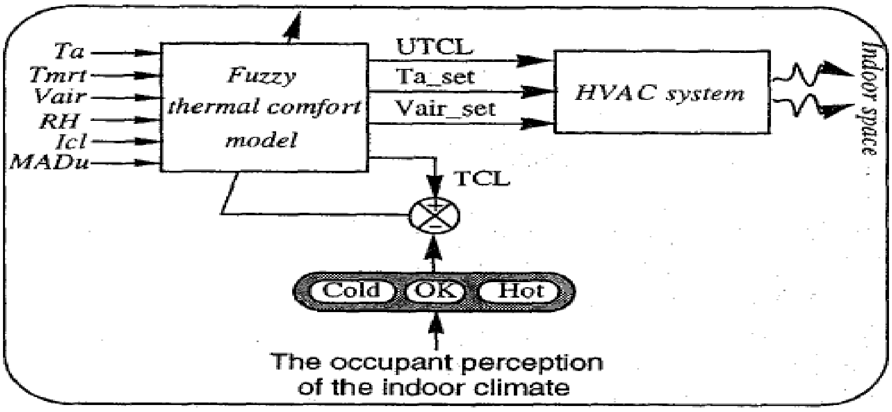


FIGURE 3-4: Thermal Comfort Levels Based Control of HVAC Systems (Hamdi, Lachiver 1998)

The simulation results obtained from the MATLAB and TRNSYS software shows better indoor comfort at reduced cost compared to the conventional thermostatic control model. While this controller could be of great advantage where occupants' preference for personal & environmental condition is uniform, it cannot be of much use in the airport terminal without a major modification.

D.Kolokotsa *et al* (2001) evaluated different control strategies for thermal and visual comfort, indoor air quality and energy consumption in buildings. Three types of local control methods were applied i.e. fuzzy PID, fuzzy PD, adaptive fuzzy and an ON-OFF controller. The input for every controller were PMV (Predicted Mean Vote) index, CO2 concentration and illuminance level. The simulation was performed using MATLAB/SIMULINK. This research (Kolokotsa, Tsiavos et al. 2001) also compared a fuzzy PD with seven input-output membership function (fuzzy PD-7) with the one having three input-output membership functions (fuzzy PD-3). It was found that there was no visible difference between the results but the computational time for fuzzy PD-7 was much higher than fuzzy PD-3. From simulation results it was found that adaptive fuzzy PD gave optimum responses and also less energy was consumed because the controller experienced lower overshoot. It was concluded that adaptive fuzzy PD controller minimized thermal energy consumption but for visual comfort the non-adaptive controller is sufficient.

Gouda *et al* (2001) uses the PMV index of zero corresponding to a PPD of 5% as the threshold for indoor thermal comfort control (Gouda, Danaher et al. 2001). The resulting fuzzy logic controller evaluates PMV and compares it with the comfort standard to define the indoor comfort requirement; it then adjusts the indoor air temperature value appropriately. This controller was reported to be free from set-up and tuning problems of conventional HVAC control strategy. Simulations results shows that the control strategy maximises indoor comfort and reported a 20% energy savings compare the conventional strategy.

Other fuzzy logic local control research are (Alcalá, Alcalá-Fdez et al. 2009, Dounis, Santamouris et al. 1993, Hamdi, Lachiver 1998, Soyguder, Alli 2009b, Bruant, Guarracino et al. 2001, Shahnawaz Ahmed, Shah Majid et al. 2007) or a combination of fuzzy logic, genetic algorithm and neural network (Li, Zhang et al. 2005)etc.

PID is still very popular in the building industry in spite of the mentioned efforts at supplanting it. This is because of its versatility, robustness and proposed replacements especially those based on neural network, genetic algorithm and predictive control have often proven to be more complex and computationally demanding. However, solutions that retain the PID element in a hybrid mix such as (Tavakoli, Tavakoli 2003, Wang, Jin 2000, Kolokotsa, Stavrakakis et al. 2002, Nassif, Kajl et al.

2005a) are now becoming popular and are being embraced widely in the industries (Salsbury 2005). These are mostly implemented at the supervisory level.

3.2.4 Open Looped Control

This is also known as feedforward control. Here, there is no direct link between the control input and the action of the controller (see Figure 3-5). Open-loop controllers in the form of time clocks or occupancy sensors have been used in building's HVAC and lighting control. These have been implemented as ON/OFF and not continuous control (McDowall 2009). When used in conjunction with feedback control, feedforward control can compensate for load offset before they are detected by feedback loop. The greatest advantage of this controller type is that the capacity of the plant increases as the load increases thereby greatly enhancing controllability. Also, feedforward control normally yields much faster correction than feedback control because often compensation is effected in such a way that the influence of the disturbance is not noticed in the output (Hordeski 2001). Although lack of pure model of plant can be major hindrances to open loop operation, expert and learning systems have been implemented to cater for this limitation. Feedforward control find application in building control mainly at the supervisory level.

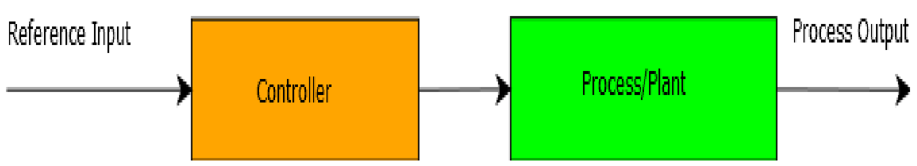


FIGURE 3-5: Open Loop Control Action

3.2.5 SUPERVISORY CONTROL

Supervisory controllers operate at a higher level than the local control loops in the hierarchy of control strategy. This is a building-wide control that coordinates all of the building control strategies. It coordinates the specialized activities and provides global direction (Hordeski 2001).

The most effective way to save energy is to shut down systems when they are not needed and matching system's capacity to changing loads. For energy conservation, HVAC and lighting systems required both switching off and regulation. Switching ensures that systems availability is tied to some triggers in the form of time clocks or some occupancy sensing or occupancy logic. Regulation on the other hand ensures that plants capacity matches changing load (Underwood 1999) or demands as in the case of lighting. Supervisory control enables the achievement of and integration in both regulation and switching of systems.

They can also provide integrated control action, supervision and network management services to one or more local networks of field controllers via setpoints and mode changes. They could be made to provide satisfactory indoor comfort and health at minimum energy and/or operating cost taking into account the dynamics of indoor and outdoor conditions and the overriding characteristics of the plants (Wang, Ma 2008). A supervisory controller can augment the function of an existing low level controller by adjusting its parameters according to design strategy so that control objectives are attained (Li, Zhang et al. 2005, Babuska, Mamdani 2008). By this means the behaviour of the low level controller can be tuned to cope with non-linearity and changes in operational and environmental setpointss. According to Babuska (2009); a supervisory control structure can be added on to existing control systems and tuned to improve their performances. A supervisory control structure allows the implementation of several control strategies in a single controller. So, the control of lighting, ventilation and indoor climate could combine in a single control strategy.

Supervisory control methods used in buildings could be classed as model-based, model-free methods and hybrid systems (Wang, Ma 2008).

3.2.6 Model-Based Supervisory Controllers

Model-based controllers require the model of the system to control. The models simulate system energy, cost and environmental performance as well as the system's responses to changes in control settings (Wang, Ma 2008).

The models used in model-based supervisory control are either physical model based on the fundamental law of the system's physics, grey-box models in which simplified mathematical relations describing the behaviour of the system is used as the model and the black-box model where mathematical relations between inputs and outputs variable without any prior knowledge of the systems are used as the systems model (Wang, Ma 2008). For example, Zhang *et al* (2006) described a model based supervisory controller that combines active and passive thermal storage. This controller decides whether to deploy generated energy from renewable energy sources now or to store those for future use using optimisation algorithm which simplifies the task compare to the rule based systems being used in the BMS systems. The building, plant and control models were obtained using commercial software and the offline results shows significant potential for improvement in system operation (Zhang, Hanby 2006b).

Optimal control is a model based approach which decides the control signal that will make a process satisfy a physical constraint and simultaneously minimise (or maximise) certain desired performance criteria (Todorov 2006). In building application, this control strategy has been used to reduce system's operating cost and energy efficiency without sacrificing comfort (Wang, Jin 2000).

Also, Model-based Predictive Control, MPC, a systematic procedure for the control of processes by using the model of such processes to predict their future output behaviours and subsequently using these predictions to minimise some cost-function to determine the 'best' control input signal for the process at the current sampling instant (Maciejowski 2002) has been used in building research. Its strength is that it can handle multivariable systems, it includes an uptake for future disturbances and its principles are easy to understand.

Other model based supervisory control studies can be found in (Salsbury, Diamond 2001, Henze, Dodier et al. 1997, Henze, Kalz et al. 2005, Liu, Henze 2005, Xu, Wang et al. 2009, Wang, Jin 2000, Zhang, Hanby 2006a, Zaheer-Uddin, Zheng 2001)

Although important researches were conducted on optimal and predictive control strategies, and it has been used successfully in many other industries, it is yet to make impact in the building industry mainly due to implementation problems (Dounis, Caraiscos 2009).

In general model-based approaches do not work very well in practice because of the difficulty in capturing building system's non-linear character in mathematical model that can be a close match to the real system over wide operating range. Many parameters used in the mathematical equations are uncertain. It is also not viable due to cost of implementation (Salsbury 2005, Wang, Ma 2008). Since Implementation issues have hampered the full adoption of optimal and predictive control in the building industries, intelligent control options based on expert systems can be better alternatives.

3.2.7 Model Free Control based on Expert systems

Model free control uses expert systems (neural networks, genetic algorithms and fuzzy logic) and reinforcement learning to replace the model of the targeted systems (Wang, Ma 2008). An expert system is a computer program that reason like an expert. Its knowledge base is gotten from the knowledge of experts operators. In robust supervisory capacity, expert systems can proactively adjust setpoints and switch equipment to resolve problems and optimise control (Hordeski 2001). The operator (expert) supply input data and the expert system suggest control configurations based on the data. These expert systems can be used alone or combined together such as in Neuro-fuzzy controller or genetic fuzzy systems to play complementary roles.

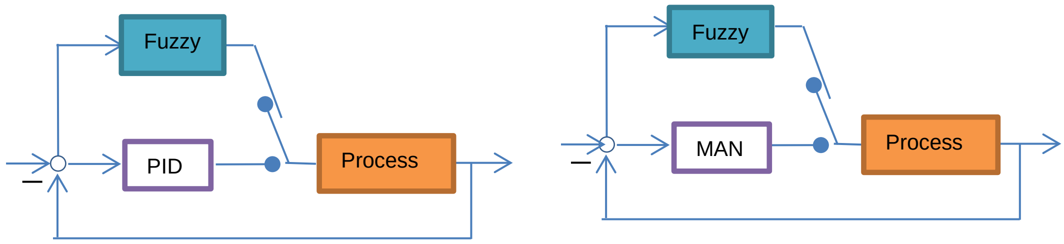
According to Henze and Schoenman (2003), reinforcement learning on the other hand is a learning paradigm in which a control system attempts to improve its behaviour based on the results of previous actions, without the requirement of a model of the environment or the effects of actions ((Henze, Schoenmann 2003). That is, a computer is giving a goal to achieve and the computer learns through trial and error to accomplish the task through interaction with the ‘environment’ (Harmon, Harmon 1996). So, it is a method that can be used to find optimal or near optimal for control problem without prior understanding of the environment (Wang, Ma 2008) The problem for reinforcement learning however is that, for complex problems, learning times to reach convergence become longer (Henze, Schoenmann 2003).

Artificial neural network are simplified brain-like mathematical models that can work as a parallel computing network. They can acquire, store and use experiential knowledge. It has been used extensively in building energy management researches. For example general regression neural networks (GRNNs) was used to optimize air conditioning setback scheduling in public buildings (Ben-Nakhi, Mahmoud 2002), also, an artificial neural network model was used for setpoint optimisation and a HVAC energy consumption prediction (Curtiss, Kreider et al. 1993), and (Yang, Rivard et al. 2005) used adaptive neural network for on-line energy prediction. Other studies using ANN supervisory control for building energy management are (Massie 2002, Chow, Zhang et al. 2002, Yokoyama, Wakui et al. 2009, Wong, Wan et al. 2010, Dodier, Henze 2004). Although ANN can be used for learning, these are generally understood as black box models and so it is difficult to extract structural information from or to add specialized information to an ANN to ease the learning process.

Genetic or evolutionary algorithm is a family of computer models fashioned after the so called theory of natural evolution. This have also been used extensively in building energy control study to auto-tuned or optimise PID or other controller type’s parameters (Huang, Lam 1997, Alcalá, Benítez et al. 2003b, Ahmad, Zhang et al. 1997), to optimised energy consumptions and building parameters (Chow, Zhang et al. 2002, Wright, Loosemore et al. 2002, Wang, Zmeureanu et al. 2005, Fong, Hanby et al. 2006, Ooka, Komamura 2009, Nassif, Kajl et al. 2005b). Genetic algorithm like neural network is computationally intensive and there is no guarantee that convergence will occur and so unnecessary for problems than can be solved out analytically.

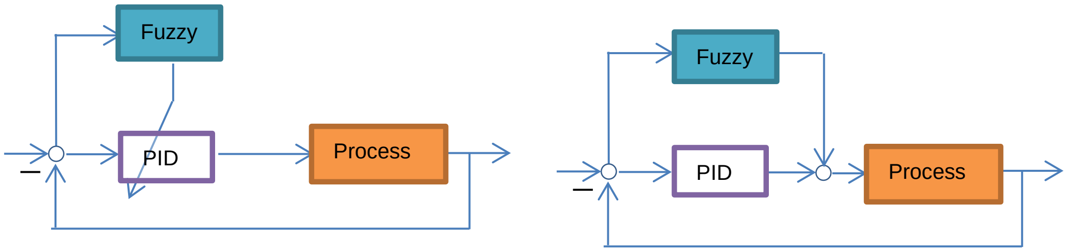
3.2.8 FUZZY SUPERVISORY CONTROL

Fuzzy logic control has now become a standard technology in control engineering and has been deployed in several control applications and products. In most of these applications, PID controllers are not replaced but rather fuzzy logic was used as a multivariable supervisory controller of the PID controller(s) (Altrock 2000). Some of these supervisory controller frameworks that have been used across many fields are shown in Figure 3-6:



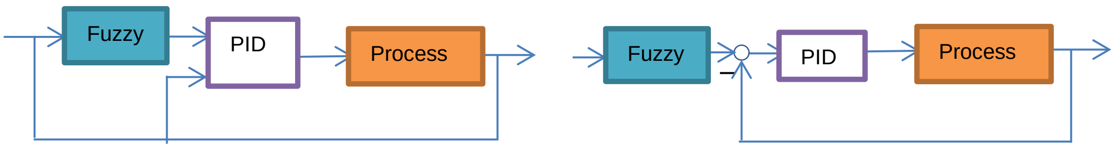
(a) Fuzzy replaces PID Control

(b) Fuzzy Replaces Manual Control



(c) Fuzzy adjusts PID parameters

(d) Fuzzy in parallel to PID Outputs



(e) Fuzzy cascaded with a PID controller

(f) Fuzzy Set Setpoint for PID controller

FIGURE 3-6: Various Fuzzy-PID Configuration Used in Supervisory Control

In Figure 3-6, the PID or Fuzzy block may consist of individual or coupled PID or fuzzy loops and may also have one or more inputs and outputs. Also the fuzzy block represents high level (supervisory) control while the PID stand for the existing conventional control loop which is in operation before the addition of the fuzzy module in all of these configuration.

Figure 3-6 (a). Here the operator can choose either of conventional control or the fuzzy high level control. He decides which of the control form will give the best results. Waste incinerator furnaces are example of equipment that was controlled using this configuration. PID loops controlled charging of waste and amount of combustion air but the loop could be by passed for the fuzzy alternative (Jantzen 1998).

Figure 3-6 (b). This happens when manual control becomes automated. The controller takes over the task of the operator in adjusting the local controller's parameters or setpoints. The operator again decides which of the alternatives is best for a particular operation (Jantzen 1998).

Figure 3-6 (c). Here the higher controller module was used to adjust the conventional controller PID parameters. PID controller used for the control of non-linear processes gives satisfactory performances within a small range of operating conditions outside of which the controller performances deteriorated. A higher fuzzy module could be used automatically to tune the parameters of the lower level controller in order to improve its performances (Jantzen 1998).

Figure 3-6 (d). This arrangement adds fuzzy outputs to the outputs of the conventional controller in order to quickly restore the conventional controller to their normal states after they are affected by sudden changes or abnormal conditions in the controlled process. During normal operation, fuzzy contributions are zero (Jantzen 1998).

Figure 3-6 (e). This is similar to *Figure 3-6 (b)*. This structure of the supervisory controller is the framework of Yokogawa electric's temperature controller (Chiu 1998). In this design, the fuzzy supervisory module leads the PID controller along a temperature trajectory that can quickly reach the actual setpoints without overshoot.

Figure 3-6 (f). This is also similar to *3-6 (b).* Vogrin & Halang, 2010, demonstrated the use of a setpoints pre-processor with a similar architecture to control robot arm. This experiment found that the controller response speed is very high, and it maintains good closed loop stability (Vogrin, Halang 2010).

3.2.9 Application of Fuzzy Supervisory Control in Building Services

Bruant et al (2001) developed a hierarchical and multi-objective fuzzy system for the control of summer conditions only. Three controllers were used in this arrangement. The first level comprises the thermal demand controller based on equivalent PMV. The second level is a neuro-fuzzy concerned with indoor air quality and the third level controls energy performance and controller stability. The model of the laboratory building was implemented in TRNSYS. This controller was compare against an on/off controller and an energy savings of over 10% was recorded (Bruant, Guarracino et al. 2001).

Gouda et al (2001) controlled indoor temperature by using predicted mean vote (PMV). In this research, the human thermal comfort criteria were used in the formulation of fuzzy logic control. This PMV-based controller was compared with pure PID-based controller. Simulations were performed using MATLAB/SIMULINK platform. The model was based on three inputs; the internal air temperature, the relative humidity and the mean radiant temperature. Occupant's activity and Clo values were kept constant. These two controllers were compared for building space with high and low thermal capacities. The results showed that by using FLC (Fuzzy Logic Controller) the energy consumption was reduced by 20%. It was found from results that FLC gives better control than the PID control with less overshoot (Gouda, Danaher et al. 2001).

A multi parameter fuzzy controller integrated with an overall optimised global controller was presented using a generic building model based on neural network (Guillemin, Morel 2001). Nine fuzzy controllers classified according to variation in the inputs of their inference system were tested. Global optimisation was achieved using genetic algorithm. One simulation for summer, winter and mid-season each was executed. The fuzzy variable for seasons was determined from average outside temperature and the membership function. Results showed that thermal and visual comfort level was achieved at a 25% energy savings.

A description of an integrated fuzzy indoor environment controller for thermal, ventilation and lighting control was presented (Pargfrieder, Jorgl 2002). Three control algorithms (fuzzy adaptive power profile, fuzzy power profile with genetic algorithm and a generalised model predictive control) were compared. Simulation results in MATLAB/Simulink for cooling and heating seasons with or without overheating were performed. In the fuzzy adaptive controller, although controller response is fast, near optimal results based on the selected criteria occurs only on two out of the seven day tested. The second algorithm which added a genetic optimisation algorithm to the previous controller resulted in better compliance to the specified setpoints with only minimal number of deviations. The generalised predicted control was implemented next but it was not clear from this paper if this approach was better than the previous efforts as the basis for the comparison was not clearly stated.

Mahroo & Marjanovic (2003, 2004) discussed the supervisory control for a test room. The controllers were designed for a single sided natural ventilation test cabin and were based on fuzzy logic. The input data to these controllers were the outside wind speed, internal and external air temperature. The controller has to position the opening according to the input data. Three controllers were developed. The differences between these controllers were membership functions and rules on which control action has to be performed. For all controllers, rain and wind membership function were same. In first controller the opening louver position was defined by two membership function (MFs). Second controller had three MFs but numbers of IF-then rules were same. The last controller was more complex having four MFs and more rules. The simulations for four different cases were performed with the help of Simulink. The cases were; Cold period with low wind and constant temperature and hot period, low wind and constant increase in temperature. All of the three controllers were simulated for these four cases. It was found that the controllers responded well to inputs and were capable of controlling window opening. It was also concluded that the controller with greater number of IF-THEN rules is more stable (Marjanovic, Eftekhari 2004, Eftekhari, Marjanovic 2003). Airport terminals are generally air conditioned enclosed space. Susceptibility of the terminal’s external environment to loud aircraft noises and high concentration of air pollutants from the aircrafts make natural ventilation unsuitable. Also openable windows could constitute high security risk in an environment that security has become a high priority.

Calvino *et al* (2004) described fuzzy control of a HVAC system focussed on the application of an adaptive fuzzy controller that avoids modelling of indoor and outdoor environment. Simulation and then experimental validation of this controller was done in a university room (Calvino, La Gennusa et al. 2004). The control was aimed to regulate Predicted Mean Vote (PMV) of the occupied space. In this research it was demonstrated that the output "u" of fuzzy PID controller can be expressed as; $u = A + P * e + D * \Delta e$; e is the absolute error, Δe is the variation in the error with respect to time and A, P, D are non-linear functions of the variables. Also, $e(n) = PMV_{(ref)} - PMV_{(act)}$. The main variables were power supplied to HVAC system, error between$PMV_{(act)}\ and\ PMV_{(ref)}$, and heat supplied to the occupied space. During experiment, the following values were assumed; $Icl = 1clo$, $metabolic\ rate = 1met, water\ vapour\ pressure, P = 1.2\ kpa$. Initially PMV value was set at -1 and for this value fan was running at its maximum speed. Five minutes was taken to stabilize PMV into comfort zone. It was concluded that this was the fastest and stable way of controlling indoor environment. It was also suggested that this method could be used for controlling solar radiations entering the room.

He *et al* (2005) presented the design of multiple model predictive control based on Takagi–Sugeno (T–S) fuzzy models for air handling unit (AHU) of a HVAC system. It was a two level hierarchical structure with the upper level occupied by a fuzzy partition to schedule fuzzy weighting of models in the lower level using air flow rates as a deciding factor. The lower level comprises $T - S$ models based on input-output manipulations from the higher level. Simulations and pilot plant testing on a school building model was reported to have proved the effectiveness of such a complex controller in HVAC control application (He, Cai et al. 2005).

Kolokotsta et al (2005) presented the design and testing results for an integrated indoor energy management system based on fuzzy logic. User comfort votes via a smart card were an input into the fuzzy controller. The system was installed in two school buildings in Greece and overall estimated energy savings of more than 35% was reported (Kolokotsa, Niachou et al. 2005).

Doukas *et al* (2007) presented a decision support model using rule sets. Results based on energy and comfort rating shows that the application is capable of ensuring comfort while assuring possible savings in energy. This also proved that indeed expert knowledge with the help of rule sets can provide intelligent interventions (Doukas, Patlitzianas et al. 2007).

Kristl et al (2007) used a test chamber with a south opening equipped with an external blind roller to investigate the thermal and optical responses of a fuzzy controller system. The thermal loop comprises two fuzzy controllers for winter and summer cases and uses the temperature differentia between the external and internal environment to decide which of the two controllers to activate. The illuminance controller on the other hand was tuned by experimentation and controls the roller blind according to the profile of illumination setpoints as shown in Figure 3-7. Results shows that the fuzzy controller actions are more in tune to human reasoning compare to the classical controllers (Kristl, Košir et al. 2008).

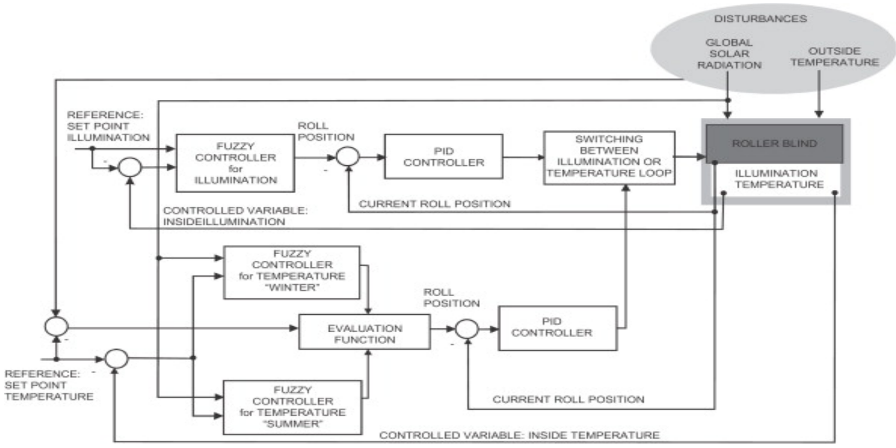


FIGURE 3-7: Control Scheme of the Illumination and the Thermal Loop (Kristl, Košir et al. 2008)

Soyguder *et al* (2009) designed a HVAC system to serve two zones. In this research fan motor speed was controlled using PID controller. The input-output data set were firstly stored and then these data set were used to predict fan speed. This prediction was based on Adaptive network based fuzzy inference system (ANFIS). The paper found that values used to predict fan speed using ANFIS were accurate (Soyguder, Alli 2009a).

Soyguder *et al* (2009b) obtained PID parameters using fuzzy sets. In multipurpose buildings, desired indoor air temperatures may be different depending on the use of the area. For this type of building, flexible HVAC system has to be designed in order to decrease initial and operational costs. This study was aimed to decrease design cost and design process by using modelling and simulation process (Soyguder, Karakose et al. 2009). A HVAC system with variable flow rate was modelled using Matlab/SIMULINK. Kp, Ki and Kd (parameters of PID) were determined by using self-tuning PID fuzzy adaptive controller. This controller was compared with classical PID and fuzzy PD type controllers. It was found that there were no steady state error and the adaptive controller also has minimum settling time. It was also found that self-tuning PID type fuzzy adaptive controller was the best as compared to other two controllers.

Soyguder et al (2009c) controlled damper gap rate of a HVAC system with the help of PID controller. This paper described the experimental work on basis of previous theoretical work. Two controllers were selected with one to be controlled by using the required indoor temperature and other by using the required humidity. The damper opening rate was proportional to the air mass flow-rate. The damper opening rate was predicted by ANFIS (Artificial Neural Fuzzy Interface System). RMS (Root Mean Square) and the coefficient of multiple determination R^2 methods were used to compare predicted and actual results. It was found that for both dampers pi-shaped curve membership function gave best performance. It was stated that this is the first study in which temperature and humidity is controlled with ANFIS. From results, it was shown that ANFIS predicted values are very similar to actual values. It was concluded that ANFIS are the faster and simple ways to control HVAC system (Soyguder, Alli 2009a).

A table summarizing application of fuzzy supervisory control to building types is given in Table 3-1 below.

TABLE 3-1: Application of Fuzzy Control to Building Types

Building Types	References
MATLAB Zone/Room Models	(Dounis, Santamouris et al. 1995, Kolokotsa, Stavrakakis et al. 2002, Soyguder, Alli 2009a, Yu, Dexter 2010)
Neural Network Generic Room Model	(Guillemin, Morel 2001)
Wooden/ Concrete Test Cabin	(Marjanovic, Eftekhari 2004, Eftekhari, Marjanovic 2003, Kristl, Košir et al. 2008, Lah, Zupančič et al. 2005)
Home and or Office Room/Building	(Dounis, Santamouris et al. 1993, Calvino, La Gennusa et al. 2004, Kolokotsa, Niachou et al. 2005, Doukas, Patlitzianas et al. 2007)
School Building	(Kolokotsa, Niachou et al. 2005)
TRNSYS Green House Model	(Kolokotsa, Saridakis et al. 2010)
Laboratory Building	(Bruant, Guarracino et al. 2001)

A summary table summing up these existing works have been provided in Table 3-2.

TABLE 3-2: Summary of Existing Works

Control Systems	Temperature Control	Ventilation Control	Lighting Control	Energy Reduction	Learning or Adaptation	Tuning Local Controllers	Setpoint Pre-Processing	Occupancy Control	References
ON/OFF	✓	-	-	-	-	-	-	-	(Levermore 2000)
PID	✓	✓	✓	-	-	-	-	-	(Levermore 2000, Salsbury 2005, Dounis, Caraiscos 2009, Bhatia 2012, Skogestad 2003, Cominos, Munro 2002, Visioli 2006)
Optimal Control	✓	✓	-	✓	✓	-	-	-	(Salsbury 2005, Tavakoli, Tavakoli 2003, Wang, Jin 2000, Wang, Jin 2000, Li, Zhang et al. 2005, Todorov 2006, Todorov 2006, Henze, Dodier et al. 1997, Xu, Wang et al. 2009)
Predictive Control	✓	✓	-	✓	✓	-	-	✓	(Xu, Li 2007, Oldewurtel, Parisio et al. 2010, Maciejowski 2002, Henze, Dodier et al. 1997, Henze, Dodier et al. 1997, Henze, Kalz et al. 2005, Curtiss, Kreider et al. 1993, He, Cai et al. 2005)
Genetic Algorithm	✓	-	-	✓	✓	✓	-	-	(Wang, Jin 2000, Alcalá, Benítez et al. 2003a, Kolokotsa, Stavrakakis et al. 2002, Nassif, Kajl et al. 2005a, Wang, Jin 2000, Chow, Zhang et al. 2002, Ahmad, Zhang et al. 1997, Wright, Loosemore et al. 2002, Wang, Zmeureanu et al. 2005, Ooka, Komamura 2009, Nassif, Kajl et al. 2005b)
Neural Network Control	✓	-	-	✓	✓	-	-	✓	(Kalogirou, Bojic 2000, Hepworth, Dexter et al. 1994, Han, Xiu et al. 1997, Ben-Nakhi, Mahmoud 2002, Curtiss, Kreider et al. 1993, Yang, Rivard et al. 2005, Chow, Zhang et al. 2002, Yokoyama, Wakui et al. 2009, Wong, Wan et al. 2010, Dodier, Henze 2004)
Fuzzy Local control	✓	✓	✓	-	✓	-	-	-	(Alcalá, Alcalá-Fdez et al. 2009, Gouda, Danaher et al. 2001, Hamdi, Lachiver 1998, Soyguder, Alli 2009b, Shahnawaz Ahmed, Shah Majid et al. 2007, Li, Zhang et al. 2005, Li, Zhang et al. 2005, Kolokotsa, Stavrakakis et al. 2002, Soyguder, Karakose et al. 2009)
Fuzzy Supervisory Control	✓	✓	✓	✓	✓	✓	-	-	(Gouda, Danaher et al. 2001, Visioli 2001, Bruant, Guarracino et al. 2001, Guillemin, Morel 2001, Pargfrieder, Jorgl 2002, Eftekhari, Marjanovic 2003, Calvino, La Gennusa et al. 2004, He, Cai et al. 2005, Kolokotsa, Niachou et al. 2005, Doukas, Patlitzianas et al. 2007, Kristl, Košir et al. 2008, Soyguder, Alli 2009a, Soyguder, Karakose et al. 2009, Guillaume, Charnomordic 2012)

3.3 CONCLUSIONS

From the literature review in this chapter, the following conclusions could be extracted;

1. Several reports exist of superior performances of fuzzy control in terms of provision of comfort at reduced energy compare to conventional control systems.

2. Many fuzzy control systems have been developed for building environment system application, majority based on Mamdani models (a detail description of this model is provided in section 6.3.3 latter). This shows the popularity and acceptability of Mamdani's models in BEMS fuzzy control studies.

3. Most of the control frame work used were either pure fuzzy, fuzzy with optimisation algorithms such as Genetic algorithm and Neural Networks and/or fuzzy controller for the tuning of PID parameters.

4. Almost all the supervisory control strategies researched for application in buildings have been mostly devoted to gain scheduling, tuning or optimisation of PID or other local controllers' parameter. Variable setpoint setting is still largely a manual operation; a very difficult task for large building operators such as the airport's terminal buildings.

5. What was clear from all of the reviewed studies (see table 3-2) is that none of studies has forayed into providing customised indoor control solutions for airport terminal buildings.

6. Although, several higher level fuzzy controllers have been developed, they largely consider occupancy variation and change in external conditions as disturbances.

For many zones within the airport buildings in which indoor environments comfort demand tallies with presence or otherwise of passengers and the state of external conditions, a control systems that varies the setpoints provided within these spaces based on passenger flow and external condition will be novel and can lead to great saving in energy. This study therefore develops a fuzzy setpoint pre-processor for the low level classical controllers regulating thermal, ventilation and lighting system in an airport building zone based on variation in external condition and passenger flow information. This is a new strategy in HVAC and lighting control application with a lot of potential for application in buildings which shares similar occupancy pattern to airport terminal buildings. Because, it is an add-on to the conventional system, it is suitable as a control retrofit pathway with less installation cost.

CHAPTER 4: THE DEVELOPMENT & TESTING OF AIRPORT TERMINAL BUILDING CONTROL

4.1 INTRODUCTION

The objectives of this research is to investigate and develop strategies for the control and integration of indoor thermal, ventilation and lighting systems, in response to passenger flows to provide an acceptable thermal and visual environment with minimum energy consumption and CO2 emissions.

This chapter provides answers to the why, how and what of the research method used to achieve the stated objective. Therefore, the discussions presented here dwell on the technique, equipment and motivation for site assessment and primary data collection, justification for the use of computer modelling and the description of selected computer software for building systems and controller modelling. Also provided is the information on how the selected software interacts with one another and with the building systems. Lastly, this chapter discusses the development of an airport building base case model by explaining the modelling procedure, the nature input and output data to the model and some of the limitations of the method used for the study.

4.2 GENERAL RESEARCH METHOD

The research method adopted for this study was based on the outcome of a detailed literature review on airport building's indoor comfort and automatic indoor environmental control issues which was presented in chapter two and three respectively.

Chapter two highlighted the peculiar nature of the airport indoor environment; reviews indoor thermal comfort studies carried out previously on airport terminal buildings and provided reasons for the selection of the controller inputs and outputs variables that can allow the achievement of indoor comfort for passengers and staffs of an airport terminal. Chapter three on the other hand reviewed the various control system types that has been used for building energy management and by comparing and contrasting their strength and weakness, the choice of fuzzy supervisory control method was made to be used in this study.

The approach used was both quantitative and qualitative. These include; airport site visits to gain familiarity with the airport indoor environment and develop insight into the current airport indoor environment system's operation through observation, assessment, interaction with the Building Management Systems (BMS) Engineers and indoor environmental monitoring to collect primary data in order to probe the workings of the systems. The results of primary data gathered from the indoor monitoring highlighting the areas of suboptimal performance of the indoor environment systems is presented in the next chapter.

Using the findings from this site evaluation, literature review on airport terminal's building characteristic, indoor comfort and building control systems; a new fuzzy supervisory control system was designed. The performance of the controller in terms of provision of comfort, energy and CO_2 emission savings was tested through computer simulation using the airport building base case model introduced latter in this chapter to provide the needed comfort in airport at reduced energy based on variation in passenger flow information and external condition. The controller design and simulation results will be presented in chapter six.

4.3 SITE ASSESSMENT VISITS

Several visits were undertaken to Manchester airport in order to discuss with the onsite BMS engineers in particular and the staff of the airport's environment department in general such as the Head of the Environment Group, Environment Advisors and other support staffs. These staffs helped the work by making available data such as the flight schedules, architectural and mechanical CAD drawings and survey reports. Another area of support was in arranging escorts and passes for access to all the relevant parts of the airport on the landside, airside and air field.

These periodic interactions with the airport staffs and site tours helped shore up understanding of the airport building layout, the airport arrival and departure processes and the existing airport building control practice and suggestion of what can be done to improve upon it. For example, it was revealed that many of the sensors used for metering the control system were not working, that lighting, relative humidity and a number of air conditioning units were not included in the BMS system's control loop. Initial attempt to fetch some data from the BMS system for some of the designated indoor spaces of interest was not successful. This prompts the resolve to deploy sensors and data loggers to collect some of the primary data needed to probe the performance of the indoor environment systems.

Interaction with the staffs also revealed the function of the Chroma suite, the airport information management system. It was suggested that there is need for a meddlesome technique that can use the passenger flow information available in the Chroma suite to regulate indoor environment systems for energy management in the buildings. The system in Manchester Airport was already interfaced with several businesses of the airport and can provide advance information such as: When aircraft is on final approach, aircraft due and landing times, where aircraft is to be parked, when first and last bags will be available for arriving passengers and much more. With this system, it is therefore possible to determine with relative accuracy when and what aircraft will arrive and where the passengers will pass through the terminal in advance. The information from the Chroma system has huge potential in energy management within and outside the airport. So, this work is partly a response to this mandate.

Part of the airport assessment also involves studying the HVAC system physical survey report and CAD drawings on terminal 1 & 2 of Manchester Airport produced by an engineering company in 2011. The report largely granted a good bill of health to most of the HVAC systems and plants in the airport. For example, in its scale of health A-E (A means new and E means damaged); about 80% of the equipment were graded either A or B and the rest were graded C. The report however recommends among other things that "energy efficiency measures across the terminal should include improving controls and metering in the buildings to allow the setting back of temperatures and the operation of systems outside of occupied hours for the terminal". This recommendation reinforces the choice to focus on the control systems rather the HVAC plants.

4.4 SITE INDOOR MONITORING

An indoor site monitoring was carried out for winter period from about 11.00 am on 26 October 2011 to 10.00 am on the 2nd November 2011 and for summer period from 11.00 am on 22 August 2012 to 11.00 am on 29 August 2012. This site monitoring involves mounting HOBO U12 Data logger and CO_2 sensors for a week to measure temperature, relative humidity and lighting level in four separate areas within the airport. The summer monitoring also incorporates the use of the CO_2 sensors for measuring CO_2 levels.

The HOBO U12-013 Temp/RH/2xExt Data Logger (Figure 4-1A) is an easy to read device with a 64 K memory capacity. It can measure temperature of -20 to +70^{o}C, humidity of 55 to 95%, and lighting in the range of 1 to 32,000 Lux. It has a programmable start time date and a sampling rate of between 1 second to 18 hours (a sampling rate of 5 minutes was adopted for this measurement since arrival and departure times are in multiple of 5 minutes). Data from the device can be displayed in graphical and tabular format and via HOBOware Pro software for Windows or Mac data can also be easily exported to excel and other programs.

To read CO_2 Level, HOBO U12 was combined with Telaire 7001i CO2 Sensor. The Telaire CO_2 sensors (Figure 4-1B) (Telaire) measures and displays CO_2 and temperature with a resolution of ± 1 PPM. It operates on 6VDC or 4 AA batteries with an operating life of up to 80 Hours (so for one week data collection, the batteries were replaced midway into the week). The HOBO U12 data loggers were connected to the CO_2 sensors over the test week to serve as the storage device since the sensor does not have a storage capacity (see Figure 4-2A for typical setup).

FIGURE 4-1: (A) HOBO U12 DATA LOGGERS (B) TELAIRE 7001I CO_2 SENSOR

The places monitored include baggage reclaim area, duty free shops, departure gate and the arrival hall. The reason for the choice of these places is to focus on the airside of the terminal where passenger occupancy varies directly with flight schedules as against the landside where the structure occupancy pattern is complex and is not entirely based on passenger flow pattern and so difficult to predict. Some pictures of the places are shown in Figure 4-2A-D; the position of the sensors is indicated with a red arrow. The more expensive CO_2 sensors have to be hidden from view in some places in order to protect the equipment from theft since the airport is a public place.

Also the airport building's architectural (AutoCAD) drawing which was used for the building geometric and systems modelling was collected at this stage.

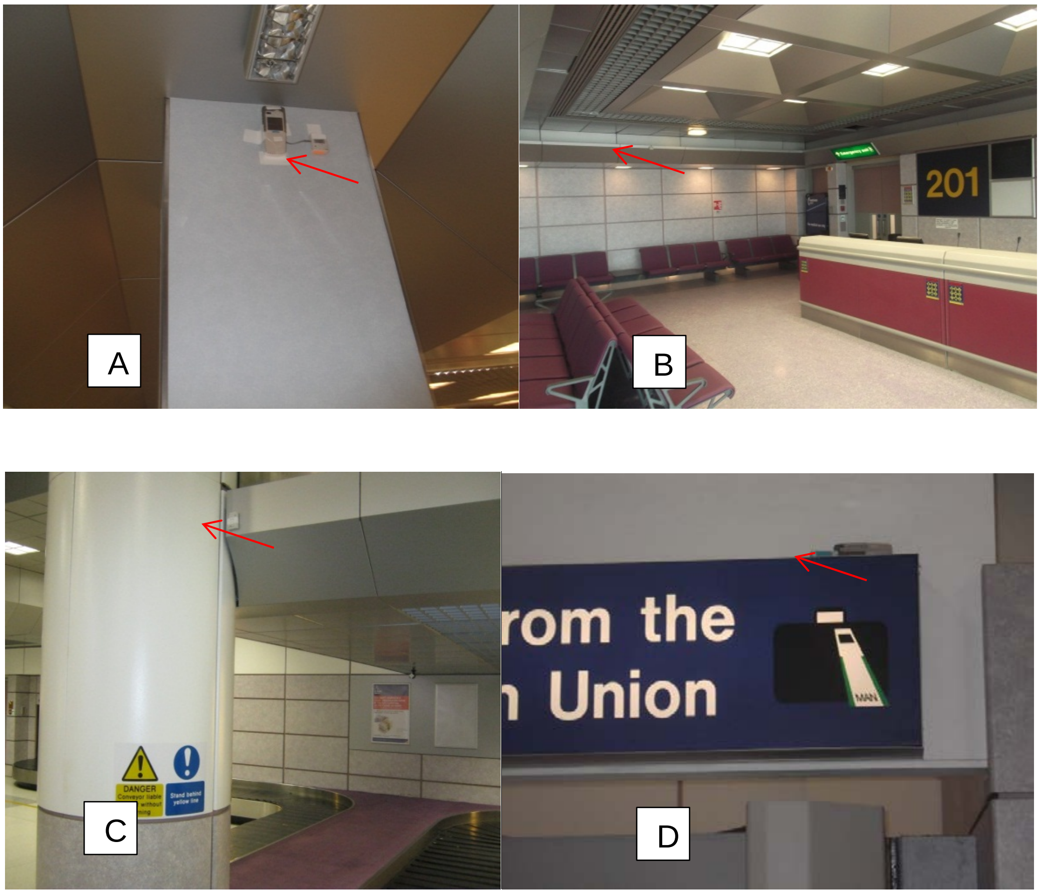


FIGURE 4-2: (A) Passport Control (B) Departure Gate (C) Baggage Reclaim (D) Arrival Hall

4.5 Computer Modelling of Building Energy Systems

Building energy modelling comprised the modelling of building fabrics - wall, ceilings, floors, and windows), contents - occupants and equipment and plants - HVAC, lighting and environmental control systems. This research uses computer based software to model building fabrics, contents and control systems.

Computer based building design and development is a cost effective and unobtrusive way of studying complex buildings and for testing new technology but the fragmentations within the building industry has reflected in the development of these tools, such that whole-building simulation is still an open issue (Salsbury 2005). For example, while most building simulation tools can perform fabrics and contents modelling, simulating advanced controller is still limited in most state-of-art building simulation tools. Some are better at specifying local controllers such as TRNSYS (Klein 1979) and ESP-r (Strachan, Kokogiannakis et al. 2008) while EnergyPlus (Crawley, Lawrie et al. 2001) offer ease in specifying supervisory control. Although domain independent simulation platforms such as MATLAB (MathWorks 2005)/Simulink (MATLAB 2012), LABview (Travis, Kring 2006), and Dymola (Dynasim) are efficient in design and testing of controllers but they do not have all the models to accurately simulate buildings forms and systems (Trčka, Hensen 2010). Although computer simulation has become a standard tool for testing new technology, the real test of a control system still lies with its practical implementation and this is a natural next level for this research.

Airport terminal building and systems are very complex and this complexity compels the experimentation with these building modelling tools in order to select the one capable of providing a good model. Since our research thrust is on supervisory control; to get the best of both worlds, the supervisory controller was designed in the MATLAB/Simulink environment while the airport terminal building fabrics, contents and its indoor plants were modelled in DesigBuilder/EnergyPlus. Both simulations are linked via a data exchange interface. This approach avoids the difficult and error prone task of recreating a model covering the complex nature of airport terminal building and systems from first principle in the MATLAB/Simulink environment by using the extensively tested and validated EnergyPlus software for building energy modelling.

4.5.1 EnergyPlus

EnergyPlus is a U.S Department of Energy's new generation building energy analysis and thermal simulation tool that is suitable for analysing building performances with unusual building systems (Pan, Zuo et al. 2011) such as the airport terminal building. Its roots are in BLAST (Building Loads Analysis and Systems Thermodynamics) and DOE-2 (Department of Energy -2). Its code was built with Fotran90 which allows object orientation, ASCII text-based weather files, inputs and output files adapted for sub-hourly simulations, user configurable modularity linked to heat and mass balanced based zone simulation and backward and forward compatibility with its legacy software and several other GUIs such as the DesignBuilder, Google Sketchup, OpenStudio, Ecotect etc. More so, it is based upon third-order lumped parameter simulation. These capabilities made it possible to model complex buildings and systems which was beyond its legacy software. EnergyPlus has been validated using the comparative Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs BESTEST/ASHARE STD 140.

Additionally, Griffith et al (2003) actually used the earliest form of EnergyPlus (Version 1.0.3) to study the influence of advanced building technologies such as optimised envelope systems and schedules for a proposed Air Rescue and Fire Fighting Administration Building at Teterboro airport and found that the results obtained compare well with those obtained using DOE-2.1E (Griffith, Pless et al. 2003). Ellis and Torcellini (2005) confirmed the reliability and accuracy of EnergyPlus in simulating tall buildings (Ellis, Torcellini 2005).

Standard control tools within EnergyPlus includes low level control, high level control and the Energy Management System (EMS) based on the EnergyPlus runtime language (Ellis, Torcellini et al. 2008). The low level control simulates a particular closed-loop hardware controls that have a specific task to accomplish. They are usually found in the input of an EnergyPlus object. High level (Supervisory control) operates at a higher level than the local loop in control hierarchy. This type of control affects the operation of local control and can jump across system boundaries and can be used to manage and control the running of other component objects, part of or the entire system.

The major type of supervisory control in EnergyPlus are; setpoints managers (specify setpoints based on data from the control environment), system availability mangers (decides on when to turn systems on/off), plant operation schemes (used to sequence plant operations by priority according to loads) and demand managers (which attempt to keep total electricity use below certain energy use by shutting or reducing power to non-essential equipment's at times of high energy demand) (Ellis, Torcellini et al. 2008). This work supplants setpoints manager's control data with the outputs from the designed fuzzy setpoints pre-processor controller.

4.5.2 DESIGNBUILDER

The major short-coming of EnergyPlus is that it does not have a friendly user interface. To overcome this problem, DesignBuilder was used for the modelling process. DesignBuilder is the first and most comprehensive user interface to the EnergyPlus dynamic thermal simulation engine. It combines rapid building geometry, Indoor environmental system's modelling and ease of use with state of the art dynamic energy simulation based on EnergyPlus. Through the DesignBuilder and for the first time, the advanced HVAC and Dayligthing features in EnergyPlus are now accessible in a user-friendly graphical environment. The latest DesignBuilder v3 provides a powerful and flexible new way to model both air and water sides together in full detail with a good range of components including all ASHRAE 90.1 baseline HVAC systems. The interaction between EnergyPlus and DesignBuilder is shown is Figure 4-3. What this diagram depicts is that the building system described in DesignBuilder form an input into EnergyPlus, simulation is carried out in EnergyPlus and the output of this simulation is displayed in DesignBuilder.

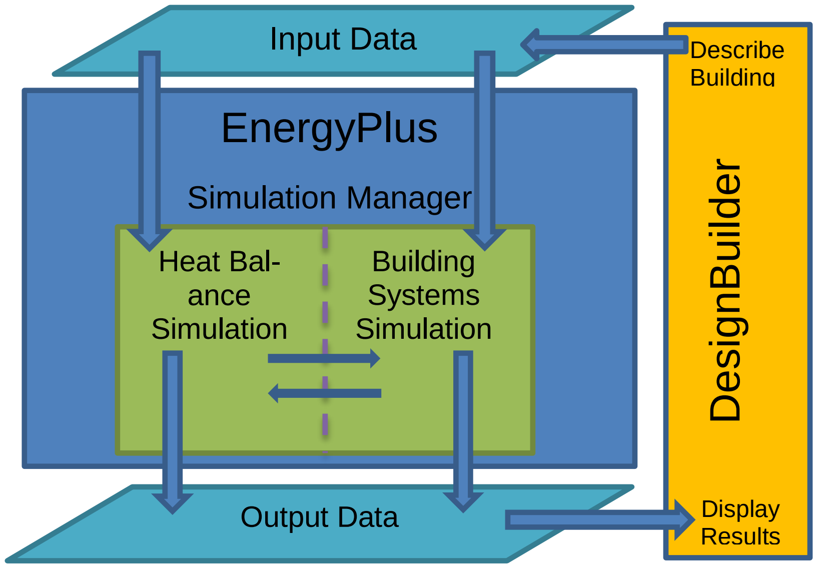


FIGURE 4-3: Interaction between EnergyPlus and DesignBuilder

4.5.3 MATLAB & SIMULINK

MATLAB is a high-performance language for technical computing. It combines computation, visualization, and programming in a simple environment where problems and solutions are shown in an accustomed mathematical format. Application will include: Math and computation, Algorithm development, Data acquisition, Modelling, simulation, and prototyping, Data analysis, exploration, and visualization, Scientific and engineering graphics, Application development, including graphical user interface development (MathWorks 2005).

MATLAB comprise a basket of add-on application-specific applications termed toolboxes. Toolboxes are very important to many users since it allows the learning and application of a particular technology. MATLAB and Simulink also have a pool of MATLAB functions (M-files) that stretched the MATLAB environment to solve specific types of problems. Toolboxes are available for signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others (MathWorks 2005).

Simulink Toolbox is an interactive platform for modelling, simulating, and analysing dynamic, multi-domain systems. It can be used for building block diagram, simulate system's behaviour, evaluate its performance, and refine its design. Simulink integrates seamlessly with MATLAB, providing useful access to huge range of analysis and design tools (see Figure 4-27). For these reasons therefore Simulink is the preferred tool for control system design and other simulation applications (MATLAB 2012).

4.5.4 Fuzzy Logic Toolbox

The Fuzzy Logic Toolbox on the other hand is also a collection of functions built on the MATLAB's numeric computing environment. It offers tools for creating and edit-ing fuzzy inference systems within the framework of MATLAB, or if preferred, it can integrate fuzzy systems into simulations with Simulink, or even build stand-alone C programs that call on fuzzy systems built with MATLB (see Figure 4-4) (Jang 2013). This toolbox relies heavily on graphical user interface (GUI) tools to accomplish work, although it can work entirely from the command line if preferred (MathWorks, Wang 1998).

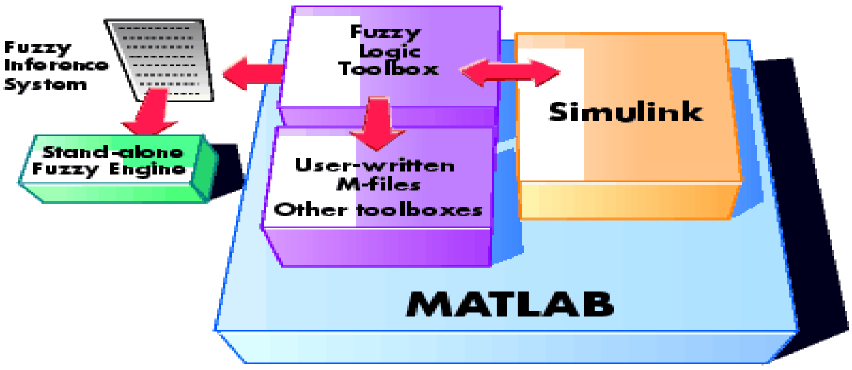


FIGURE 4-4: MATLAB, Simulink, Fuzzy Logic Toolboxes and M-Files (JANG 2013)

The overall interaction between all the software (Fuzzy Logic toolbox, MATLAB/Simulink and DesignBuilder) is presented in Figure 4-5. So here, fuzzy logic controller housed in a Simulink shell was developed using fuzzy logic toolbox in MATLAB, the inputs and outputs of the controller is made available in the MATLAB workspace via Simulink inputs and outputs ports. The controller outputs (indoor environment setpoints) in the workspace is converted into DesignBuilder/EnergyPlus compact schedules and used as the setpoints for local controllers in the airport building model. Simulation results are collected from the DesignBuilder graphical interphase and analysed.

This arrangement facilitated importing the building geometry directly from AutoCAD drawing, model detail HVAC, lighting and control system configuration in Design-Builder, importing schedules from MATLAB and modelling control strategies.

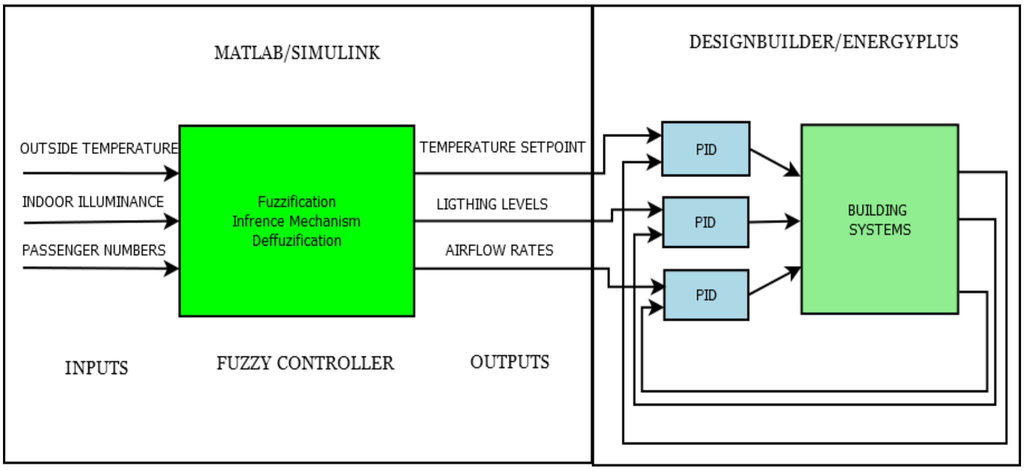


FIGURE 4-5: MATLAB/Simulink & DesignBuilder

4.6 Description of Case Study Airport Terminal

Manchester airport being our project partner was naturally the case example selected for this study. This airport is the busiest airport in the UK outside London with an annual turnover of 21 million air passengers transiting through it and about 16,250 employees on site (Knowles 2006). It has two runways operated in two ways depending on the wind directions. It has three terminals; Terminal 1, Terminal 2 and Terminal 3.

Terminal 1 is the biggest and the busiest of the three with twenty-two gates and has two piers. Most of the intercontinental flights arrived at this terminal. This terminal hosts the largest passenger airplane, airbus 380 and Terminal 3 mostly handles the domestic traffic and short international connections.

Terminal 2 (shown Figure 4-6) is our terminal of interest because although it is the farthest of the three from the runaways the indoor environment systems are currently being upgraded. This makes it a suitable candidate for low energy refurbishing study. This terminal was constructed in 1992 on the North-West part of the airport site. It is made up of five-floor central building covering a gross floor area of about 18,000 m^2 and has two piers of four floor levels measuring about 5,400 m^2 spanning to the left and right direction of the central building. The ground and the first floor contain the arrivals halls, the third floor, the departure halls, and the fourth floor is made up of lounges, offices and the control room on the central building mainly housed the plant rooms on the piers. The fifth floor is mainly plant rooms. So the airport building's function is already well segregated.

FIGURE 4-6: Manchester Airport Terminal Two (DooYoo 2012)

The terminal is heated by gas boilers located in the central and eastside of the terminal. There are air-cooled chillers externally located on steelwork frames in the main plant rooms. The air handling units comprises of Inlet damper, mixing box, HPHW Frost Coil, Panel Filter, Bag Filter, Carbon Filter, Cooling Coil, HPHW Reheat Coil, Supply Fan, Extract Fan. The building has no lighting and Dayligthing control. However, the luminaires were recently upgraded, and the introduction of lighting control is being considered.

4.7 Modelling of Building Geometry and HVAC Systems

The first step in building modelling in DesignBuilder (see Figure 4-7) is the definition of location and choice of weather data (either from the fairly large collection available in the DesignBuilder library or imported from elsewhere but must be in the .epw format) to match the location.

Weather data for Manchester Airport used in this modelling was the hourly ASHRAE International Weather for Energy Calculation (IWEC) GBR Manchester Ringway MN6 data based on thirty years average in EnergyPlus Weather format (.epw), since these data are easily available for use in the EnergyPlus user forum portal and are also very similar to the CIBSE weather data.

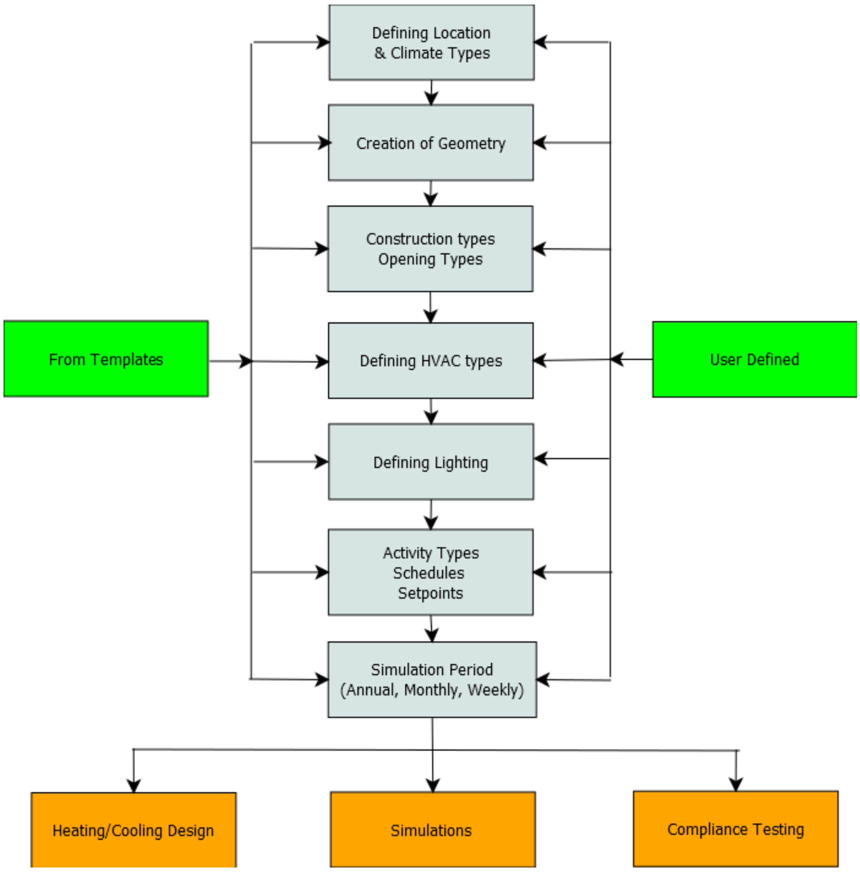


FIGURE 4-7: DesignBuilder Building Modelling Workflow

Although there are a number of customisable building templates available in the DesignBuilder library none came close to the description required for airport building. Therefore, the building geometry was modelled fresh by importing the 2D AutoCAD drawings of the airport building using the dxf import facility. The building models were assembled by positioning blocks in the 3D space to define the external walls based on the CAD drawings. Figure 4-8 provides 3D geometric form of the building.

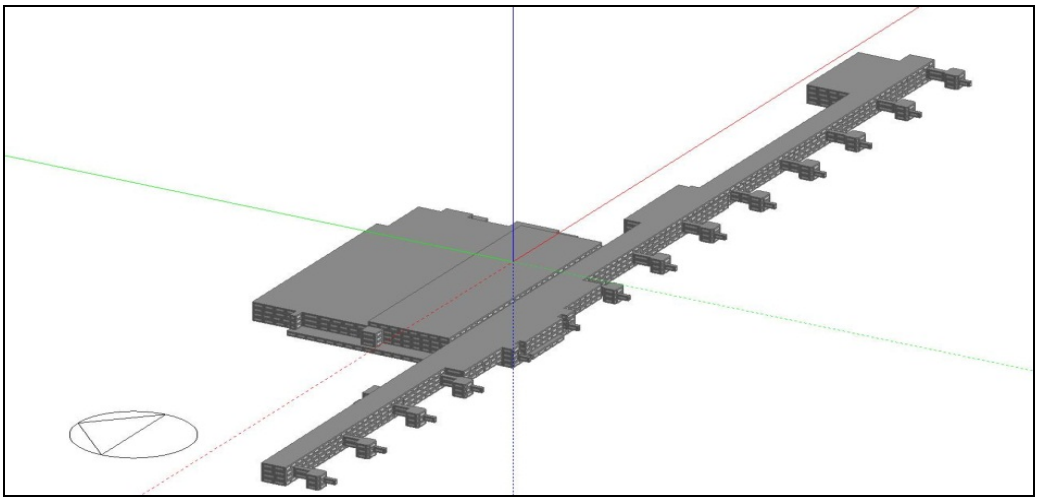


FIGURE 4-8: 3D View of the Designed Model

Thermal zones (internal partition walls) were defined based on the functions of the space and type of the HVAC system in the indoor space for each of the floors based on the description obtained from Jacobs Engineering's HVAC system physical survey report and CAD drawings on terminal 2.

For this case study, there are twenty-two thermal zones in the building. However, these zones are further sub-grouped into six zone groups according to the HVAC system type. Delineation of the thermal zones is very important because EnergyPlus calculates the energy required to maintain each zone at a specified setpoint for each hour of the day. In EnergyPlus, A "zone" is different from a geometric form; it is an air volume of uniform temperature and all the heat transfer and heat storage surfaces surrounding or internal to the air volume. The building model was zoned according to passenger flow such that the areas accessible to the public were separated from the areas that were restricted to only passengers and staff. Occupancy in the restricted areas such as the Check-in, Customs, Security, passport control and baggage reclaim areas can easily be linked to arriving/departing passenger planes. However, in the public spaces such as the booking hall, some retail areas and some offices, the flow of people needs to be estimated and therefore more complicated to control.

The building construction data, lighting and opening types was chosen from the template to satisfy the Part L Building Regulation for commercial buildings in England and Wales (1990-1994) since according to the report; the building was constructed in 1992 and the details of the airport building material was not available. The following table 4-1 summarizes the construction details used in the model.

TABLE 4-1: Building Model Construction Details

Stock reference building characteristics based on 1990-94 Part L (England & Wales)	
Building Element	**U (W/m2 K)**
External walls	0.45
Ground floor	0.20
Flat roof	0.35
Windows, Doors and Roof light	3.00

The HVAC modelling was done using a recently approved Version 3 which allows access to a wide range of EnergyPlus HVAC systems through an easy to use diagrammatic interface and satisfied compliance rating for LEED, BREEAM and Green Star. The HVAC system specification (Figure 4-9) was also based on the airport's HVAC system survey report.

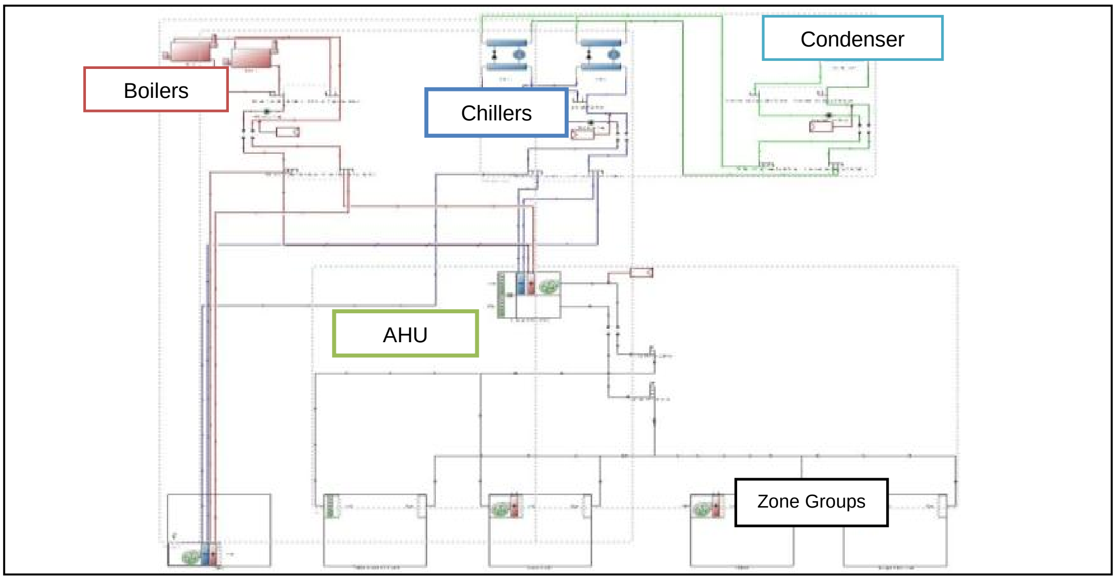


FIGURE 4-9: Schematics of the HVAC System

The HVAC model includes the boilers, chillers, condenser, air handling units (AHU) and the zone groups as described previously.

The activity template was based on the BRE National Calculation method specifications for passenger terminal spaces contained in the DesignBuilder activity templates. This template covers occupancy profiles, internal gain data, equipment usage and plant schedules, design indoor temperature, illuminance levels and ventilation rates per person. DesignBuilder also allows users the use of schedules to define occupancy times, equipment, lighting and HVAC availability and heating setpoints, cooling setpoints and minimum outside air flow rates.

These schedules are of two types:

- 7/12 schedules: in this, each day, week, or month of the year has its daily variation computed using profiles. It is less flexible.

- Compact Schedules: this is a more flexible easy to edit text based data format that can be customised by a user to import profiles. Its format is similar to EnergyPlus compact schedules.

In this research, compact schedules interface was utilised to import thermal setpoints, lighting setpoints and air flow rates to DesignBuilder from the MATLAB/Simulink simulation workspace. More technical details concerning this interphase including the base and test cases input gain schedules using EnergyPlus compact schedule format can be found in the appendix 2. The model was checked by ensuring that occupancy data was inherited correctly so that changes at block and building level produce the needed effect.

Also, DesignBuilder allows the selection of simulation period. This could be annual, monthly, weekly, daily, summer design period, winter design period, typical winter week, typical summer week etc. The weekly option was used by supplying the summer and winter week dates to coincide with the monitoring period i.e. 26/10/2011 to 2^{nd}/11/2012 for winter operations and 22-29/08/2012 for summer operations.

The output of the simulation was the total electricity and gas usage in kWh combined to give the total energy usage in kWh, total carbon dioxide emission in kg of CO_2 and Fanger PMV rating. These results were plotted for both the base case and the low energy test cases in bar charts to allow for easy comparison.

4.8 Conclusions

This chapter described the research methodology in greater details, provides justification for the need of a new control strategy for the airport building studied, explained the reason for the selection of the various software tools and provided detailed description of the developed airport building model that will be used to probe the efficacy of the new fuzzy supervisory controller for the airport building described. The major limitation of this study is that it is mainly for passengers and staff in passenger exclusive areas within the airport and so did not cover non-passenger areas within the airport. Also, although computer modelling is cost-effective and unobtrusive means of testing design alternatives, the best test of a control system is in practical implementation. However, due to operational and logistic factors in airport operations, the online testing of this controller has been recommended as future work.

CHAPTER 5: PRIMARY DATA COLLECTION AND ANALYSIS

5.1 INTRODUCTION

As part of the effort to investigate the current management of the airport indoor environment systems and its relationships with the passenger flow and external temperature, this work embark on collection of data on indoor temperature, relative humidity, lighting levels, CO_2 levels and the arriving and departing flight schedules for winter and summer scenarios using the equipment and methods described previously in chapter 4. The indoor spaces were selected on the airside so that both arrival and departure processes were included. The summer and winter week's flight schedule data used for examining arriving and departing flight pattern was uploaded from the Chroma suite one week in advance.

The chapter will first discuss the indoor environmental systems' comfort performance and compare it with the standard comfort requirement for such spaces using Chartered Institute of Building Services Engineers (CIBSE) standards for indoor temperature, relative humidity and lighting levels and Occupational Health and Safety Administration (OHSA) for indoor CO_2 Level. Opportunities for implementing energy conservation strategy such as setbacks and switch offs will be explored.

5.2 WINTER

The indoor temperature of the spaces - Arrival Hall, Baggage Reclaim, Departure Gate and Duty-Free Shops of Manchester Airport Terminal 2 was monitored from 26th October to 2nd November 2011. The external temperature for this period was collected and Figure 5-1 shows the hourly outside temperature. This was the actual hourly weather data for Manchester Airport was derived from freemeteo.com and wunderground.com.

It is a common knowledge that there is a strong correlation between external and internal weather data. It is known that external temperature influence solar heat gains, temperature of ventilation air and the convective and conductive heat exchange across the building fabrics. Therefore, when external temperature profile is compared with the indoor temperature profile it can give an indication of heating or cooling effort needed to achieve the indoor comfort. It can also indicate the opportunities available from the outside environment to meet indoor thermal requirement either purely through passive means and/or with active means.

From Figure 5-1, outside temperature varies from about 3^{o}C on the night of the 28th to the highest day temperature of about 16^{o}C on the 30th and 31st.

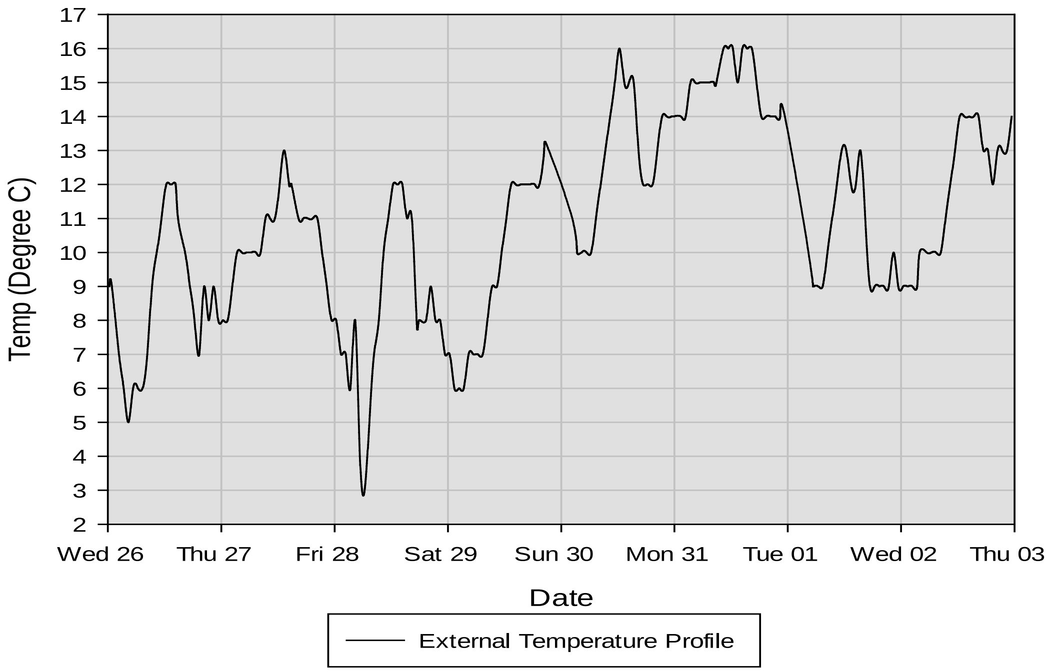


FIGURE 5-1: Outside Hourly Temperature for Manchester Airport

5.2.1 INDOOR THERMAL COMFORT VARIABLES

The results of measurement for the Arrival Hall, Baggage Reclaim, Departure Gate and Duty Free Shop area are as shown in Figure 5-2. This shows that indoor temperature range for Arrival Hall (21 – 22.5^{o}C), Baggage Reclaim (20 - 22.5), Departure Gate (22 - 23^{o}C) and Duty Free Shop (24 - 26^{o}C) throughout the week as against the CIBSE recommended temperature of 19 – 21^{o}C for Arrival Hall, Departure Gate, Duty Free Shop and 12-19^{o}C for baggage reclaim for such spaces. The variability in the measured indoor temperature among the spaces could have been influenced by many factors. Such factors could include the use of space, adjacency to external building fabrics, heat gains, ceiling to floor height, and positions of the measuring device (sensors) etc. It was clear in this winter scenario that the indoor spaces are warmer than necessary as the comfort plots on psychometric chart will latter reveal.

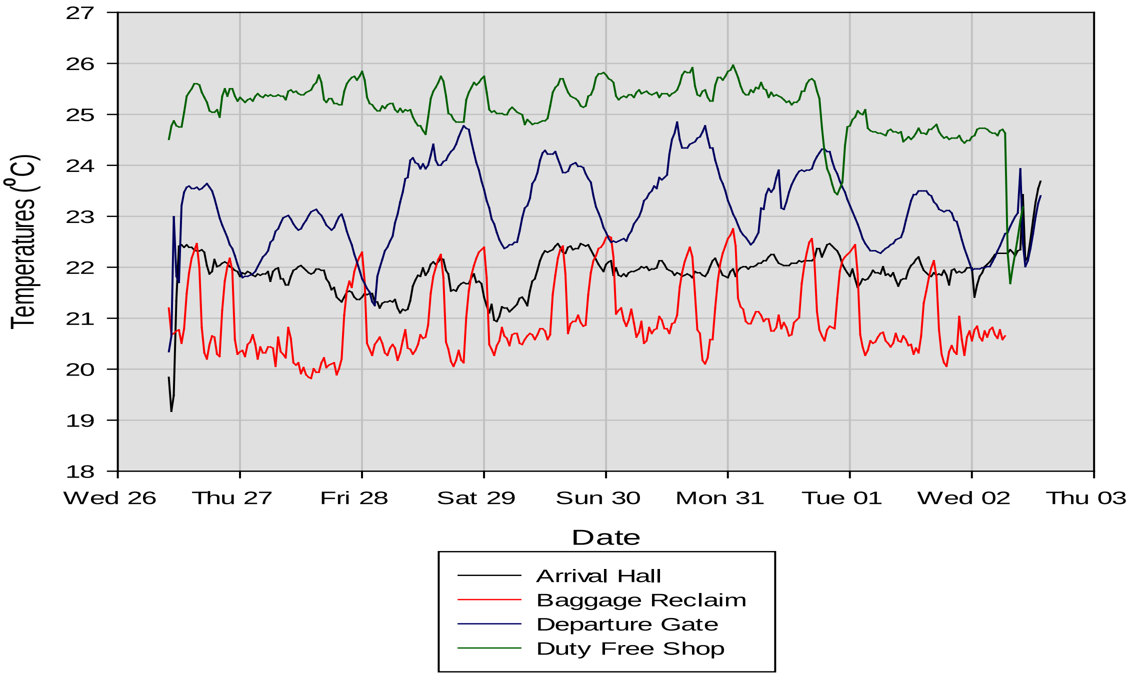


FIGURE 5-2: Indoor Temperature Profiles

Also Figure 5-3 shows the relative humidity profile for the four indoor spaces. The range of values for Arrival Hall, Baggage Reclaim, Departure Gate and Duty Free Shop is 36-55%, 38-60%, 32-55% and 28-46% respectively as against the 40-70% as the CIBSE recommended values for all kinds indoor spaces. However, CIBSE Guide A also mentioned that a relative humidity lower than 30% is acceptable where risk of static electricity is low and above 70% where risk of microbial growth is minimal as such it was not uncommon to see practitioners quoting 20 - 80% as the acceptable range for comfort. Additionally and more important to the passenger exclusive areas of the airport, it also stated that lower relative humidity is acceptable in areas of short duration of occupancy. In this context, therefore, the relative humidity values recorded for all the indoor space except the Duty Free Shop are acceptable. In the shops, attendants remain in the space for a long duration of time, so while it may not matter to the passenger, 28% relative humidity may be not be acceptable to the staff but then this level was only reached briefly on Friday afternoon, otherwise, it has been within acceptable level for the rest of the times.

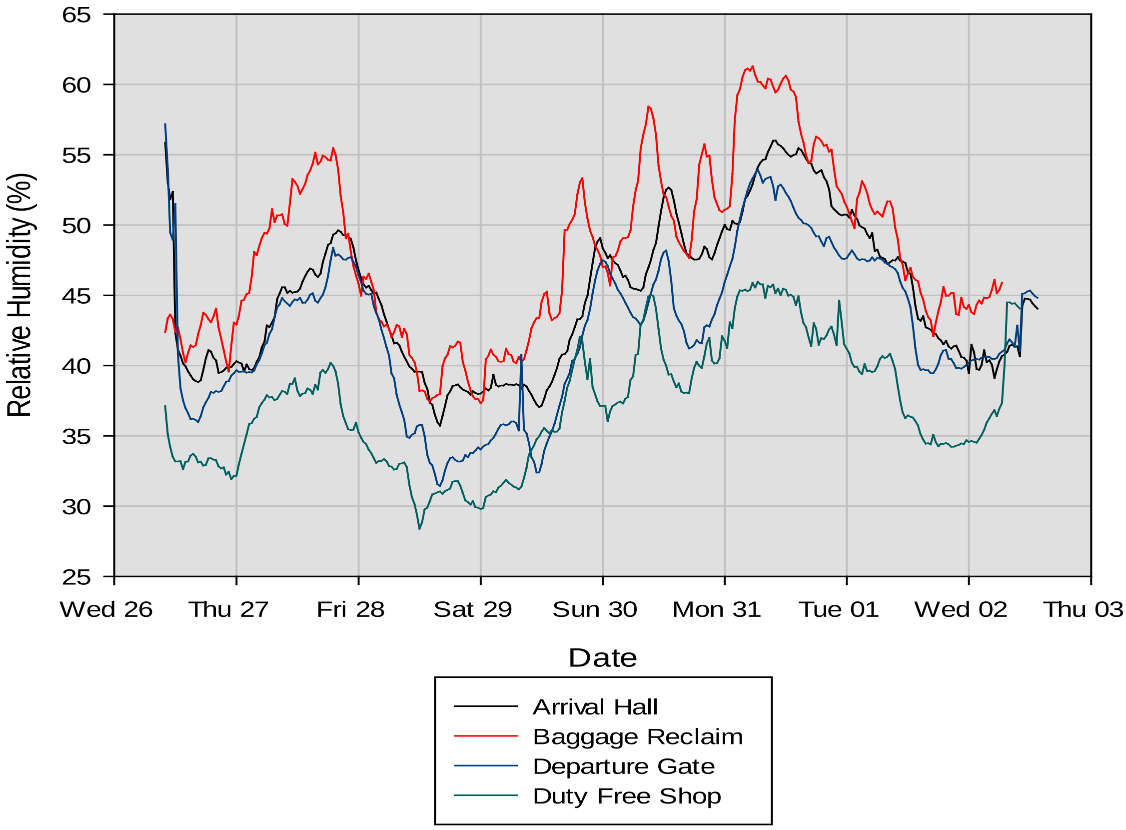


FIGURE 5-3: Indoor Relative Humidity Profile

By plotting the measured indoor temperature and relative humidity represented by the yellow shade and the CIBSE recommended setpoints for the same variables depicted with the blue shade on the psychometric chart shown in Figure 5-4; it can be seen that the indoor environments are warmer than they should be. In terms of relative humidity however and in virtually all the space monitored, the level is within the acceptable limits.

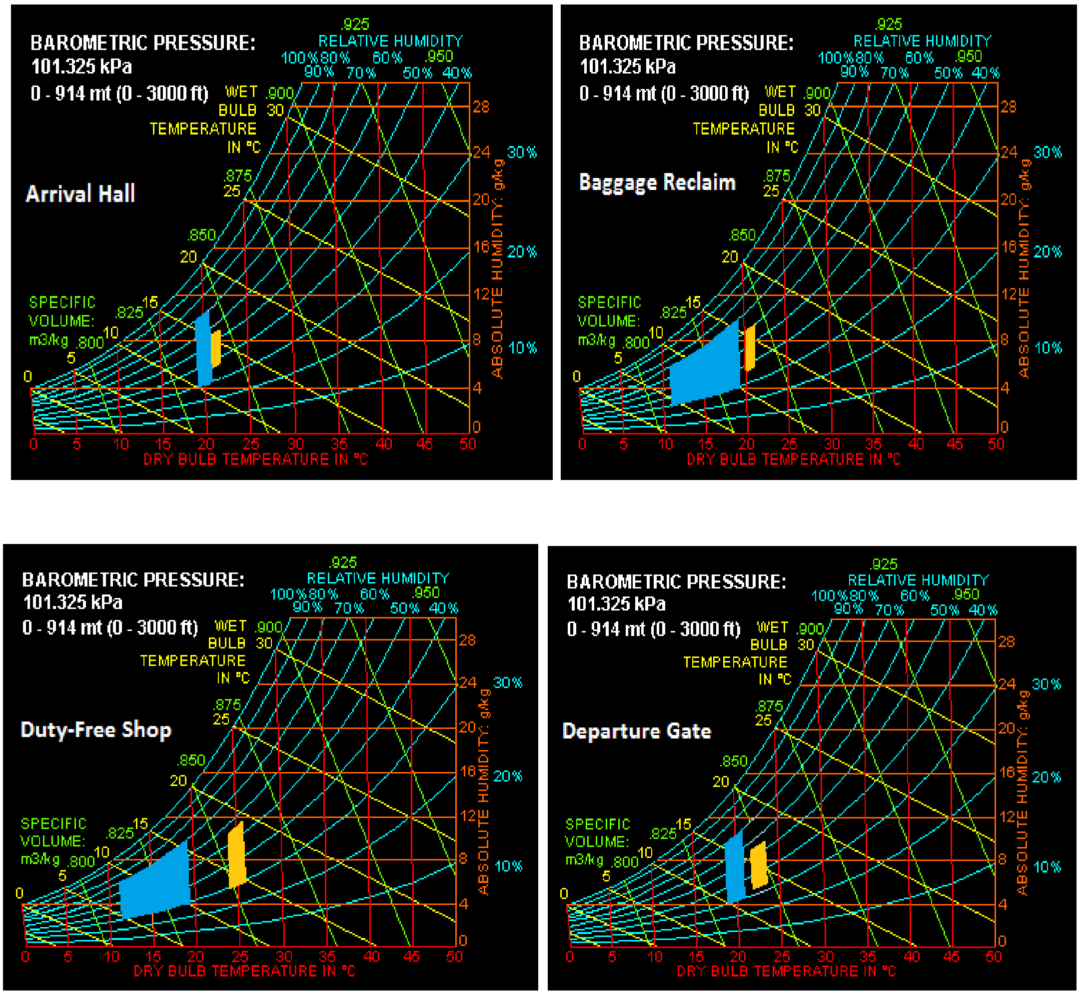


FIGURE 5-4: Measured vs. Recommended Comfort Variable

5.2.2 Indoor Illuminance Levels

As can be seen from Figure 5-5, the indoor illuminance level for Arrival Hall, Baggage Reclaim, Departure Gate and Duty Free Shop is 250-400 Lux, 310-370 Lux, 320-600 Lux and over 310 Lux respectively. These levels are higher than the recommended 200 lux for these spaces. The indoor illuminance level depends on whether the space in question was exposed to direct daylight and that was the reasons for the high illuminance spikes during the day time in the Departure Gate Area. This made this space suitable for Dayligthing control. During site assessment tour, it was noticed that virtually all the artificial lights are on even in spaces where the daylight illuminance was very high such as the departure gates and departure concourses generally. The reason being that the airport does not have lighting control as at that time but that the airport was already upgrading to the LED luminaires and that lighting control was also being considered.

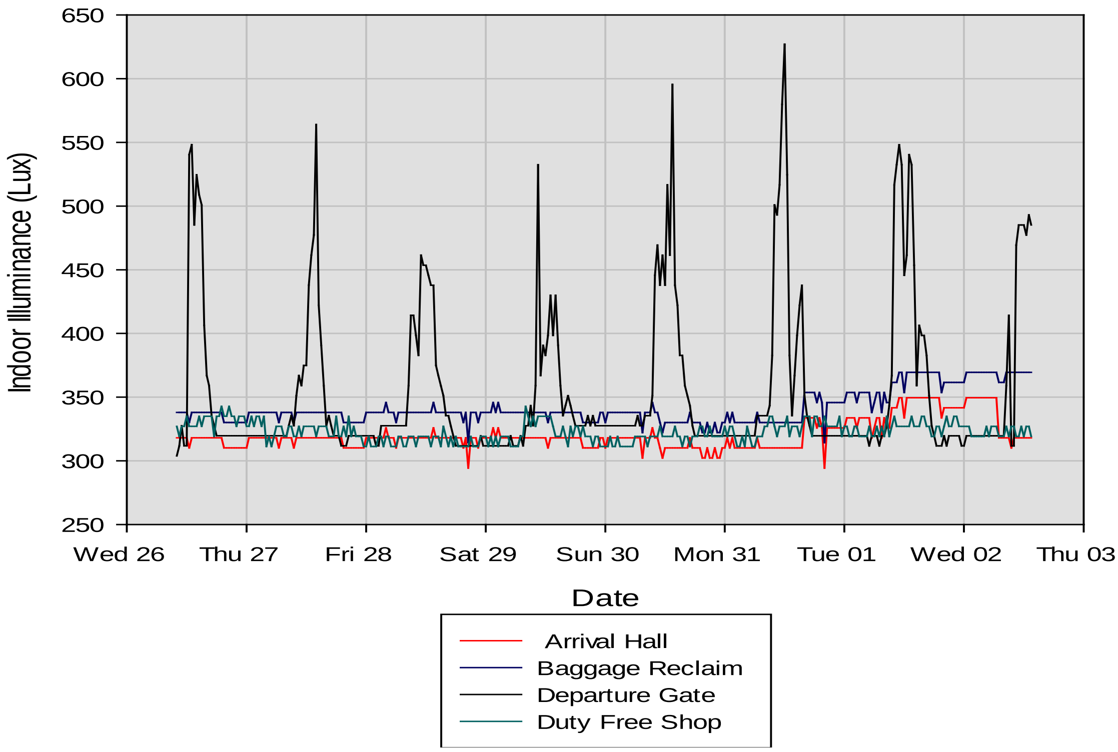


FIGURE 5-5: Indoor Illuminance

It is clear from the analysis of the winter monitored results of the environmental system's performance that the lighting and temperature setpoints for winter has been exceeded. This alone will lead to substantial loss in energy. Also, the need for temperature setback during unoccupied hours was possible for all the spaces reviewed except for the shopping area where occupancy by shop attendants continues even after the passengers have left. The comfort temperature for winter for could be set at around 19 - 20^{o}C for most passenger non seating indoor spaces within the airport terminal during occupied hours. The setback temperature during unoccupied hours will be dictated by the external temperature and occupancy. Although relative humidity level was not controlled as part of the HVAC control strategy as previously mentioned in chapter 4, the level recorded is about right for comfort in all the spaces monitored except for a short time in the shops which are not part of our research focus. Lighting and Dayligthing control has great potential to save energy.

5.3 Summer

The indoor temperature of the spaces in airport terminal was again monitored from 22nd-29th August 2012. Figure 5-6 shows the hourly outside temperature for the week under review. As stated previously, external temperature is an indicator of what heating/or cooling effort is needed to achieve comfort in the indoor environment and a pointer to the opportunities available to meet indoor thermal requirement purely through passive means. The temperature variation was of about 11^{o}C in some nights to about 19^{o}C on some days. This fluctuation clearly demonstrates how a single temperature setpoints for the whole week without setback could lead to waste in energy. Although, it is a summer week, the temperature profile suggests that there may be need for some little or no cooling and that there may also be some need for little heating especially during the night operations in most of the indoor spaces to provide thermal comfort.

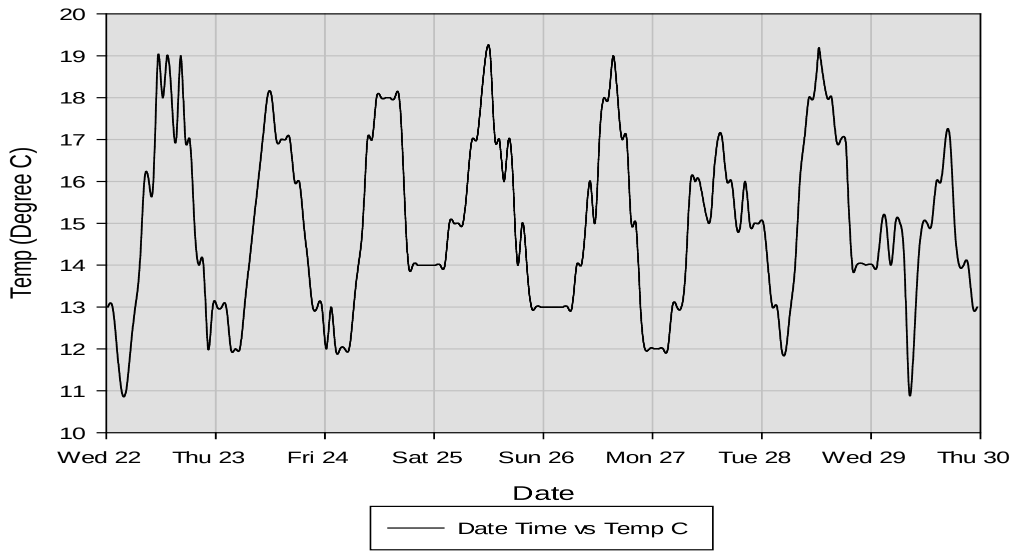


FIGURE 5-6: Outside Hourly Temperature 22nd – 29th August 2012

5.3.1 INDOOR THERMAL COMFORT VARIABLES

The temperature profile shown on Figure 5-7 belongs to the Arrival Hall, Baggage Reclaim, Departure Gate and Duty Free Shop. The figure shows a week long temperature range of 22 - 25^{o}C for Arrival Hall, 24 - 26.5^{o}C for Baggage Reclaim, 22 - 23^{o}C for Departure Gate, 22.5 - 23.5^{o}C for Duty Free as against the CIBSE recommended range of 21 - 25^{o}C for all the spaces. There was no adjustment of setpoint during unoccupied hours to proximate external temperature profile. So although, the recommended setpoints is the same for all the spaces, recorded temperature shows considerable variation with the Baggage Reclaim area, a deep plan space with no connection to an outside window was much warmer while the Departure Gate, the only space with an external wall, was the least. You can always experience this differences in warmth as you transit through the airport; some places feels slightly cool while the other slightly warm. Considering that outside night time and daytime temperatures ranges between 11 - 13°C and 17 - 19°C, it appears that some heating was on in these spaces. Enquiry about this reveals that since many of the sensors used in metering the HVAC controls are out of function, sometimes the heating or cooling might come up at unexpected times.

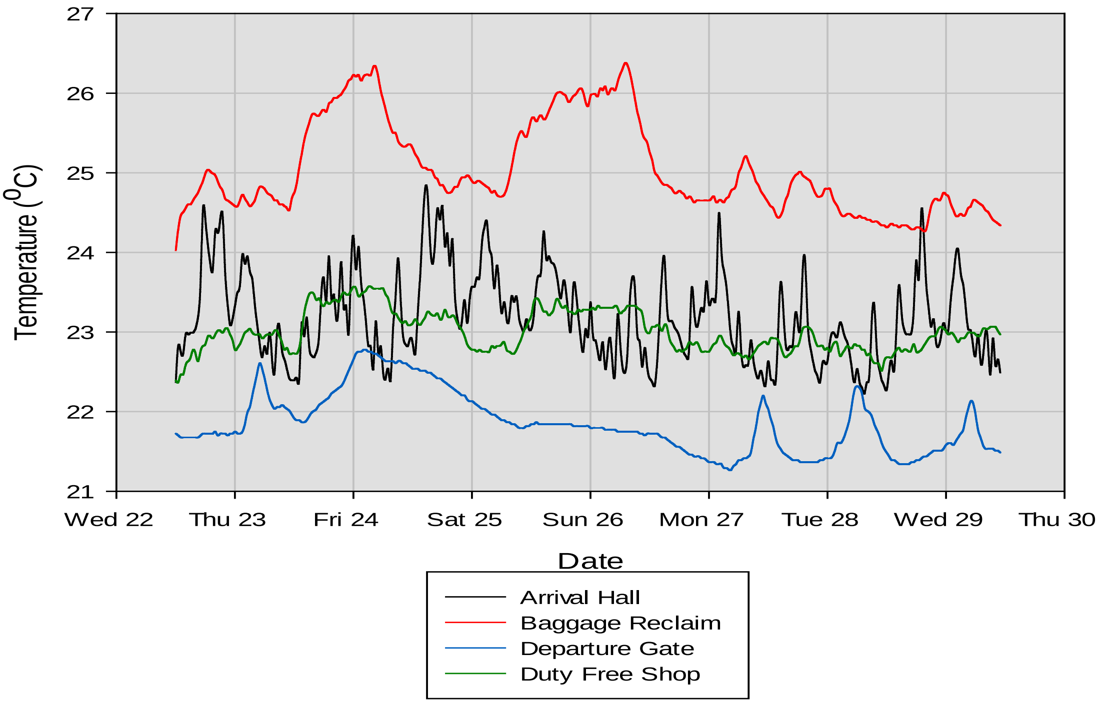


FIGURE 5-7: Summer Indoor Temperature

Just like the indoor temperature, the indoor relative humidity value for the indoor places shows considerable variation (Figure 5-8). For example, the range of values measured for the Arrival Hall, Baggage Reclaim, Departure Gate and the Duty Free Shop was 43-58%, 37-53%, 46-65% and 37-53% respectively. In spite of this variability, the range in all the spaces monitored fell within the acceptable level for comfort even though as mentioned earlier in chapter four, relative humidity control was not included in the airport control strategy. Also, as mentioned earlier, according to CIBSE, relative humidity is not too critical for comfort in transient indoor spaces except where damage to artefacts, growth of mould, or susceptibility to static electricity is an issue. Humidification and dehumidification requires energy and so it is deployed to control humidity in air conditioning only where such is necessary. Perhaps, it was to save cost and energy that informs the airport's decision not to control humidity and as pointed out, for both winter and summer operations, there was no serious concern related to the level of humidity recorded in the indoor spaces.

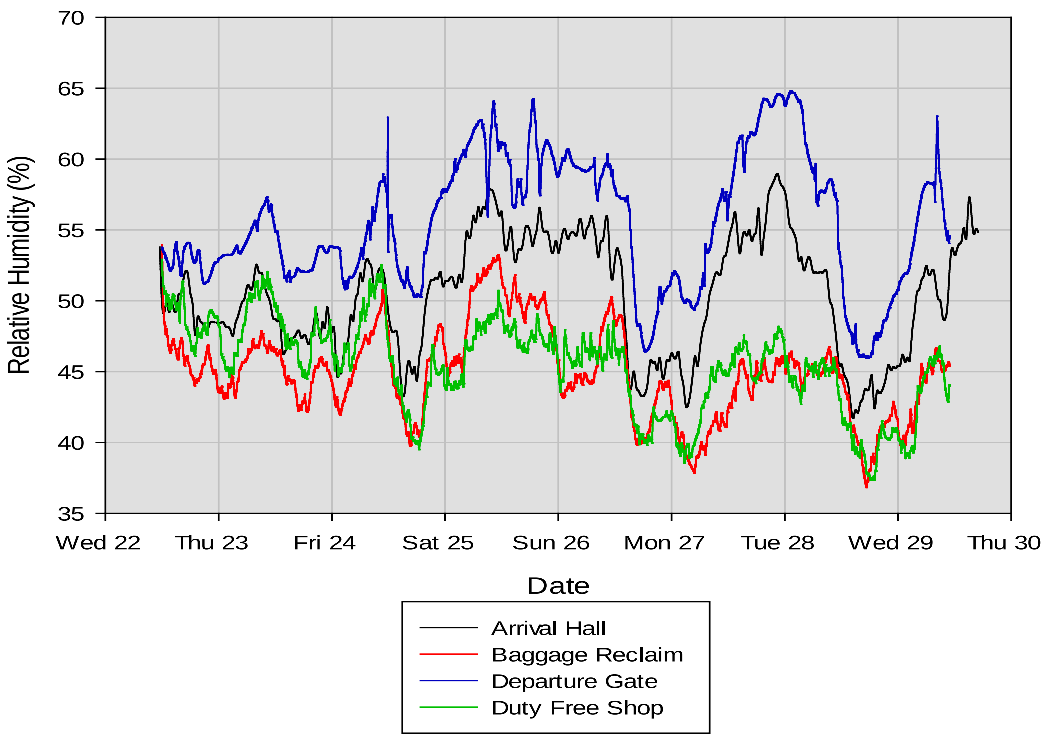


FIGURE 5-8: Summer Indoor Relative

By juxtaposing the plotted measured indoor relative humidity and temperature (Yellow shade) and the acceptable values (Blue shade) for these variables on the psychometric chart as shown in Figure 5-9, it can be seen that the indoor spaces are a bit warmer. Space temperature control for comfort usually has a deadband (interval between higher and lower comfort setpoint) of several degrees for most indoor spaces, in fact ASHRAE Standard 90 requires a deadband of about 5 degrees over which controls can modulate (ASHRAE Standard 2010). What can be deduced from the indoor data collected for both winter and summer operation was that the HVAC is applying tight control (small area covered by yellow compare to the large area covered by the blue shade) of the variables compare to what is acceptable. Alt-hough, this is typical of many air conditioned space, it results in high energy cost (Hoyt, Lee et al. 2009).

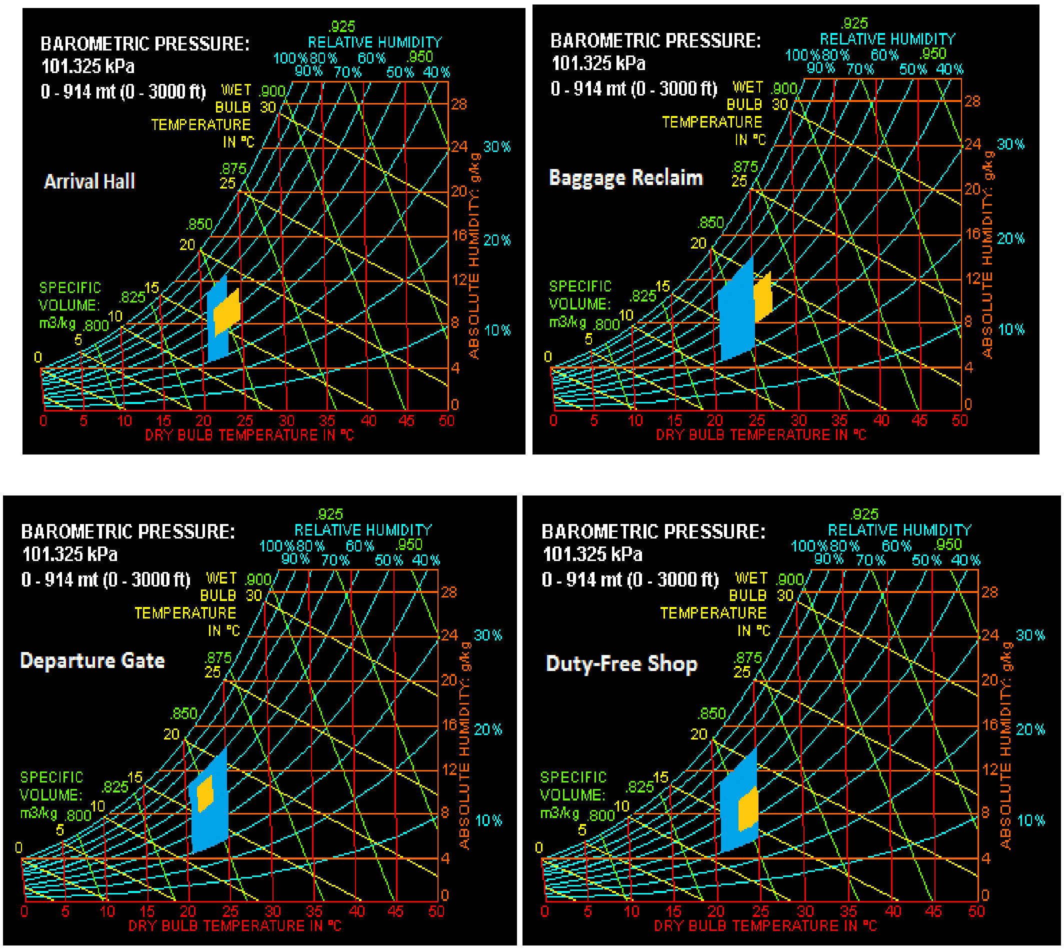


FIGURE 5-9: Measured as Recommended Comfort Variable

5.3.2 INDOOR ILLUMINANCE LEVELS

Also, a look at the indoor illuminance values for the indoor spaces in Figure 5-10 shows a range of over 250 Lux for Arrival Hall, 300 lux for Baggage Reclaim, 250 Lux for the Departure Gate and 280 lux for Duty Free Shop as against the recommended 200 Lux for most of these spaces. The difference in the illuminance level between winter (2011) and summer (2012) times especially in arrival and departure area could be due to upgrade of the terminals luminaires from florescent to LED lighting. According to the installer company, Philips, this has already resulted in about 50% energy savings (Philips 2012) but the fact that these high illuminance levels were sustained throughout the week under study shows that there is still room for more energy conservation if the artificial lights can be dimmed or switched off during period of unoccupancy. Because the Departure Gate is a day lit space, Daylighting availability ranges from 240 lux to a daily peak of between 300-1000 lux. This was more than sufficient for the requirement of this space, so, incorporating a Daylighting control in this area and similar areas within the terminals will lead to additional energy savings. The difference in illuminance levels among all the spaces monitored in the departure and arrival area might be due to the positioning of the lighting sensors. Illuminance levels will depends on the distance between the sensors and the luminaire and for the security of the equipment and airport operational needs it was not possible to place them at the working plane (about 0.85 m above the floor level) as required.

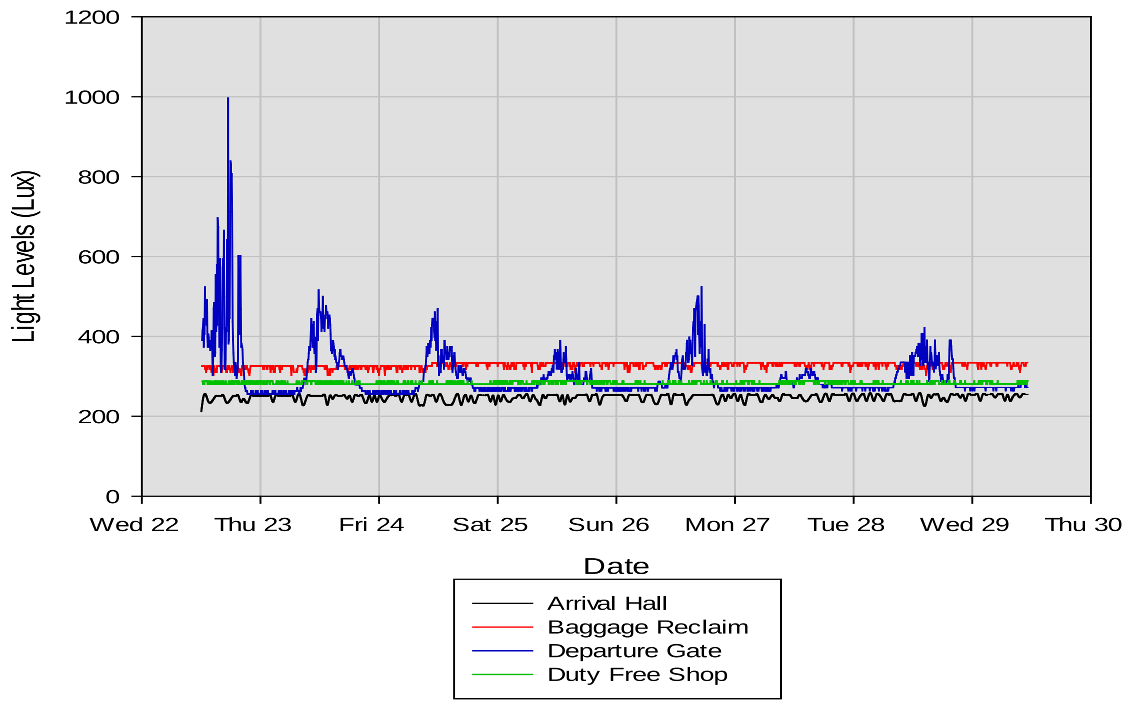


FIGURE 5-10: Summer Indoor Illuminance

5.3.3 INDOOR CO_2 LEVELS

CO_2 is a surrogate gas in indoor spaces that can indicate human occupancy. It is also an indication of the amount of fresh air injected into the space to dilute pollutants and provides oxygen necessary for respiration. So, elevated CO_2 is a likely indicator of the presence of other air pollutants and a pointer to inadequate ventilation. Although, ANSI/ASHRAE Standard 62-2007 (a very conservative standard for transient spaces) specified that an indoor concentration of no more than 700 ppm above the outdoor concentration will satisfy majority (80%) of building occupants and National Institute of Occupational Safety and Health (NIOSH) recommends that a concentration of over 1000 ppm was a marker for inadequate ventilation. European standards however limit carbon dioxide to 3500 ppm and Occupational Health and

Safety Administration (OHSA) limits carbon dioxide concentration in the workplace to 5,000 ppm for prolonged periods, and 35,000 ppm for 15 minutes.

As shown in Figure 5-11, the indoor CO_2 Levels recorded in the candidate spaces monitored ranges from 370-1150 ppm for Arrival Hall, 370-950 ppm for Baggage Reclaim, 400-850 ppm for Departure Gate and 430-850 ppm for Duty Free Shop. Atmospheric CO_2 Level is generally between 370-400 ppm, therefore all the spaces monitored are below the threshold of the conservative standards (ASHRAE and NIOSH) except the Arrival Hall but in the light of the moderate UK and European Standard, these spaces are over ventilated. This was because as stated earlier in chapter two, the ICAO standard processing time for departure and arrival process was about one hour with field investigation showing even much less duration.

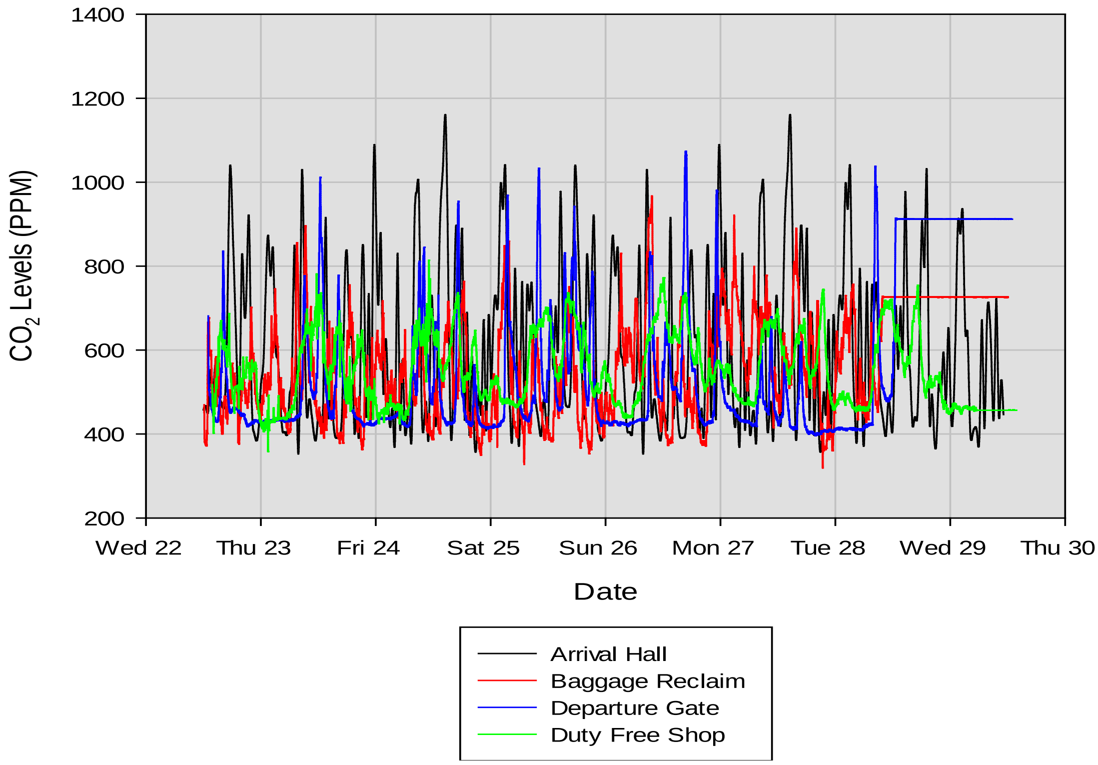


FIGURE 5-11: Indoor CO_2 Levels

From the summer and winter results it was clear that opportunities for energy savings abounds within this airport building services. The energy conservation strategy will include providing the right setpoints for indoor air quality, thermal and visual comfort during occupancy and setback to energy saving mode during unoccupancy. Relative humidity level was generally OK and so to save energy used in humidification or dehumidification, such intervention may not be necessary for comfort in transient areas.

5.4 REAL-TIME FLIGHT SCHEDULES

5.4.1 WINTER (ARRIVAL)

Figure 5-12 below shows plane arrival times plotted against the time-interval between any two consecutive arrivals for the period 26th October to 3rd November 2011 (8 days). If we assume that it takes one hour for passenger to clear from disembarkation to baggage collection as depicted by the area above the blues line in the figure, Up to 51.16 hours opportunity exist for the period under review to implement energy saving strategies. The one hour provision is the ICAO recommended standard period (actually 45 minutes) for passenger processing in an airport as stated earlier.

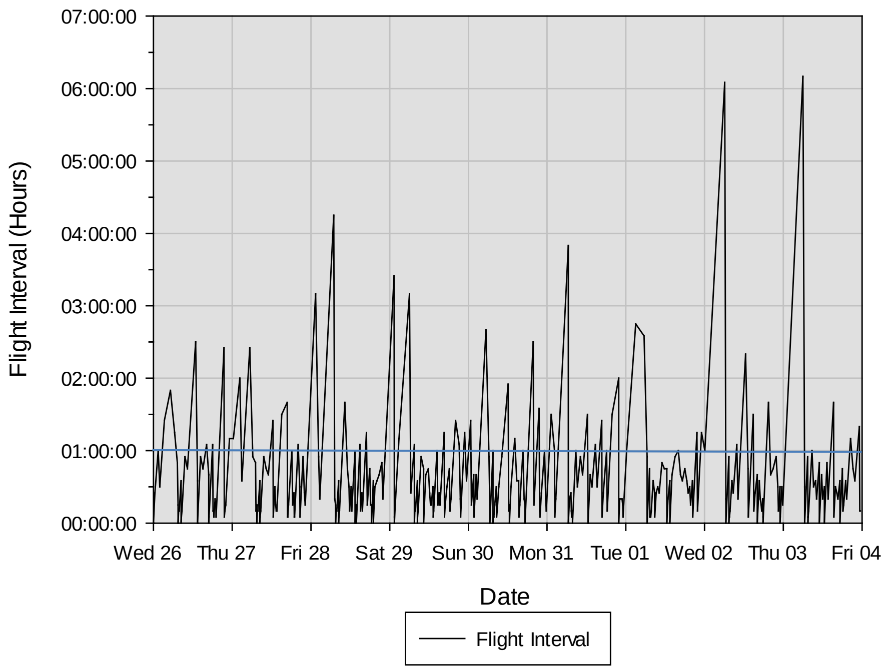


FIGURE 5-12: Plane Arrival's Time Versus Arrival's Time Intervals

5.4.2 WINTER (DEPARTURE)

Figure 5-13 below also shows real-time plane departure times plotted against the time interval between any two consecutive departures for 8 days. Also if we assume that passengers departs after an hour of starting the departure process based on the ICAO standard, Up to 69.05 hours opportunity exist for the period under review to implement energy conservation measures.

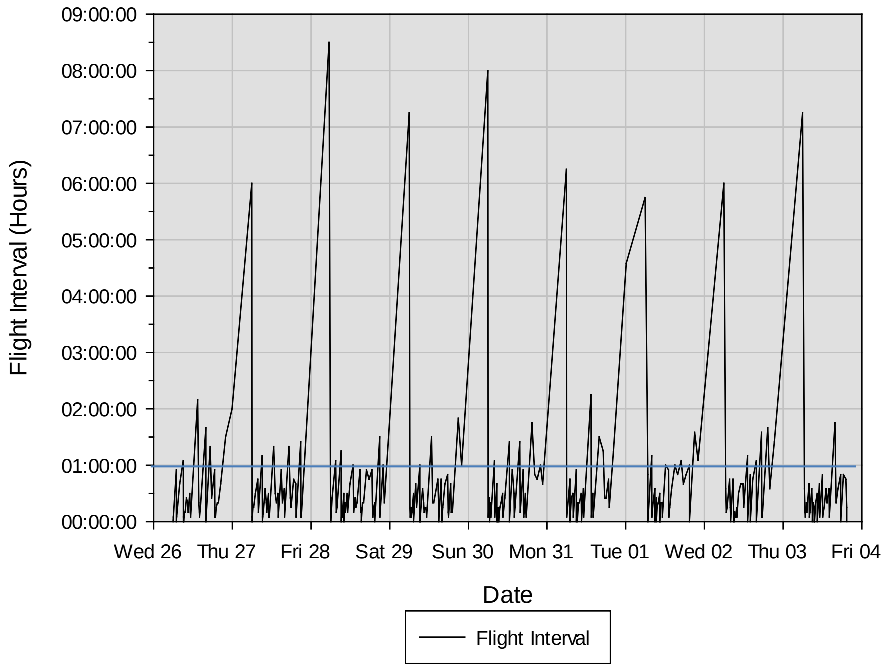


FIGURE 5-13: A Plot of Plane Departure's Time Versus Departure's Time Intervals

5.4.3 SUMMER (ARRIVAL)

Similarly, Figure 5-14 below shows real-time plane arrival times plotted against the time-interval between any two consecutive arrivals for the period 22nd to 29th (8 days)

August 2012. Based on the one hour clearing time, Up to 21 hours (0.9 days) opportunity exist for the week under review to switch to energy saving mode.

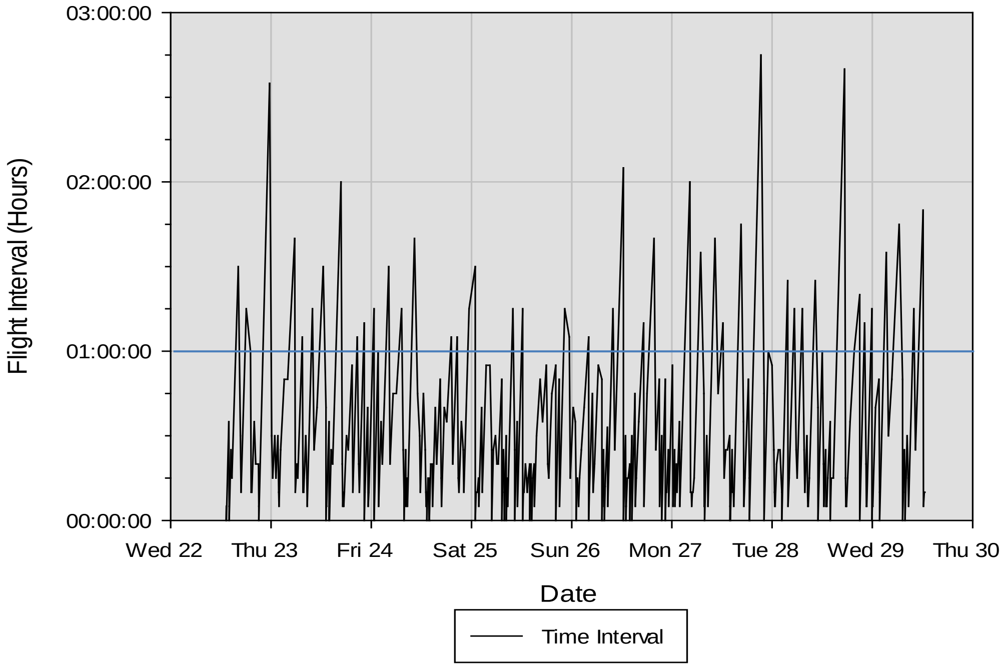


FIGURE 5-14: A Plot of Plane Arrival's Time Versus Arrival's Time Intervals

5.4.4 SUMMER (DEPARTURE)

Figure 5-15 below shows real time plane departure times plotted against the time-interval between any two consecutive departures for the period 22nd to 29th (about 8 days) August 2012. If we assume that setback should be set for interval of over 1 hour, Up to 50.667 hours (2.11 days) worth opportunity exist for energy conservation.

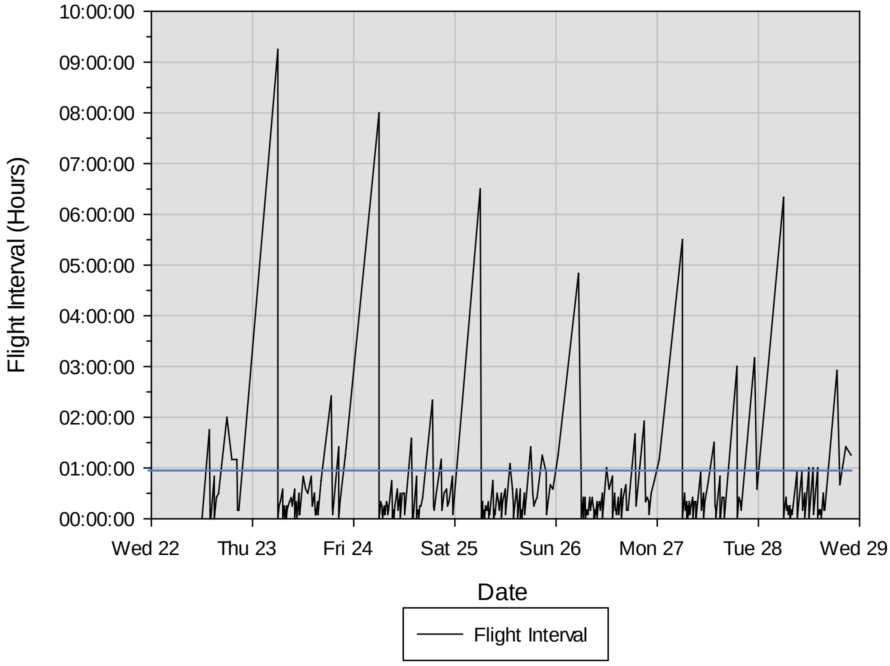


FIGURE 5-15: A Plot of Plane Departure's Time Versus Departure's Time Intervals

From the winter and summer arrival and departure schedules and as summarised in Table 5-1, it can be seen that there are more flights in summer time than in winter period (less time interval between flights for the same number of days) and also there are more arriving than departing flights for both seasons.

TABLE 5-1: Energy Conservation Opportunities in 8 Days Monitoring

Spaces	**Winter (Hours)**	**Summer (Hours)**
Arrival	51.10	**21.5**
Departure	**69.05**	**50.67**

A close look at the histographs in Figure 5-16 showing the distribution of the interval duration for the week under review shows that 70% of the time intervals was in the range of over 1 hour duration in the Winter Arrival, about 82% of the time for the winter departure and about 85% of the time for summer departure. This shows that the time available to implement energy conservation measure for duration of over an hour is in the majority. The distribution in summer arrival however shows that this is a particularly busy period for the airport and so the intervals are tighter and the duration shorter (0-1 forms 70% of the range). The entire distribution shows that there are more arrivals than departure flights for both winter and summer.

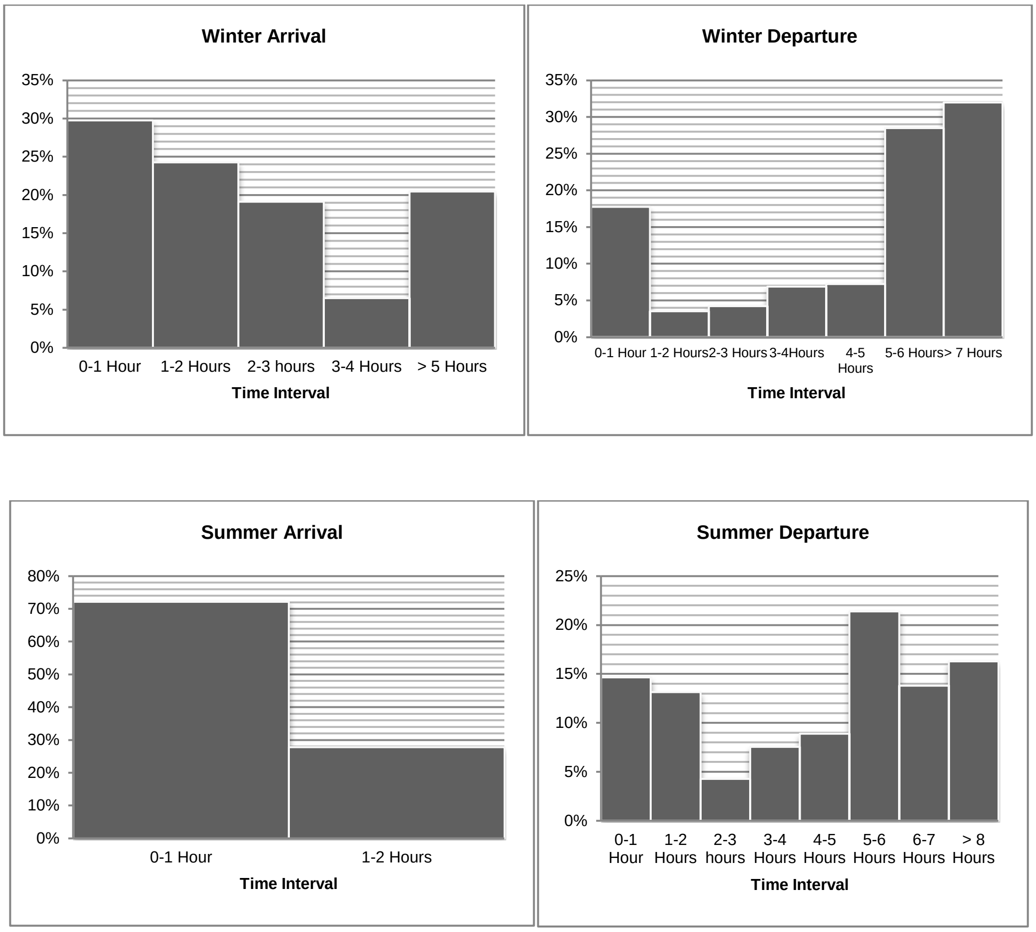


FIGURE 5-16: Distribution of Flight Interval

When all these energy conservation opportunities are extrapolated across the whole airport terminals and for a whole year, the savings in energy will be significant.

This results was an important motivation in the resolve to develop an airport environment management system capable of providing the required comfort setpoint during occupancy and implementing energy conservation measure during unoccupancy by taking into account passenger flow pattern and external conditions.

5.5 CONCLUSIONS

This chapter presented the analysis of the primary data collected for both the arrival and departure indoor spaces in Manchester airport during winter and summer scenarios. From the comfort variables data analysed, it was seen that that the indoor spaces' temperature, lighting and ventilation was higher than the stipulation in the standards and although relative humidity is not being control, the threshold recorded satisfy the acceptable level for comfort. Tight controls were also noticed in the regulation of temperature; a situation that may lead to higher energy consumption compared to if an adequate deadband is implemented. Also, analysis of the flight schedules reveals that there are sufficient opportunities to implement energy conservation measures especially in the passenger exclusive spaces.

The suggestion for meddlesome intervention to harness airport passenger flow information available in the airport Chroma suite for building energy management by the airport's BMS and environment engineers, the airport HVAC system's survey report suggesting the need to improve control metering to switch off systems during the unoccupied period, the literature review comparing the strengths and weaknesses of the various control system types implemented in buildings presented in the previous chapters and the results from the analysis presented in this chapter showing sub-optimal performance of the indoor environment systems, provided the basis for the design of a fuzzy supervisory controller for the management of indoor environment system that will provide the right setpoints for comfort and will lead to a further energy reduction in the airport compared to current operations.

CHAPTER 6: FUZZY CONTROLLER DESIGN AND IMPLEMENTATION

6.1 INTRODUCTION

As stated previously, the purpose of this controller is to provide setpoints required by the local controllers to ensure that the building is comfortable to the passengers while at the same time saving energy. So, where possible based on inputs data of ambient conditions (Temperature and illuminance) from the sensors and occupant's (Passenger's) flow information from the airport information management system, the controller will outputs optimised setpoints for lighting, temperature and airflow rates.

This chapter is arranged to detail discussion on fuzzy logic control modelling and covers areas such as the theory of fuzzy sets and its basic operations, discussions on fuzzy logic control theory in general and the design of supervisory controller for airport building in particular.

6.2 FUZZY CONTROL MODELLING

Many problems in real life are known to exhibit nonlinear dynamic behaviour with uncertain and time invariant parameters coupled with unmeasured disturbances. These characteristics make modelling them from first principle difficult and sometimes impossible. However, no matter how vague or imprecise a problem is, its solution could be described by an expert in human or non-machine language. This expert knowledge can be embedded in controllers using fuzzy rules to regulate a process. Fuzzy control is therefore a practical way to implement challenging control applications which provides an easy method for constructing nonlinear controllers based on the use of heuristic information. This concept helps improves relation between humans and computers because it is the way humans think in real-time and can be presented by linguistic variables drafted in ordinary language terms.

The first fuzzy logic algorithm by Mamdani (1974) was design to mimic an experienced human operator and so the rules are heuristic. MacVicar (1976) however proposed a general structure of fuzzy rules which approaches deterministic controller as quantization levels becomes very fine to overcome the weakness in Mamdani's dependence on operator experience (MacVicar-Whelan 1976).

The advantage Fuzzy logic control offers to building energy management is that it does not require information about plant dynamics and is capable of approximating any real function on a compact fuzzy set (Singh 1996). And because human sensation of thermal comfort is not crispy but fuzzy and subjective, classical adaptive controllers requiring crisp comfort inputs compared poorly to fuzzy logic controllers which are robust as well and are well adapted to regulate fuzzy items in buildings (Dounis, Santamouris et al. 1995, Hamdi, Lachiver 1998).

Fuzzy logic provides a convenient way to map an input space to an output space. Specifically, a fuzzy inference system interprets the values in the input vector and, based on some set of rules, assigns values to the output vector. The mapping then provides a basis from which decisions are made, or patterns discerned (Mamdani 1974).

Therefore, unlike black box modelling that can only use numerical data, fuzzy modelling is capable of combining both qualitative and quantitative data such as information supplied by an experienced operator, measurements and first principle modelling.

This characteristic was explored in our controller design by taking inputs from measured data and using operator expertise to define the fuzzy rules to produce optimised outputs.

6.2.1 FUZZY SETS

The first step in fuzzy control modelling is to convert signals into fuzzy sets. In 1965 Professor Lofti Zadeh of University of California, Berkeley, introduced the concept of fuzzy sets not as a control tool but an alternative way of processing data; allowing partial membership rather the conventional bivalent crisp method of membership or non-membership. Fuzzy sets are therefore an extension of classical sets and as such fuzzy logic is a superset of standard Boolean logic where the truth value of any statement is a matter of degree except for full members $\mu_{\tilde{A}}(x) = 1$ and non-members $\mu_{\tilde{A}}(x) = 0$. A fuzzy set consist of a universe of discourse and a membership function that maps every element in the universe of discourse to a membership value of between 0 and 1. In other words fuzzy sets allow objects within the universe of discourse to have a continuum of grade of membership.

For example, If an element is denoted by $x \in X$ where X is the universe of discuss, the membership function of a fuzzy set $\tilde{X}$ is mathematically expressed as

$\mu_{\tilde{X}}(x), \mu_{\tilde{X}}$ or simply as μ. A universe should contain the entire element that can come into consideration.

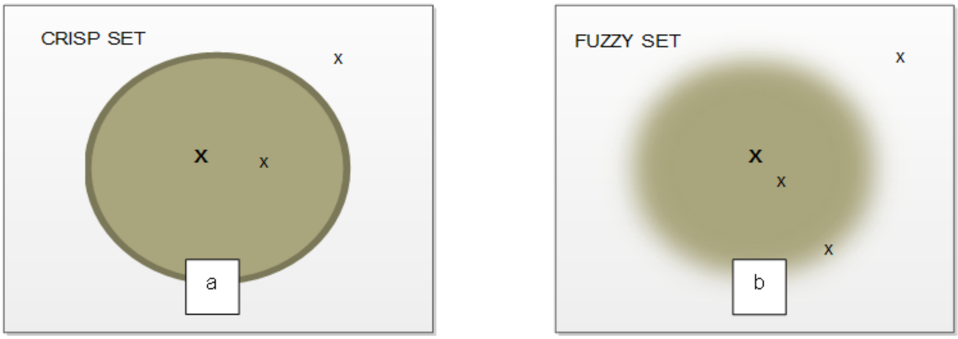


FIGURE 6-1: Illustration of Crisp & Fuzzy Sets

Figure 6-1a, illustrates that crisps or Boolean set is either true ($x \in X$) if x is locate in the circle X or it is false if it is located outside. A fuzzy set on the other hand is expressed by its membership function. Membership functions allow a gradual rather than abrupt transition from membership to non-membership. As shown in 6-1b at the core of X, $\mu_{\tilde{X}}(x) = 1$, at the boundary of X, $0 < \mu_{\tilde{A}}(x) < 1$, and the outside of X $\mu_{\tilde{A}}(x) = 0$. Again fuzzy set is adequate in describing human comfort which is usually subjective and fuzzy.

6.2.2 Operation of Fuzzy Sets

Fuzzy control decision block uses fuzzy equivalent of logical “AND”, “OR” and “NOT”. The terms used in describing fuzzy set operation is very similar to that of bivalent logic. The operation of fuzzy sets such as equality, containment, complement, union and intersection are important in understanding fuzzy logic control.

If A and B are fuzzy sets defined in the universe of discus U with membership function $\mu_A(x)$ and $\mu_B(x)$ respectively, the operation of fuzzy set as explained in (Wang 1999) is listed as follows:

A and B are equal, denoted by A = B, if and only if $\mu_A(x)$ = $\mu_B(x)$ for all $x \in U$.

The complement of A is a fuzzy set $\overline{A}$ in U defined as $\mu_{\overline{A}}(x) = 1 - \mu_A(x)$ (see Figure 6-2A).

A contains B, denoted by $A \subset B$, if $\mu_A(x) \geq \mu_B(x)$ for all $x \in U$ (see Figure 6-2B).

The union of A and B, is a compound preposition denoted as $A \cup B$ and is defined as $\mu_{A \cup B}(x) = \max\left[\mu_A(x), \mu_B(x)\right]$ Zadeh fuzzy logic OR operator or as $\mu_{A \cup B}(x) = \min(\left[\mu_A(x) + \mu_B(x)\right], 1)$ also known as Lukasiewicz fuzzy OR operator (See Figure 6-2C).

The intersection of A and B, is also a compound preposition denoted as $A \cap B$ is defined as $\mu_{A \cap B}(x) = \min\left[\mu_A(x), \mu_B(x)\right]$ known as Zadeh fuzzy logic AND operator or as $\mu_{A \cap B}(x) = \left[\mu_A(x) \times \mu_B(x)\right]$ known as product fuzzy AND Operator (see Figure 6-2D)

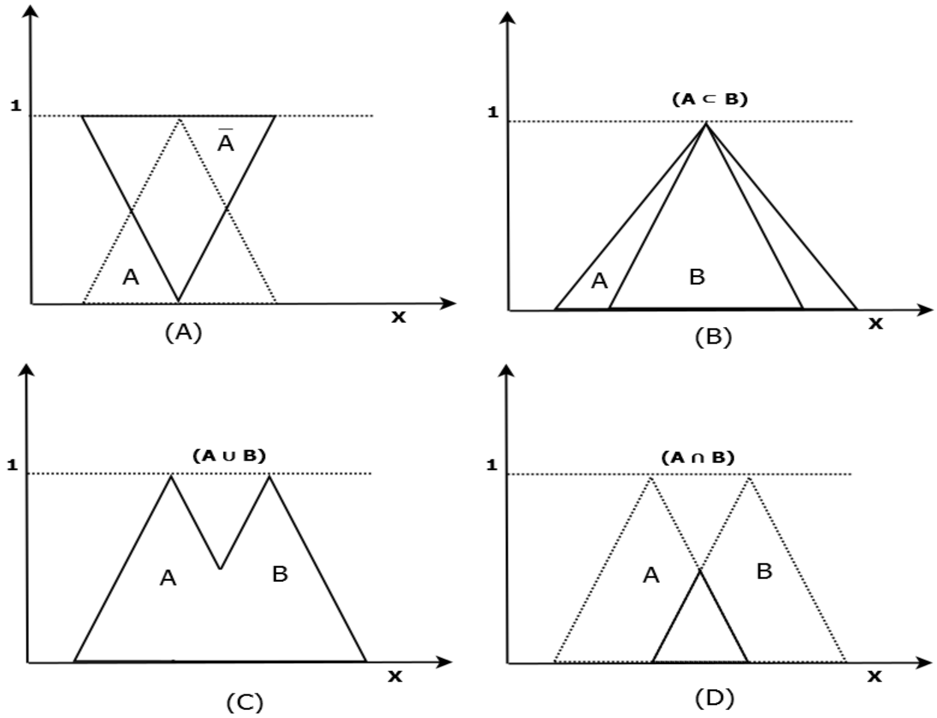


FIGURE 6-2: (A) The Complement of A (B) A Contains B (C) Union of A & B (D) Intersection of A & B

6.2.3 Shapes and Membership Function

Fuzzy membership allows us to present fuzzy sets graphically. It is any convenient shape dictated by the nature of the problem in view. According to Reznik (1997), the problem of membership shape of choice is yet to be solved theoretically and practitioners have stuck to simple shapes because, although higher order fuzzy sets has provided extra smoothness, it impacts greater computational load and has not really improved the quality of the fuzzy model. Also, according to Jantzen, 1998, in fuzzy set theory the choice of shape and shape width is still subjective. So selection of a particular shape and shape width is often dictated by the exegesis of the control problem at hand. The shapes also need not necessarily be symmetrical (Ruan, Fedrizzi 2001).

Four membership functions (MF) type often deployed in most applications are; singleton (Figure 6-3A), trapezoidal (Figure 6-3B), triangular (Figure 6-3C), and Gaussian (s-function, π-function and z-function) (Figure 6-3D).

A singleton fuzzy set has a non-zero membership only at one element of the Universal set. It is a limiting case of the triangular shape as the base length approached zero (Ruan, Fedrizzi 2001).   From the example of singleton shown in Figure 6-3A, Universe "A" has a non-zero membership only at "a".

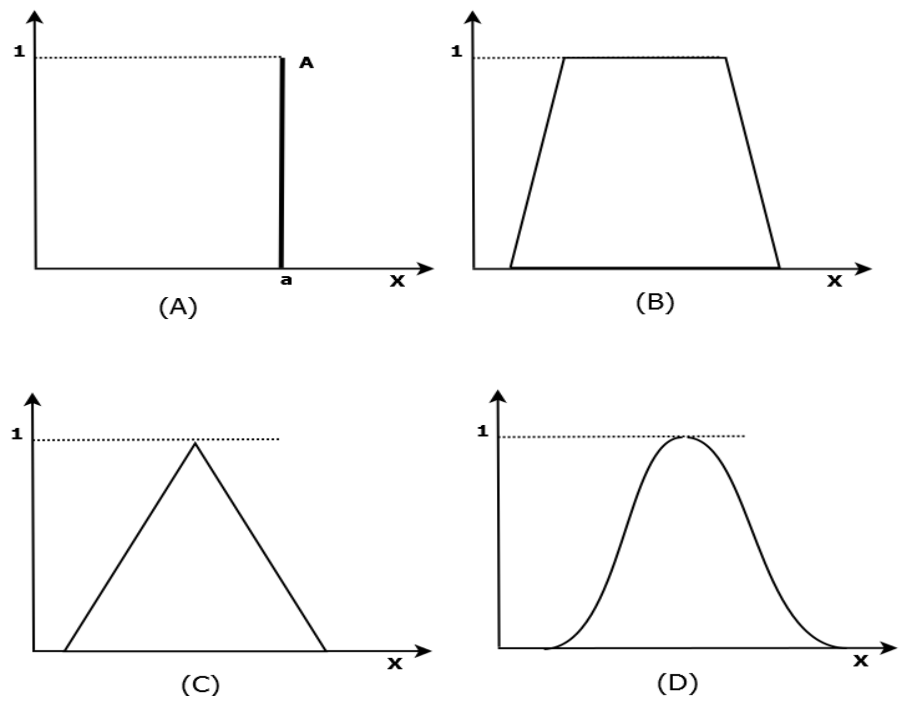


FIGURE 6-3: (A) Fuzzy Singleton (B) Triangular MF (C) Trapezoidal MF (D) Gaussian (Exponential) MF

6.3 Structure of Fuzzy Logic Controller

Fuzzy logic has three main features: 1) use of linguistic variables; 2) use of simple relations between variables by fuzzy conditional statements; and 3) characterization of complex relations by fuzzy algorithms.

Fuzzy logic controllers comprise of four major components as presented in Figure 6-4 which are fuzzification, inference engine, rule base and defuzzification.

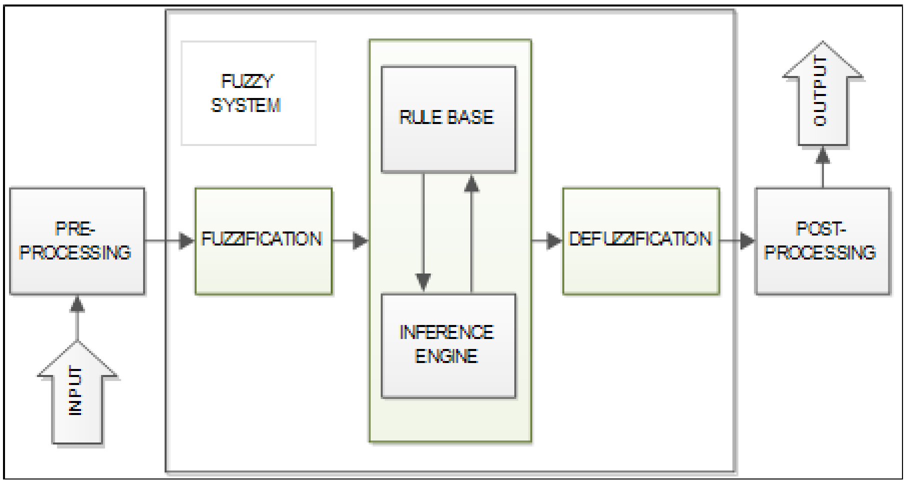


FIGURE 6-4: Basic Structure of a Fuzzy System

6.3.1 Fuzzification

This is the first block inside a fuzzy controller. Fuzzification is the process by which a controller transforms crisp input data to grades of membership based on defined membership function. The fuzzification block compares the input variable to the condition of rules to determine which rule match better a particular inputs. Fuzzification for each input variable is achieved by defining about two, three or more membership function (usually triangular or trapezoidal) and assigning a qualitative value to them (such as High, Medium and Low). Through these means a crisp input can acquires a fuzzy value by locating how its crisp value compares against the selected membership function and the fuzzy rule base.

6.3.2 Fuzzy Rule

Once the input and output variables and MF are defined, the rule-base (or decision matrix of the fuzzy knowledge-base) need to be constituted. The fuzzy rules are expert knowledge in the form of linguistic *if-then* statements containing fuzzy sets, fuzzy logic and fuzzy inference. They establish the relationship between inputs and outputs variables. The “if” part of the rule is called the rule antecedent while the “then” part is known as the rule consequent and these rules transform the input variables to an output (the output variable, also have to be defined with MF and assigned qualitative description such as *low, normal or high*).

The connectives between the inputs are mostly logical ‘and’ or logical ‘or’. The rule with an ‘and’ connective is referred to as ‘minimum’ while the one that uses the ‘or’ connective is called the ‘maximum’. Increasing the number of rules leads to increase in controller stability and responsiveness but could lead to increase complexity.

Five means through which fuzzy rules can be generated are (Takagi, Sugeno 1985):

- Expert experience and control engineering knowledge – common sense and intuitive knowledge and experience of a design engineer or scientist or text book knowledge about a given process can be used to construct rules to control that process.
- Operator’s control action: fuzzy rules can also be formulated from a human operator who is familiar with the control sequence (actions, tasks, procedures) of a physical process.

- Fuzzy learning: by using artificial neural network or genetic algorithm; it is possible to design a fuzzy system that is capable of self-learning or self-organising. These fuzzy controllers are capable of adapting their rule base to changing characteristic of the controlled system.
- Fuzzy modelling of a process: linguistic expressions describing the nature of dynamic system could serve as a model for the system through which further optimal rule base could be derived.
- General Physical principle: physical principles and law governing the process can be used to derive rule base. Such principles and law could be generated from the process geometrical structures such as connections, locations, states of components and processes such as variable behaviours, relations, and thresholds.

6.3.3 Fuzzy Inference

Fuzzy inference is a method that interprets the values in the input vector and, based on user-defined rules, assigns values to the output vector. Fuzzy inference is an aggregation of membership function, logical operation and the if–then rules. This provides the means to make decisions and discern patterns. The two most popular fuzzy inference methods, which varies in the way output is computed, are the Mamdani-type and Sugeno-type methods.

Mamdani’s method finds the centroid of two dimensional functions producing an output that is fuzzy. Sugeno method is used on inference system whose output is constant or linear. The advantages of the Sugeno Method are that It is computationally more efficient, works well with linear techniques (e.g., PID control), works well with optimization and adaptive techniques, has guaranteed continuity of the output surface and It is well suited to mathematical analysis. On the other hand Mamdani Method is more intuitive, has wider acceptance and it is well suited to human input.

Five steps comprise fuzzy inference process:

1. Fuzzifying inputs variable,

2. Application of logic operator (AND or OR) in the antecedent,

3. Implication from the antecedent to the consequent,

4. Aggregation of the consequent across the rules

5. and defuzzification.

6.3.4 DEFUZZIFICATION

This is the converse of Fuzzification in that it converts a fuzzy set defined by the inference engine into a crisp value. The most popular defuzzification method is the centre of gravity (COG) or centroid of area method. Others are bisector of area (BOA), mean of maxima (MOM) etc.

In the COG method for a crisp output *u,* will be

$$u = \frac{\sum_i \mu(xi)Xi}{\sum_i \mu(xi)}$$

Where xi is a point in the discrete universe, and $\mu(xi)$is it membership values in the membership function.

6.3.5 Pre (Post)-Processing

Usually, at the input and output of a fuzzy system are the pre and post-processing units. Because the magnitude of physical values of fuzzy inputs may differ; normalizing (pre-scaling) on to a particular standard range, quantisation in connection with sampling, filtering in order to remove noise, averaging, differentiating and integrating are often necessary for fuzzy system to perform adequately (Jantzen 1998). Denormalization is also used to transform the output of the fuzzy system to the physical domain as control signals for actuators. These operations are performed by the post-processing units; in some cases, post-filtering of output signals is also performed by this unit.

6.4 Design of Fuzzy Supervisory Controller for Airport Terminal

The forgoing part of the chapter laid out the foundation and important characteristic of fuzzy systems and fuzzy control. This section discusses the design of fuzzy supervisory controller using the concepts discussed earlier.

In general, the process of fuzzy controller design may comprise of; identifying problem characteristics, developing control strategy based on the identified characteristics, organising the strategy into a fuzzy logic format by defining the fuzzy inputs and outputs, selecting (if necessary) normalising method for the inputs/outputs, partitioning the universe of discuss and testing and validation of the controller (Passino, Yurkovich 1998). So, unlike in classical controller design, there are no design procedures such as root-locus, frequency response, pole placement, and stability margins because fuzzy systems are often for nonlinear control (Jantzen 1998).

Similar processes as listed above was adhered to in the design of this controller and testing and validation of the controller involves using pilot studies to check the system with test data to ensure acceptable performance and quality.

6.4.1 Control Objective And Strategy For The Airport Terminal

Control objectives were formulated after the probing the airport environment systems performance and interaction with the BMS engineers as previously discussed in chapter 4 and 5. The airport buildings the control objectives are:

- the adjustment and maintenance of thermo-visual comfort in response to occupancy of the passengers flow at the airport terminal.
- to give preference to passive techniques such as daylighting where appropriate since security and noise reduction demands could limit the use of some passive options such as natural ventilation in airports.
- to ensure that more energy is saved compare to the conventional systems in use.

To achieve these objectives, the task involves the control of:

- Airflow in the occupied space based on the passenger flow information for the arrival or departure passenger exclusive area of the airport. So that control is based on the expected level of occupancy.
- Artificial lighting based on availability of day lighting (for day lit areas) and indoor occupancy profile for all the passenger exclusive zones. In visual comfort the input variable of concern is indoor daylight illuminance level at the

working surfaces. This is measured by daylighting illuminance sensors. Although glare also affects perception of visual comfort, it is difficult to measure (Fontoynont 1999) and for transitional space like the airport terminal where occupancy is transient it may not be very important. External shading and blinds are used to control glare, again to allow the outside view such devices are mostly not used in the airport terminal.

- Auxiliary heating and cooling control is in response to external thermal condition and occupancy. Although activity level and clothing insulation also affects comfort but they are highly variable and often immeasurable and so are considered as constants. Humidity control will not be considered for reasons earlier stated.

6.4.2 Supervisory Control Strategy

This supervisory control strategy was developed for the zones that are used mainly by the passengers and staff of the airport (or any building with similar occupancy characteristics); such that the occupancy flow pattern is directly related to flight schedules. Airport buildings are often zoned such that the landside areas accessible to the general public are separated from the airside areas that are restricted to the passengers and staff with relevant documents. This study will focus on the departure/arrival areas of the airside, because they typically have well understood occupancy patterns. Other zones such as shops and leisure areas have more complex occupancy patterns that are beyond the scope of this work. This differentiation is necessary in order to capture areas within the terminal in which occupancy can be predicted using available information on arriving and departing passenger planes.

In the simulation design, the controller was tested to provide comfort setpoints for 45 minutes, 1 hour and 2 hours before the next departure and in the case of arrival flight, relapse comfort setpoints to setback mode 45 minutes, 1 hour and 2 hours after the previous arrival as shown in Figure 6-5.

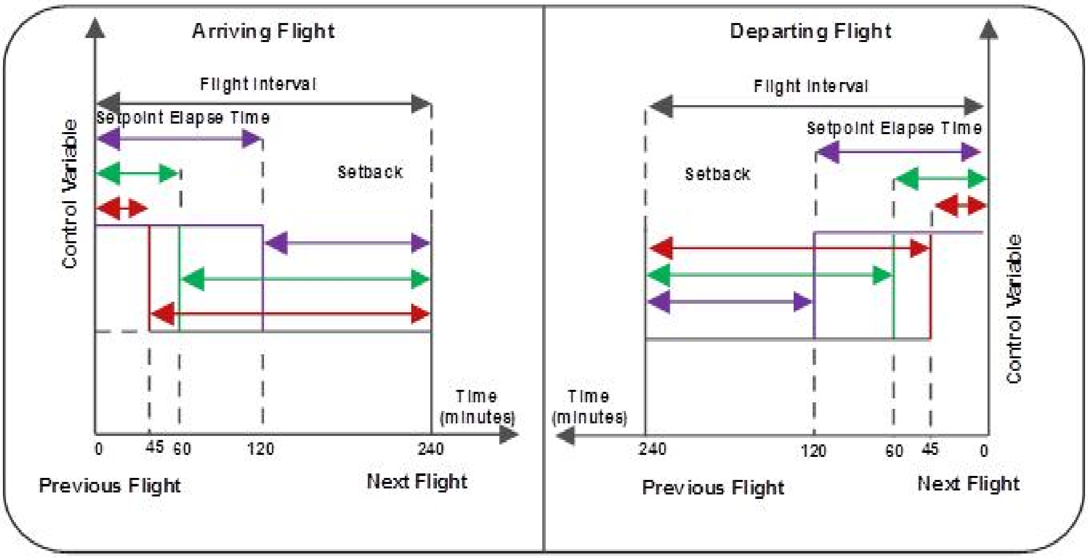


FIGURE 6-5: Setpoints and Setback Time for Arriving and Departing Aircraft

These times were chosen to gauge the benefit in terms of energy use and comfort when comfort setpoints from the controller are ran for:

1. a period less than standard processing times (45 minutes) to simulate the maximum passenger processing times estimated from the CAA survey (DfT 2010), (Also see section 2-2: Figure 2-4, 2-5, 2-6 and 2-7 for further discussions on this)
2. a standard processing time (1 hour) as recommended by ICAO (ICAO 2005) and

3. a rare extended processing time (2 hour) perhaps to accommodate delays.

This fuzzy controller is a supervision on top of the conventional control system and its main goal is to increase the operating availability of the process under control based on the functionality of the control space (Figure 6-6). To achieve this, the controller coordinates the actions of the distributed controllers according to the evolution of the passenger flows and external conditions. The heuristic tools in this strategy are based on operator knowledge obtained from building operation and in-situ measurements of control variable carried out in the building.

The structure of the supervisory controller follows the framework of Yokogawa Electric's temperature controller (Please refer to Figure 3-6e) where the fuzzy supervisory module leads the PID controller along a temperature trajectory that can quickly reach the actual setpoints without overshoot. The major difference is that Yokogawa supervisory controller is a close-loop system while the one described here is an open-loop (feedforward) system. This change simplifies the design of the supervisory controller, and it avoids potential stability issues caused by the interference of two or more feedback loops. Also Yokogawa supervisory controller is only about temperature control while the one described here includes lighting and ventilation control. The architecture of the controller is shown in Figure 6-6 and the meaning of the terms used in the figure is presented in Table 6-1.

TABLE 6-1: Variables Used in the Supervisory Control Structure (FIGURE 6-6)

Symbol	Significance
$Y_A(t)$	Fuzzy controller inputs
$Y_B(t)$	Optimised setpoints schedules for the controlled variable
$E(t)$	Controller error
$Y(t)$	Measured output

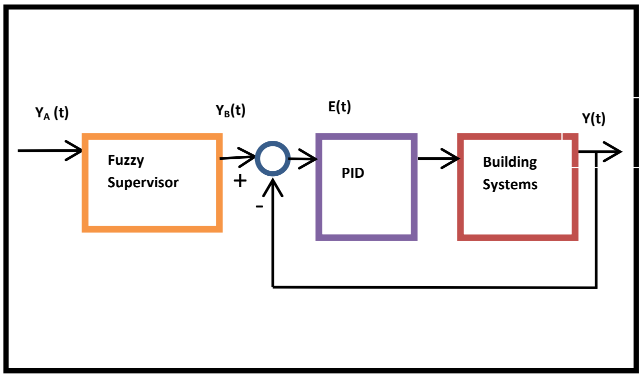


FIGURE 6-6: Architecture of Control Strategy

This type of feedforward supervisory controller computes internal setpoints schedules for the control variables. The conventional controller in series with this fuzzy supervisor has its error $E(t)$ as the difference between the internal setpoint graph $YB(t)$ and the measured value of the feedback from the controlled system(t) , that is $E(t) = YB(t) - Y(t)$ as against $E(t) = YA(t) - Y(t)$ without the supervisor.

One of the advantages of this controller scheme is that fuzzy supervisory controller can compensate for an expected error $E(t)$ in the PID control loop by moving the setpoints $YB(t)$ beyond the value that is actually desired. This means that the controller error$E(t)$, the difference between the setpoints graph and the actual value $[YB(t) - Y(t)]$ is less than the controlled error $[YA(t) - Y(t)]$ obtained by using conventional controller alone. Vogrin & Halang, 2010, demonstrated the use of a setpoints pre-processor of similar nature to control robot arm (Vogrin, Halang 2010). This experiment found that the controller response speed is very high resulting in good closed-loop controller stability. The major limitation of a static controller such as this one is that it does not take the dynamics of the system into account but dynamic control is of course applied on the lower level, so that the system will respond perfectly to changing operating conditions. So compared to the high level control goals set for this work, this is still a good approach.

In this case, contributions to improve the overall performance of the supervised systems is achieved mainly from mapping availability of operating comfort setpoints for identified zones and coordination and management of local control based on passenger flows and variation in external condition. This simple fuzzy control architecture has made it possible for multiple and sometime conflicting control objective to be met in a single controller.

The controller designed using Simulink and Fuzzy Logic Tool box (Figure 6-7) in MATLAB was fed with time series information on when a plane is to land/take-up and the number of people on board estimated from the aircraft type. This information can be acquired from the passengers' information desk several days in advance of the actual flight. The controller also receives as input the real-time external temperature and zone Illuminance data from the outside temperature sensors and lighting sensors respectively. The controller will then provide the required thermal, lighting and indoor air-quality comfort setpoints to the identified zones in the terminal where the passengers will be transiting. These setpoints are available at the landing time of the aircraft allowing the systems to raise or lower the indoor conditions as the case may be to the required comfort range before occupation about fifteen minutes later for the arrival scenario.

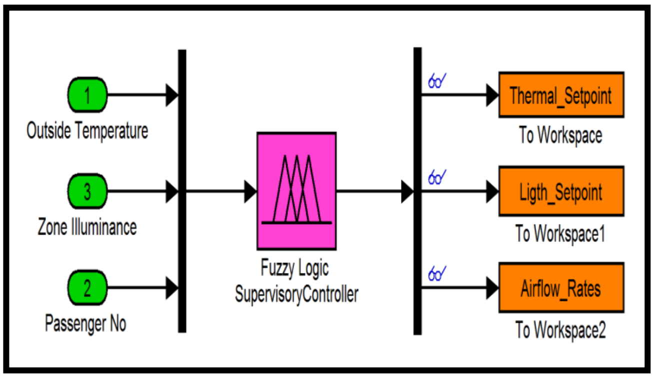


FIGURE 6-7: Simulink Model of the Supervisory Controller

6.4.3 CONTROLLER STRUCTURE

A more detailed discussion on the general structure of a fuzzy controller was earlier introduced as such this controller is of similar composition. That is, it also comprise of the *fuzzifier* which determines the membership degrees of the controller's *crisps* input values for passenger number, zone illuminance, and outside temperature in the antecedent fuzzy sets, the *inference mechanism* which combines this information with the knowledge stored in the rules and determines what the *output* of the *rule-based* system should be. The output for temperature setpoint, lighting levels and airflow rates is a fuzzy set but for control purposes, a *crisp* control signal is required. The *defuzzifier* calculates the value of this *crisp* signal from the fuzzy controller outputs.

6.4.4 Determination of Membership Functions

As pointed out above, the controller takes Outdoor Temperature (OT), Zone Illuminance (ZI), Passenger Numbers (PN) at a given flight time as inputs and outputs indoor Lighting Levels (LL), Temperature Setpoints (TS) and Airflow Rates (AR) for the zones (see Figure 6-8). The varying range of OT, ZI, PN, LL, TS and AR are described using linguistic terms. The discourse domains in the fuzzy set are between *0 to 40* degree Celsius for OT (Figure 6-9), *0 to 600* for NP (Figure 6-10), *0 to 400* lux for ZI (Figure 6-11), *5 to 30* degree Celsius for TS (Figure 6-12), *0 to 250* lux for LL (Figure 6-13) and *0 to 6000* litres per seconds for AR (Figure 6-14). It can be seen that data types influence the choice of the universe for these variables. So, the width of the universe was selected to cover all the noise in the variables. Triangular membership was used for the inputs variables while the outputs were built using the trapezoidal membership. Defuzzification was achieved using the centroid of area method.

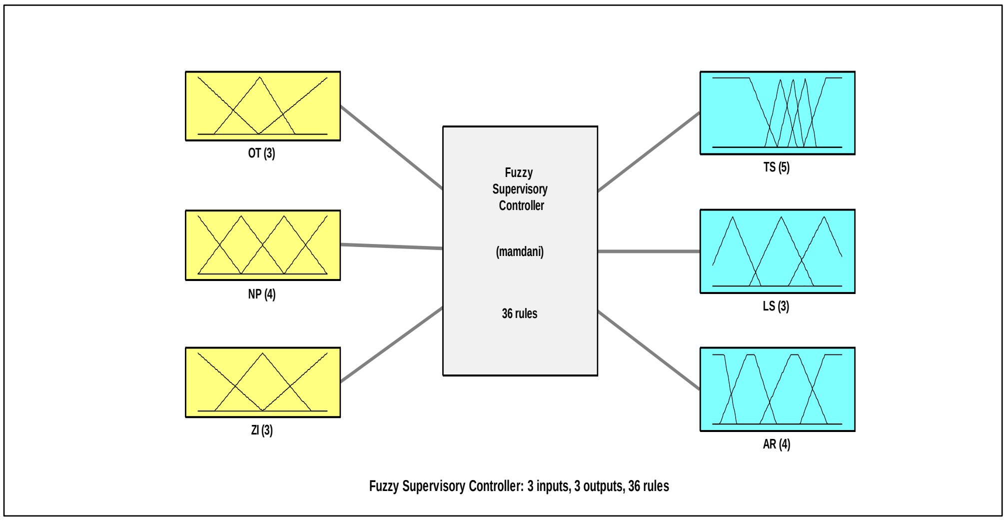


FIGURE 6-8: Fuzzy Supervisory Controller

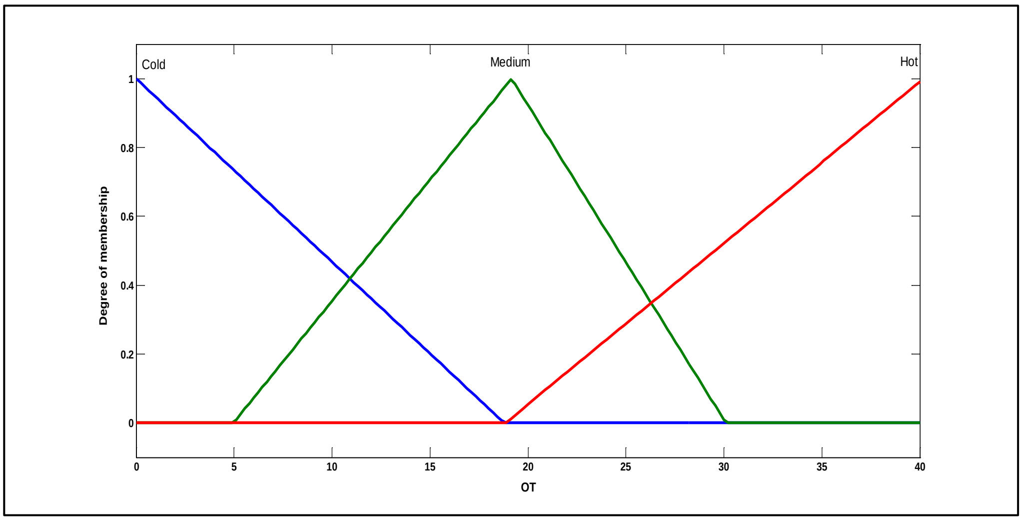


FIGURE 6-9: Membership Function for OT

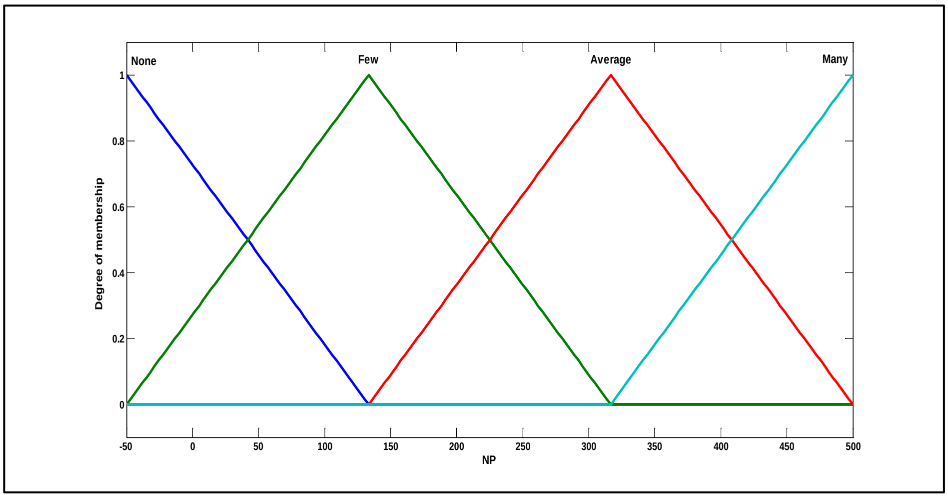


FIGURE 6-10: Membership Function for NP

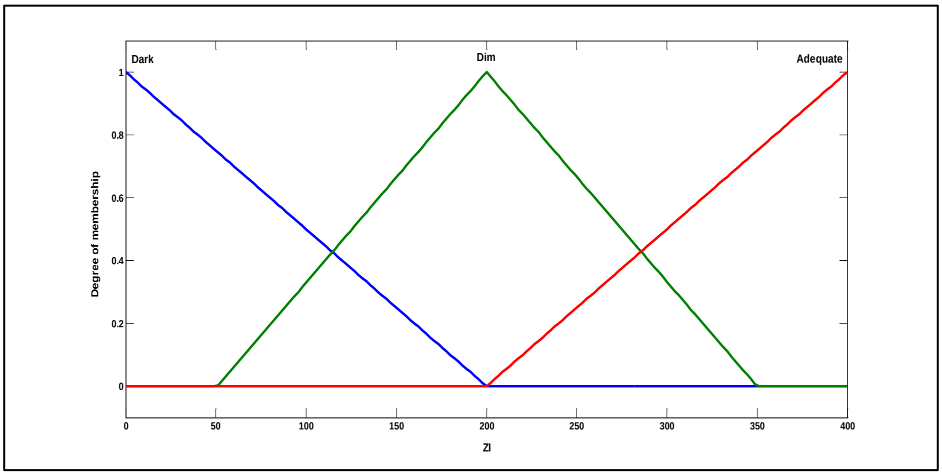


FIGURE 6-11: Membership Function for ZI

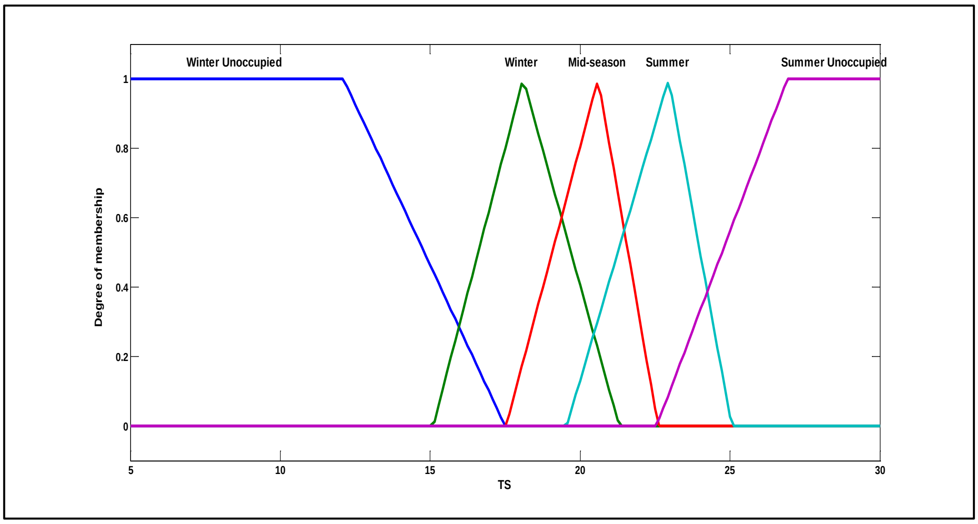


FIGURE 6-12: Membership Function for TS

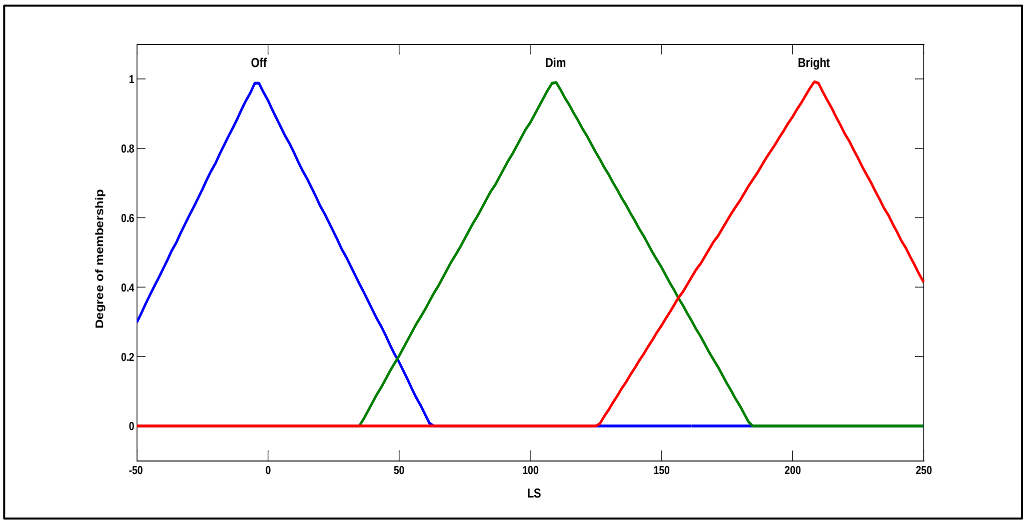


FIGURE 6-13: Membership Function for LS

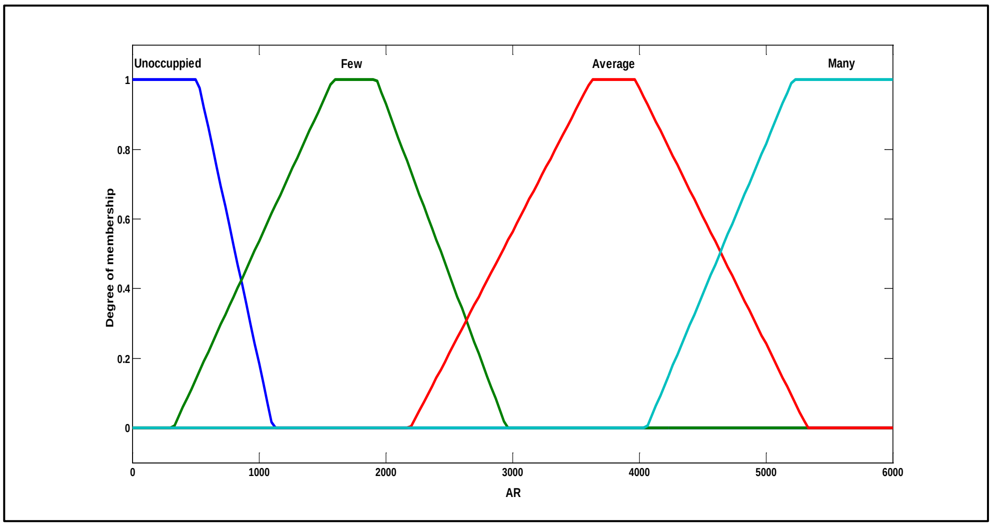


FIGURE 6-14: Membership Function for AR

6.4.5 Construction Of Fuzzy Rules

The heuristic rules mapping inputs to outputs were defined using linguistic terms (Table 6-2) such as if ***Outside Temperature*** is **Cold**, ***Zone Illuminance*** is ***Dark*** and the ***Passenger Number*** is ***Many*** then provide ***Winter*** temperature setpoints, lighting is ***Bright*** and ***Airflow Rates*** is ***Many***. A unoccupancy scenario might read if ***Outside Temperature*** is ***Cold, Passenger Number*** is ***None*** and ***Zone Illuminance*** is ***Dark*** then provide Winter-un-occupied temperature setpoints, ***Light Levels*** is ***Off*** and ***Airflow Rate*** is ***Unoccupied***.

TABLE 6-2: Linguistic Terms for Input and Output Variables

Parameters	Type	Linguistic Expression
OT	Input	Cold, Medium and Hot
ZI	Input	Dark, Dim and Adequate
PN	Input	None, Few, Average and Many
TS	Output	Winter-Unoccupied, Winter, Medium, Summer and Summer-Unoccupied
LL	Output	Off, Dim and Bright
AR	Output	Unoccupied, Few, Average and Many

The thirty-six fuzzy rules for this controller were defined using Mamdani Fuzzy Modelling; that is, the antecedent and the consequent proposition were expressed linguistically. The full detail of the rules is included in the *appendix 3*.

6.5 CASE STUDY OF MANCHESTER AIRPORT BUILDING

Terminal 2 is a jet only terminal with Low Cost, Charter and Long Haul carriers. Smallest regular aircraft type is the B737-300 with 148 seats. Largest is Virgin's B747-400 with around 500 seats. This information was used to estimates the passenger number per giving flight time. The flight arrival and departure data was collected from Airport information desk as explained in chapter 4 and 5. The external temperature data was retrieved from the archive of *freemeteo.com* and *wunderground.com*. The airport building has extensive use of glass window and wall façade making a number of places suitable candidates for Dayligthing. So it was assumed that the test zone is day lit. Available illuminance for the period of October 26th to November 2nd and 22nd to 29th August was estimated from mean total illuminance variation based on ten years of measurements by the Building Research Establishment (BRE) (Hunt 1979).

6.5.1 MATLAB Simulation Results and Discussion

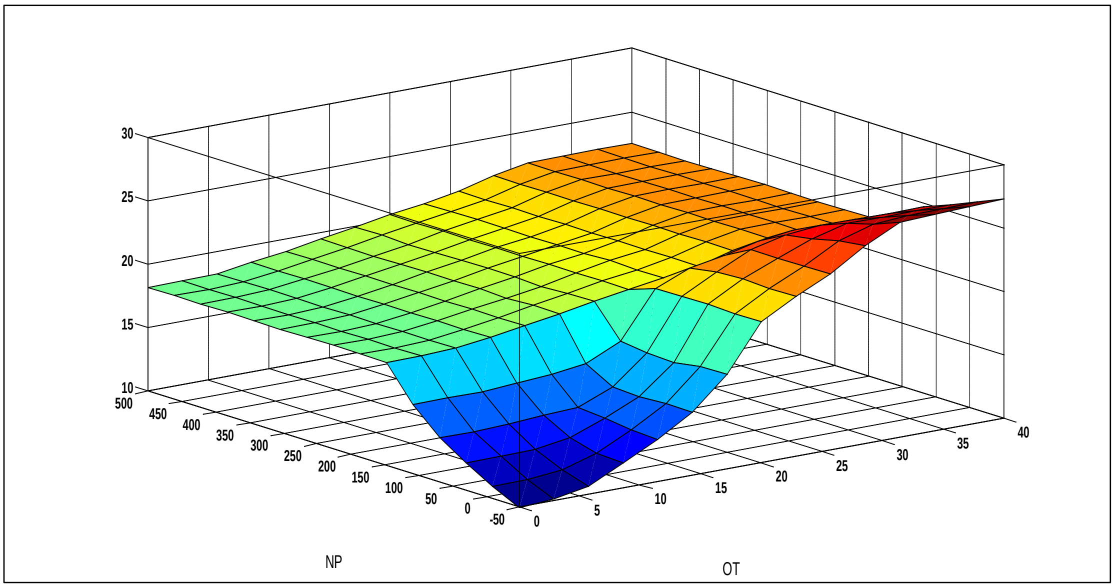


FIGURE 6-15: Surface View Results Mapping Inputs NP, OT & Output TS

Figure 6-15 shows how temperature setpoints (TS) change in relation to passenger numbers (NP) and external temperature (OT). For example; when the zone was unoccupied (passenger number is zero) and external temperature was less than 10 °C (during winter) or over 20 °C (summer); the controller relapses the setpoints to its setback temperature of about 12 °C (winter) or 23 °C (summer) to conserve energy. However, when the place becomes occupied, the controller provides comfort set-points commensurate with the comfort requirement for that zone based on whether outside condition is winter, midseason or summer. There is still a variation in set-points to accommodate for different temperature perception depending on the season, but the changes are much smaller relative to standard room temperature of 20 °C. Therefore, temperature setpoints depend both on occupancy and changes in external conditions

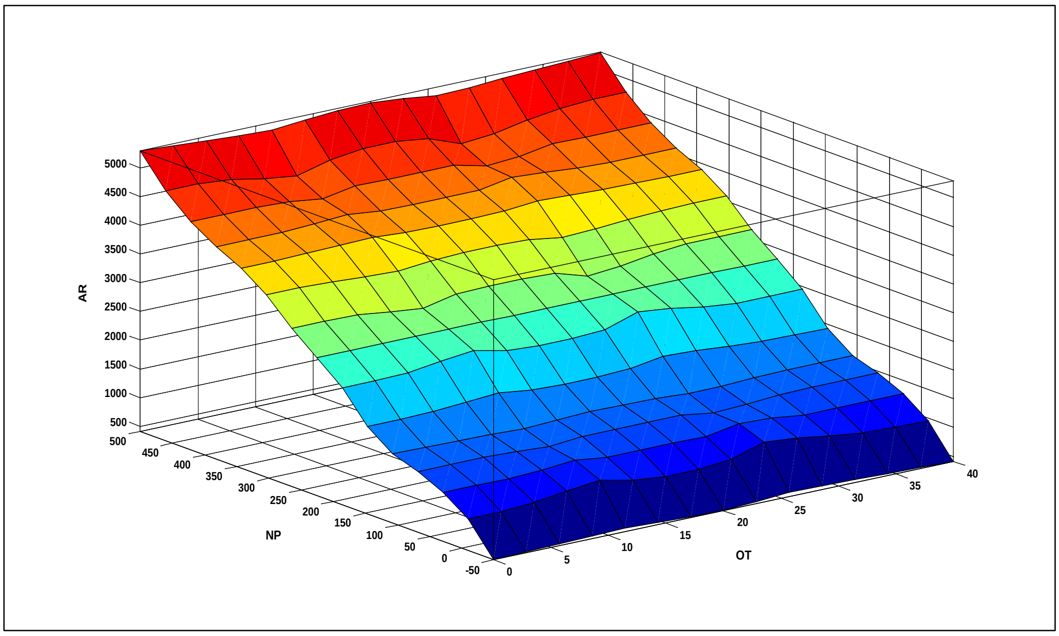


FIGURE 6-16: Surface View Results of Mapping Inputs NP, OT & Outputs AR

Air Flow rates as in Figure 6-17 on the other hand varies directly with the estimated arriving or departing passengers at a giving time. This explained the rise in airflow rates as the passenger numbers increases. Ten litres per second per person was provided for each passenger being the minimum fresh air requirement recommended by CIBSE (CIBSE 2006b) for such place.

During period of unoccupancy, up to 1000 litres per second was still provided to support non-passenger activities.

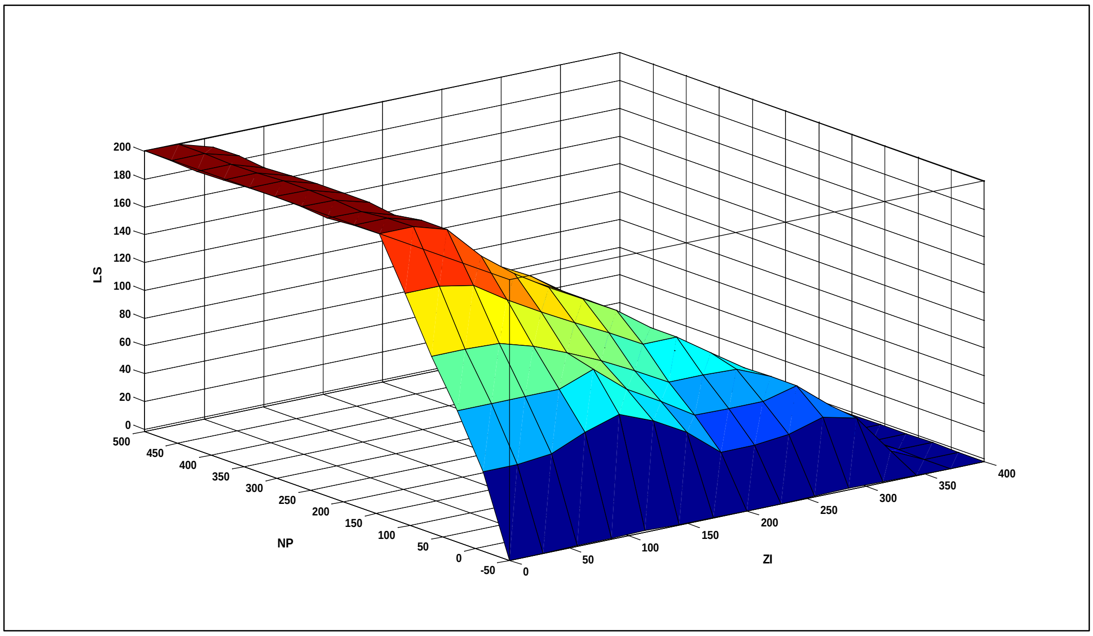


FIGURE 6-17: Surface View Results of Mapping NP & ZI Inputs & Outputs for LS

Lighting setpoints of 200 lux was provided when occupancy was predicted to occur and it is off when the zone was unoccupied as shown in Figure 6-17. This was because according to CIBSE Guide A (CIBSE 2006b) 200 lux is recommended for most indoor spaces within the terminal except offices and shop areas. Dayligthing control was also included as the lights are dimed or switched-off depending on the adequacy of the daylight illuminance within the zone. This lighting control does not include security and a task light that may be used by the staff if higher illuminance values are required at the desk for passenger processing.

6.5.2 WINTER SCENARIO

One-week simulation results for winter using Manchester Airport external weather data (see Figure 5-1), flight arrival time for T2 and estimated available zone illuminance from 26 October to 2nd November 2011, Figure 6-19, Figure 6-20 and Figure 6-20. The results presented were based on the 1 hour elapse time. To avoid excessive repetition, simulations graphs for 45mins and 2 hours elapse time will not be shown but benefit in terms of comfort and energy will be presented latter.

These figures clearly showed that the comfort setpoints based on CIBSE recommendations for arrival area of the airport in winter is being provided and they vary with passengers' occupancy schedule and external temperature.

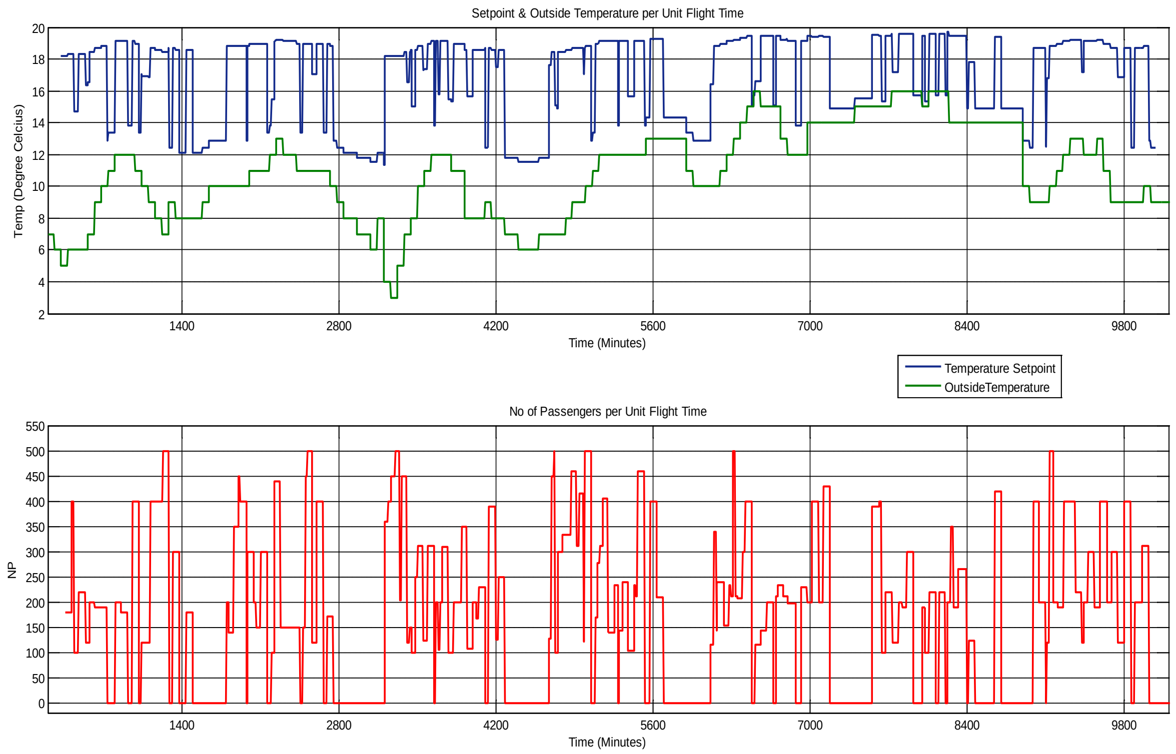


FIGURE 6-18: Temperature Setpoints Output from the Controller

Figure 6-18 shows a temperature setpoints compared to passenger occupancy profile. The setback temperature compares well with occupancy and external temperature profile. For example, temperature setpoint is about 19-20°C during occupancy irrespective of the time of the day but the setback value varies depending on the external conditions. On colder nights the setback is around 12°C during period of unoccupancy while setback temperature value is higher in the daytime and warmer nights during unoccupancy.

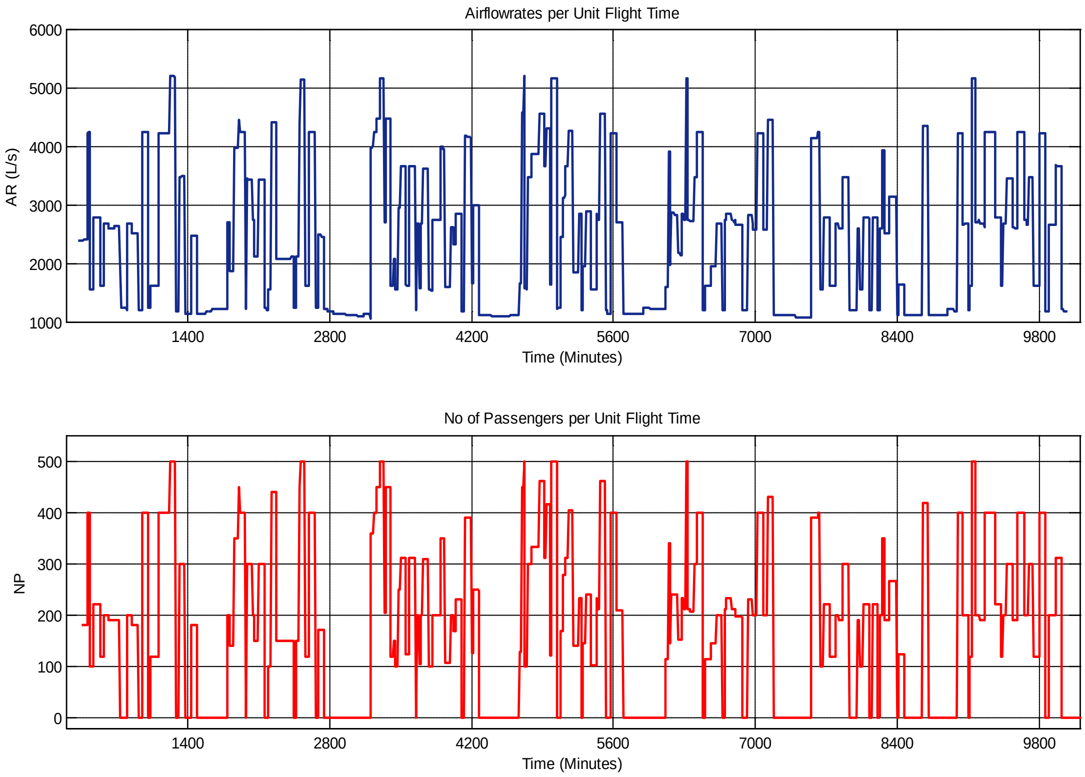


FIGURE 6-19: Airflow Rate Output of the Fuzzy Controller

Figure 6-19 shows that about a 1000 litres per second minimum fresh air was provided during unoccupancy while the ventilation rates during occupancy varies with the number of passengers. In fact the ventilation profile was very similar to the occupancy profile. This shows that the controller provides set-points commensurate with occupancy expectation.

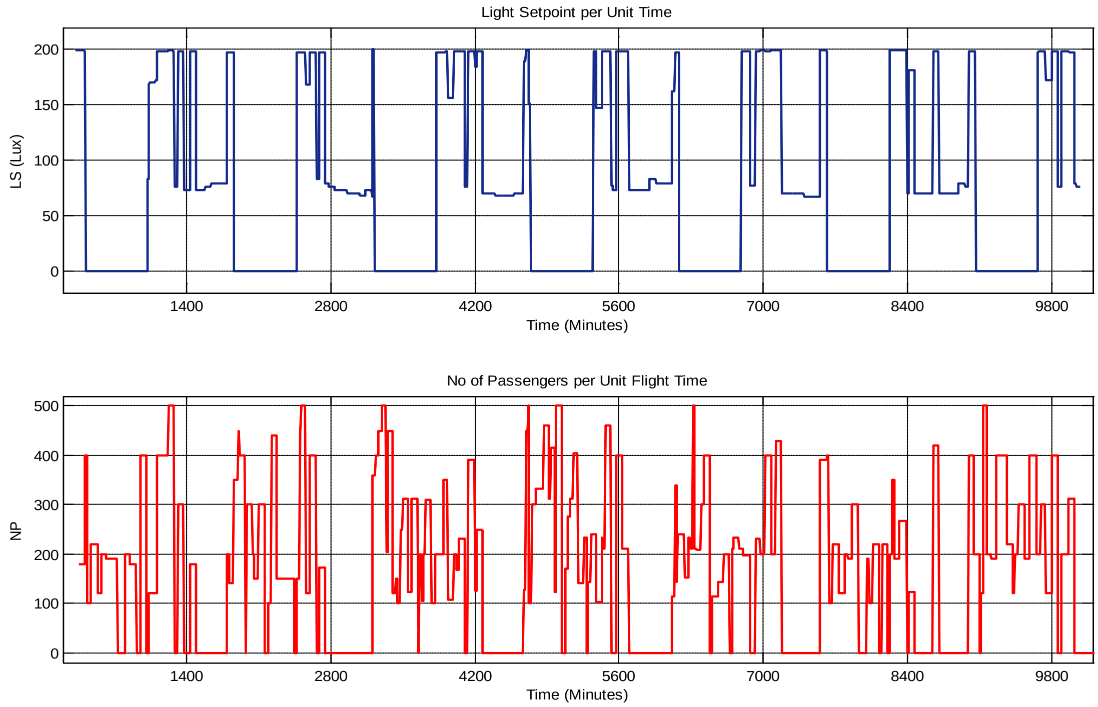


FIGURE 6-20: Illuminance Output of the Fuzzy Controller

Figure 6-20 shows that about 200 lux setpoints of artificial lighting was provided for the zone during occupancy and when available natural daylight was inadequate while the artificial lighting remained switched-off or deemed during unoccupancy and when there is adequate daylight within the zone.

6.5.3 SUMMER SCENARIO

Another One-week simulation results for summer scenario using Manchester Airport external temperature data (see Figure 5-6), flight arrival time for T2 and estimated available zone illuminance from 22nd to 29th August 2012 presented in Figure 6-18, Figure 6-19 and Figure 6-20. These figures clearly showed that the comfort set-points was provided and they vary with passengers' occupancy schedule, available illuminance and external temperature.

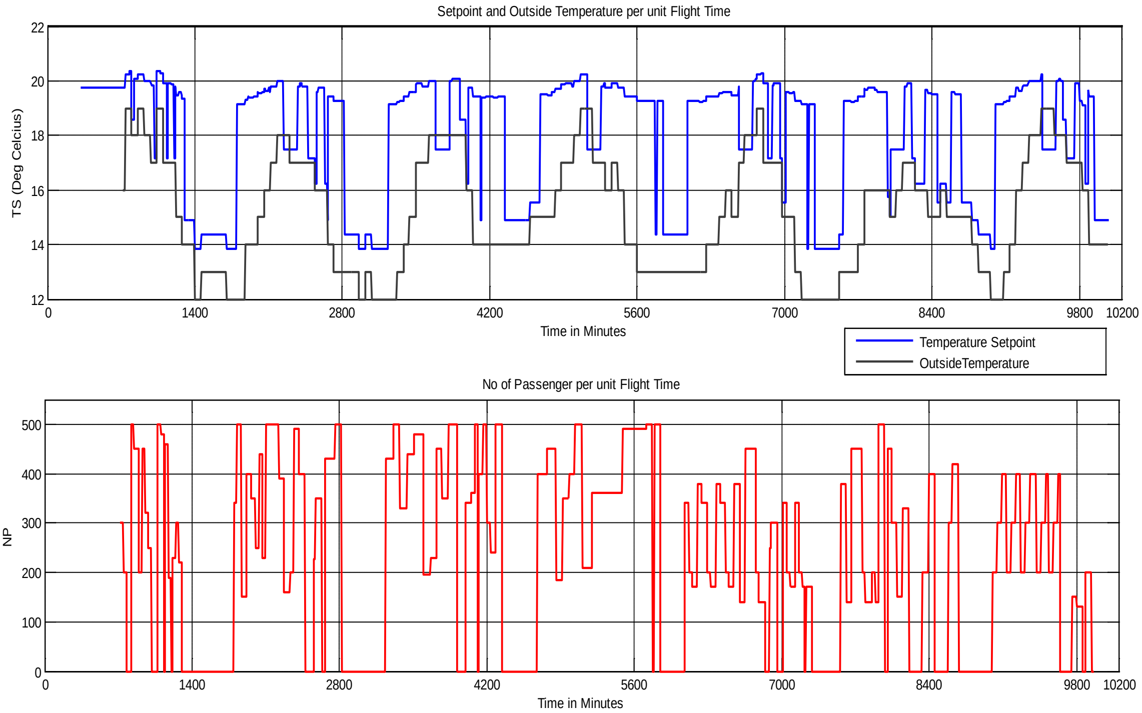


FIGURE 6-21: Temperature Setpoint Output from the Controller

Figure 6-18 shows a temperature set point of about 19.5°C and 20.5°C during occupancy and less than 14-17°C during period of unoccupancy depending on external temperature level. Although it was a summer period and CIBSE recommend a static summer temperature setpoints of 21-23°C, this controller takes cognisance of the external temperature in computing the required setpoints values.

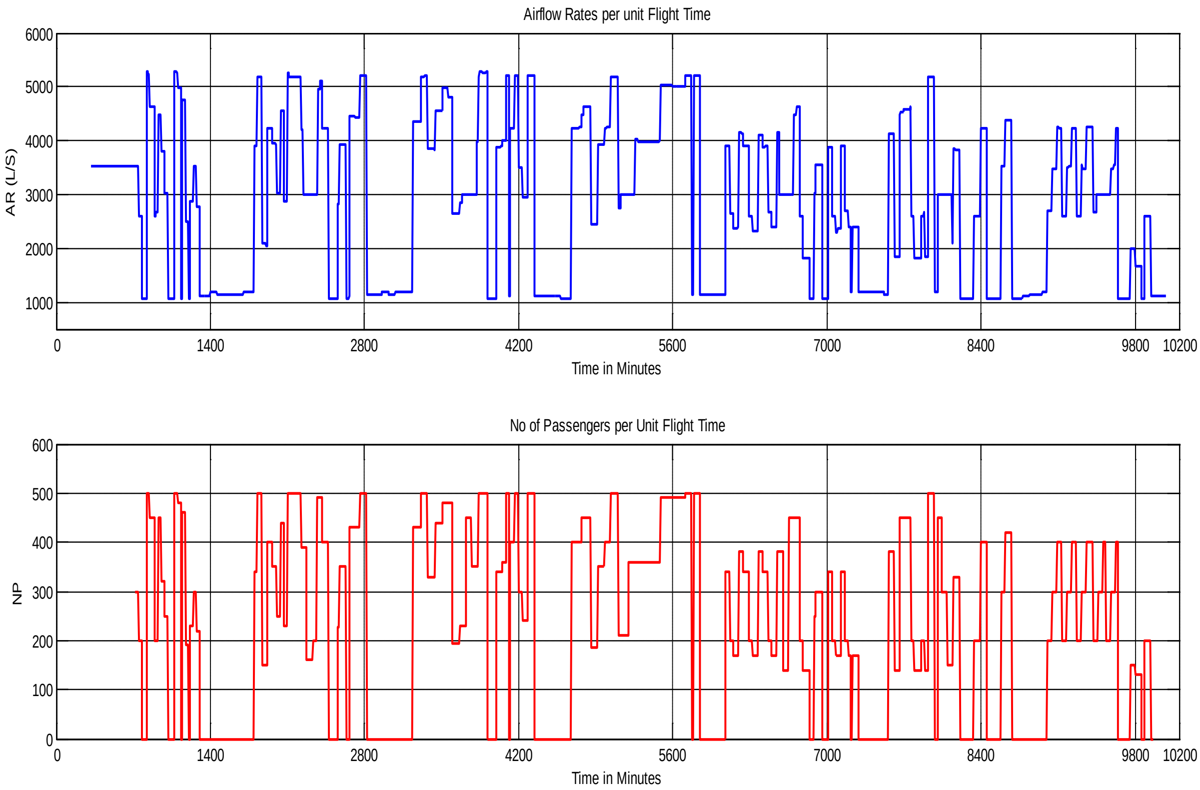


FIGURE 6-22: Airflow Rate Output of the Fuzzy Controller

Figure 6-19 shows that about a 1000 litres per second minimum fresh air was provided during unoccupancy while the ventilation rates during occupancy varies directly with the number of passengers.

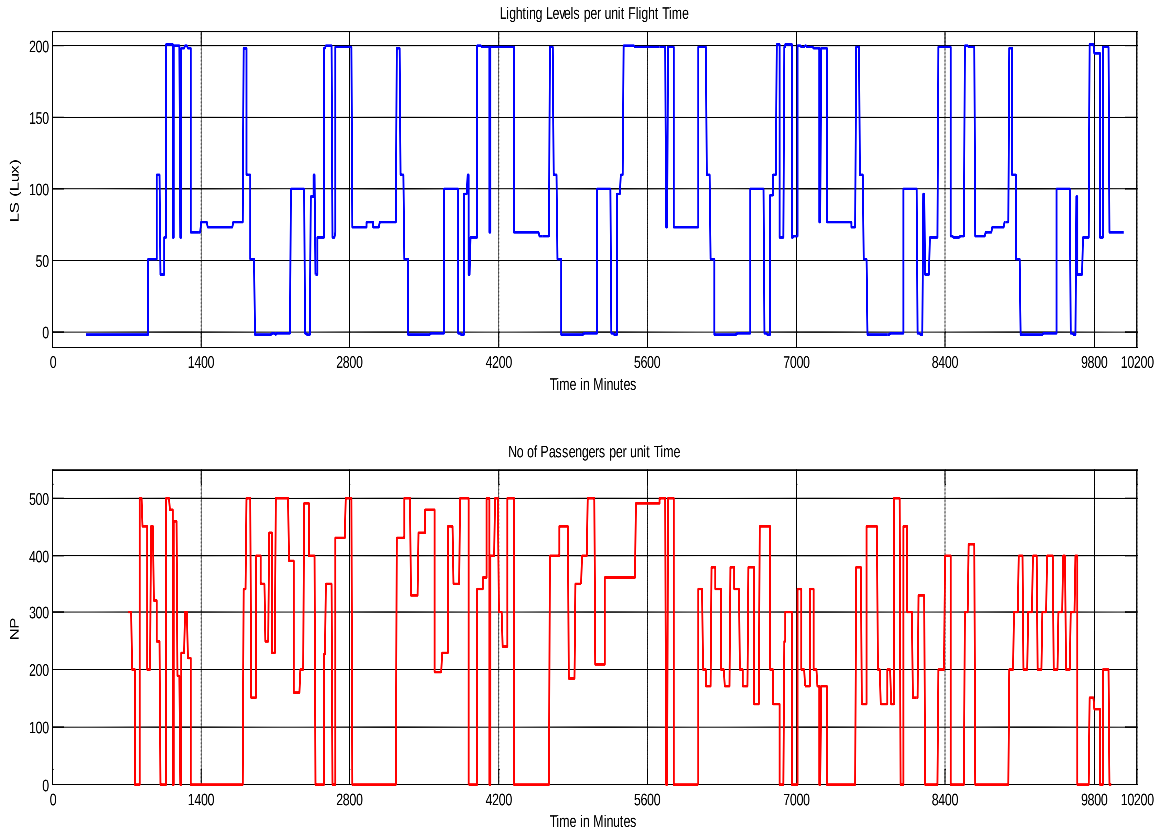


FIGURE 6-23: Illuminance Output of the Fuzzy Controller

Figure 6-20 shows that about 200 lux setpoints of artificial lighting was provided for the zone during occupancy and when available natural daylight was inadequate while the artificial lighting remained switched-off or deemed during unoccupancy and when there is adequate daylight within the zone.

6.6 DesignBuilder Simulation Results and Discussion

Chapter 4, Section 4.6 has already provided the description of the airport building used as the case study. Section 4.7 has also reported the base case airport building's geometric and environmental systems modelling procedure using the DesignBuilder software. The nature of the interaction between DesignBuilder/EnergyPlus and MATLAB/Simulink/Fuzzy Logic Toolbox with which the supervisory controller was developed has also been provided in Chapter 4. Preceding sections of this chapter also provided further detailed description of the fuzzy supervisory controller and especially relevant to this section, it provided the analysis of the controller's simulation outputs and showed that the setpoints provided by the controller was not only capable of providing comfort but that it will lead to energy and CO_2 emission savings.

This section therefore uses the controller outputs described earlier in section 6.5 as schedules for the airport base case model. In the baseline scenario, HVAC and lighting systems were scheduled to run for 24 hours and a temperature setpoints of between 21 °C and 23 °C was applied to all the indoor spaces of the terminal building to simulate the average condition of what was observed from the indoor monitoring results carried out in the airport. For the energy saving scenario, compact schedules generated from the fuzzy controller outputs for temperature setpoints, lighting setpoints and airflow rates schedules (see section 6.5.1, 6.5.2 and 6.5.3 and appendix 2 for the full description of model input gain schedules) were incrementally applied to the selected indoor spaces on the airside (check-in, customs area, gates etc.) while other indoor spaces (offices, shops etc.) and other spaces on the landside were run on full schedules. The reasons for this differentiation were provided earlier in 6.4.2. The energy saving model was rated against the base case model and the results are presented.

Table 6-3 provides the full meaning of the abbreviations used in the charts.

TABLE 6-3: Scenarios in the Simulation Results

Abbreviation	Meaning
BC	Base Case
TS	Temperature Setpoints
AR	Airflow rates
LS	Lighting Setpoints
PMV	Predicted Mean Vote

6.6.1 WINTER

From Figure 6-24 below, it can be seen that due to temperature setback during un-occupancy period; comfort during occupancy increased from slightly warm to almost neutral, airflow rates setback on the other hand caused an increase in discomfort which was restored by the fall in lighting gains due to lighting control. That is; comfort level increased from a PMV value of between 1.1 and 0.9 to between 0.2 and 0.4 for the winter week considered. An indoor thermal environment that has a PPD of less than 10% corresponding to a PMV of about ± 0.50 is considered acceptable (Oughton, Hodkinson 2008). For transitional spaces like the airport a PMV of ± 1 is still acceptable (Pitts, bin Saleh , Kwong, Adam 2011). Energy savings of between 45 to 48% and CO_2 savings of around 42 to 45% respectively can be observed for this scenario.

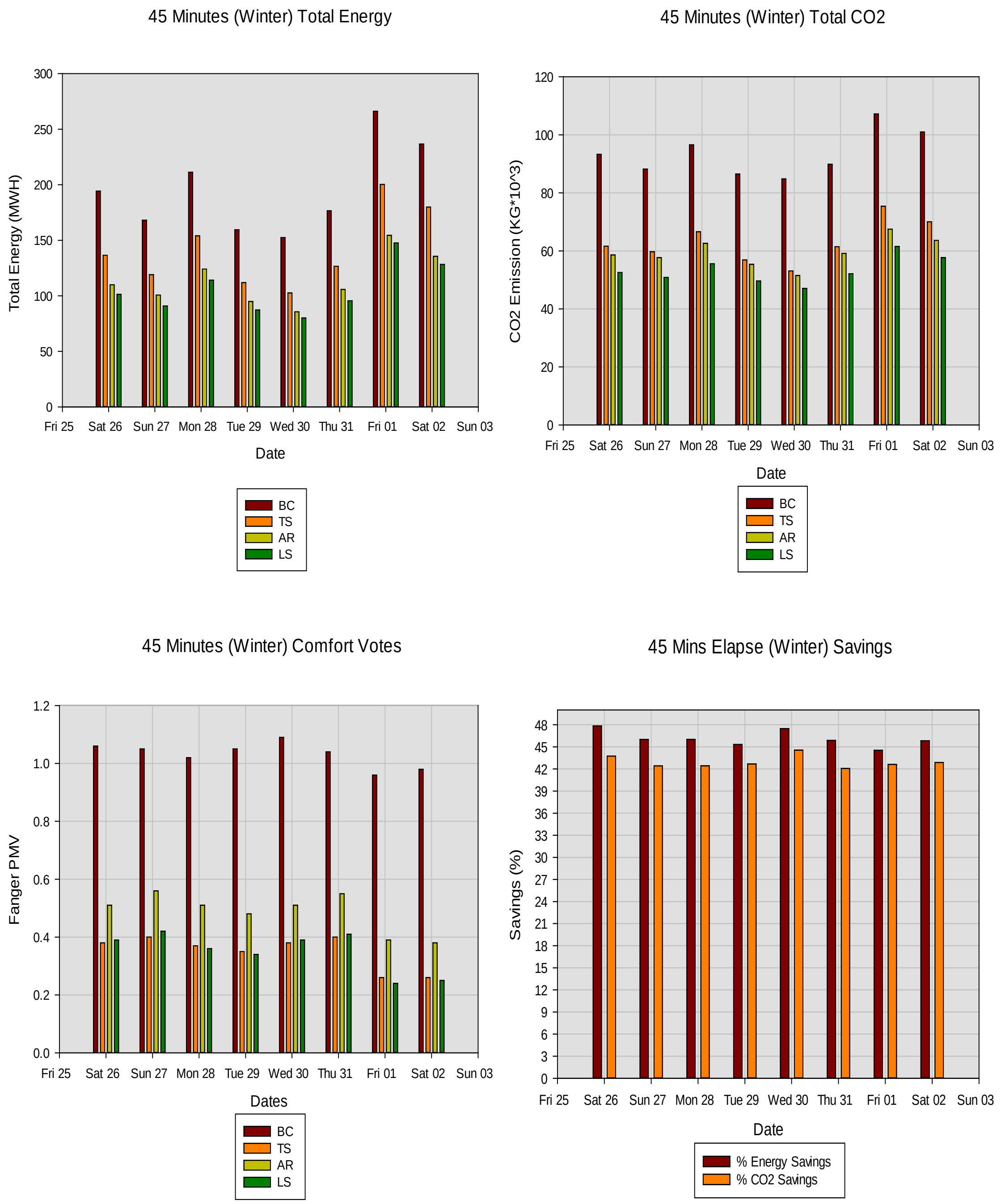


FIGURE 6-24: Results for 45 Minutes Setpoint Elapse Time (Winter)

From Figure 6-25 and as is the case with the previous scenario in Figure 6-24; temperature setback improves comfort rating, scheduled airflow rates degrade comfort, but lighting schedules improve comfort the most. The total effects of these interventions were that comfort level increased from a PMV value of between 1.1 and 0.9 to between 0.8 and 1 for the winter week considered; also, energy savings of between 41 to 50% and CO_2 savings of 33 to 37% can be observed for this scenario.

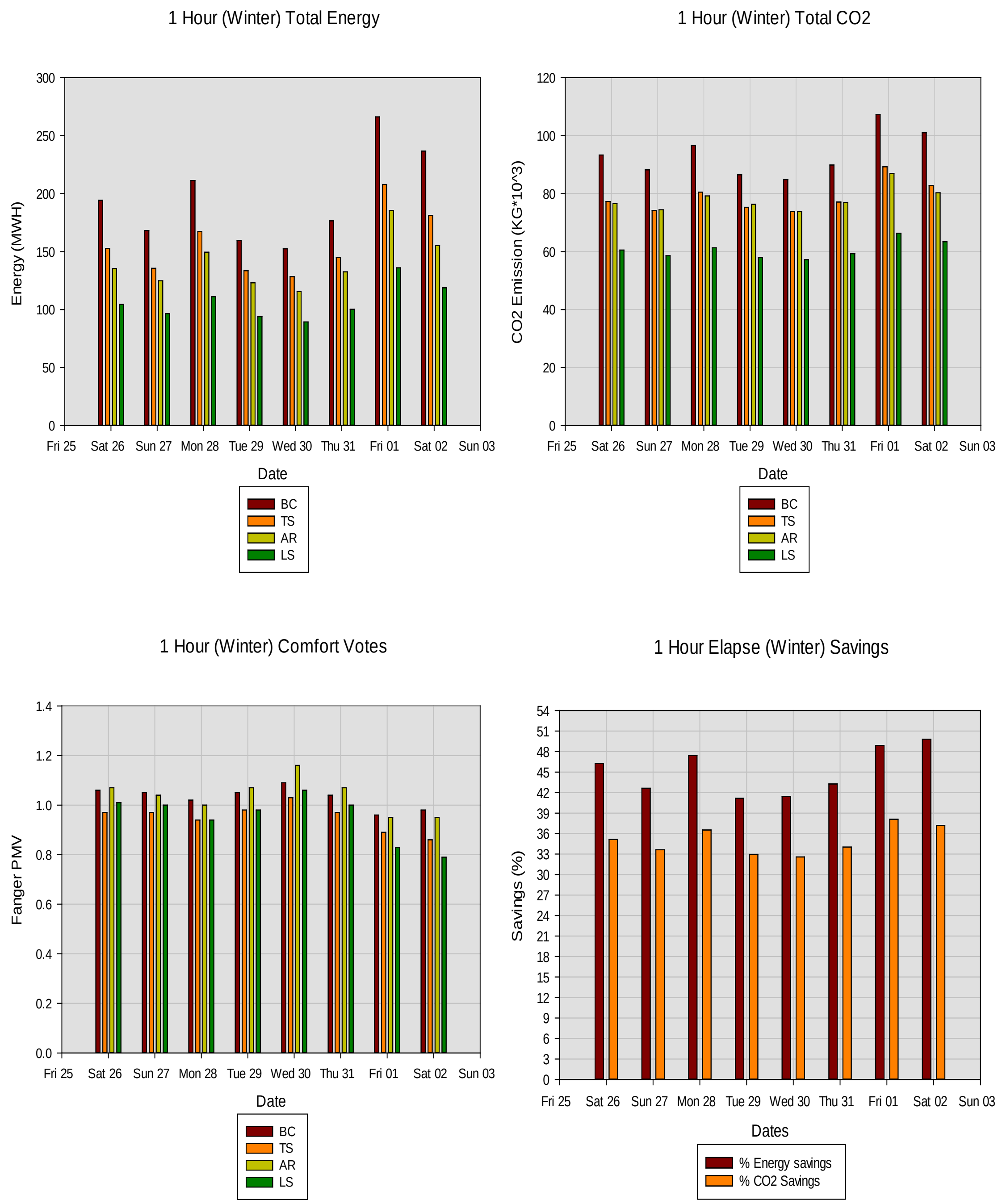


FIGURE 6-25: Results for 1 Hour Setpoint Elapse Time (Winter)

From Figure 6-26, because of the longer setpoints elapse time, energy savings of around 41 to 48% and CO_2 savings of between and 30 to 34% can be observed for this scenario. The comfort level also increased from a PMV value of between 1.1 and 0.9 to between 0.5 and 0.7 for the winter week considered.

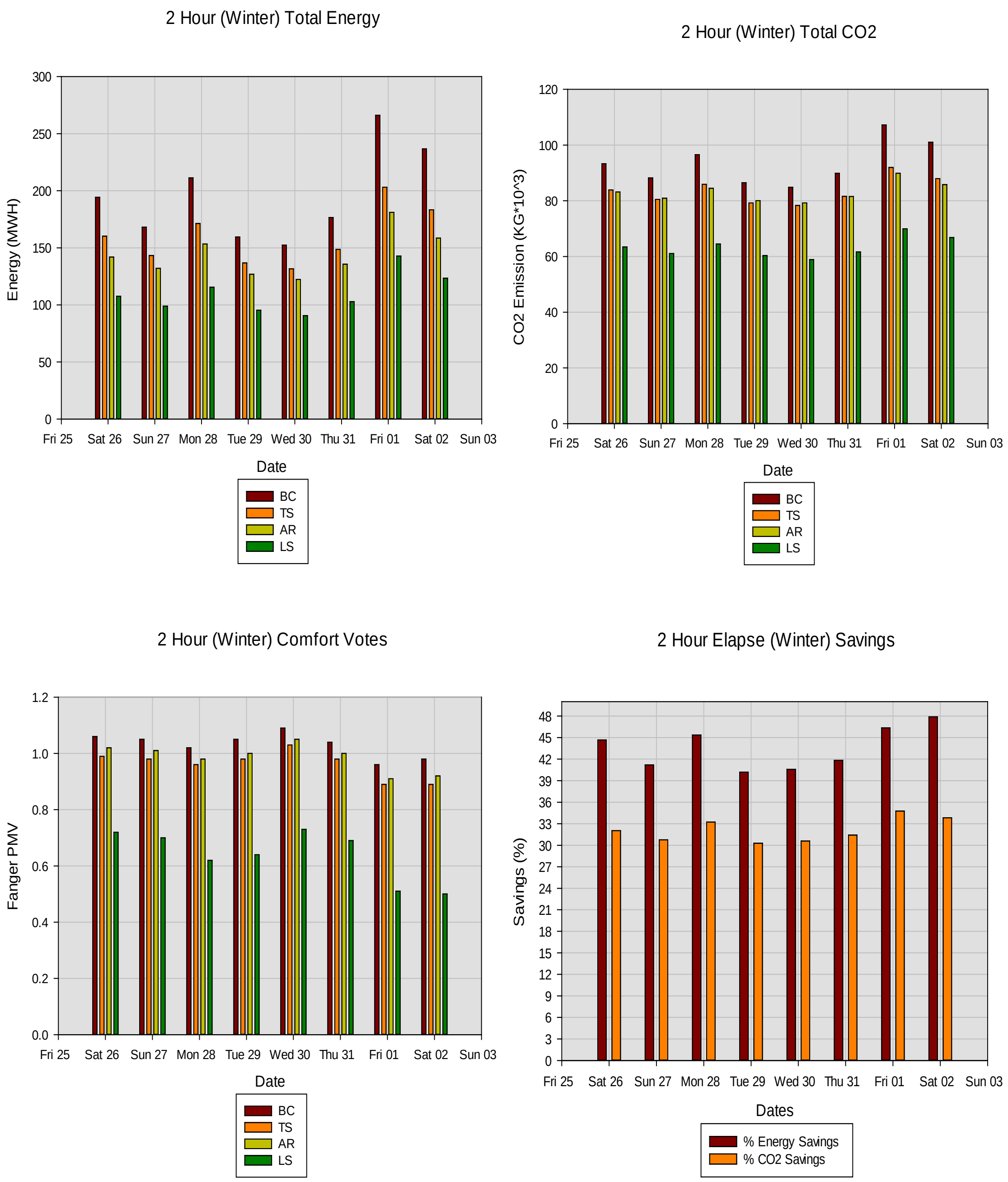


FIGURE 6-26: Results for 2 Hours Setpoint Elapse Time (Winter)

6.6.2 Summer

From Figure 6-27, as a result of thermal energy conservation measure during unoccupancy period, comfort during occupancy increased from slightly warm and tended towards the almost neutral value, airflow rates setback on the other hand does not seem to impact much on energy savings. The fall in lighting gains due to lighting control however resulted in significant savings and comfort. In general, comfort level increases from a PMV value of between 0.58 and 0.68 to between 0.28 and 0.42 for the summer week considered. Energy and CO2 savings of between 27 to 28% for both energy and Carbon emission can be observed for this scenario.

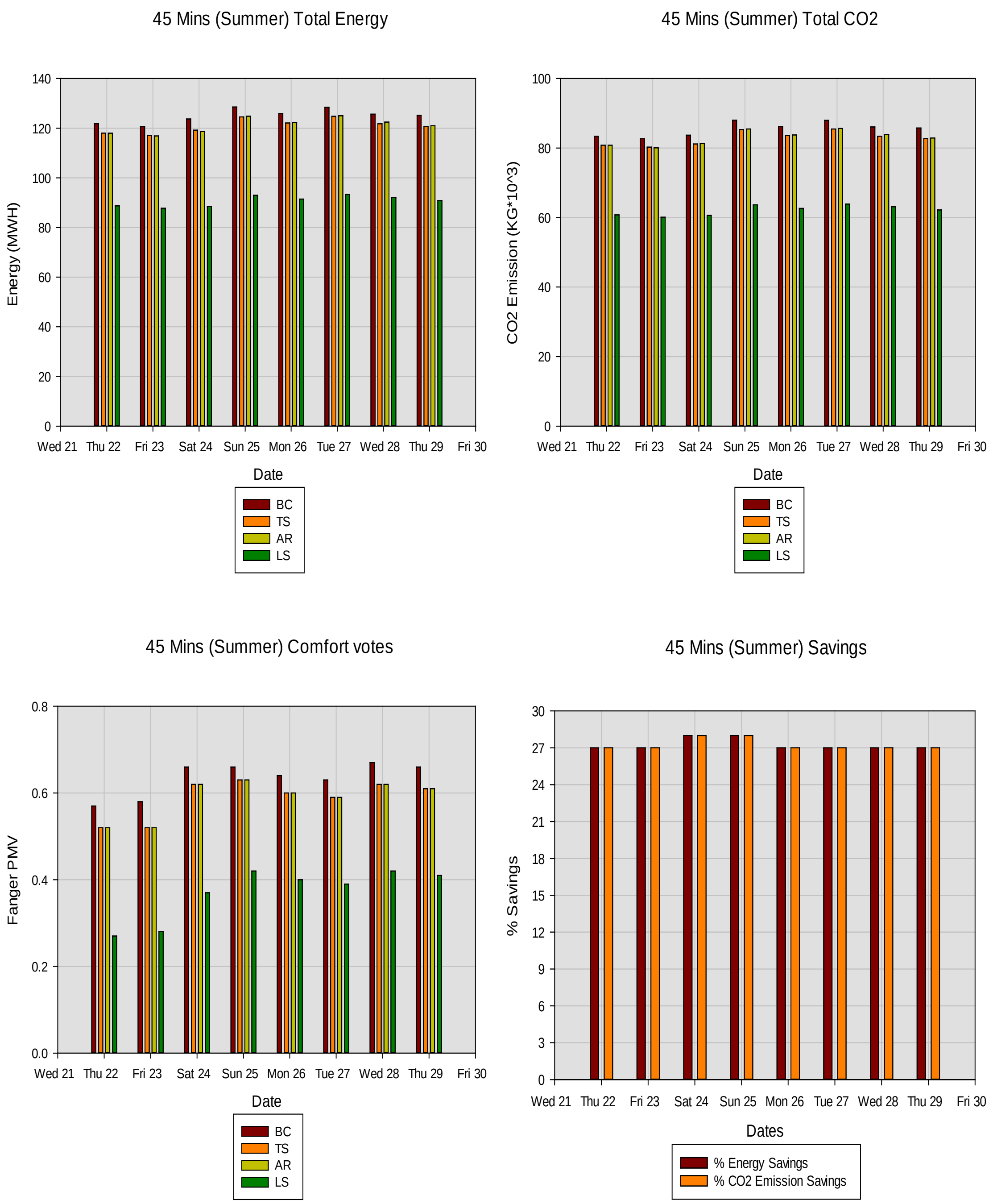


FIGURE 6-27: Results for 45 Minutes Setpoint Elapse Time (Summer)

Similarly, From Figure 6-28, thermal energy conservation measures improves comfort rating, scheduled airflow rates does not seems to affect comfort but lighting schedules improve comfort the most. The comfort level also increased from a PMV value of between 0.58 and 0.68 to between 0.28 and 0.43 for the week considered. Also energy and CO2 savings of about 27 -29% can be observed for this scenario.

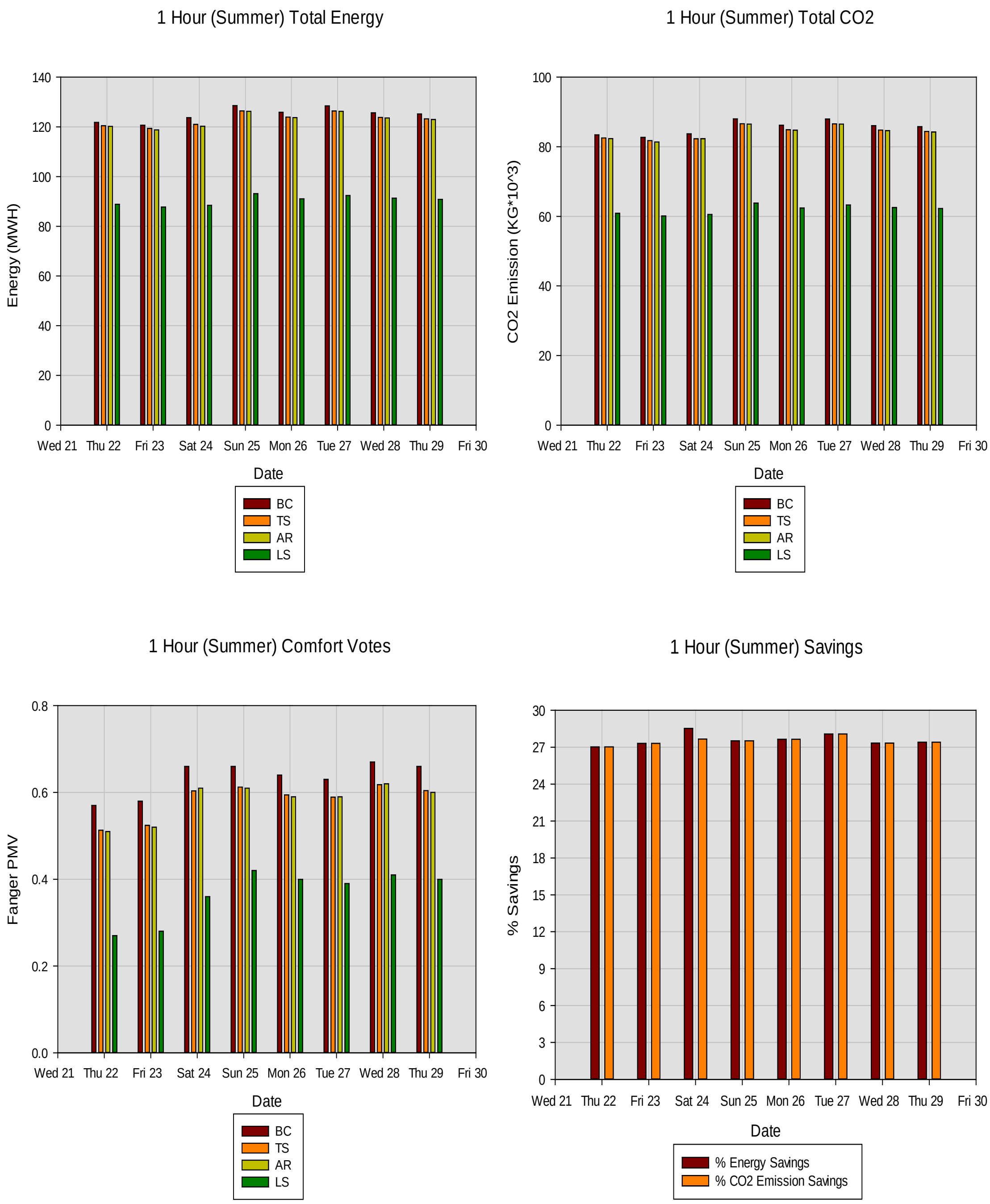
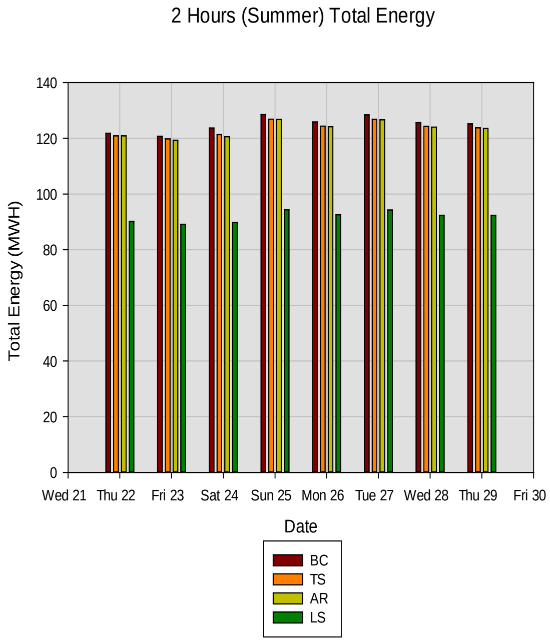
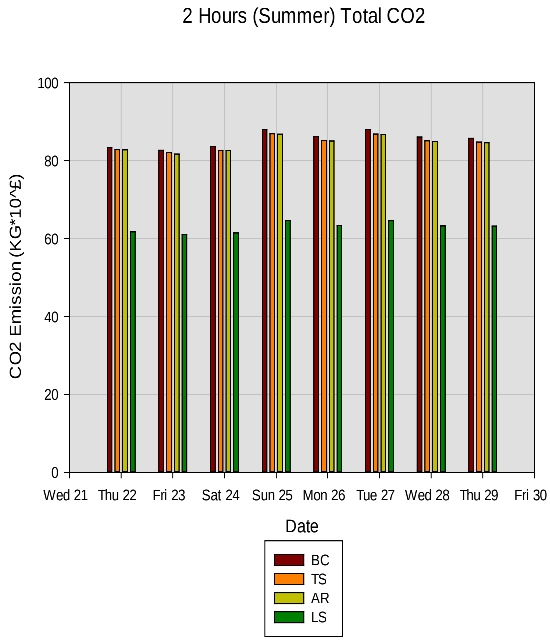
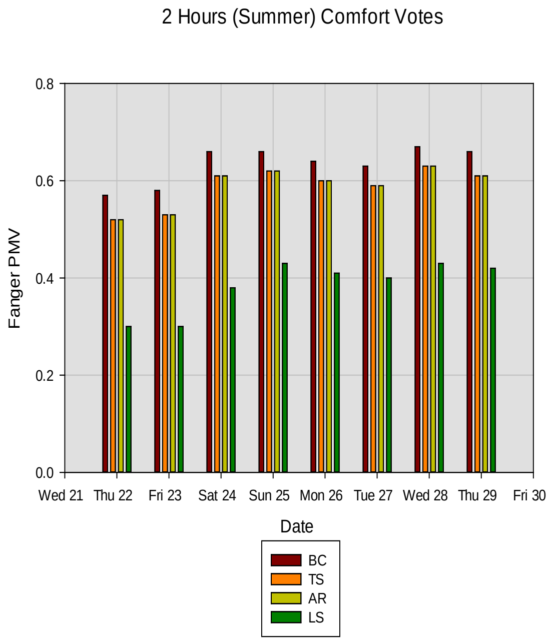


FIGURE 6-28: Results for 1 Hour Setpoint Elapse Time (Summer)

Figure 6-29 has the longest setpoints elapse time for the summer case, so energy and CO2 savings of between 25-27% respectively can be observed for this scenario. The comfort level also rose from a PMV value of between 0.58 and 0.68 to between 0.30 and 0.45 for the week.







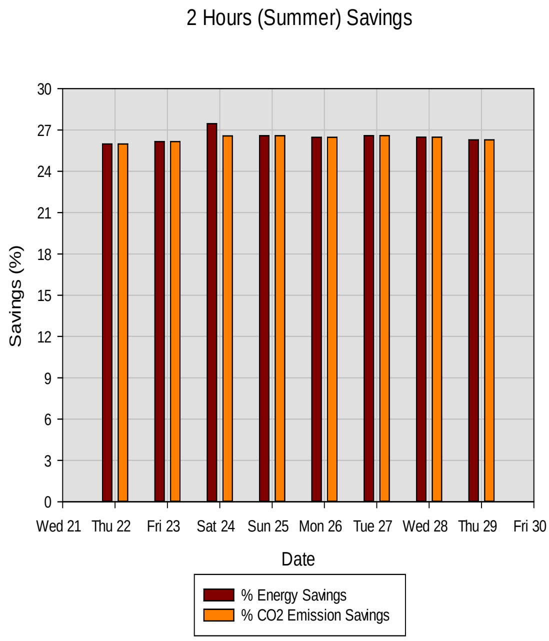


FIGURE 6-29: Results for 2 Hours Setpoint Elapse Time (Summer)

6.6.3 WINTER SAVINGS

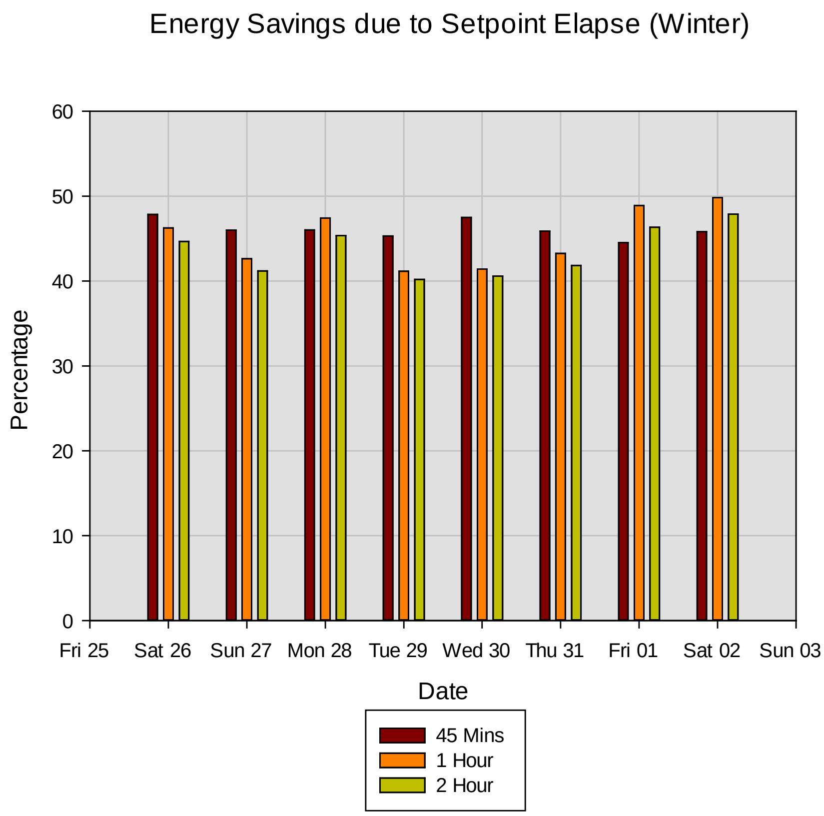


FIGURE 6-30: % Energy Savings from Energy Conservation Method in Winter

By comparing energy savings due to 45 minutes, 1 hour and 2 hours setpoint elapse time as in Figure 6-30, it can be seen that generally, the longer the setpoint elapse time the smaller the savings. Also the savings varies from day to day but generally within 40-50%. This slight daily variation may be due to variation in external conditions and number of passengers used. The higher the external temperature, the less energy consumed in heating and also, the more the number of passengers in the building , the more the heat gains and so less heating energy consumption but there may be increase in electrical power consumption due to increase in fan and dampers activity to provide commensurate air volume to the increased passengers' number.

If the gradation in elapse time's energy saving benefits appears a little unclear in the last two days of the case week, the CO_2 savings of 30-45% on the other hand as presented in Figure 6-31 has made it clearer that savings is proportional to the duration of the elapse time; the longer the duration the less the savings. So the shorter the passenger processing time the greater the benefit accruable from the setback and setpoints elapse time.

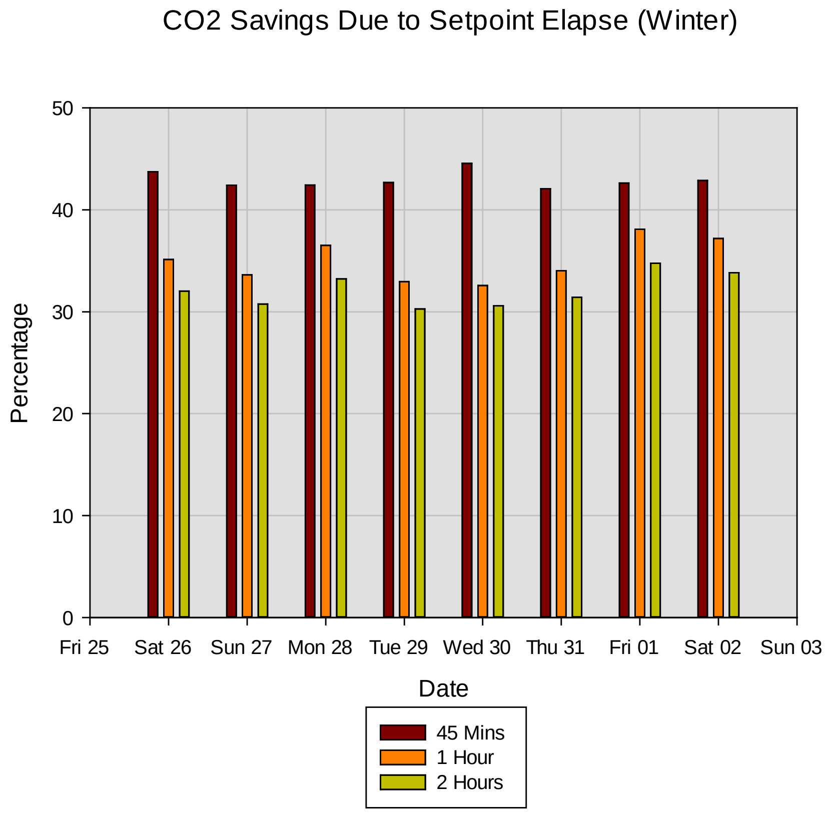


FIGURE 6-31: % Carbon Emission Savings from Energy Conservation Method in Winter

6.6.4 SUMMER SAVINGS

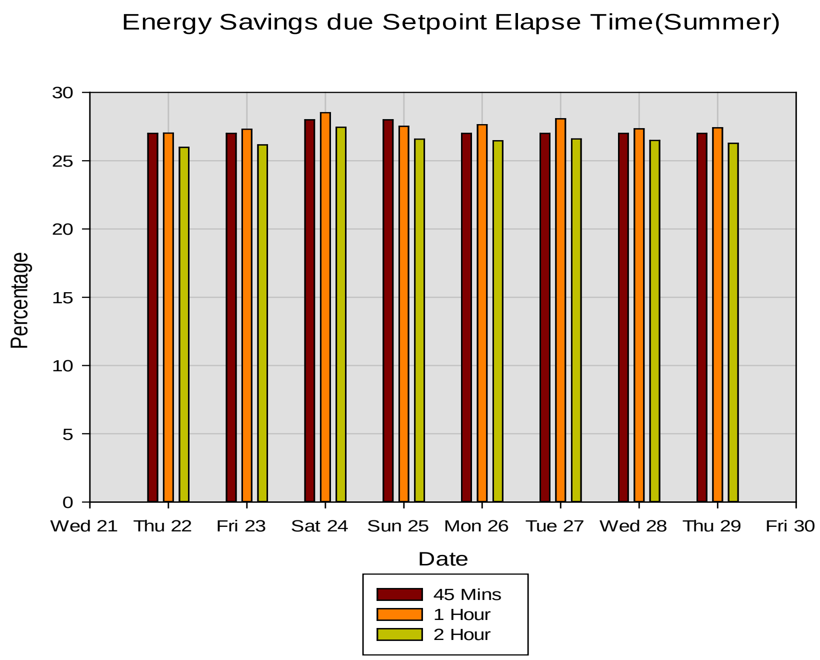


FIGURE 6-32: % Energy Savings from Energy Conservation Method in Summer

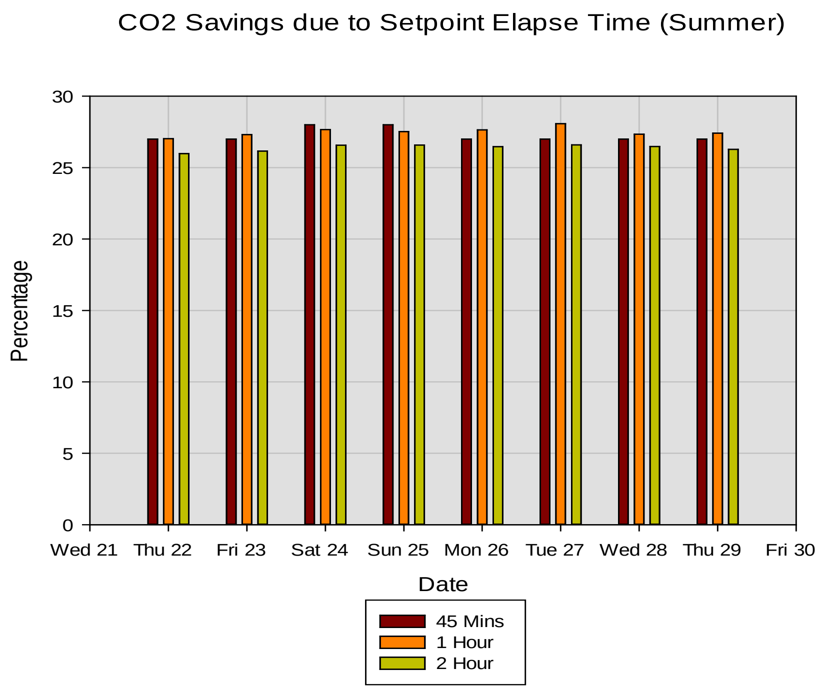


FIGURE 6-33: % Co_2 Savings from Energy Conservation Method in Winter

From Figure 6-32 and Figure 6-33 above it can be seen that the energy savings of 21 to 27% achieved for the summer case was less than the 40 to 50% recorded for the winter time. This is because summer times are busier for the airports as such there are less time available to implement energy conservation measure other than just applying the right comfort setpoints. Also, the need for active cooling or heating is generally less considering the prevailing external weather data. The result for energy savings seems to suggest that the 1 hour setpoints elapse time provided the greatest savings compare to 45 minutes and 2 hours while expectedly, the 2 hours elapse time provided the fewest savings.

6.7 CONCLUSIONS

This chapter presented the fuzzy logic control theory and described the steps for designing a fuzzy controller. It also designed a fuzzy supervisory controller for the control of airport building's indoor environment systems, tested the controller using data collected from/for airport building and presented simulation results proving the capacity of the designed controller to provide comfort setpoints during occupancy and energy conservation setpoints during period of unoccupancy.

This controller is a high level controller which supplies variable setpoints to the low level controllers for temperature, ventilation and lighting based on changes in occupancy and external conditions. So although it is a static controller which does not referenced the dynamics of the systems under control, an important factor needed for the accuracy of local control, this controller performs well for our high level control objectives.

This chapter also provided the results of energy and carbon emission savings due to the energy saving supervisory controller strategy implemented in the building's simulation. About 40 to 50% energy savings and about 30 to 45% carbon emission savings was realised in the winter scenario and about 21-27% for both energy and CO_2 was realised in the summer case.

CHAPTER 7: SUMMARY, CONCLUSIONS, RECOMMENDATION AND FUTURE WORKS

7.1 SUMMARY AND CONCLUSIONS

Comfort affects the quality of buildings but to provide comfort in indoor space, it is often necessary to expend energy. Airport buildings are different in layouts, contents and functions to other types of buildings; in fact, airport terminal buildings are among the most energy intensive buildings. A highly cost effective way to provide comfort at reduced energy use in buildings is through the use of automatic control. This thesis was therefore set to explore the development of a novel controller for airport terminal indoor environment systems. The motivations for this research is in the need to provide comfort at reduce energy use and less environmental impact in airport buildings which was arrived at after extensive study of the airport indoor environment and airport indoor environment systems which shows significant opportunity to implement energy conservation.

This fuzzy logic controller was designed in the MATLAB/Simulink environment and rigorous simulations were carried out both in MATLAB/Simulink and DesignBuilder/EnergyPlus platforms to test the efficacy of the designed controller in providing comfort at reduced energy use. The novelty in this work is in the capacity of the controller to provide variable thermal, visual and indoor air quality setpoints for comfort during passenger's occupancy and for energy conservation during unoccupancy and by taking accounts of variations in external conditions.

Firstly, the background to the research was introduced where; the overall research theme which was titled “integration of active and passive indoor environment systems to minimise the carbon footprint of airport building” was stated and the nature of research collaboration with other researchers in five UK universities was explained, so this research is a small part of the bigger research theme. Also, the motivation for the research was outlined, the research aims, objectives, methodology, stated and a brief outline of the chapters was mentioned to set the tone for the thesis.

Secondly, energy issues, the nature occupancy flow, and environmental characteristics of airport buildings were described to demonstrate their uniqueness compared to other type of buildings. This was followed by brief discussion on comfort theories, the definition of comfort parameters and variables, and the choice of desired comfort setpoints for airport terminals was explained. Also, the review of previous efforts in the area of airport terminal indoor comfort was presented. In conclusion, this section of the thesis demonstrates that factors affecting indoor comfort do not have crisp limit, are imprecise, uncertain, time varying and nonlinear and so could be described using fuzzy logic.

Thirdly, the next discussions gave a general overview of building control systems and reviewed the literature on the general application of various control systems types. These control system types were rated especially based on their capacity to satisfy the airport building control objectives earlier mentioned. This section specifically showed that classical controllers currently used in building control are not able to provide satisfactory performances in spite of their renowned robustness due to the impreciseness, uncertainty, time varying and nonlinear characteristics of the building systems. Fuzzy logic control was therefore selected for the design of the supervisory controller which will provide variable setpoints for comfort and energy conservation based on airport passenger's occupancy and external condition.

Fourthly, the methodology of the research was described. This provided the why's and how's of the research. It explained that site visits and monitoring were carried out to understand the workings and failings of the current HVAC and lighting control systems, it described the reasons for and limitations in selecting computer modelling and simulation tools (MATLAB, Simulink, Fuzzy logic toolbox, DesignBuilder/EnergyPlus) and approach. For example, while computer simulation is a standard method for evaluating new technology, the real performance of a controller is in practical implementation. It also restated that this control strategy was only for areas within airport where occupancy varies strictly with passenger flow such as the arrival halls, baggage reclaim, gates etc. it cannot be deployed in areas with complex occupancy pattern especially areas open to the general public on the landside. It ends with the description of the airport, the airport case study building and the airport base case building model.

Fifthly, the thesis presented a one week airport indoor monitoring results and the flight schedules for winter and summer scenario for Terminal 2 of Manchester airport. It discusses the current airport indoor environmental systems' comfort performance and compares it with the standard comfort requirement for such places while also exploring the opportunities for implementing energy conservation based on variation in passenger flow and external conditions. It shows that airport environmental systems are run on the assumption of a 24/7 occupancy contrary to the results derived from the analysis of passenger flight schedules which shows that there are available opportunities to implement energy saving strategy. Lastly, it also showed that the setpoints being provided was not commensurate with the comfort standards for such spaces. This section provided reasons for the desirability of a control system capable of providing the right comfort setpoint during occupancy and implementing energy conservation measure during unoccupancy.

Finally a detailed discussion on fuzzy logic control modelling which expounds on the theory of fuzzy sets and its basic operations, fuzzy logic control theory in general and the design of supervisory controller for airport building in particular was presented. This fuzzy supervisory controller provided thermal, visual and lighting setpoints to the classical controllers of these systems based on variation of passenger flow information and external conditions. The controller's structure, inputs-outputs variables, rule formations, the variable's universe-of-discuss, triangular and trapezoidal membership function definition and the fuzzification and defuzzification method based on Mamdani's model were described. The controller's performance characteristics were studied first based on the 3D MATLAB surface view simulation results mapping the airport case study inputs to the controller outputs and the winter and summer controller's outputs MATLAB plots showing its capacity to provide adequate comfort based on variation in passenger flight data, external temperature and zone illuminance was also presented. Secondly, the controller outputs based on 45 minutes, 1 hour and 2 hours setpoint elapse times were then used as schedules in the base case airport building model described earlier and rated in terms of energy savings, carbon emission savings and comfort provisions. The choice of these times was to reflect a period less than the standard passenger processing times, the standard processing times and a relax time frame to account for possible delays respectively.

The results showed that the developed controller is capable of supplying comfort setpoints to classical controllers that take into account changes in passenger flow data and changes in external conditions. The controller can save 40-50%/21-27% energy and 30-35%/21-27% carbon emission in winter and summer respectively. It also shows that the longer the setpoint elapse time, the less the energy savings, carbon emission savings and comfort especially in winter which has greater energy saving due to decrease flight activity and so more opportunity to implement setback.

The objectives of this thesis which was to design a controller for the management airport indoor environment system based on variation in occupancy and external conditions which will satisfy occupants comfort and save more energy compare to the current system in use was accomplished.

7.2 RECOMMENDATION TO INDUSTRIES

The research showed that controlling temperature, ventilation and lighting according to the flow of passengers will save energy and reduce carbon emissions from the airport terminals and not necessarily by sacrificing comfort.

The following recommendations are given for the implementation of the supervisory controller:

1. The supervisory controller (explained in chapter 6) can be connected to the BMS. The Human Machine Interface (HMI) of the BMS can be used for running the controller.
2. The practical implementation of the supervisory controller will provide required comfort set points at reduced energy consumption and carbon emission in accordance to variation in the follow of passengers and external conditions.
3. This work should elicit further research and industry interest in this area.
4. This work has also shown that the assumption that all airport buildings operate on a 24/7 schedules especially in the passenger exclusive areas is misleading and costly in terms of energy consumption although there could be some exemption to this. A strong reason for the implementation of better control strategy.
5. Airports building and control engineers must begin to prepare the buildings for eventual implementation of occupancy based control of airport indoor environment system by ensuring that the indoor environment is properly zoned to demarcate passenger exclusive areas from the general public areas in the installation of services. This work has shown that this type of controller is feasible and beneficial.

7.3 Suggestions for Future Work

The work presented in this thesis has provided a significant contribution to the issue of energy management in airport buildings which also has potential for application in other buildings that share similar occupancy patterns with the passenger exclusive areas of the airport; however more work has to be done before real industrial application. For example, the controller has to be implemented practically in a real airport building to rate its real performance.

This is a static controller that does not take account of the internal dynamics of the systems being controlled, a very important factor for the accuracy of low level controllers, although this seems alright for our high level controller strategy but has to be checked in practical implementation.

The rule based controller has to be gauged against real indoor factors such as the exact nature of indoor illuminance of the space (because global illuminance was used in our study) and thermal response of the building fabrics.

For this research, only one week long summer and winter scenario was used. For a thorough assessment, the controller needs to be investigated for longer durations and across more scenarios such as the spring and autumn performances.

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Journal:

- **Mambo, A. D.**, Eftekhari, M. M., Steffen, T. & Ahmad M.W (2013). Investigating Energy and Comfort for Occupancy Flow-Based Control of Indoor Airport Terminal Environment Systems. Energy and Buildings (Reviewed, Corrected and Resubmitted). (Appendix 4).

- **Mambo, A. D**., Eftekhari, M. M., Steffen, T., Ahmad M.W & Kotopouleas A., (2013). Evaluation of HVAC system's Operational Strategy for Airport Buildings. Indoor & Built Environment Journal (Under Review). (Appendix 5).

- Ahmad M.W, Eftekhari, M. M., Steffen, T. & **Mambo, A. D**. Investigating the Performance of a Combined Solar System With Heat Pump For Houses. Energy and Buildings 63 (2013) 138 -146.

Book Chapters:

- **Mambo, A. D.**, Eftekhari, M. M., Steffen, T. (2013). Occupancy-Driven Supervisory Control Strategies to Minimise Energy Consumption of Airport Terminal Building. In A. Håkansson, M. Höjer, R. J. Howlett, & L. C. Jain (Eds.), Sustainability in Energy and Buildings: Smart Innovation, Systems and Technologies Series. (Vol. 22, pp. 479-489). New York, Dordrecht, London: Springer-Verlag Berlin Heidelberg. (Appendix 6).

- **Mambo, A. D.**, & Eftekhari, M. (2012). Supervisory Control of Indoor Environment Systems to Reduce the Carbon Footprint of Airport Buildings - A

Review. In N. M'Sirdi, A. Namaane, R. J. Howlett, & L. C. Jain (Eds.), Sustainability in Energy and Buildings: Smart Innovation, Systems and Technologies Series (Vol. 12, pp. 413-424). New York, Dordrecht, London: Springer-Verlag Berlin Heidelberg. (Appendix 7).

Conferences:

- **Mambo, A. D.**, Eftekhari, M. M., & Steffen, T. (2012). Fuzzy Supervisory Control Strategies to Minimize Energy Use of Airport Terminal Buildings. In S. Qin, W. Shen, J. Liu, & C. Guan (Eds.), The 18th International Conference On Automation And Computing (pp. 43-48). Uxbridge, Middlesex UB8 3PH: Brunel University Press. (Appendix 8).

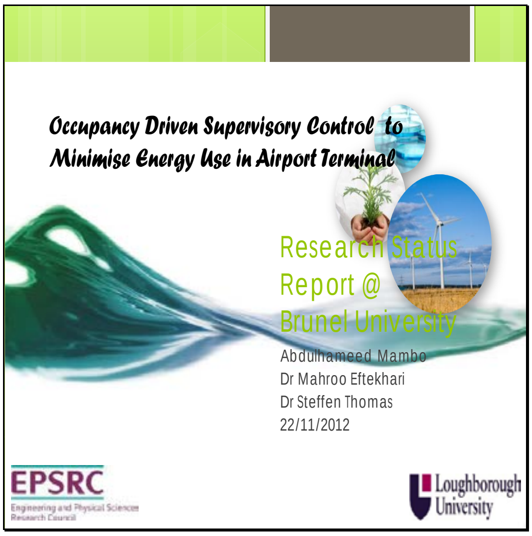
- **Mambo, A. D.**, Eftekhari, M. M., & Steffen, T. (2013). Occupancy-Driven Supervisory Control Strategies to Minimise Energy Consumption of Airport Terminal Building. Energy Efficiency and condition monitoring, UKACC PhD Presentation Showcase, London, 17 October 2012. Available at: http://ukacc.group.shef.ac.uk/?page_id=351. (Appendix 9).

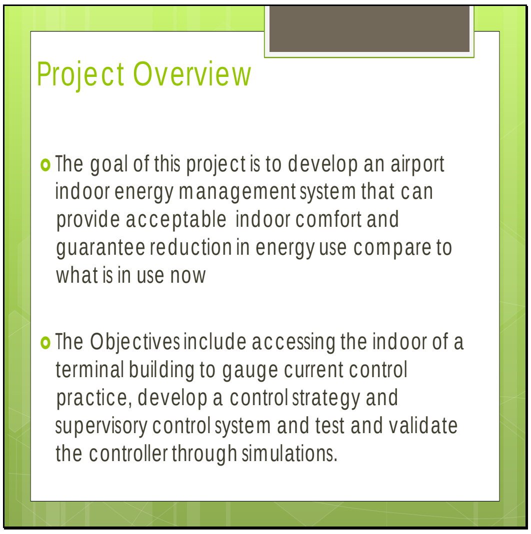
APPENDICES

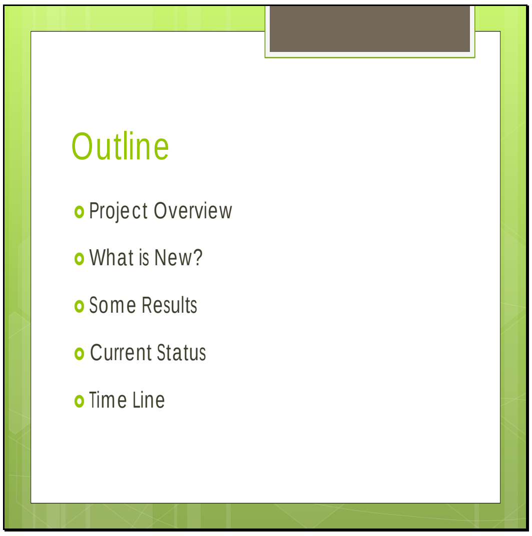
Appendix 1: Research collaboration

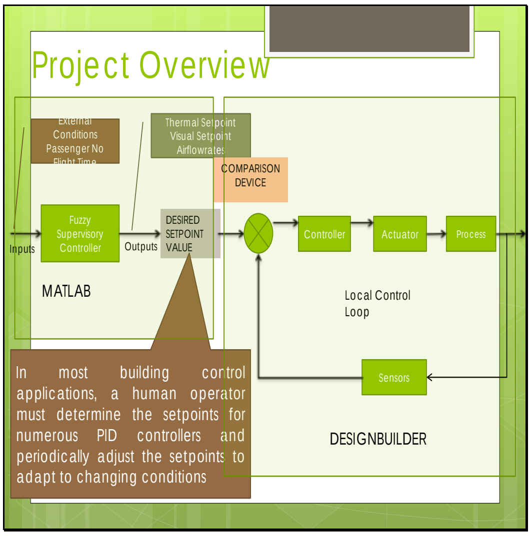
The group meets every six months to review the progress of the project. These meetings are chaired by Professor Savvas Tassau, Principal investigator and Head of School of Engineering and Design, Brunel University. Other Participants in these meetings comprise the research students, research associates and research supervisors (Investigators). Meetings usually start with presentation of research progress from the research students and associates, followed by questions and answers on the presentations and suggestions for improvements. The group also attends The Sandpit: Airport Energy Technologies Network (AETN) meeting, a larger group comprising several universities with a pool of investigators and researchers (focusing on reducing the environmental impacts of airport operations such as carbon reduction technologies and practice, power generation, design and layout optimisation in the airport built environment, energy efficiency operational practices and technologies, measurement and monitoring technologies and practices, active and passive emissions control, Reducing airside and landside congestion and noise abatement) on one hand and the aviation industry experts on the other hand. This collaboration allows cross fertilization of ideas and dissemination of the project between academics and industry expert. It has also allowed transfer of skill and knowledge horizontally among the researchers and vertically among the group.

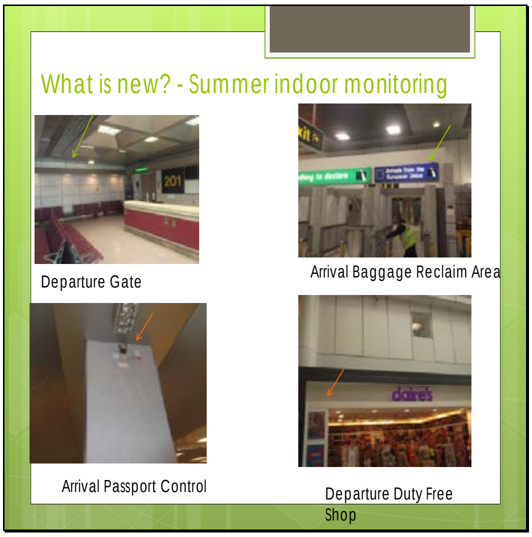
One of the Presentations during meeting is as follows:

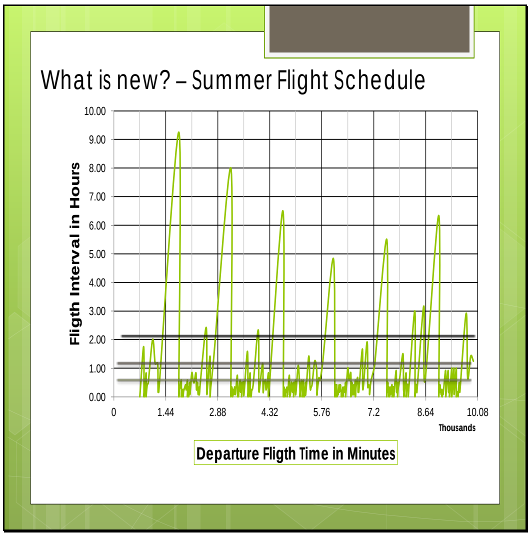

Occupancy Driven Supervisory Control to Minimise Energy Use in Airport Terminal
Research Status Report @ Brunel University
Abdulhameed Mambo
Dr Mahroo Eftekhari
Dr Steffen Thomas
22/11/2012
EPSRC
Engineering and Physical Sciences Research Council
Loughborough University

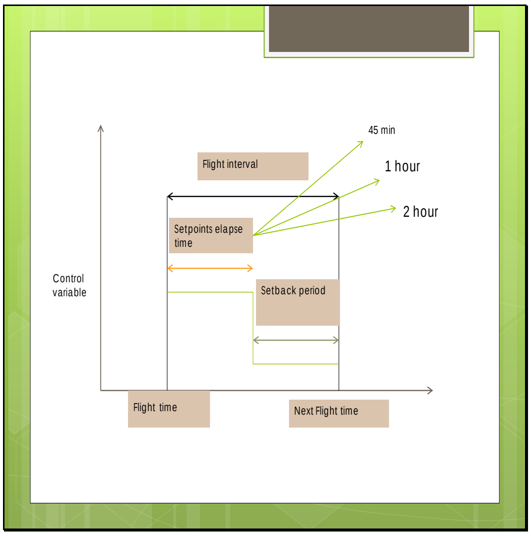

Project Overview
The goal of this project is to develop an airport indoor energy management system that can provide acceptable indoor comfort and guarantee reduction in energy use compare to what is in use now
The Objectives include accessing the indoor of a terminal building to gauge current control practice, develop a control strategy and supervisory control system and test and validate the controller through simulations.

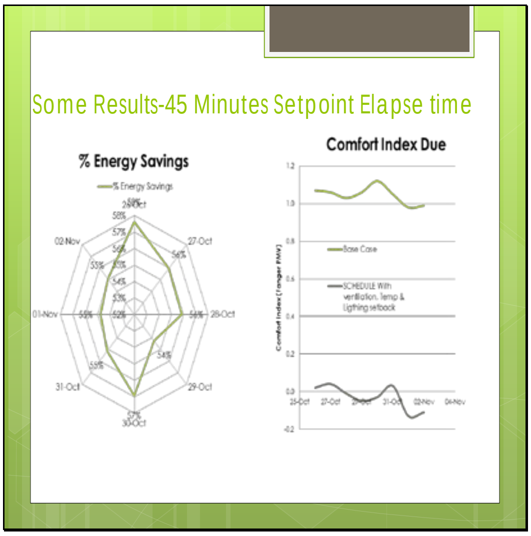

Outline
Project Overview
What is New?
Some Results
Current Status
Time Line

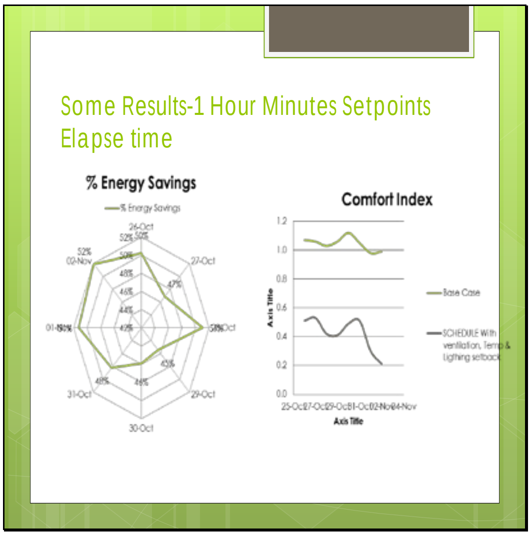

Project Overview
External Conditions
Passenger No
Flight Time
Thermal Setpoint
Visual Setpoint
Airflowrates
COMPARISON DEVICE
Inputs
Fuzzy Supervisory Controller
Outputs
DESIRED SETPOINT VALUE
Controller
Actuator
Process
MATLAB
Local Control Loop
Sensors
In most building control applications, a human operator must determine the setpoints for numerous PID controllers and periodically adjust the setpoints to adapt to changing conditions
DESIGNBUILDER

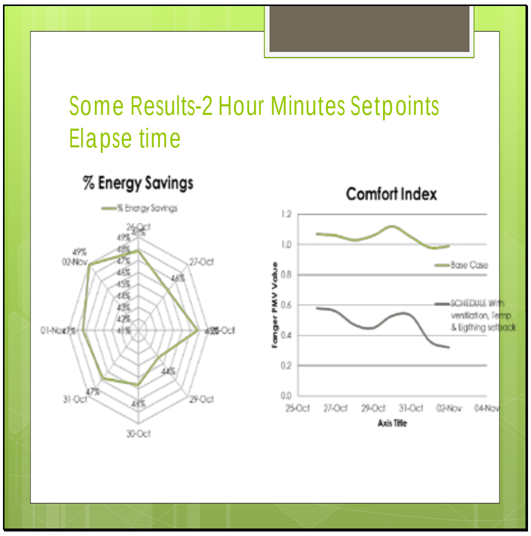

What is new? - Summer indoor monitoring
Departure Gate
Arrival Baggage Reclaim Area
Arrival Passport Control
Departure Duty Free Shop

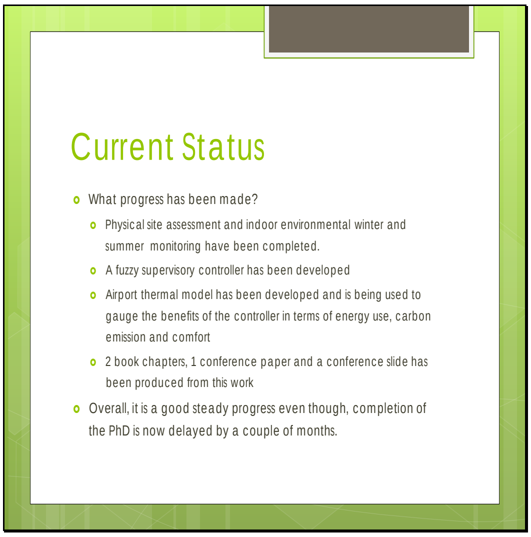

What is new? – Summer Flight Schedule
Fligth Interval in Hours
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
1.44
2.88
4.32
5.76
7.2
8.64
10.08
Thousands
Departure Fligth Time in Minutes

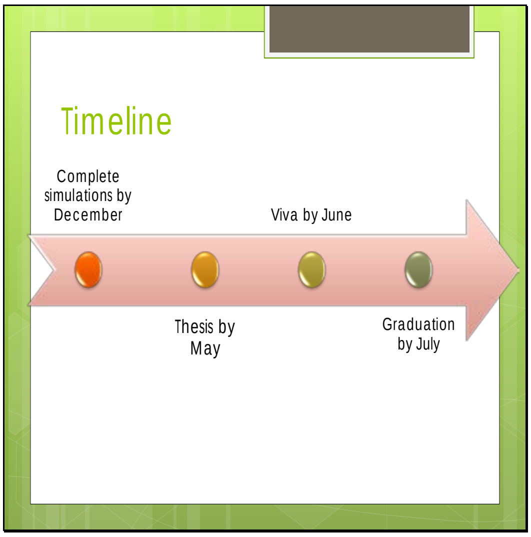

45 min
Flight interval
1 hour
2 hour
Setpoints elapse time
Control variable
Setback period
Flight time
Next Flight time


Some Results-45 Minutes Setpoint Elapse time
% Energy Savings
Comfort Index Due


Some Results-1 Hour Minutes Setpoints Elapse time
% Energy Savings
Comfort Index


Some Results-2 Hour Minutes Setpoints Elapse time
% Energy Savings
Comfort Index


Current Status
What progress has been made?
Physical site assessment and indoor environmental winter and summer monitoring have been completed.
A fuzzy supervisory controller has been developed
Airport thermal model has been developed and is being used to gauge the benefits of the controller in terms of energy use, carbon emission and comfort
2 book chapters, 1 conference paper and a conference slide has been produced from this work
Overall, it is a good steady progress even though, completion of the PhD is now delayed by a couple of months.


Timeline
Complete simulations by December
Viva by June
Thesis by May
Graduation by July

APPENDIX 2: CONVERTING MATLAB OUTPUTS TO COMPACT SCHEDULES

Schedule in EnergyPlus is started by creating one or more day schedules to form a week schedule which could be combine to form a month and then an annual schedule. With compact schedules, it can be done in one command. The syntax for compact schedule must include the following fields:

1. **Name** of space, zone, or equipment to be scheduled such as "Check_in_Light".
2. **Schedule Type Limit Name** usually Fraction followed by "," even for temperature settings. The fraction is ratio of maximum over the minimum value of the gain.
3. **Through** is followed by ":" and the ending date for the schedule followed by "," such as ***Through: 31 Dec,*** to show that the schedule is for the whole year.
4. **For** is followed by ":" then applicable number of days such as Thursdays, Summerdays, Holidays, Allotherdays, WintersDesignDays etc., followed by ",". For example *For: WinterDesignDays.*
5. **Until** followed by ":" then the ending time for a particular setpoint followed by "," and then the value of the setpoint followed by "," and the last field value followed by ";" one a line such as *Until:15:00,0.8, and Until:24:00,0;* respectively.
6. The table below shows the gain schedules for occupancy, light, heat and ventilations for both the base case and the test cases for winter and summer scenario used in this work.

Winter Base Cases		
Occupancy & Gain Schedules		
45 Minutes	**1 Hour**	**2 Hours**
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,
On,	On,	On,
Fraction,	Fraction,	Fraction,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For: AllDays,	For: AllDays,	For: AllDays,
Until: 24:00, 1,;	Until: 24:00, 1 ,	Until: 24:00, 1,;
For: SummerDesignDay AllOtherDays,	For: SummerDesignDay AllOtherDays,	For: SummerDesignDay AllOtherDays,
Until: 24:00,0;	Until: 24:00,0;	Until: 24:00,0;

Winter Test Cases		
Occupancy Schedules		
45 mins	**1 hour**	**2 Hours**
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,
Terminal_Check_Occ,	Terminal_Check_Occ,	Terminal_Check_Occ,
Fraction,	Fraction,	Fraction,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For: Wednesday WinterDesignDay,	**For: Wednesday WinterDesignDay,**	**For: Wednesday WinterDesignDay,**
Until:05:55,0.36,	Until:07:10,0.9,	Until:06:50,0.4,
Until:06:40,0.36,	Until:07:50,0.7,	Until:07:10,0.8,
Until:06:50,0,	Until:08:55,0.9,	Until:07:50,0.2,
Until:07:10,0.8,	Until:09:30,0.8,	Until:08:55,0.4,
Until:07:50,0.2,	Until:10:15,0.9,	Until:09:30,0.2,
Until:08:35,0.44,	Until:11:15,0.9,	Until:13:05,0.4,
Until:08:55,0,	Until:12:05,0.9,	Until:13:20,0,
Until:09:30,0.24,	Until:13:20,0.7,	Until:15:50,0.4,
Until:10:15,0.4,	Until:15:10,1,	Until:17:10,0.8,
Until:11:50,0.38,	Until:15:50,0.7,	Until:18:30,0.2,
Until:13:20,0,	Until:16:15,1,	Until:20:20,0.8,
Until:14:55,0.36,	Until:16:50,0.9,	Until:21:50,1,
Until:15:50,0,	Until:17:10,0.7,	Until:23:50,0.6,
Until:16:35,0.8,	Until:18:30,0.8,	until:24:00,0.4,
Until:17:10,0,	Until:19:15,0.9,	**For: Thursday,**
Until:18:25,0.24,	Until:21:15,0.9,	Until:01:50,0.4,
Until:20:20,0.8,	Until:21:50,0.6,	Until:06:10,0.4,
Until:21:05,1,	Until:22:15,0.9,	Until:06:55,0.3,
Until:21:05,1,	Until:22:15,0.9,	Until:06:55,0.3,

45 Minutes	1 Hour	2 Hours
Until:21:50,0,	Until:22:50,0.9,	Until:07:40,0.7,
Until:22:35,0.6,	Until:23:50,0.6,	Until:07:50,0.9,
Until:24:00,0,	Until:24:00,0.6,	Until:09:00,0.8,
For: Thursday,	**For:Thursday,**	Until:09:55,0.6,
Until:00:35,0.36,	Until:00:50,0.9,	Until:10:15,0.4,
Until:05:50,0,	Until:05:50,0.6,	Until:10:55,0.3,
Until:06:10,0.4,	Until:08:50,0.9,	Until:12:30,0.6,
Until:06:55,0.28,	Until:09:00,0.6,	Until:13:00,0.2,
Until:07:40,0.7,	Until:09:15,0.9,	Until:13:50,0.9,
Until:07:50,0.9,	Until:11:55,0.9,	Until:17:35,0.3,
Until:08:35,0.8,	Until:12:15,0.7,	Until:17:50,0.9,
Until:09:00,0,	Until:12:30,0.7,	Until:18:35,1,
Until:09:55,0.6,	Until:13:00,0.8,	Until:19:15,0.2,
Until:10:15,0.4,	Until:16:15,1,	Until:20:45,0.8,
Until:10:55,0.3,	Until:16:45,0.9,	Until:22:45,0.3,
Until:11:40,0.6,	Until:17:10,0.7,	until:24:00,0,
Until:12:30,0,	Until:18:35,0.9,	**For: Friday,**
Until:13:00,0.2,	Until:19:15,0.9,	Until:05:25,0,
Until:13:50,0.88,	Until:20:15,0.9,	Until:05:50,0.7,
Until:14:35,0.3,	Until:20:45,0.7,	Until:06:20,0.8,
Until:14:55,0,	Until:21:15,0.9,	Until:06:55,0.9,
Until:16:30,0.3,	Until:21:45,0.9,	Until:07:35,1,
Until:17:10,0,	Until:24:00,0.6,	Until:07:50,0.4,
Until:17:35,0.3,	**For:Friday,**	Until:08:40,0.9,
Until:18:35,1,	Until:05:25,0.6,	Until:09:05,0.2,
Until:19:15,0.24,	Until:08:40,0.9,	Until:09:25,0.3,
Until:19:50,0.8,	Until:09:05,0.8,	Until:09:55,0.2,
Until:20:45,0,	Until:09:25,0.9,	Until:10:15,0.5,
Until:21:30,0.344,	Until:09:55,0.8,	Until:11:05,0.6,
Until:24:00,0,	Until:10:15,0.9,	Until:11:45,0.2,
For: Friday,	Until:11:05,0.9,	Until:12:55,0.6,
Until:05:25,0,	Until:11:45,0.9,	Until:13:20,0.4,
Until:05:50,0.72,	Until:12:15,0.9,	Until:13:35,0.2,
Until:06:20,0.8,	Until:12:45,1,	Until:13:55,0.4,
Until:06:55,0.9,	Until:12:55,0.7,	Until:14:50,0.6,
Until:07:35,1,	Until:13:20,1,	Until:15:35,0.2,
Until:07:50,0.408,	Until:13:35,0.8,	Until:16:50,0.4,
Until:08:35,0.9,	Until:14:50,1,	Until:17:35,0.7,
Until:09:05,0.24,	Until:17:15,0.9,	Until:19:00,0.4,
Until:09:25,0.3,	Until:17:35,0.9,	Until:19:20,0.3,

45 Minutes	**1 Hour**	**2 Hours**
Until:09:55,0.2,	Until:18:30,0.8,	Until:20:50,0.5,
Until:10:15,0.5,	Until:20:15,0.9,	Until:21:55,0.8,
Until:11:05,0.624,	Until:20:20,0.9,	Until:22:15,0.3,
Until:11:45,0.246,	Until:20:50,0.6,	until:24:00,0,
Until:12:30,0.624,	Until:21:15,0.9,	**For: Saturday,**
Until:12:55,0,	Until:21:55,0.9,	Until:00:15,0.5,
Until:13:20,0.4,	Until:22:15,0.9,	Until:05:50,0,
Until:13:35,0.21,	Until:23:15,0.9,	Until:06:10,0.3,
Until:13:55,0.4,	Until:24:00,0.6,	Until:06:35,0.9,
Until:14:40,0.618,	**For:Saturday,**	Until:06:40,1,
Until:14:50,0,	Until:05:50,0.6,	Until:07:10,0.2,
Until:15:35,0.2,	Until:06:40,0.9,	Until:07:50,0.6,
Until:16:40,0.4,	Until:07:10,0.7,	Until:09:05,0.7,
Until:16:50,0,	Until:09:15,0.9,	Until:09:55,0.9,
Until:17:35,0.7,	Until:10:55,0.9,	Until:10:15,0.6,
Until:18:20,0.214,	Until:11:05,0.9,	Until:10:55,0.8,
Until:18:30,0,	Until:12:05,0.9,	Until:11:05,0.2,
Until:19:00,0.4,	Until:12:40,0.7,	Until:12:40,1,
Until:19:20,0.336,	Until:13:15,0.9,	Until:13:00,0.3,
Until:20:05,0.46,	Until:16:05,1,	Until:13:20,0.6,
Until:20:50,0,	Until:16:15,0.7,	Until:13:50,0.6,
Until:21:40,0.78,	Until:17:35,1,	Until:14:35,0.8,
Until:21:55,0,	Until:18:30,0.8,	Until:15:35,0.3,
Until:22:15,0.252,	Until:20:00,1,	Until:16:05,0.5,
Until:23:00,0.5,	Until:20:50,0.7,	Until:16:45,0.3,
Until:24:00,0,	Until:22:50,1,	Until:17:35,0.5,
For: Saturday,	Until:24:00,0.6,	Until:18:30,0.2,
Until:05:50,0,	**For:Sunday,**	Until:18:40,0.5,
Until:06:10,0.256,	Until:02:15,0.7,	Until:19:00,0.4,
Until:06:40,1,	Until:03:15,0.7,	Until:20:50,0.9,
Until:07:10,0.2,	Until:05:50,0.6,	Until:21:50,0.8,
Until:07:50,0.6,	Until:06:20,0.8,	Until:23:50,0.4,
Until:08:50,0.666,	Until:08:15,0.9,	until:24:00,0,
Until:09:05,0,	Until:12:00,1,	**For: Sunday,**
Until:09:55,0.92,	Until:13:20,0.8,	Until:05:50,0,
Until:10:15,0.622,	Until:15:10,1,	Until:06:20,0.2,
Until:10:55,0.83,	Until:15:35,0.8,	Until:06:40,0.7,
Until:11:05,0.244,	Until:16:15,1,	Until:06:45,0.3,
Until:11:50,1,	Until:18:30,1,	Until:07:50,0.5,
Until:12:40,0,	Until:19:20,0.7,	Until:08:35,0.3,

45 Minutes	1 Hour	2 Hours
Until:13:00,0.34,	Until:23:35,1,	Until:08:50,0.5,
Until:13:50,0.624,	Until:24:00,0.6,	Until:09:10,0.4,
Until:14:35,0.81,	**For:Monday,**	Until:09:30,1,
Until:15:35,0.28,	Until:03:15,0.7,	Until:10:35,0.4,
Until:16:05,0.468,	Until:05:50,0.8,	Until:11:00,0.6,
Until:16:15,0,	Until:07:15,1,	Until:12:25,0.8,
Until:16:45,0.288,	Until:07:50,0.8,	Until:13:20,0.2,
Until:17:30,0.48,	Until:08:50,1,	Until:14:10,0.3,
Until:17:35,0,	Until:09:50,0.9,	Until:15:50,0.4,
Until:18:30,0.206,	Until:12:00,1,	Until:16:40,0.5,
Until:19:00,0.422,	Until:13:20,0.8,	Until:19:20,0.4,
Until:19:45,0.92,	Until:13:45,1,	Until:20:10,0.5,
Until:20:50,0,	Until:14:20,0.8,	Until:20:55,0.4,
Until:21:35,0.8,	Until:15:20,1,	Until:21:55,0.8,
Until:21:50,0,	Until:15:50,0.8,	Until:22:35,0.4,
Until:22:35,0.42,	Until:16:45,1,	until:24:00,0,
Until:24:00,0,	Until:17:05,0.8,	**For: Monday,**
For: Sunday,	Until:19:55,1,	Until:00:35,0.9,
Until:05:50,0,	Until:20:10,0.7,	Until:05:50,0,
Until:06:20,0.23,	Until:21:10,0.9,	Until:07:15,0.8,
Until:06:40,0.68,	Until:24:00,0.6,	Until:07:50,0.2,
Until:06:45,0.288,	**For:Tuesday,**	Until:08:50,0.4,
Until:07:30,0.48,	Until:00:05,0.7,	Until:09:50,0.2,
Until:07:50,0,	Until:01:05,1,	Until:10:20,0.4,
Until:08:35,0.306,	Until:04:15,0.7,	Until:11:00,0.4,
Until:08:50,0.466,	Until:05:50,0.6,	Until:13:00,0.6,
Until:09:10,0.422,	Until:07:40,0.9,	Until:13:20,0,
Until:09:30,1,	Until:07:50,0.6,	Until:13:45,0.4,
Until:10:35,0.416,	Until:08:15,0.8,	Until:14:20,0.2,
Until:11:00,0.6,	Until:10:15,0.9,	Until:17:30,0.4,
Until:11:45,0.8,	Until:13:00,1,	Until:17:55,0.7,
Until:12:25,0,	Until:13:20,0.9,	Until:18:40,0.4,
Until:13:10,0.23,	Until:16:15,1,	Until:20:10,0.5,
Until:13:20,0,	Until:18:20,0.9,	Until:22:10,0.2,
Until:14:10,0.288,	Until:19:20,0.8,	until:24:00,0,
Until:14:55,0.4,	Until:20:20,0.9,	**For: Tuesday,**
Until:15:35,0,	Until:20:55,0.6,	Until:00:05,0,
Until:16:30,0.466,	Until:23:00,0.9,	Until:01:05,0.8,
Until:18:15,0.396,	**For: AllOtherDays,**	Until:05:50,0,
Until:19:20,0,	Until: 24:00, 0;	Until:06:40,0.8,

45 Minutes	**1 Hour**	**2 Hours**
Until:20:05,0.46,		Until:07:50,0.4,
Until:20:10,0,		Until:08:15,0.2,
Until:20:55,0.398,		Until:08:50,1,
Until:21:40,0.8,		Until:10:20,0.4,
Until:21:55,0,		Until:12:05,0.8,
Until:22:35,0.398,		Until:13:00,0.4,
Until:23:20,0.86,		Until:13:20,0.2,
Until:24:00,0,		Until:13:55,0.4,
For: Monday,		Until:14:55,0.6,
Until:05:50,0,		Until:15:45,0.4,
Until:07:15,0.8,		Until:16:50,0.8,
Until:07:50,0.2,		Until:17:30,0.4,
Until:08:40,0.44,		Until:18:20,0.6,
Until:08:50,0,		Until:19:20,0.2,
Until:09:50,0.24,		Until:20:55,0.8,
Until:10:20,0.4,		Until:22:00,0.4,
Until:11:00,0.38,		until:24:00,0,
Until:11:45,0.6,		For: AllOtherDays,
Until:13:20,0,		Until: 24:00,0;
Until:13:45,0.38,		
Until:14:20,0.2,		
Until:15:05,0.44,		
Until:15:50,0,		
Until:16:35,0.44,		
Until:17:05,0,		
Until:17:30,0.4,		
Until:17:55,0.7,		
Until:18:40,0.38,		
Until:19:40,0.532,		
Until:20:10,0,		
Until:20:55,0.246,		
Until:24:00,0,		
For: Tuesday,		
Until:00:05,0,		
Until:00:50,0.838,		
Until:05:50,0,		
Until:06:40,0.8,		
Until:07:25,0.4,		
Until:07:50,0,		
Until:08:15,0.24,		

45 Minutes	1 Hour	2 Hours
Until:08:50,1,		
Until:09:30,0.4,		
Until:10:20,0.38,		
Until:11:50,0.8,		
Until:12:05,0,		
Until:12:50,0.44,		
Until:13:00,0,		
Until:13:20,0.24,		
Until:13:55,0.4,		
Until:14:40,0.6,		
Until:14:55,0,		
Until:15:40,0.38,		
Until:15:45,0,		
Until:16:30,0.8,		
Until:16:50,0,		
Until:17:30,0.4,		
Until:18:15,0.6,		
Until:18:20,0,		
Until:19:05,0.24,		
Until:19:20,0,		
Until:20:05,0.8,		
Until:20:55,0,		
Until:21:40,0.4,		
Until:22:00,0,		
Until:22:45,0.624,		
Until:24:00,0,		
For: SummerDesignDay Al-lOtherDays,		
Until: 24:00,0;		
Lighting Schedules		
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,
Terminal_Check_Light,	Terminal_Check_Light	Terminal_Check_Light
Fraction,	Fraction,	Fraction,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For: Wednesday WinterDesignDay,	**For: Wednesday Winter-DesignDay,**	**For: Wednesday Winter-DesignDay,**
Until:05:30,1,	Until:06:55,1,	Until:06:55,1,
Until:06:30,1,	Until:17:00,0,	Until:17:00,0,
Until:17:00,0,	Until:17:10,1,	Until:17:10,1,
Until:18:00,0.9,	Until:18:30,0.9,	Until:18:30,0.9,
Until:18:30,0.4,	Until:24:00,1,	Until:24:00,1,

45 Minutes	1 Hour	2 Hours
Until:21:00,1,	**For:Thursday,**	**For:Thursday,**
Until:21:30,0.4,	Until:01:50,1,	Until:01:50,1,
Until:22:30,1,	Until:05:50,0.4,	Until:05:50,0.4,
Until:23:30,0.4,	Until:07:00,1,	Until:07:00,1,
Until:24:00,0,	Until:17:05,0,	Until:17:05,0,
For: Thursday,	Until:18:35,1,	Until:18:35,1,
Until:00:30,1,	Until:19:15,0.8,	Until:19:15,0.8,
Until:05:30,0.4,	Until:22:45,1,	Until:22:45,1,
Until:07:00,1,	Until:24:00,1,	Until:24:00,0.4,
Until:17:00,0,	**For:Friday,**	**For:Friday,**
Until:18:30,1,	Until:05:15,0.4,	Until:05:15,0.4,
Until:19:00,0.8,	Until:05:25,0.3,	Until:05:25,0.3,
Until:19:30,1,	Until:15:45,0,	Until:15:45,0,
Until:20:30,0.4,	Until:17:35,1,	Until:17:35,1,
Until:21:30,1,	Until:18:30,0.8,	Until:18:30,0.8,
Until:24:00,0,	Until:21:55,1,	Until:21:55,1,
For: Friday,	Until:22:15,0.9,	Until:22:15,0.9,
Until:04:00,0.3,	Until:24:00,1,	Until:24:00,1,
Until:05:00,0.4,	**For:Saturday,**	**For:Saturday,**
Until:05:30,1,	Until:00:15,1,	Until:00:15,1,
Until:15:30,0,	Until:05:50,0.3,	Until:05:50,0.3,
Until:17:30,1,	Until:06:10,0.9,	Until:06:10,0.9,
Until:18:00,0.8,	Until:06:40,1,	Until:06:40,1,
Until:18:30,0.4,	Until:07:00,0.8,	Until:07:00,0.8,
Until:20:00,1,	Until:17:05,0,	Until:17:05,0,
Until:20:30,0.4,	Until:17:35,1,	Until:17:35,1,
Until:21:30,1,	Until:18:30,0.7,	Until:18:30,0.7,
Until:22:00,0.9,	Until:23:50,1,	Until:23:50,1,
Until:23:00,1,	Until:24:00,1,	Until:24:00,0.4,
Until:24:00,0,	**For:Sunday,**	**For:Sunday,**
For: Saturday,	Until:05:50,0.4,	Until:05:50,0.4,
Until:05:30,0.3,	Until:06:20,0.8,	Until:06:20,0.8,
Until:06:30,1,	Until:07:00,1,	Until:07:00,1,
Until:07:00,0.8,	Until:17:05,0,	Until:17:05,0,
Until:17:00,0,	Until:24:00,1,	Until:24:00,1,
Until:17:30,1,	**For:Monday,**	**For:Monday,**
Until:19:30,1,	Until:05:50,0.3,	Until:05:50,0.3,
Until:20:30,0.4,	Until:07:00,1,	Until:07:00,1,
Until:22:30,1,	Until:17:05,0,	Until:17:05,0,

45 Minutes	1 Hour	2 Hours
Until:24:00,0,	Until:20:10,1,	Until:20:10,1,
For: Sunday,	Until:22:10,0.9,	Until:22:10,0.9,
Until:05:30,0.4,	Until:24:00,1,	Until:24:00,0.3,
Until:06:00,0.8,	**For:Tuesday,**	**For:Tuesday,**
Until:07:00,1,	Until:00:05,0.3,	Until:00:05,0.3,
Until:17:00,0,	Until:01:05,1,	Until:01:05,1,
Until:18:00,1,	Until:02:05,0.9,	Until:02:05,0.9,
Until:19:00,0.4,	Until:04:15,0.3,	Until:04:15,0.3,
Until:23:00,1,	Until:05:50,0.4,	Until:05:50,0.4,
Until:24:00,0,	Until:07:00,1,	Until:07:00,1,
For: Monday,	Until:17:05,0,	Until:17:05,0,
Until:05:30,0.3,	Until:18:20,1,	Until:18:20,1,
Until:07:00,1,	Until:19:20,0.9,	Until:19:20,0.9,
Until:17:00,0,	Until:24:00,1,	Until:24:00,1,
Until:19:30,1,	**For: AllOtherDays,**	**For: AllOtherDays,**
Until:20:00,0.3,	Until: 24:00, 0;	Until: 24:00, 0;
Until:20:30,0.9,		
Until:24:00,0,		
For: Tuesday,		
Until:00:00,0.3,		
Until:00:30,1,		
Until:05:30,0.4,		
Until:07:00,1,		
Until:17:00,0,		
Until:18:00,1,		
Until:19:00,0.9,		
Until:24:00,0,		
For: Holidays,		
Until: 24:00, 0,		
For:SummerDesignDay AllOtherDays,		
Until: 24:00, 0;		
Temperature Schedules		
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,
Terminal_Check_Heat,	Terminal_Check_Heat,	Terminal_Check_Heat,
Temperature,	Temperature,	Temperature,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For: Wednesday WinterDesignDay,	**For: Wednesday WinterDesignDay,**	**For: Wednesday WinterDesignDay,**
Until:07:00,0.9,	Until:07:10,0.9,	Until:07:10,0.9,

45 Minutes	**1 Hour**	**2 Hours**
Until:07:30,0.9,	Until:07:50,0.7,	Until:07:50,0.7,
Until:08:30,0.9,	Until:08:55,0.9,	Until:08:55,0.9,
Until:09:30,0.9,	Until:09:30,0.8,	Until:09:30,0.8,
Until:10:00,0.9,	Until:11:15,0.9,	Until:13:05,0.9,
Until:11:30,0.9,	Until:13:05,0.9,	Until:13:20,0.7,
Until:13:00,0.9,	Until:13:20,0.7,	Until:16:15,1,
Until:14:30,0.7,	Until:16:15,1,	Until:17:10,0.9,
Until:15:30,1,	Until:17:10,0.9,	Until:18:30,0.8,
Until:16:30,0.7,	Until:18:30,0.8,	Until:24:00,0.6,
Until:17:00,0.7,	Until:24:00,0.6,	**For:Thursday,**
Until:18:00,0.9,	**For: Thursday,**	Until:01:50,0.9,
Until:18:30,0.7,	Until:01:50,0.9,	Until:05:50,0.6,
Until:21:00,0.9,	Until:03:15,0.6,	Until:12:15,0.9,
Until:21:30,0.9,	Until:05:50,0.6,	Until:12:30,1,
Until:22:30,0.9,	Until:09:15,0.9,	Until:13:00,0.8,
Until:23:30,0.9,	Until:12:15,0.9,	Until:16:15,1,
Until:24:00,0.6,	Until:12:30,1,	Until:22:45,0.9,
For: Thursday,	Until:13:00,0.8,	Until:24:00,0.6,
Until:00:30,0.6,	Until:13:15,1,	**For:Friday,**
Until:05:30,0.6,	Until:14:15,1,	Until:05:25,0.6,
Until:08:30,0.9,	Until:16:15,1,	Until:08:40,0.9,
Until:09:00,0.9,	Until:18:35,0.9,	Until:09:05,0.8,
Until:11:30,0.9,	Until:19:15,0.9,	Until:09:25,0.9,
Until:12:30,0.9,	Until:21:15,0.9,	Until:09:55,0.8,
Until:13:00,0.9,	Until:22:15,0.9,	Until:12:15,0.9,
Until:16:00,1,	Until:22:45,0.9,	Until:13:20,1,
Until:16:30,1,	Until:24:00,0.6,	Until:13:35,0.8,
Until:17:00,1,	**For:Friday,**	Until:14:50,1,
Until:18:30,0.7,	Until:04:15,0.6,	Until:15:35,0.8,
Until:19:00,0.9,	Until:05:15,0.6,	Until:17:35,0.9,
Until:19:30,0.9,	Until:05:25,0.6,	Until:18:30,0.8,
Until:20:30,0.9,	Until:08:40,0.9,	Until:24:00,0.6,
Until:21:30,0.7,	Until:09:05,0.8,	**For:Saturday,**
Until:24:00,0.6,	Until:09:25,0.9,	Until:00:15,0.9,
For: Friday,	Until:09:55,0.8,	Until:05:50,0.6,
Until:05:00,0.6,	Until:10:15,0.9,	Until:06:40,0.9,
Until:08:00,0.9,	Until:11:05,0.9,	Until:07:10,0.7,
Until:08:30,0.9,	Until:11:45,0.9,	Until:13:15,0.9,
Until:09:30,0.9,	Until:12:15,0.9,	Until:17:35,1,
Until:12:00,0.9,	Until:13:20,1,	Until:18:30,0.8,

45 Minutes	**1 Hour**	**2 Hours**
Until:13:00,0.9,	Until:13:35,0.8,	Until:23:50,1,
Until:13:30,0.9,	Until:14:50,1,	Until:24:00,0.6,
Until:14:30,1,	Until:15:35,0.8,	**For:Sunday,**
Until:15:30,1,	Until:17:15,0.9,	Until:03:15,0.7,
Until:17:30,0.9,	Until:17:35,0.9,	Until:05:50,0.6,
Until:18:00,0.9,	Until:18:30,0.8,	Until:06:20,0.8,
Until:18:30,0.9,	Until:21:55,0.9,	Until:08:15,0.9,
Until:20:00,0.6,	Until:22:15,0.9,	Until:12:25,1,
Until:20:30,0.9,	Until:24:00,0.6,	Until:13:20,0.8,
Until:23:00,0.9,	**For:Saturday,**	Until:24:00,0.6,
Until:24:00,0.6,	Until:00:15,0.9,	**For:Monday,**
For: Saturday,	Until:05:50,0.6,	Until:00:35,1,
Until:05:30,0.6,	Until:06:10,0.9,	Until:03:15,0.7,
Until:06:30,0.6,	Until:06:40,0.9,	Until:05:50,0.8,
Until:07:00,0.6,	Until:07:10,0.7,	Until:07:15,1,
Until:08:30,0.8,	Until:10:55,0.9,	Until:07:50,0.8,
Until:09:00,0.9,	Until:11:05,0.9,	Until:08:50,1,
Until:11:30,0.9,	Until:12:15,0.9,	Until:09:50,0.9,
Until:12:00,0.9,	Until:13:20,1,	Until:13:00,1,
Until:12:30,0.9,	Until:17:35,1,	Until:13:20,0.8,
Until:13:00,0.9,	Until:18:30,0.8,	Until:13:45,1,
Until:17:30,1,	Until:20:15,1,	Until:14:20,0.8,
Until:18:30,1,	Until:23:50,1,	Until:20:10,1,
Until:19:30,0.8,	Until:24:00,0.6,	Until:22:10,0.9,
Until:20:30,1,	**For:Sunday,**	Until:24:00,0.6,
Until:22:30,1,	Until:02:15,0.7,	**For:Tuesday,**
Until:24:00,0.6,	Until:03:15,0.7,	Until:00:05,0.7,
For: Sunday,	Until:05:50,0.6,	Until:01:05,1,
Until:02:00,0.7,	Until:06:20,0.8,	Until:02:05,0.9,
Until:05:30,0.6,	Until:07:15,0.9,	Until:04:15,0.7,
Until:06:00,0.6,	Until:08:15,0.9,	Until:05:50,0.6,
Until:08:00,0.9,	Until:09:15,1,	Until:07:50,0.9,
Until:11:30,1,	Until:10:15,1,	Until:08:15,0.8,
Until:12:00,1,	Until:11:15,1,	Until:10:15,0.9,
Until:13:00,1,	Until:12:15,1,	Until:13:00,1,
Until:14:30,0.8,	Until:12:25,1,	Until:13:20,0.9,
Until:18:00,1,	Until:16:15,1,	Until:18:20,0.9,
Until:23:00,1,	Until:17:15,1,	Until:24:00,0.9,
Until:24:00,0.6,	Until:20:15,1,	**For: AllOtherDays,**
For: Monday,	Until:20:55,1,	Until: 24:00, 0;

45 Minutes	**1 Hour**	**2 Hours**
Until:03:00,0.7,	Until:21:55,1,	
Until:05:30,0.8,	Until:24:00,0.6,	
Until:07:00,0.8,	**For:Monday,**	
Until:07:30,1,	Until:00:35,1,	
Until:08:30,1,	Until:03:15,0.7,	
Until:09:30,1,	Until:05:50,0.8,	
Until:11:30,1,	Until:07:15,1,	
Until:13:00,1,	Until:07:50,0.8,	
Until:13:30,0.8,	Until:08:50,1,	
Until:14:00,0.8,	Until:09:50,0.9,	
Until:15:00,1,	Until:13:00,1,	
Until:15:30,0.8,	Until:13:20,0.8,	
Until:16:30,1,	Until:13:45,1,	
Until:17:00,0.8,	Until:14:20,0.8,	
Until:19:30,1,	Until:17:05,1,	
Until:20:00,1,	Until:17:15,1,	
Until:20:30,1,	Until:20:10,1,	
Until:24:00,0.6,	Until:22:10,0.9,	
For: Tuesday,	Until:24:00,0.6,	
Until:00:00,0.7,	**For:Tuesday,**	
Until:00:30,0.7,	Until:00:05,0.7,	
Until:04:00,0.7,	Until:01:05,1,	
Until:05:30,0.7,	Until:02:05,0.9,	
Until:07:00,0.6,	Until:04:15,0.7,	
Until:07:30,0.9,	Until:05:15,0.6,	
Until:08:00,0.9,	Until:05:50,0.6,	
Until:10:00,0.9,	Until:07:50,0.9,	
Until:11:30,0.9,	Until:08:15,0.8,	
Until:12:00,1,	Until:09:15,0.9,	
Until:12:30,1,	Until:10:15,0.9,	
Until:13:00,1,	Until:11:15,1,	
Until:15:00,1,	Until:13:00,1,	
Until:16:00,1,	Until:13:20,0.9,	
Until:18:00,0.9,	Until:15:15,1,	
Until:19:00,0.9,	Until:16:15,1,	
Until:20:00,0.8,	Until:17:15,0.9,	
Until:20:30,0.8,	Until:18:20,0.9,	
Until:22:00,0.6,	Until:22:15,0.9,	
Until:22:30,0.9,	Until:23:15,0.9,	
Until:24:00,0.9,	Until:24:00,0.9,	

45 Minutes	1 Hour	2 Hours
For: Holidays,	**For: AllOtherDays,**	
Until: 24:00, 0,	Until: 24:00, 0;	
For: AllOtherDays,		
Until: 24:00, 0;		
Ventilation Schedules		
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,
Terminal_Check_Equip,	Terminal_Check_Equip,	Terminal_Check_Equip,
Fraction,	Fraction,	Fraction,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For: Wednesday WinterDesignDay,	**For: Wednesday Winter-DesignDay,**	**For: Wednesday Winter-DesignDay**
Until:06:30,0.5,	Until:06:50,0.5,	Until:06:50,0.5,
Until:07:00,0.8,	Until:07:10,0.8,	Until:07:10,0.8,
Until:07:30,0.3,	Until:07:50,0.3,	Until:07:50,0.3,
Until:08:30,0.5,	Until:08:55,0.5,	Until:08:55,0.5,
Until:09:30,0.3,	Until:09:30,0.3,	Until:09:30,0.3,
Until:11:30,0.5,	Until:12:05,0.5,	Until:12:05,0.5,
Until:13:00,0.2,	Until:13:20,0.2,	Until:13:20,0.2,
Until:14:30,0.5,	Until:15:10,0.5,	Until:15:10,0.5,
Until:15:30,0.2,	Until:15:50,0.2,	Until:15:50,0.2,
Until:16:30,0.8,	Until:16:50,0.8,	Until:16:50,0.8,
Until:17:00,0.2,	Until:17:10,0.2,	Until:17:10,0.2,
Until:18:00,0.3,	Until:18:30,0.3,	Until:18:30,0.3,
Until:18:30,0.2,	Until:20:20,0.8,	Until:20:20,0.8,
Until:20:00,0.8,	Until:21:20,1,	Until:21:20,1,
Until:21:00,1,	Until:21:50,0.2,	Until:21:50,0.2,
Until:21:30,0.2,	Until:22:50,0.7,	Until:22:50,0.7,
Until:22:30,0.7,	Until:23:50,0.2,	Until:23:50,0.2,
Until:23:30,0.2,	Until:24:00,0.2,	Until:24:00,0.2,
Until: 24:00,0.2,	**for:Thursday,**	**for:Thursday,**
For: Thursday,	Until:00:50,0.5,	Until:00:50,0.5,
Until:00:30,0.5,	Until:05:50,0.2,	Until:05:50,0.2,
Until:05:30,0.2,	Until:06:10,0.5,	Until:06:10,0.5,
Until:06:00,0.5,	Until:06:55,0.4,	Until:06:55,0.4,
Until:06:30,0.4,	Until:07:40,0.8,	Until:07:40,0.8,
Until:08:30,0.8,	Until:07:50,0.9,	Until:08:50,0.8,
Until:09:00,0.2,	Until:08:50,0.8,	Until:09:00,0.2,
Until:09:30,0.7,	Until:09:00,0.2,	Until:09:55,0.7,
Until:10:00,0.5,	Until:09:55,0.7,	Until:10:15,0.5,
Until:10:30,0.4,	Until:10:15,0.5,	Until:10:55,0.4,

45 Minutes	**1 Hour**	**2 Hours**
Until:11:30,0.7,	Until:10:55,0.4,	Until:11:55,0.7,
Until:12:30,0.2,	Until:11:55,0.7,	Until:12:30,0.2,
Until:13:00,0.3,	Until:12:30,0.2,	Until:13:00,0.3,
Until:13:30,0.8,	Until:13:00,0.3,	Until:13:50,0.8,
Until:16:30,0.4,	Until:13:50,0.8,	Until:16:45,0.4,
Until:17:00,0.2,	Until:16:45,0.4,	Until:17:10,0.2,
Until:17:30,0.4,	Until:17:10,0.2,	Until:17:35,0.4,
Until:18:30,1,	Until:17:35,0.4,	Until:17:50,0.8,
Until:19:00,0.3,	Until:17:50,0.8,	Until:18:35,1,
Until:19:30,0.8,	Until:18:35,1,	Until:19:15,0.3,
Until:20:30,0.2,	Until:19:15,0.3,	Until:20:15,0.8,
Until:21:30,0.5,	Until:20:15,0.8,	Until:20:45,0.2,
Until: 24:00,0.2,	Until:20:45,0.2,	Until:21:45,0.5,
For: Friday,	Until:21:45,0.5,	Until:24:00,0.2,
Until:05:00,0.2,	Until:24:00,0.2,	**for:Friday,**
Until:06:00,0.8,	**for:Friday,**	Until:05:25,0.2,
Until:06:30,0.9,	Until:05:25,0.2,	Until:06:20,0.8,
Until:07:30,1,	Until:06:20,0.8,	Until:06:55,0.9,
Until:08:30,0.9,	Until:06:55,0.9,	Until:07:35,1,
Until:09:30,0.3,	Until:07:35,1,	Until:07:50,0.5,
Until:10:00,0.6,	Until:07:50,0.5,	Until:08:40,0.9,
Until:11:00,0.7,	Until:08:40,0.9,	Until:09:05,0.3,
Until:11:30,0.3,	Until:09:05,0.3,	Until:09:25,0.4,
Until:12:30,0.7,	Until:09:25,0.4,	Until:09:55,0.3,
Until:13:00,0.5,	Until:09:55,0.3,	Until:10:15,0.6,
Until:13:30,0.3,	Until:10:15,0.6,	Until:11:05,0.7,
Until:14:30,0.7,	Until:11:05,0.7,	Until:11:45,0.3,
Until:15:30,0.3,	Until:11:45,0.3,	Until:12:45,0.7,
Until:16:30,0.5,	Until:12:45,0.7,	Until:12:55,0.2,
Until:17:30,0.8,	Until:12:55,0.2,	Until:13:20,0.5,
Until:18:00,0.3,	Until:13:20,0.5,	Until:13:35,0.3,
Until:18:30,0.2,	Until:13:35,0.3,	Until:13:55,0.5,
Until:20:00,0.6,	Until:13:55,0.5,	Until:14:50,0.7,
Until:20:30,0.2,	Until:14:50,0.7,	Until:15:35,0.3,
Until:21:30,0.8,	Until:15:35,0.3,	Until:16:50,0.5,
Until:22:00,0.3,	Until:16:50,0.5,	Until:17:35,0.8,
Until:23:00,0.6,	Until:17:35,0.8,	Until:18:30,0.3,
Until: 24:00,0.2,	Until:18:30,0.3,	Until:19:00,0.5,
For: Saturday,	Until:19:00,0.5,	Until:19:20,0.4,
Until:05:30,0.2,	Until:19:20,0.4,	Until:20:20,0.5,

45 Minutes	**1 Hour**	**2 Hours**
Until:06:00,0.3,	Until:20:20,0.5,	Until:20:50,0.2,
Until:06:30,0.9,	Until:20:50,0.2,	Until:21:55,0.8,
Until:07:00,0.3,	Until:21:55,0.8,	Until:22:15,0.3,
Until:08:30,0.7,	Until:22:15,0.3,	Until:23:15,0.6,
Until:09:00,0.2,	Until:23:15,0.6,	Until:24:00,0.2,
Until:09:30,0.9,	Until:24:00,0.2,	**for:Saturday,**
Until:10:00,0.7,	**For:Saturday,**	Until:05:50,0.2,
Until:10:30,0.8,	Until:05:50,0.2,	Until:06:10,0.3,
Until:11:00,0.3,	Until:06:10,0.3,	Until:06:35,0.9,
Until:11:30,1,	Until:06:35,0.9,	Until:06:40,1,
Until:12:30,0.2,	Until:06:40,1,	Until:07:10,0.3,
Until:13:00,0.5,	Until:07:10,0.3,	Until:07:50,0.7,
Until:13:30,0.7,	Until:07:50,0.7,	Until:09:05,0.7,
Until:14:30,0.8,	Until:09:05,0.7,	Until:09:55,0.9,
Until:15:30,0.4,	Until:09:55,0.9,	Until:10:15,0.7,
Until:16:00,0.5,	Until:10:15,0.7,	Until:10:55,0.8,
Until:16:30,0.4,	Until:10:55,0.8,	Until:11:05,0.3,
Until:17:30,0.6,	Until:11:05,0.3,	Until:12:05,1,
Until:18:30,0.3,	Until:12:05,1,	Until:12:40,0.2,
Until:19:00,0.5,	Until:12:40,0.2,	Until:13:00,0.5,
Until:19:30,0.9,	Until:13:00,0.5,	Until:13:20,0.6,
Until:20:30,0.2,	Until:13:20,0.6,	Until:13:50,0.7,
Until:21:30,0.8,	Until:13:50,0.7,	Until:14:35,0.8,
Until:22:30,0.5,	Until:14:35,0.8,	Until:15:35,0.4,
Until: 24:00,0.2,	Until:15:35,0.4,	Until:16:05,0.5,
For: Sunday,	Until:16:05,0.5,	Until:16:15,0.2,
Until:05:30,0.2,	Until:16:15,0.2,	Until:16:45,0.4,
Until:06:00,0.3,	Until:16:45,0.4,	Until:17:35,0.6,
Until:06:30,0.8,	Until:17:35,0.6,	Until:18:30,0.3,
Until:07:00,0.6,	Until:18:30,0.3,	Until:19:00,0.5,
Until:07:30,0.5,	Until:19:00,0.5,	Until:20:00,0.9,
Until:08:30,0.4,	Until:20:00,0.9,	Until:20:50,0.2,
Until:09:00,0.5,	Until:20:50,0.2,	Until:21:50,0.8,
Until:10:30,0.5,	Until:22:50,0.5,	Until:24:00,0.2,
Until:11:00,0.7,	Until:24:00,0.2,	**for:Sunday,**
Until:11:30,0.8,	**for:Sunday,**	Until:05:50,0.2,
Until:12:00,0.2,	Until:05:50,0.2,	Until:06:20,0.3,
Until:13:00,0.3,	Until:06:20,0.3,	Until:06:40,0.8,
Until:14:00,0.4,	Until:06:40,0.8,	Until:06:45,0.4,
Until:14:30,0.5,	Until:06:45,0.4,	Until:07:50,0.5,

45 Minutes	1 Hour	2 Hours
Until:15:30,0.2,	Until:07:50,0.5,	Until:08:35,0.4,
Until:18:00,0.5,	Until:08:35,0.4,	Until:09:10,0.5,
Until:19:00,0.2,	Until:09:10,0.5,	Until:09:30,1,
Until:20:30,0.5,	Until:09:30,1,	Until:10:35,0.5,
Until:21:30,0.8,	Until:10:35,0.5,	Until:11:00,0.7,
Until:22:30,0.5,	Until:11:00,0.7,	Until:12:00,0.8,
Until:23:00,0.9,	Until:12:00,0.8,	Until:12:25,0.2,
Until: 24:00,0.2,	Until:12:25,0.2,	Until:13:20,0.3,
For: Monday,	Until:13:20,0.3,	Until:14:10,0.4,
Until:05:30,0.2,	Until:14:10,0.4,	Until:15:10,0.5,
Until:07:00,0.8,	Until:15:10,0.5,	Until:15:35,0.2,
Until:07:30,0.3,	Until:15:35,0.2,	Until:18:30,0.5,
Until:08:30,0.5,	Until:18:30,0.5,	Until:19:20,0.2,
Until:09:30,0.3,	Until:19:20,0.2,	Until:20:55,0.5,
Until:11:00,0.5,	Until:20:55,0.5,	Until:21:55,0.8,
Until:11:30,0.7,	Until:21:55,0.8,	Until:22:35,0.5,
Until:13:00,0.2,	Until:22:35,0.5,	Until:23:35,0.9,
Until:13:30,0.5,	Until:23:35,0.9,	Until:24:00,0.2,
Until:14:00,0.3,	Until:24:00,0.2,	**for:Monday,**
Until:15:00,0.5,	**for:Monday,**	Until:05:50,0.2,
Until:15:30,0.2,	Until:05:50,0.2,	Until:07:15,0.8,
Until:16:30,0.5,	Until:07:15,0.8,	Until:07:50,0.3,
Until:17:00,0.2,	Until:07:50,0.3,	Until:08:50,0.5,
Until:18:30,0.5,	Until:08:50,0.5,	Until:09:50,0.3,
Until:19:30,0.6,	Until:09:50,0.3,	Until:11:00,0.5,
Until:20:00,0.2,	Until:11:00,0.5,	Until:12:00,0.7,
Until:20:30,0.3,	Until:12:00,0.7,	Until:13:20,0.2,
Until:24:00,0.2,	Until:13:20,0.2,	Until:13:45,0.5,
For: Tuesday,	Until:13:45,0.5,	Until:14:20,0.3,
Until:00:30,0.8,	Until:14:20,0.3,	Until:15:20,0.5,
Until:05:30,0.2,	Until:15:20,0.5,	Until:15:50,0.2,
Until:06:30,0.8,	Until:15:50,0.2,	Until:16:45,0.5,
Until:07:30,0.2,	Until:17:05,0.2,	Until:17:30,0.5,
Until:08:00,0.3,	Until:17:30,0.5,	Until:17:55,0.8,
Until:08:30,1,	Until:17:55,0.8,	Until:18:40,0.5,
Until:10:00,0.5,	Until:18:40,0.5,	Until:19:55,0.6,
Until:11:30,0.8,	Until:19:55,0.6,	Until:20:10,0.2,
Until:12:00,0.2,	Until:20:10,0.2,	Until:21:10,0.3,
Until:12:30,0.5,	Until:21:10,0.3,	Until:24:00,0.2,
Until:13:00,0.2,	Until:24:00,0.2,	**for:Tuesday,**

45 Minutes	1 Hour	2 Hours
Until:13:30,0.5,	**for:Tuesday,**	Until:00:05,0.2,
Until:14:30,0.7,	Until:00:05,0.2,	Until:01:05,0.8,
Until:15:30,0.5,	Until:01:05,0.8,	Until:05:50,0.2,
Until:16:30,0.8,	Until:05:50,0.2,	Until:06:40,0.8,
Until:17:30,0.5,	Until:06:40,0.8,	Until:07:40,0.5,
Until:18:00,0.7,	Until:07:40,0.5,	Until:07:50,0.2,
Until:19:00,0.3,	Until:08:15,0.3,	Until:08:15,0.3,
Until:20:00,0.8,	Until:08:50,1,	Until:08:50,1,
Until:20:30,0.2,	Until:10:20,0.5,	Until:10:20,0.5,
Until:21:30,0.5,	Until:12:05,0.8,	Until:12:05,0.8,
Until:22:00,0.2,	Until:13:00,0.5,	Until:13:00,0.5,
Until:22:30,0.7,	Until:13:20,0.3,	Until:13:20,0.3,
Until:24:00,0.2,	Until:13:55,0.5,	Until:13:55,0.5,
For: Holidays,	Until:14:55,0.7,	Until:14:55,0.7,
Until: 24:00, 0,	Until:15:45,0.5,	Until:15:45,0.5,
For: SummerDesignDay AllOtherDays,	Until:16:50,0.8,	Until:16:50,0.8,
Until: 24:00, 0;	Until:17:30,0.5,	Until:17:30,0.5,
	Until:18:20,0.7,	Until:18:20,0.7,
	Until:19:20,0.3,	Until:19:20,0.3,
	Until:20:20,0.8,	Until:20:20,0.8,
	Until:20:55,0.2,	Until:20:55,0.2,
	Until:22:00,0.5,	Until:22:00,0.5,
	Until:23:00,0.7,	Until:23:00,0.7,
	Until:24:00,0.2,	Until:24:00,0.2,
	For: AllOtherDays,	**For: AllOtherDays,**
	Until: 24:00, 0;	Until: 24:00, 0;
Base Case Summer		
Occupancy Profile & Gain Schedules		
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,
On,	On,	On,
Fraction,	Fraction,	Fraction,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For: AllDays,	For: AllDays,	For: AllDays,
Until: 24:00, 1,;	Until: 24:00, 1 ,	Until: 24:00, 1,;
For: WinterDesignDay AllOtherDays,	**For: WinterDesignDay AllOtherDays,**	**For: WinterDesignDay AllOtherDays,**
Until: 24:00,0;	Until: 24:00,0;	Until: 24:00,0;
Test Case Summer		
Occupancy Profile Schedules		
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,

45 Minutes	1 Hour	2 Hours
Terminal_Check_Occ,	Terminal_Check_Occ,	Terminal_Check_Occ,
Fraction,	Fraction,	Fraction,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For:Thursday SummerDesignDay,	**For:Thursday SummerDesignDay,**	**For:Thursday SummerDesignDay,**
Until:05:55,0,	Until:05:55,0,	Until:05:55,0,
Until:06:20,0.6,	Until:06:20,0.6,	Until:06:20,0.6,
Until:07:05,1,	Until:07:05,1,	Until:07:05,1,
Until:07:55,0.3,	Until:07:55,0.3,	Until:07:55,0.3,
Until:08:40,0.7,	Until:08:40,0.7,	Until:08:40,0.7,
Until:09:20,0.6,	Until:09:20,0.6,	Until:09:20,0.6,
Until:09:55,0.4,	Until:09:55,0.4,	Until:09:55,0.4,
Until:10:25,0.7,	Until:10:25,0.7,	Until:10:25,0.7,
Until:10:55,0.4,	Until:10:55,0.4,	Until:10:55,0.4,
Until:11:55,0,	Until:11:55,1,	Until:11:55,1,
Until:12:25,0.5,	Until:12:25,0.5,	Until:12:25,0.5,
Until:12:40,0.3,	Until:12:55,0.3,	Until:13:40,0.3,
Until:13:40,0,	Until:13:40,0,	Until:14:50,0.8,
Until:14:00,0.8,	Until:14:50,0.8,	Until:15:20,0.3,
Until:14:45,0.8,	Until:15:20,0.3,	Until:15:50,0.9,
Until:14:50,0,	Until:15:50,0.9,	Until:16:20,0.5,
Until:15:20,0.3,	Until:16:20,0.5,	Until:16:50,0.4,
Until:15:50,0.9,	Until:16:50,0.4,	Until:18:20,1,
Until:16:20,0.5,	Until:17:50,0,	Until:19:30,0.8,
Until:16:35,0.4,	Until:18:20,1,	Until:20:10,0.3,
Until:17:50,0,	Until:18:50,0.8,	Until:20:40,0.4,
Until:18:20,1,	Until:19:00,0,	Until:22:40,0.5,
Until:18:35,0.8,	Until:19:30,0.8,	Until:24:00,0,
Until:19:00,0,	Until:20:00,0.3,	**For:Friday,**
Until:19:30,0.8,	Until:20:10,0,	Until:05:55,0,
Until:19:45,0.3,	Until:20:40,0.4,	Until:06:20,0.6,
Until:20:10,0,	Until:21:10,0.5,	Until:07:05,1,
Until:20:40,0.4,	Until:21:40,0.4,	Until:07:55,0.3,
Until:21:10,0.5,	Until:24:00,0,	Until:08:40,0.7,
Until:21:25,0.4,	**For: Friday,**	Until:09:20,0.6,
Until:24:00,0,	Until:05:55,0,	Until:09:55,0.4,
For: Friday,	Until:06:20,0.6,	Until:10:25,0.7,
Until:05:55,0,	Until:07:05,1,	Until:10:55,0.4,
Until:06:20,0.6,	Until:07:55,0.3,	Until:11:55,1,
Until:07:05,1,	Until:08:40,0.7,	Until:13:00,0.8,
Until:07:55,0.3,	Until:09:20,0.6,	Until:13:50,0.7,

45 Minutes	1 Hour	2 Hours
Until:08:40,0.7,	Until:09:55,0.4,	Until:15:25,0.3,
Until:09:20,0.6,	Until:10:25,0.7,	Until:16:10,1,
Until:09:55,0.4,	Until:10:55,0.4,	Until:17:10,0.7,
Until:10:25,0.7,	Until:11:55,1,	Until:18:10,0.5,
Until:10:55,0.4,	Until:13:00,0.8,	Until:18:35,0,
Until:11:50,1,	Until:13:50,0.7,	Until:18:50,0.4,
Until:11:55,0,	Until:14:45,0.3,	Until:20:20,0.6,
Until:13:00,0.8,	Until:15:25,0.3,	Until:21:55,0.7,
Until:13:45,0.7,	Until:16:10,1,	Until:23:55,0.8,
Until:13:50,0,	Until:17:10,0.7,	Until:24:00,0,
Until:14:45,0.3,	Until:18:35,0,	**For:Saturday,**
Until:15:25,0.3,	Until:18:50,0.4,	Until:05:55,0,
Until:16:10,1,	Until:19:50,0.6,	Until:07:10,0.7,
Until:16:55,0.7,	Until:20:20,0,	Until:08:10,1,
Until:18:35,0,	Until:21:55,0.7,	Until:09:20,0.6,
Until:18:50,0.4,	Until:22:55,0.8,	Until:10:25,0.9,
Until:19:35,0.6,	Until:24:00,0,	Until:11:55,1,
Until:20:20,0,	**For: Saturday,**	Until:13:00,0.3,
Until:21:25,0.7,	Until:05:55,0,	Until:14:00,0.4,
Until:21:55,0,	Until:07:10,0.7,	Until:14:50,0.8,
Until:22:40,0.8,	Until:08:10,1,	Until:15:50,0.9,
Until:24:00,0,	Until:09:20,0.6,	Until:17:15,1,
For: Saturday,	Until:11:55,1,	Until:18:15,0.8,
Until:05:55,0,	Until:14:00,0.4,	Until:18:35,0,
Until:07:10,0.7,	Until:14:50,0.8,	Until:20:05,0.6,
Until:08:10,1,	Until:15:50,0.9,	Until:20:40,0.8,
Until:09:20,0.6,	Until:17:15,1,	Until:21:20,0.7,
Until:11:55,1,	Until:18:35,0,	Until:21:55,1,
Until:12:45,0.3,	Until:20:05,0.6,	Until:22:30,0.5,
Until:13:00,0,	Until:20:30,0.8,	Until:23:20,0.4,
Until:14:00,0.4,	Until:20:40,0,	Until:24:00,1,
Until:14:45,0.8,	Until:21:55,1,	**For:Sunday,**
Until:14:50,0,	Until:22:30,0.5,	Until:01:20,1,
Until:15:50,0.9,	Until:23:20,0.4,	Until:05:55,0,
Until:17:00,1,	Until:24:00,0,	Until:07:30,0.7,
Until:18:35,0,	**For: Sunday,**	Until:08:55,0.9,
Until:20:05,0.6,	Until:00:20,1,	Until:09:55,0.3,
Until:20:15,0.8,	Until:05:55,0,	Until:10:55,0.6,
Until:20:40,0,	Until:07:30,0.7,	Until:11:50,0.7,
Until:21:20,0.7,	Until:08:55,0.9,	Until:13:00,1,

45 Minutes	**1 Hour**	**2 Hours**
Until:21:55,1,	Until:09:55,0.3,	Until:14:35,0.4,
Until:22:30,0.5,	Until:10:55,0.6,	Until:19:25,0.6,
Until:23:15,0.4,	Until:11:50,0.7,	Until:23:10,0.8,
Until:23:20,0,	Until:13:00,1,	Until:24:00,1,
Until:24:00,0,	Until:14:35,0.4,	**For:Monday,**
For: Sunday,	Until:19:25,0.6,	Until:00:10,1,
Until:00:05,1,	Until:23:10,0.8,	Until:01:25,0.8,
Until:05:55,0,	Until:24:00,0,	Until:02:25,1,
Until:07:30,0.7,	**For: Monday,**	Until:05:15,0,
Until:08:55,0.9,	Until:00:10,1,	Until:05:55,0.6,
Until:09:55,0.3,	Until:00:25,0,	Until:07:15,0.3,
Until:10:55,0.6,	Until:01:25,0.8,	Until:08:50,0.6,
Until:11:50,0.7,	Until:05:15,0,	Until:10:15,0.3,
Until:12:40,1,	Until:05:55,0.6,	Until:11:45,0.6,
Until:12:55,0,	Until:06:25,0.3,	Until:13:05,0.3,
Until:13:00,1,	Until:07:15,0.3,	Until:14:00,0.6,
Until:14:35,0.4,	Until:07:55,0.6,	Until:14:50,0.2,
Until:17:15,0.6,	Until:08:50,0.6,	Until:16:30,0.8,
Until:17:30,0,	Until:09:20,0.3,	Until:17:00,0.3,
Until:19:25,0.6,	Until:10:15,0.3,	Until:18:00,0.2,
Until:20:10,0.8,	Until:10:55,0.6,	Until:18:55,0.4,
Until:20:25,0,	Until:11:45,0.6,	Until:19:55,0.5,
Until:21:25,0.8,	Until:12:15,0.3,	Until:20:55,0.2,
Until:21:35,0,	Until:13:05,0.3,	Until:21:25,0.6,
Until:23:10,0.8,	Until:14:00,0.6,	Until:22:45,0.3,
Until:23:55,1,	Until:14:50,0.2,	Until:23:20,0.6,
Until:24:00,0,	Until:16:30,0.8,	Until:24:00,0.3,
For: Monday,	Until:17:00,0.3,	**For:Tuesday,**
Until:00:25,0,	Until:18:00,0.2,	Until:01:25,0.3,
Until:01:10,0.8,	Until:18:40,0,	Until:01:30,0.6,
Until:05:15,0,	Until:18:55,0.4,	Until:02:25,0.3,
Until:05:55,0.6,	Until:19:55,0.5,	Until:05:55,0,
Until:06:25,0.3,	Until:20:50,0,	Until:06:50,0.6,
Until:07:15,0.3,	Until:21:25,0.6,	Until:07:40,0.2,
Until:07:55,0.6,	Until:21:55,0.3,	Until:09:20,0.8,
Until:08:50,0.6,	Until:22:45,0.3,	Until:09:50,0.3,
Until:09:20,0.3,	Until:23:20,0.6,	Until:10:55,0.2,
Until:10:15,0.3,	Until:23:50,0.3,	Until:11:25,0.3,
Until:10:55,0.6,	Until:24:00,0,	Until:11:55,0.2,
Until:11:40,0.6,	**For: Tuesday,**	Until:14:00,0.8,

45 Minutes	1 Hour	2 Hours
Until:11:55,0,	Until:00:15,0.3,	Until:14:50,0.5,
Until:12:15,0.3,	Until:00:25,0,	Until:15:45,0.3,
Until:13:05,0.3,	Until:01:25,0.3,	Until:16:45,0.6,
Until:13:15,0.6,	Until:05:55,0,	Until:17:45,0.8,
Until:13:20,0,	Until:06:50,0.6,	Until:18:50,0,
Until:14:00,0.6,	Until:07:40,0.2,	Until:19:50,0.3,
Until:14:50,0.2,	Until:09:20,0.8,	Until:20:50,0.7,
Until:16:30,0.8,	Until:09:50,0.3,	Until:21:50,0.8,
Until:17:00,0.3,	Until:10:55,0.2,	Until:23:00,0,
Until:17:45,0.2,	Until:11:25,0.3,	Until:23:35,0.5,
Until:18:40,0,	Until:11:55,0.2,	Until:24:00,0.7,
Until:18:55,0.4,	Until:12:55,0.8,	**For:Wednesday,**
Until:19:40,0.5,	Until:13:25,0,	Until:00:35,0.7,
Until:20:50,0,	Until:14:00,0.8,	Until:01:35,0.8,
Until:21:25,0.6,	Until:14:50,0.5,	Until:05:55,0,
Until:21:55,0.3,	Until:15:45,0.3,	Until:06:40,0.3,
Until:22:45,0.3,	Until:16:45,0.6,	Until:07:25,0.5,
Until:23:20,0.6,	Until:18:50,0,	Until:08:10,0.7,
Until:23:50,0.3,	Until:19:50,0.3,	Until:08:55,0.3,
Until:24:00,0.3,	Until:20:50,0.7,	Until:09:40,0.5,
For: Tuesday,	Until:23:00,0,	Until:10:25,0.7,
Until:00:25,0,	Until:23:35,0.5,	Until:11:10,0.3,
Until:01:10,0.3,	Until:24:00,0,	Until:11:55,0.5,
Until:05:55,0,	**For: Wednesday,**	Until:12:55,0.7,
Until:06:50,0.6,	Until:00:35,0.7,	Until:13:40,0.3,
Until:07:40,0.2,	Until:05:55,0,	Until:14:25,0.5,
Until:09:20,0.8,	Until:06:40,0.3,	Until:14:50,0.7,
Until:09:50,0.3,	Until:07:25,0.5,	Until:15:35,0.3,
Until:10:00,0.2,	Until:08:10,0.7,	Until:16:20,0.5,
Until:10:15,0,	Until:08:55,0.3,	Until:16:40,0.7,
Until:10:55,0.2,	Until:09:40,0.5,	Until:17:40,0.8,
Until:11:25,0.3,	Until:10:25,0.7,	Until:18:35,0,
Until:11:55,0.2,	Until:11:10,0.3,	Until:19:15,0.3,
Until:12:40,0.8,	Until:11:55,0.5,	Until:20:40,0.2,
Until:13:25,0,	Until:12:55,0.7,	Until:22:00,0.3,
Until:14:00,0.8,	Until:13:40,0.3,	Until:24:00,0,
Until:14:45,0.5,	Until:14:25,0.5,	**For: WinterDesignDay Al-lOtherDays,**
Until:14:50,0,	Until:14:50,0.7,	Until: 24:00,0;
Until:15:45,0.3,	Until:15:35,0.3,	
Until:16:30,0.6,	Until:16:20,0.5,	

45 Minutes	1 Hour	2 Hours
Until:18:50,0,	Until:16:40,0.7,	
Until:19:50,0.3,	Until:18:35,0,	
Until:20:35,0.7,	Until:20:15,0.2,	
Until:23:00,0,	Until:20:40,0,	
Until:23:35,0.5,	Until:21:40,0.3,	
Until:24:00,0,	Until:22:00,0,	
For: Wednesday,	Until:24:00,0,	
Until:00:20,0.7,	**For: WinterDesignDay Al-lOtherDays,**	
Until:05:55,0,	Until: 24:00,0;	
Until:06:40,0.3,		
Until:07:25,0.5,		
Until:08:10,0.7,		
Until:08:55,0.3,		
Until:09:05,0,		
Until:09:40,0.5,		
Until:10:05,0.7,		
Until:10:15,0,		
Until:10:25,0.7,		
Until:11:10,0.3,		
Until:11:40,0.5,		
Until:11:55,0,		
Until:12:40,0.7,		
Until:12:55,0,		
Until:13:40,0.3,		
Until:13:45,0.5,		
Until:14:00,0,		
Until:14:25,0.5,		
Until:14:50,0.7,		
Until:15:35,0.3,		
Until:16:20,0.5,		
Until:16:25,0.7,		
Until:18:35,0,		
Until:19:15,0.3,		
Until:20:00,0.2,		
Until:20:40,0,		
Until:21:25,0.3,		
Until:22:00,0,		
Until:24:00,0,		
For: Holidays,		

45 Minutes	1 Hour	2 Hours
Until: 24:00, 1,		
For: WinterDesignDay AllOtherDays,		
Until: 24:00,0;		
Lighting Schedules		
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,
Terminal_Check_Light,	Terminal_Check_Light,	Terminal_Check_Light,
Fraction,	Fraction,	Fraction,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For:Thursday SummerDesignDay,	**For:Thursday SummerDesignDay,**	**For:Thursday SummerDesignDay,**
Until:05:55,0.4,	Until:05:55,0.4,	Until:05:55,0.4,
Until:06:25,1,	Until:06:25,1,	Until:06:25,1,
Until:07:40,0.3,	Until:07:00,0.5,	Until:07:00,0.5,
Until:15:00,0,	Until:07:40,0.3,	Until:07:45,0,
Until:16:20,0.3,	Until:15:00,0,	Until:15:00,0,
Until:16:35,0.5,	Until:16:20,0.3,	Until:16:20,0.3,
Until:17:30,0.2,	Until:16:50,0.5,	Until:17:30,0.5,
Until:17:50,0.3,	Until:17:30,0.2,	Until:22:40,1,
Until:18:35,1,	Until:17:50,0.3,	Until:23:15,0.3,
Until:19:00,0.3,	Until:18:50,1,	**for:Friday,**
Until:19:45,1,	Until:19:00,0.3,	Until:05:55,0.4,
Until:20:10,0.3,	Until:20:00,1,	Until:06:25,1,
Until:21:25,1,	Until:20:10,0.3,	Until:07:00,0.5,
Until:23:15,0.3,	Until:21:40,1,	Until:07:45,0,
Until:24:00,0,	Until:23:15,0.3,	Until:13:20,0,
For: Friday,	Until:24:00,0.3,	Until:15:30,0.5,
Until:05:55,0.4,	**For:Friday,**	Until16:25,0,
Until:06:25,1,	Until:05:55,0.4,	Until:17:25,0.5,
Until:07:40,0.3,	Until:06:25,1,	Until:18:10,1,
Until:13:20,0,	Until:07:00,0.5,	Until:18:35,0.3,
Until:15:30,0.5,	Until:07:40,0.3,	Until:23:55,1,
Until:16:25,0,	Until:13:20,0,	**for:Saturday,**
Until:16:55,0.5,	Until:15:30,0.5,	Until:05:55,0.4,
Until:17:30,0.2,	Until:16:25,0,	Until:06:30,1,
Until:18:35,0.3,	Until:17:10,0.5,	Until:07:05,0.5,
Until:19:35,1,	Until:17:30,0.2,	Until:07:45,0.3,
Until:20:20,0.3,	Until:18:35,0.3,	Until:13:25,0,
Until:21:25,1,	Until:19:50,1,	Until:15:35,0.5,
Until:21:55,0.4,	Until:20:20,0.3,	Until:16:30,0,
Until:22:40,1,	Until:22:55,1,	Until:17:30,0.5,

45 Minutes	**1 Hour**	**2 Hours**
Until:24:00,0,	Until:24:00,0.3,	Until:18:15,1,
For: Saturday,	**For:Saturday,**	Until:18:35,0.3,
Until:05:55,0.4,	Until:05:55,0.4,	**for:Sunday,**
Until:06:30,1,	Until:06:30,1,	Until:01:20,1,
Until:07:05,0.5,	Until:07:05,0.5,	Until:05:55,0.3,
Until:07:45,0.3,	Until:07:45,0.3,	Until:06:30,1,
Until:13:25,0,	Until:13:25,0,	Until:07:05,0.5,
Until:15:35,0.5,	Until:15:35,0.5,	Until:07:45,0.3,
Until:16:30,0,	Until:16:30,0,	Until:13:25,0,
Until:17:00,0.5,	Until:17:15,0.5,	Until:15:35,0.5,
Until:17:30,0.2,	Until:17:30,0.2,	Until:16:30,0,
Until:18:35,0.3,	Until:18:35,0.3,	Until:17:00,0.5,
Until:20:15,1,	Until:20:30,1,	Until:17:30,0.5,
Until:20:40,0.3,	Until:20:40,0.3,	**for:Monday,**
Until:23:15,1,	Until:24:00,0.3,	Until:02:25,1,
Until:23:20,0.3,	**For: Sunday,**	Until:05:15,0.4,
Until:24:00,1,	Until:00:20,1,	Until:06:30,1,
For: Sunday,	Until:05:55,0.3,	Until:07:05,0.5,
Until:00:05,1,	Until:06:30,1,	Until:07:45,0.3,
Until:05:55,0.3,	Until:07:05,0.5,	Until:13:25,0,
Until:06:30,1,	Until:07:45,0.3,	Until:15:35,0.5,
Until:07:05,0.5,	Until:13:25,0,	Until:16:30,0,
Until:07:45,0.3,	Until:15:35,0.5,	Until:17:30,0.5,
Until:13:25,0,	Until:16:30,0,	**for:Tuesday,**
Until:15:35,0.5,	Until:17:30,0.5,	Until:02:25,1,
Until:16:30,0,	Until:24:00,0.3,	Until:05:55,0.4,
Until:17:15,0.5,	**For: Monday,**	Until:06:30,1,
Until:17:30,0.2,	Until:00:10,1,	Until:07:05,0.5,
Until:20:10,1,	Until:00:25,0.4,	Until:07:45,0.3,
Until:20:25,0.3,	Until:01:25,1,	Until:13:25,0,
Until:21:25,1,	Until:05:15,0.4,	Until:15:35,0.5,
Until:21:35,0.4,	Until:06:30,1,	Until:16:30,0,
Until:23:55,1,	Until:07:05,0.5,	Until:17:30,0.5,
Until:24:00,0.4,	Until:07:45,0.3,	Until:17:45,1,
For: Monday,	Until:13:25,0,	Until:18:50,0.3,
Until:00:25,0.4,	Until:15:35,0.5,	Until:21:50,1,
Until:01:10,1,	Until:16:30,0,	Until:23:00,0.3,
Until:05:15,0.4,	Until:17:30,0.5,	**For:Wednesday,**
Until:06:30,1,	Until:18:00,1,	Until:01:35,1,
Until:07:05,0.5,	Until:18:40,0.3,	Until:03:15,0.3,

45 Minutes	**1 Hour**	**2 Hours**
Until:07:45,0.3,	Until:19:55,1,	Until:05:55,0.4,
Until:13:25,0,	Until:20:50,0.3,	Until:06:30,1,
Until:15:35,0.5,	Until:24:00,0.3,	Until:07:05,0.5,
Until:16:30,0,	**For:Tuesday,**	Until:07:45,0.3,
Until:17:30,0.5,	Until:00:15,1,	Until:13:25,0,
Until:17:45,1,	Until:00:25,0.4,	Until:15:35,0.5,
Until:18:40,0.3,	Until:01:25,1,	Until:16:30,0,
Until:19:40,1,	Until:05:55,0.4,	Until:17:30,0.5,
Until:20:50,0.3,	Until:06:30,1,	Until:17:40,1,
Until:24:00,1,	Until:07:05,0.5,	Until:18:35,0.3,
For: Tuesday,	Until:07:45,0.3,	Until:23:00,1,
Until:00:25,0.4,	Until:13:25,0,	**For: WinterDesignDay Al-lOtherDays,**
Until:01:10,1,	Until:15:35,0.5,	Until: 24:00,0;
Until:05:55,0.4,	Until:16:30,0,	
Until:06:30,1,	Until:16:45,0.5,	
Until:07:45,0.3,	Until:17:30,0.2,	
Until:13:25,0,	Until:18:50,0.3,	
Until:15:35,0.5,	Until:20:50,1,	
Until:16:30,0,	Until:23:00,0.3,	
Until:17:30,0.2,	Until:24:00,0.3,	
Until:18:50,0.3,	**For:Wednesday,**	
Until:20:35,1,	Until:00:35,1,	
Until:23:00,0.3,	Until:05:55,0.4,	
Until:24:00,0.3,	Until:06:30,1,	
For: Wednesday,	Until:07:05,0.5,	
Until:00:20,1,	Until:07:45,0.3,	
Until:03:15,0.3,	Until:13:25,0,	
Until:05:55,0.4,	Until:15:35,0.5,	
Until:06:30,1,	Until:16:30,0,	
Until:07:05,0.5,	Until:16:40,0.5,	
Until:07:45,0.3,	Until:17:30,0.2,	
Until:13:25,0,	Until:18:35,0.3,	
Until:15:35,0.5,	Until:20:15,1,	
Until:16:30,0,	Until:20:40,0.3,	
Until:17:30,0.2,	Until:21:40,1,	
Until:18:35,0.3,	Until:24:00,0.3,	
Until:20:00,1,	**For: WinterDesignDayAl-lOtherDays,**	
Until:20:40,0.3,	Until: 24:00, 0;	
Until:21:25,1,		

45 Minutes	1 Hour	2 Hours
Until:24:00,0.3,		
For: WinterDesignDay AllOtherDays,		
Until: 24:00, 0;		
Temperature Schedules		
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,
Terminal_Check_Cool,	Terminal_Check_Cool,	Terminal_Check_Cool,
Temperature,	Temperature,	Temperature,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For:Thursday SummerDesignDay,	**For:Thursday SummerDesignDay,**	**For:Thursday SummerDesignDay,**
Until:05:55,0.7,	Until:05:55,0.7,	Until:05:55,0.7,
Until:13:15,1,	Until:08:20,1,	Until:22:40,1,
Until:13:40,0.9,	Until:13:15,1,	Until:24:00,0.7,
Until:16:35,1,	Until:13:40,0.9,	**For:Friday,**
Until:17:15,0.9,	Until:16:50,1,	Until:05:55,0.7,
Until:18:35,1,	Until:17:15,0.9,	Until:13:20,1,
Until:19:00,0.9,	Until:18:50,1,	Until:15:30,0.9,
Until:19:45,1,	Until:19:00,0.9,	Until:18:10,1,
Until:20:10,0.9,	Until:20:00,1,	Until:18:35,0.8,
Until:21:25,1,	Until:20:10,0.9,	Until:23:55,1,
Until:24:00,0,	Until:21:40,1,	Until:24:00,0.7,
For: Friday,	Until:24:00,0.7,	**For:Saturday,**
Until:05:55,0.7,	**for:Friday,**	Until:05:55,0.7,
Until:11:50,1,	Until:05:55,0.7,	Until:13:25,1,
Until:11:55,0.8,	Until:13:20,1,	Until:15:35,0.9,
Until:13:20,1,	Until:15:30,0.9,	Until:18:15,1,
Until:15:30,0.9,	Until:17:10,1,	Until:18:35,0.8,
Until:16:55,1,	Until:18:15,0.9,	Until:24:00,1,
Until:18:15,0.9,	Until:18:35,0.8,	**For:Sunday,**
Until:18:35,0.8,	Until:19:50,1,	Until:01:20,1,
Until:19:35,1,	Until:20:15,0.8,	Until:04:15,0.7,
Until:20:15,0.8,	Until:20:20,0.7,	Until:05:55,0.8,
Until:20:20,0.7,	Until:22:55,1,	Until:13:25,1,
Until:21:25,1,	Until:24:00,0.7,	Until:15:35,0.9,
Until:21:55,0.7,	**For:Saturday,**	Until:24:00,1,
Until:22:40,1,	Until:05:55,0.7,	**For:Monday,**
Until:24:00,0,	Until:08:20,1,	Until:02:25,1,
For: Saturday,	Until:13:25,1,	Until:05:15,0.7,
Until:05:55,0.7,	Until:15:35,0.9,	Until:13:25,1,
Until:12:45,1,	Until:17:15,1,	Until:15:35,0.9,

45 Minutes	1 Hour	2 Hours
Until:13:00,0.9,	Until:18:15,0.9,	Until:24:00,1,
Until:13:25,1,	Until:18:35,0.8,	**For:Tuesday,**
Until:15:35,0.9,	Until:20:30,1,	Until:02:25,1,
Until:17:00,1,	Until:20:40,0.7,	Until:05:55,0.7,
Until:18:15,0.9,	Until:24:00,0.7,	Until:13:25,1,
Until:18:35,0.8,	**For:Sunday,**	Until:15:35,0.9,
Until:20:15,1,	Until:00:20,1,	Until:17:45,1,
Until:20:40,0.7,	Until:04:15,0.7,	Until:18:50,0.8,
Until:23:15,1,	Until:05:55,0.8,	Until:21:50,1,
Until:23:20,0.7,	Until:13:25,1,	Until:23:00,0.8,
Until:24:00,0,	Until:15:35,0.9,	Until:24:00,1,
for:Sunday,	Until:24:00,0.7,	**For:Wednesday,**
Until:00:05,1,	**For:Monday,**	Until:01:35,1,
Until:04:15,0.7,	Until:00:10,1,	Until:05:55,0.7,
Until:05:55,0.8,	Until:00:25,0.7,	Until:13:25,1,
Until:13:25,1,	Until:01:25,1,	Until:15:35,0.9,
Until:15:35,0.9,	Until:05:15,0.7,	Until:17:40,1,
Until:17:15,1,	Until:13:25,1,	Until:18:35,0.9,
Until:20:10,1,	Until:15:35,0.9,	Until:24:00,1,
Until:20:25,0.7,	Until:18:00,1,	**For: WinterDesignDay AllOtherDays,**
Until:21:25,1,	Until:18:40,0.9,	Until: 24:00, 0;
Until:21:35,0.7,	Until:19:55,1,	
Until:23:55,1,	Until:20:15,0.9,	
Until:24:00,0,	Until:20:50,0.8,	
For: Monday,	Until:22:15,1,	
Until:00:25,0.7,	Until:24:00,1,	
Until:01:10,1,	**For:Tuesday,**	
Until:05:15,0.7,	Until:00:15,1,	
Until:11:40,1,	Until:00:25,0.7,	
Until:11:55,0.8,	Until:01:25,1,	
Until:13:15,1,	Until:05:55,0.7,	
Until:13:20,0.8,	Until:12:55,1,	
Until:15:35,0.9,	Until:13:25,0.8,	
Until:17:45,1,	Until:15:35,0.9,	
Until:18:40,0.9,	Until:16:45,1,	
Until:19:40,1,	Until:17:15,0.9,	
Until:20:15,0.9,	Until:18:50,0.8,	
Until:20:50,0.8,	Until:20:50,1,	
Until:24:00,1,	Until:23:00,0.8,	

45 Minutes	**1 Hour**	**2 Hours**
For:Tuesday,	Until:24:00,1,	
Until:00:25,0.7,	**For:Wednesday,**	
Until:01:10,1,	Until:00:35,1,	
Until:05:55,0.7,	Until:02:15,0.8,	
Until:10:00,1,	Until:05:55,0.7,	
Until:10:15,0.8,	Until:08:15,1,	
Until:12:40,1,	Until:13:25,1,	
Until:13:25,0.8,	Until:15:35,0.9,	
Until:15:35,0.9,	Until:16:40,1,	
Until:16:30,1,	Until:18:35,0.9,	
Until:17:15,0.9,	Until:19:15,1,	
Until:18:50,0.8,	Until:20:15,1,	
Until:20:35,1,	Until:20:40,0.8,	
Until:23:00,0.8,	Until:21:40,1,	
Until:24:00,0,	Until:24:00,0.7,	
For:Wednesday,	**For: WinterDesignDay Al-lOtherDays,**	
Until:00:20,1,	Until: 24:00, 0;	
Until:02:15,0.8,		
Until:05:55,0.7,		
Until:08:55,1,		
Until:09:05,0.7,		
Until:10:05,1,		
Until:10:15,0.8,		
Until:11:40,1,		
Until:11:55,0.9,		
Until:12:40,1,		
Until:12:55,0.9,		
Until:13:25,1,		
Until:15:35,0.9,		
Until:16:25,1,		
Until:18:35,0.9,		
Until:20:00,1,		
Until:20:40,0.8,		
Until:21:25,1,		
Until:24:00,0.7,		
For: WinterDesignDay Al-lOtherDays,		
Until: 24:00, 0;		
Ventilation Schedules		
Schedule:Compact,	Schedule:Compact,	Schedule:Compact,

45 Minutes	**1 Hour**	**2 Hours**
Terminal_Check_Equip,	Terminal_Check_Equip,	Terminal_Check_Equip,
Fraction,	Fraction,	Fraction,
Through: 31 Dec,	Through: 31 Dec,	Through: 31 Dec,
For:Thursday SummerDesignDay,	**For:Thursday SummerDesignDay,**	**For:Thursday SummerDesignDay,**
Until:05:55,0.2,	Until:05:55,0.2,	Until:05:55,0.2,
Until:06:20,0.7,	Until:06:20,0.7,	Until:06:20,0.7,
Until:07:05,1,	Until:07:05,1,	Until:07:05,1,
Until:07:55,0.4,	Until:07:55,0.4,	Until:07:55,0.4,
Until:09:20,0.7,	Until:08:40,0.8,	Until:08:40,0.8,
Until:09:55,0.6,	Until:09:20,0.7,	Until:09:20,0.7,
Until:10:25,0.9,	Until:09:55,0.6,	Until:09:55,0.6,
Until:10:55,0.5,	Until:10:25,0.9,	Until:10:25,0.9,
Until:11:50,1,	Until:10:55,0.5,	Until:10:55,0.5,
Until:11:55,0.2,	Until:12:25,0.7,	Until:12:25,0.7,
Until:12:25,0.7,	Until:12:55,0.5,	Until:13:40,0.5,
Until:12:40,0.5,	Until:13:40,0.2,	Until:14:50,0.9,
Until:13:40,0.2,	Until:14:00,1,	Until:15:20,0.5,
Until:14:00,1,	Until:14:50,0.9,	Until:15:50,1,
Until:14:45,0.9,	Until:15:20,0.5,	Until:16:20,0.7,
Until:14:50,0.2,	Until:15:50,1,	Until:16:50,0.6,
Until:15:20,0.5,	Until:16:20,0.7,	Until:19:00,1,
Until:15:50,1,	Until:16:50,0.6,	Until:19:30,0.9,
Until:16:20,0.7,	Until:17:50,0.2,	Until:20:40,0.5,
Until:16:35,0.6,	Until:18:50,1,	Until:22:40,0.7,
Until:17:50,0.2,	Until:19:00,0.2,	Until:24:00,0.2,
Until:18:35,1,	Until:19:30,0.9,	**for:Friday,**
Until:19:00,0.2,	Until:20:00,0.5,	Until:05:55,0.2,
Until:19:30,0.9,	Until:20:10,0.2,	Until:06:20,0.7,
Until:19:45,0.5,	Until:20:40,0.5,	Until:07:05,1,
Until:20:10,0.2,	Until:21:10,0.7,	Until:07:55,0.4,
Until:20:40,0.5,	Until:21:40,0.5,	Until:08:40,0.8,
Until:21:10,0.7,	Until:24:00,0.2,	Until:09:20,0.7,
Until:21:25,0.5,	**For: Friday,**	Until:09:55,0.6,
Until:24:00,0.2,	Until:05:55,0.2,	Until:10:25,0.9,
For: Friday,	Until:06:20,0.7,	Until:10:55,0.5,
Until:05:55,0.2,	Until:07:05,1,	Until:13:00,1,
Until:06:20,0.7,	Until:07:55,0.4,	Until:13:20,0.8,
Until:07:05,1,	Until:08:40,0.8,	Until:15:30,0.6,
Until:07:55,0.4,	Until:09:20,0.7,	Until:16:10,1,
Until:09:20,0.7,	Until:09:55,0.6,	Until:17:10,0.8,

45 Minutes	**1 Hour**	**2 Hours**
Until:09:55,0.6,	Until:10:25,0.9,	Until:18:10,0.7,
Until:10:25,0.9,	Until:10:55,0.5,	Until:18:35,0.2,
Until:10:55,0.5,	Until:13:00,1,	Until:18:50,0.5,
Until:11:50,1,	Until:13:20,0.8,	Until:20:20,0.7,
Until:11:55,0.2,	Until:15:30,0.6,	Until:21:55,0.8,
Until:13:00,1,	Until:16:10,1,	Until:23:55,1,
Until:13:20,0.8,	Until:17:10,0.8,	Until:24:00,0.2,
Until:15:30,0.6,	Until:18:35,0.2,	**For:Saturday,**
Until:16:10,1,	Until:18:50,0.5,	Until:05:55,0.2,
Until:16:55,0.8,	Until:19:50,0.7,	Until:07:10,0.8,
Until:18:35,0.2,	Until:20:20,0.2,	Until:08:10,1,
Until:18:50,0.5,	Until:21:55,0.8,	Until:09:20,0.7,
Until:19:35,0.7,	Until:22:55,1,	Until:11:55,1,
Until:20:20,0.2,	Until:24:00,0.2,	Until:13:25,0.5,
Until:21:25,0.8,	**For: Saturday,**	Until:15:35,0.6,
Until:21:55,0.2,	Until:05:55,0.2,	Until:18:15,1,
Until:22:40,1,	Until:07:10,0.8,	Until:18:35,0.2,
Until:24:00,0.2,	Until:08:10,1,	Until:20:05,0.8,
For: Saturday,	Until:09:20,0.7,	Until:20:40,1,
Until:05:55,0.2,	Until:11:55,1,	Until:21:20,0.8,
Until:07:10,0.8,	Until:15:35,0.6,	Until:21:55,1,
Until:08:10,1,	Until:17:15,1,	Until:22:30,0.7,
Until:09:20,0.7,	Until:18:35,0.2,	Until:23:20,0.6,
Until:11:55,1,	Until:20:05,0.8,	Until:24:00,1,
Until:12:45,0.5,	Until:20:30,1,	**For:Sunday,**
Until:13:00,0.2,	Until:20:40,0.2,	Until:01:20,1,
Until:15:35,0.6,	Until:21:20,0.8,	Until:05:55,0.2,
Until:17:00,1,	Until:21:55,1,	Until:07:30,0.8,
Until:18:35,0.2,	Until:22:30,0.7,	Until:08:55,1,
Until:20:05,0.8,	Until:23:20,0.6,	Until:09:55,0.5,
Until:20:15,1,	Until:24:00,0.2,	Until:10:55,0.7,
Until:20:40,0.2,	**For: Sunday,**	Until:11:50,0.8,
Until:21:20,0.8,	Until:00:20,1,	Until:13:00,1,
Until:21:55,1,	Until:05:55,0.2,	Until:13:25,0.5,
Until:22:30,0.7,	Until:07:30,0.8,	Until:15:35,0.6,
Until:23:15,0.6,	Until:08:55,1,	Until:19:25,0.8,
Until:23:20,0.2,	Until:09:55,0.5,	Until:23:10,0.9,
Until:24:00,0.2,	Until:10:55,0.7,	Until:24:00,1,
For: Sunday,	Until:11:50,0.8,	**For:Monday,**
Until:00:05,1,	Until:13:00,1,	Until:02:25,1,

45 Minutes	**1 Hour**	**2 Hours**
Until:05:55,0.2,	Until:15:35,0.6,	Until:05:15,0.2,
Until:07:30,0.8,	Until:19:25,0.8,	Until:05:55,0.7,
Until:08:55,1,	Until:24:00,1,	Until:06:25,0.5,
Until:09:55,0.5,	**For: Monday,**	Until:07:15,0.5,
Until:10:55,0.7,	Until:00:10,1,	Until:07:55,0.8,
Until:11:50,0.8,	Until:00:25,0.2,	Until:08:50,0.7,
Until:12:40,1,	Until:01:25,1,	Until:09:20,0.5,
Until:12:55,0.2,	Until:05:15,0.2,	Until:10:15,0.4,
Until:13:00,1,	Until:05:55,0.7,	Until:11:45,0.7,
Until:13:25,0.5,	Until:06:25,0.5,	Until:13:05,0.5,
Until:15:35,0.6,	Until:07:15,0.5,	Until:13:25,0.8,
Until:17:15,0.8,	Until:08:50,0.7,	Until:15:35,0.6,
Until:17:30,0.2,	Until:10:15,0.4,	Until:16:00,0.8,
Until:19:25,0.8,	Until:11:45,0.7,	Until:16:30,0.9,
Until:20:10,0.9,	Until:12:15,0.5,	Until:17:00,0.5,
Until:20:25,0.2,	Until:13:05,0.5,	Until:18:00,0.3,
Until:21:25,0.9,	Until:13:25,0.8,	Until:18:55,0.6,
Until:21:35,0.2,	Until:15:35,0.6,	Until:19:55,0.7,
Until:23:55,1,	Until:16:30,0.9,	Until:20:55,0.3,
Until:24:00,0.2,	Until:17:00,0.5,	Until:21:25,0.7,
For: Monday,	Until:18:00,0.3,	Until:21:55,0.5,
Until:00:25,0.2,	Until:18:40,0.2,	Until:22:45,0.4,
Until:01:10,1,	Until:18:55,0.6,	Until:23:20,0.7,
Until:05:15,0.2,	Until:19:55,0.7,	Until:24:00,0.5,
Until:05:55,0.7,	Until:20:50,0.2,	**For:Tuesday,**
Until:06:25,0.5,	Until:21:25,0.7,	Until:01:25,0.5,
Until:07:15,0.5,	Until:21:55,0.5,	Until:01:30,0.7,
Until:07:55,0.8,	Until:22:45,0.4,	Until:02:25,0.5,
Until:08:50,0.7,	Until:23:20,0.7,	Until:05:55,0.2,
Until:09:20,0.5,	Until:23:50,0.5,	Until:06:50,0.8,
Until:10:15,0.4,	Until:24:00,0.5,	Until:07:40,0.3,
Until:11:40,0.7,	**For: Tuesday,**	Until:09:20,0.9,
Until:11:55,0.2,	Until:00:15,0.5,	Until:09:50,0.5,
Until:12:15,0.5,	Until:00:25,0.2,	Until:10:55,0.3,
Until:13:05,0.5,	Until:01:25,0.5,	Until:11:25,0.5,
Until:13:15,0.8,	Until:05:55,0.2,	Until:11:55,0.3,
Until:13:20,0.2,	Until:06:50,0.8,	Until:12:55,1,
Until:13:25,0.8,	Until:07:40,0.3,	Until:13:25,0.8,
Until:15:35,0.6,	Until:09:20,0.9,	Until:15:35,0.6,
Until:16:30,0.9,	Until:09:50,0.5,	Until:15:45,0.4,

45 Minutes	1 Hour	2 Hours
Until:17:00,0.5,	Until:10:55,0.3,	Until:16:45,0.7,
Until:17:45,0.3,	Until:11:25,0.5,	Until:17:45,1,
Until:18:40,0.2,	Until:11:55,0.3,	Until:18:50,0.2,
Until:18:55,0.6,	Until:12:55,1,	Until:19:50,0.5,
Until:19:40,0.7,	Until:13:25,0.2,	Until:20:50,0.8,
Until:20:50,0.2,	Until:15:35,0.6,	Until:21:50,1,
Until:21:25,0.7,	Until:15:45,0.4,	Until:23:00,0.2,
Until:21:55,0.5,	Until:16:45,0.7,	Until:23:35,0.7,
Until:22:45,0.4,	Until:18:50,0.2,	Until:24:00,0.8,
Until:23:20,0.7,	Until:19:50,0.5,	**For:Wednesday,**
Until:23:50,0.5,	Until:20:50,0.8,	Until:00:35,0.8,
Until:24:00,0.5,	Until:23:00,0.2,	Until:01:35,1,
For: Tuesday,	Until:23:35,0.7,	Until:05:55,0.2,
Until:00:25,0.2,	Until:24:00,0.8,	Until:06:40,0.5,
Until:01:10,0.5,	**For: Wednesday,**	Until:07:25,0.7,
Until:05:55,0.2,	Until:00:35,0.8,	Until:08:10,0.8,
Until:06:50,0.8,	Until:05:55,0.2,	Until:08:55,0.5,
Until:07:40,0.3,	Until:06:40,0.5,	Until:09:40,0.7,
Until:09:20,0.9,	Until:07:25,0.7,	Until:10:25,0.8,
Until:09:50,0.5,	Until:08:10,0.8,	Until:11:10,0.5,
Until:10:00,0.3,	Until:08:55,0.5,	Until:11:55,0.7,
Until:10:15,0.2,	Until:09:40,0.7,	Until:12:55,0.8,
Until:10:55,0.3,	Until:10:25,0.8,	Until:13:25,0.5,
Until:11:25,0.5,	Until:11:10,0.5,	Until:15:35,0.6,
Until:11:55,0.3,	Until:11:55,0.7,	Until:16:20,0.7,
Until:12:40,1,	Until:12:55,0.8,	Until:16:40,0.8,
Until:13:25,0.2,	Until:13:25,0.5,	Until:17:40,1,
Until:15:35,0.6,	Until:15:35,0.6,	Until:18:35,0.2,
Until:15:45,0.4,	Until:16:20,0.7,	Until:19:15,0.4,
Until:16:30,0.7,	Until:16:40,0.8,	Until:20:40,0.3,
Until:18:50,0.2,	Until:18:35,0.2,	Until:24:00,0.2,
Until:19:50,0.5,	Until:19:15,0.4,	**For: WinterDesignDay Al-lOtherDays,**
Until:20:35,0.8,	Until:20:15,0.3,	Until: 24:00, 0;
Until:23:00,0.2,	Until:20:40,0.2,	
Until:24:00,0.2,	Until:21:40,0.5,	
For: Wednesday,	Until:24:00,0.2,	
Until:00:20,0.8,	**For: WinterDesignDay Al-lOtherDays,**	
Until:05:55,0.2,	Until: 24:00, 0;	
Until:06:40,0.5,		

45 Minutes	1 Hour	2 Hours
Until:07:25,0.7,		
Until:08:10,0.8,		
Until:08:55,0.5,		
Until:09:05,0.2,		
Until:09:40,0.7,		
Until:10:05,0.8,		
Until:10:15,0.2,		
Until:10:25,0.8,		
Until:11:10,0.5,		
Until:11:40,0.7,		
Until:11:55,0.2,		
Until:12:40,0.8,		
Until:12:55,0.2,		
Until:13:25,0.5,		
Until:15:35,0.6,		
Until:16:20,0.7,		
Until:16:25,0.8,		
Until:18:35,0.2,		
Until:19:15,0.4,		
Until:20:00,0.3,		
Until:20:40,0.2,		
Until:21:25,0.5,		
Until:24:00,0.2,		
For: WinterDesignDay AllOtherDays,		
Until: 24:00, 0;		

APPENDIX 3: FUZZY RULES

1. (OT==Cold) & (NP==None) & (ZI==Dark) => (TS=Winter_Unoccupied)(LS=Off)(AR=Unoccuppied) (1)

2. (OT==Cold) & (NP==None) & (ZI==Dim) => (TS=Winter_Unoccupied)(LS=Off)(AR=Unoccuppied) (1)

3. (OT==Cold) & (NP==None) & (ZI==Adequate) => (TS=Winter_Unoccupied)(LS=Off)(AR=Unoccuppied) (1)

4. (OT==Cold) & (NP==Few) & (ZI==Dark) => (TS=Winter)(LS=Bright)(AR=Few) (1)

5. (OT==Cold) & (NP==Few) & (ZI==Dim) => (TS=Winter)(LS=Dim)(AR=Few) (1)

6. (OT==Cold) & (NP==Few) & (ZI==Adequate) => (TS=Winter)(LS=Off)(AR=Few) (1)

7. (OT==Cold) & (NP==Average) & (ZI==Dark) => (TS=Winter)(LS=Bright)(AR=Average) (1)

8. (OT==Cold) & (NP==Average) & (ZI==Dim) => (TS=Winter)(LS=Dim)(AR=Average) (1)

9. (OT==Cold) & (NP==Average) & (ZI==Adequate) => (TS=Winter)(LS=Off)(AR=Average) (1)

10. (OT==Cold) & (NP==Many) & (ZI==Dark) => (TS=Winter)(LS=Bright)(AR=Many) (1)

11. (OT==Cold) & (NP==Many) & (ZI==Dim) => (TS=Winter)(LS=Dim)(AR=Many) (1)

12. (OT==Cold) & (NP==Many) & (ZI==Adequate) => (TS=Winter)(LS=Off)(AR=Many) (1)

13. (OT==Medium) & (NP==None) & (ZI==Dark) => (TS=Mid-season)(LS=Off)(AR=Unoccuppied) (1)

14. (OT==Medium) & (NP==None) & (ZI==Dim) => (TS=Mid-season)(LS=Off)(AR=Unoccuppied) (1)

15. (OT==Medium) & (NP==None) & (ZI==Adequate) => (TS=Mid-season)(LS=Off)(AR=Unoccuppied) (1)

16. (OT==Medium) & (NP==Few) & (ZI==Dark) => (TS=Mid-season)(LS=Bright)(AR=Few) (1)

17. (OT==Medium) & (NP==Few) & (ZI==Dim) => (TS=Mid-season)(LS=Dim)(AR=Few) (1)

18. (OT==Medium) & (NP==Few) & (ZI==Adequate) => (TS=Mid-season)(LS=Off)(AR=Few) (1)

19. (OT==Medium) & (NP==Average) & (ZI==Dark) => (TS=Mid-season)(LS=Bright)(AR=Average) (1)

20. (OT==Medium) & (NP==Average) & (ZI==Dim) => (TS=Mid-season)(LS=Dim)(AR=Average) (1)

21. (OT==Medium) & (NP==Average) & (ZI==Adequate) => (TS=Mid-season)(LS=Off)(AR=Average) (1)

22. (OT==Medium) & (NP==Many) & (ZI==Dark) => (TS=Mid-season)(LS=Bright)(AR=Many) (1)

23. (OT==Medium) & (NP==Many) & (ZI==Dim) => (TS=Mid-season)(LS=Dim)(AR=Many) (1)

24. (OT==Medium) & (NP==Many) & (ZI==Adequate) => (TS=Mid-season)(LS=Off)(AR=Many) (1)

25. (OT==Hot) & (NP==None) & (ZI==Dark) => (TS=Summer_Unoccupied)(LS=Off)(AR=Unoccuppied) (1)

26. (OT==Hot) & (NP==None) & (ZI==Dim) => (TS=Summer_Unoccupied)(LS=Off)(AR=Unoccuppied) (1)

27. (OT==Hot) & (NP==None) & (ZI==Adequate) => (TS=Summer_Unoccupied)(LS=Off)(AR=Unoccuppied) (1)

28. (OT==Hot) & (NP==Few) & (ZI==Dark) => (TS=Summer)(LS=Bright)(AR=Few) (1)

29. (OT==Hot) & (NP==Few) & (ZI==Dim) => (TS=Summer)(LS=Dim)(AR=Few) (1)

30. (OT==Hot) & (NP==Few) & (ZI==Adequate) => (TS=Summer)(LS=Off)(AR=Few) (1)

31. (OT==Hot) & (NP==Average) & (ZI==Dark) => (TS=Summer)(LS=Bright)(AR=Average) (1)

32. (OT==Hot) & (NP==Average) & (ZI==Dim) => (TS=Summer)(LS=Dim)(AR=Average) (1)

33. (OT==Hot) & (NP==Average) & (ZI==Adequate) => (TS=Summer)(LS=Off)(AR=Average) (1)

34. (OT==Hot) & (NP==Many) & (ZI==Dark) => (TS=Summer)(LS=Bright)(AR=Many) (1)

35. (OT==Hot) & (NP==Many) & (ZI==Dim) => (TS=Summer)(LS=Dim)(AR=Many) (1)

36. (OT==Hot) & (NP==Many) & (ZI==Adequate) => (TS=Summer)(LS=Off)(1)

APPENDIX 4: PAPER SUBMITTED FOR PUBLICATION IN ENERGY & BUILDINGS JOURNAL

INVESTIGATING ENERGY AND COMFORT OF OCCUPANCY FLOW BASED CONTROL OF INDOOR AIRPORT TERMINAL SYSTEMS

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ABSTRACT

The most cost effective way to save energy in commercial buildings is through adjusting the building control set-points according to the demand as determined by the flow of occupancy. Such strategies include shutting down part of the building automation or choosing energy efficient comfort set-points of indoor environment systems during the unoccupied period and then adjusting set-points for comfort during the occupancy period according to the flow of people in the building. Typically, an occupancy control strategy cannot be easily achieved through conventional control. Experience shows that adjusting set-points appropriately in large buildings such as the airport terminal can be a difficult challenge to the facility managers.

This paper presents the design of a fuzzy rule-based supervisory controller for reducing energy consumptions while simultaneously providing comfort for passengers in a large airport terminal building. The inputs to the controller are the schedule of the arrival and departure of passenger planes as well as the expected number of passengers, zone global illuminance (daylight) and external temperature. The outputs from the controller are dynamic optimised temperature, airflow rates and lighting set-points profile for the building. The supervisory controller was designed manually based on expert knowledge in MATLAB/Simulink, and then validated using detailed dynamic simulation studies in DesignBuilder. The simulation results showed that the controller is capable of maintaining comfort by adjusting set-points according to the flow of passengers. Significant potential for energy saving is demonstrated by using the fuzzy rule-based supervisory controller.

KEYWORDS

Building Control, Indoor Comfort, Airport Terminal's CO_2 emission savings, fuzzy rule-based supervisory controller

1. Introduction

HVAC and lighting systems in commercial buildings need to be carefully controlled to provide comfort under a range of changing load conditions. This is a difficult task, and therefore efficient and effective control is often the most cost-effective way to improve the energy efficiency of a building. Airport buildings are operated round-the-clock and contain many spaces that are different in function and structure; these leads to complicated building systems including heating, ventilation, air-conditioning, electric lighting and hot water systems that can be difficult to control. This complexity is enhanced by non-linear effects, time-varying and uncertain nature of the variables inside and outside of the building affecting these systems requiring frequent adjustment in comfort set-point. Consequently, typical HVAC and Lighting systems are run continuously on conservative settings chosen for maximum comfort and maximum ventilation power. This leads to a high energy consumption, a good part of which is wasted during periods of low occupancy. This paper presents the design of a fuzzy supervisory controller for managing the indoor comfort of an airport terminal and examines its benefits. A detailed simulation model is used to determine the effects in terms of energy and carbon emission reduction as well as passenger comfort in a real large UK airport terminal.

2. Selection of Simulation Tools

Computer based building simulation and modelling is a well understood and cost effective method for analysing complex buildings such as the airports. However, the simulation capabilities for advanced controllers are still very limited in most state-of-art building simulation tools [1]. Tools such as TRNSYS [2] and ESP-r [3] are more suitable at specifying local controllers while EnergyPlus [4] is mainly used for testing supervisory control [5]. Domain independent simulation platforms such as MATLAB [6] / Simulink [7], LabVIEW [8], and Dymola [9] are efficient in design and testing of controllers, but they lack the domain specific modelling capabilities to accurately simulate building forms and systems [10]. To get the best of both worlds, the supervisory controller was designed in the MATLAB/Simulink environment while the airport terminal and its environment systems were modelled in DesigBuilder/EnergyPlus. Both simulations are coupled via a data exchange interface. This approach avoids the difficult and error prone task of recreating a model covering the complex nature of airport terminal building and systems from first principle in the MATLAB/Simulink environment.

EnergyPlus is a new generation building-energy-analysis tool suitable for analysing building performances of unusual building systems [5] such as airport terminal buildings. Griffith et al [11] have used an earlier version of EnergyPlus (Version 1.0.3) to study the influence of advanced building technologies such as optimised envelop system and schedules for a proposed Air Rescue and Fire Fighting Administration Building at Teterboro Airport and found that the results obtained compare well with those obtained using DOE-2.1E. Ellis and Torcellini [12] confirmed the reliability and accuracy of EnergyPlus in simulating large buildings.

Standard control tools within EnergyPlus include low level control and high level control [13]. The Low-Level Control simulates a particular closed-loop hardware controls that has a specific task to accomplish. They are found in the input of an EnergyPlus object. High-Level operates at a higher level than the local loop in control hierarchy. This type of control affects the operation of local control and can be used to manage and control the running of other component objects, part of or the entire system. The proposed fuzzy supervisory controller replaces the higher level controller function by providing the schedules and set-points for running the heating, ventilation, air-conditioning and lighting systems.

The major shortcoming of EnergyPlus is that it does not have a friendly user interface. To overcome this problem, DesignBuilder was used for the modelling process. DesignBuilder is the most comprehensive user interface to the EnergyPlus dynamic thermal simulation engine. It combines rapid building geometry, HVAC and lighting modelling and ease of use with state-of-the-art dynamic energy simulation based on EnergyPlus. Through the interface of DesignBuilder [14], the advanced HVAC and Dayligthing features in EnergyPlus are now accessible in a user-friendly graphical environment. The latest DesignBuilder V3 provides a powerful and flexible new way to model both air and water sides together in full detail with a good range of components including all ASHRAE baseline HVAC systems.

3. Supervisory Control Strategy

A supervisory control strategy was developed for the zones that are used mainly by the passengers and staff of the airport; such that the occupancy flow pattern is directly related to flight schedules. Airport buildings are often zoned such that the landside areas accessible to the general public are separated from the airside areas that are only restricted to the passengers and staff with relevant documents. This study will focus on the departure/arrival gates only, because they typically have well understood occupancy patterns. Other zones such as shops and leisure areas have more complex occupancy patterns that are beyond the scope of this paper. This differentiation is necessary in order to capture areas within the terminal in which occupancy can be predicted using available information on arriving and departing passenger planes.

In general, terminal arrival process is less complicated than departure, since arriving passengers are mostly interested in picking their baggage and checking-out quickly. This process is usually short and largely predictable. The departure process takes a much longer time, partially because of airline procedures, and partially because passengers will arrive early to allow for possible delays in transportation to the airport. The International Civil Aviation Organisation (ICAO) recommends forty-five minutes as the maximum duration for international arrival passenger processing from disembarkation to completion of the last clearance process, and one hour for the departing passenger from clearance to embarkation [15]. In a survey [16] conducted in seven UK airports by Civil Aviation Authority [CAA] in 2009 shows that the typical processing time for most passengers in these airports is even shorter than the provisions in the standard.

4. Fuzzy Supervisory Controller

The function of this supervisory controller is to provide dynamic set-points for the conventional control system. The main goal of supervisory control is to increase the operating availability of set-points for the process under control based on the function of the control space (figure 1). To achieve this, the controller supplies set-points to coordinates the actions of the distributed controllers according to the evolution of the passenger flows and external conditions.

A fuzzy supervisory controller was chosen because it provides a direct way to translate these observations of the arrival and departure process into actions for the building control system. The heuristic elements in this strategy are based on operator knowledge obtained from building operation and in-situ measurements of control variable carried in the building.

This structure of the supervisory controller follows the framework of Yokogawa electric's temperature controller [19]. In this design, the fuzzy supervisory module leads the PID controller along a temperature trajectory that can quickly reach the actual set-points without overshoot. A key difference is that Yokogawa controller is a close-loop supervisory control system and involves only temperature, while the one described here is an open-loop (feedforward) system. This change simplifies the design of the supervisory controller, and it avoids potential stability issues caused by the interference of two feedback loops. Vogrin & Halang, 2010, demonstrated the use of a set-point pre-processor with a similar architecture to control robot arm. This experiment found that the controller response speed is very high, and it maintains good closed loop stability [18]. The structure is shown in Figure 1, and the used variables are explained in Table 1.

TABLE 1. VARIABLES USED IN THE SUPERVISORY CONTROL STRUCTURE (FIGURE 1)

Symbol	Significance
$Y_A(t)$	fuzzy controller inputs
$Y_B(t)$	optimised set point schedules for the controlled variable
E(t)	controller error
E(t)	measured output

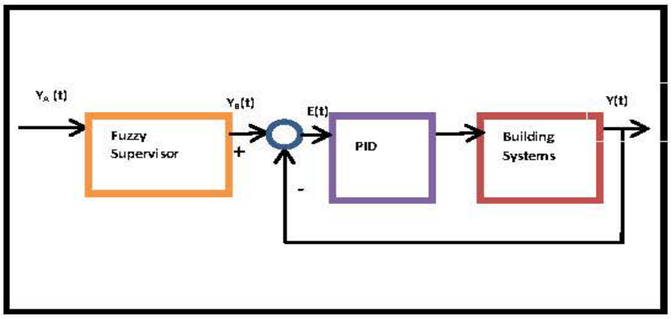

FIGURE 1. ARCHITECTURE OF CONTROL STRATEGY

One of the advantages of this scheme is that the fuzzy supervisory controller can compensate for an expected error *E(t)* in the PID control loop by moving the set-point $Y_B(t)$ beyond the value that is actually desired. This means that the controller error *E(t)*, the difference between the set-point schedule and the actual value $Y_B(t) - Y(t)$ is less than the controlled error $Y_A(t) - Y(t)$ obtained by using conventional controller alone.

The supervisory controller receives data on when a plane is to land or to take-off, and the number of passengers estimated from the capacity of the aircraft type. This kind of data is available from the passengers' information desk long before the actual flight. Further inputs are real-time hourly measurements of external temperature and sub-hourly measurements of zone horizontal illuminance from daylight sensors.

The supervisory fuzzy controller provides the required thermal, lighting and indoor air-quality comfort set-points to the identified zones in the terminal where the passengers will be transiting. These set-points are available in advance to the passengers arriving, allowing the systems to raise or lower the indoor conditions despite the time delay inherent in the heating system. For an arriving aircraft, the set-points are set when an aircraft touches down, which is typically 15 minutes before the passengers disembark into the building. They are set to elapse about an hour after arrival, at which time the passengers should have cleared the zone. For departing passengers, the opposite sequence is used: set-points are chosen for the gate zone an hour before the scheduled departure, and they are reset once boarding is completed.

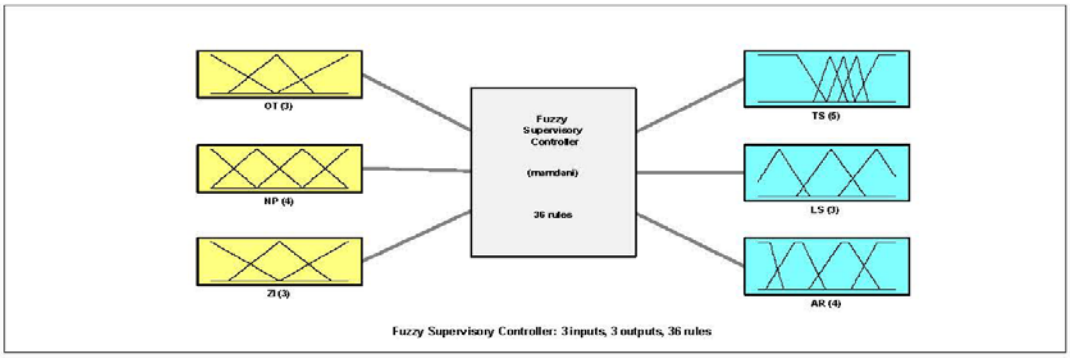

FIGURE 2. MODEL OF THE SUPERVISORY CONTROLLER

5. STRUCTURE OF FUZZY CONTROLLER

In general a fuzzy controller was developed using the Fuzzy Logic Tool Box [19] in MATLAB. It comprises the *fuzzifier* which determines the membership degrees of the controller *crisps* input values in the antecedent fuzzy sets. The *inference mechanism* combines this information with the knowledge stored in the rules and determines what the *output* of the *rule-based* system should be. The output is a fuzzy set but for control purposes, a *crisp* control signal is required. The *defuzzifier* calculates the value of this *crisp* signal from the fuzzy controller outputs [20].

This controller takes Outdoor Temperature (OT), Zone Illuminance (ZI), Passenger Numbers (PN) at a given flight time as inputs and outputs indoor Lighting Setpoints (LS), Temperature Set-point (TS) and Airflow Rates (AR) for the zones. The varying range of OT, ZI, PN, LS, TS and AR are described using linguistic terms. The discourse domains in the fuzzy set are between *-10 to 35* degree Celsius for OT, *0 to 500* for PN, *0 to 30* degree Celsius for TS, *0 to 400* lux for ZI, *0 to 250* lux for LS and *0 to 50000* litres per seconds for AR. Fuzzification was effected using the triangular membership function. Defuzzification was achieved using the centroid of area (averaging) method, because this supervisory controller does not have to resolve conflicting resolution strategies

6. CONSTRUCTION OF FUZZY RULES

The heuristic rules mapping inputs to outputs was defined using linguistic terms (Table 1) such as if *Outside Temperature* is Cold, *Zone Illuminance* is *Dark* and the *Passenger Number* is *Many* then provide *Winter* temperature set-points, lighting is *Bright* and *Airflow Rates* is *Many*. An in-occupancy scenario might read if *Outside Temperature* is *Cold, Passenger Number* is *None* and *Zone Illuminance* is *Dark* then provide Winter-un-occupied temperature set-point, *Light Levels* is *Off* and *Airflow Rate* is *Un-occupied*.

The thirty-six fuzzy rules (Appendix 1) for this controller were defined using Mamdani Fuzzy Modelling [21]. In this approach, the antecedent and the consequent proposition are expressed linguistically. The linguistic terms are summarised in table 1.

TABLE 2. LINGUISTIC TERMS FOR INPUT AND OUTPUT VARIABLES

Parameters	Meaning	Type	Linguistic Expression
OT	Outside Temperature	Input	Cold, Medium and Hot
ZI	Zone Illuminance	Input	Dark, Dim and Bright
PN	Passenger Number	Input	None, Few, Average and Many
TS	Temperature Set-Point	Output	Winter-Unoccupied, Winter, Medium, Summer and Summer-Unoccupied
LS	Lighting Set-point	Output	Off, Dim and Bright
AR	Airflow Rate	Output	Unoccupied, Few, Average and Many

7. CASE STUDY OF AIRPORT BUILDING

The case study UK airport composes of three terminals (Terminal 1, 2 and 3). The case study is based on Terminal 2 only. This terminal was constructed in 1992 on the North-West part of the airport site. The terminal is made up of five-floor central building covering a gross floor area of about 18,000 m^2 and has two piers of four floor levels measuring about 5,400 m^2 spanning to the left and right direction of the central building. The ground and the first floor contain the arrival halls, the third floor, the departure halls, and the fourth floor is made up of lounges, offices and the control room on the central building it mainly housed the plant rooms on the piers. The fifth floor is mainly plant rooms.

The building is heated by gas boilers located in the central and eastside of the terminal. For cooling, there are air-cooled chillers externally located on steelwork frames in the main plant rooms. The air handling units comprises of Inlet damper, mixing box, HPHW Frost Coil, Panel Filter, Bag Filter, Carbon Filter, Cooling Coil, HPHW Re-heat Coil, Supply Fan, Extract Fan. The building has no lighting and Dayligthing control but the luminaries are currently being upgraded and the installation of lighting control is being considered. For the purpose of this study, lighting control is included as part of the energy use model.

Terminal 2 is a jet only terminal with low cost, charter and long haul carriers. The smallest regular aircraft type is the B737-300 with 148 seats, and the largest is Virgin's B747-400 with 456 seats. This information was used to estimates the passenger number per giving flight time. The flight arrival and departure data was collected from the Airport Information Desk, a central database containing the flight information. The external temperature data for the simulation was retrieved from the British Atmospheric Data Centre (BADC). The airport building has large glass window areas which is suitable for daylight control. Available illuminance for the period of October 26th to November 2nd was estimated from global and diffuse horizontal illuminance variation based on ten years of measurements by the Building Research Establishment (BRE) [22].

8. Modelling of Building Geometry and HVAC Systems

The building geometry was modelled in DesignBuilder by importing the 2D AutoCAD drawings of the building. The external walls were traced, and the building zones are defined based on occupancy type and according to the segmentation of the HVAC system in the indoor space for each of the floors. The thermal zone calculation method in DesignBuilder is a heat balance model. The basic assumption of heat balance models is that air in each thermal zone can be modelled as well stirred with uniform temperature throughout. This is a little different from reality but computationally cost-effective compare to detailed CFD modelling. *Figure 3* shows the resulting 3D geometry of the building.

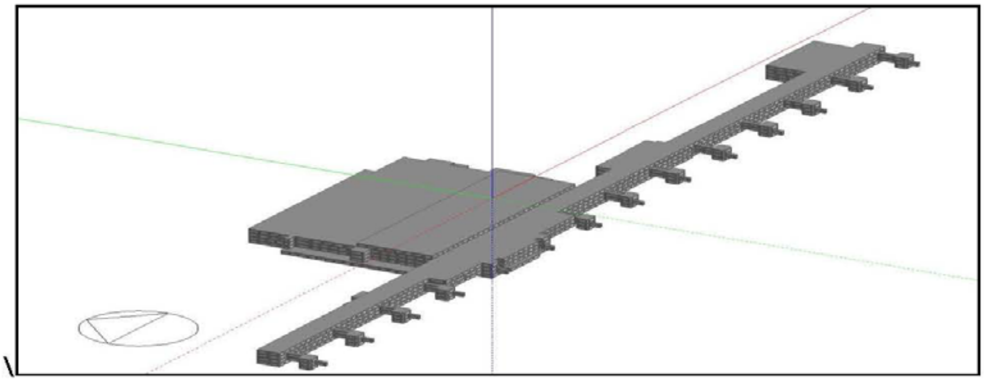

FIGURE 3. A 3D VIEW OF THE DESIGNED MODEL

The HVAC and daylight modelling was carried out using a recently approved Version 3 of EnergyPlus which allows access to a wide range of HVAC systems through an easy to use diagrammatic interface and parameter calculations.

For this case study, there were twenty-two thermal zones in the building. However, these zones were further sub-grouped into six zone groups according to the HVAC system type. The building model was zoned according to passenger flow such that the areas accessible to the public were separated from the areas that were restricted to only passengers and staff. Occupancy in the restricted areas such as the check-in, customs, security, passport control and baggage reclaim areas can easily be linked to arriving/departing passenger planes. However, in the public spaces such as the booking hall, some retail areas and some offices, the flow of people depends on many factors that are difficult to estimate, making them more complicated to control. The model was checked by ensuring that occupancy data was inherited correctly so that changes at block and building level produce the needed effect.

9. FUZZY CONTROLLER SIMULATION AND DISCUSSION

The controller supplied comfort set-point for 45 minutes, 1 hour and 2 hours before the next departure time and then relapses to the setback mode until 45 minutes, 1 hour and 2 hours before next departure. For arrival, comfort setpoints is relapsed to setback mode 45 minutes, 1 hour and 2 hours after arrival as shown in *figure 4*.

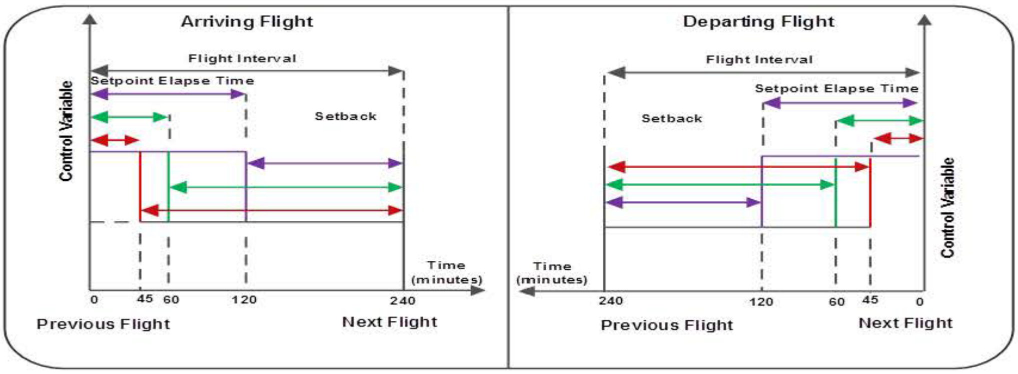

FIGURE 4. ILLUSTRATION OF SET-POINT ELAPSE TIME AND SETBACK TIME FOR ARRIVING AND DEPARTING AIRCRAFT

These times were chosen to gauge the benefit in terms of energy use and comfort when comfort set-points from the controller is run for

(1) a period less than standard processing times (45 minutes) to simulate the maximum passenger processing times recorded in CAA survey [17]

(2) a standard processing time (1 hour) as recommended by ICAO [16]

(3) a rare extended processing time (2 hour) to accommodate delays in passenger processing.

Figure 5, 6 and 7, shows how the controller rules connect input variables to output variables.

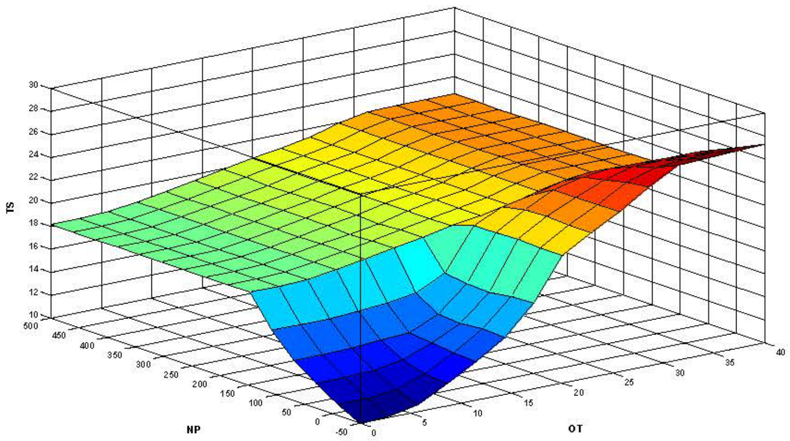

FIGURE 5. SURFACE VIEW RESULTS MAPPING INPUTS NP, OT & OUTPUT TS

Figure 5 shows how temperature set-points (TS) change in relation to passenger numbers (NP) and external temperature (OT). For example; when the zone is un-occupied (passenger number is zero) and external temperature is less 10 °C (during winter) or over 20 °C (summer); the controller relapses the set-point to its setback temperature of about 12 °C (winter) or 23 °C (summer) to conserve energy. However, when the place becomes occupied, the controller provides comfort set-points commensurate with the comfort requirement for that zone based on whether outside condition is winter, midseason or summer. There is still a variation in set-point to accommodate for different temperature perception depending on the season, but the changes are much smaller relative to standard room temperature of 20 °C. Therefore, temperature set-points depend both on occupancy and changes in external conditions.

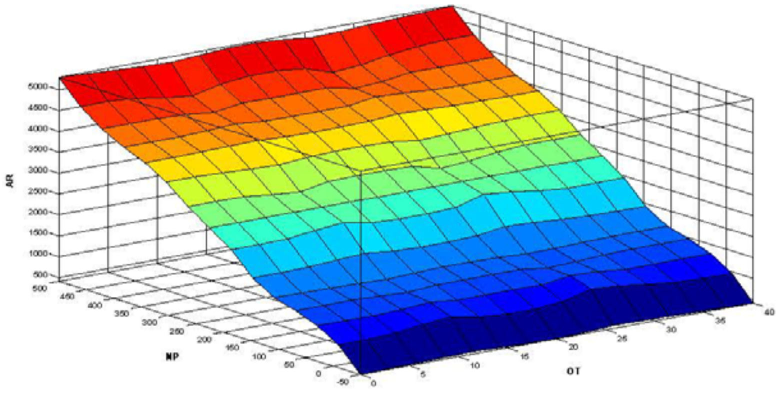

FIGURE 6. SURFACE VIEW RESULTS OF MAPPING BETWEEN INPUTS NP & OT AND OUTPUTS FOR AR

Air Flow rates (AR) as in *figure 6* on the other hand varies directly with the estimated arriving or departing passengers at a giving time. This explained the rise in airflow rates (AR) as the passenger numbers (NP) increases. Ten litres per second per person was provided for each passenger being the minimum fresh air requirement recommended by CIBSE [23] for such place.

During period of unoccupancy, up to 1000 litres per second is still provided to support non-passenger activities.

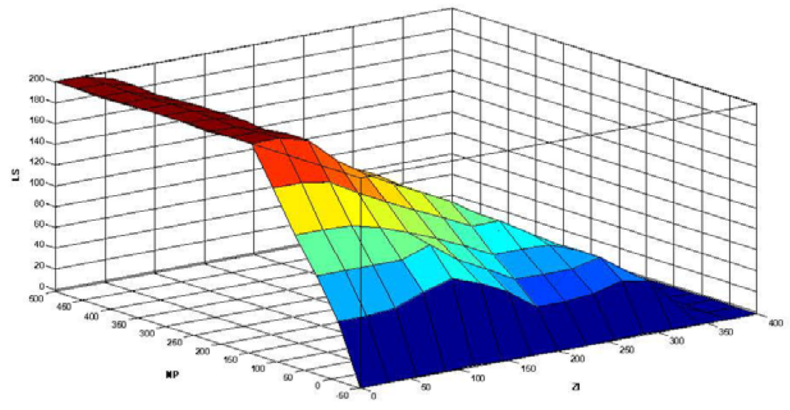

FIGURE 7. SURFACE VIEW RESULTS OF MAPPING BETWEEN INPUTS NP & ZI AND OUTPUTS LS FOR ARRIVAL HALL

Lighting set-points (LS) of 200 lux was provided when occupancy was predicted to occur and it is off when the zone was unoccupied as shown in figure 7. This was because according to CIBSE Guide A [23] 200 lux is recommended as minimum for most indoor spaces within the terminal except offices and shop areas.

Dayligthing control was also included as the lights are dimed or switched-off depending on the adequacy of the daylight illuminance within the zone. This lighting control does not include security and a task light that may be used by the staff if higher illuminance values are required at the desk for passenger processing.

The set-points for heating, airflow rate and lighting supplied by the supervisory controller in SIMULINK were converted EnergyPlus compact schedules and then applied to the building model in DesignBuilder. This simple implementation is possible because the supervisory controller uses no feedback, so it does not depend on measurements from within the building.

10. Simulations in DesignBuilder

In the baseline scenario, HVAC and lighting systems were scheduled to run for 24 hours and a temperature set-point of between 21 °C and 23 °C was applied to all the indoor spaces of the terminal building to simulate the average condition of what was observed from the indoor monitoring results carried out in the airport. For the energy saving scenario, compact schedules generated from the fuzzy controller outputs for temperature set-point, lighting set-point and airflow rates schedules were incrementally applied to the selected indoor spaces (check-in, customs area, gates etc.) while other indoor spaces (offices, shops etc.) were run on full schedules.

11. Results

The simulation results are shown in Figure 8. In the legend, the abbreviations shown in Table 3 are used.

TABLE 3. SCENARIOS IN THE SIMULATION RESULTS

Abbreviation	Meaning
BC	Base Case
TS	Temperature Set-point
AR	Airflow rates
LS	Lighting Set-point
PMV	Predicted Mean Vote

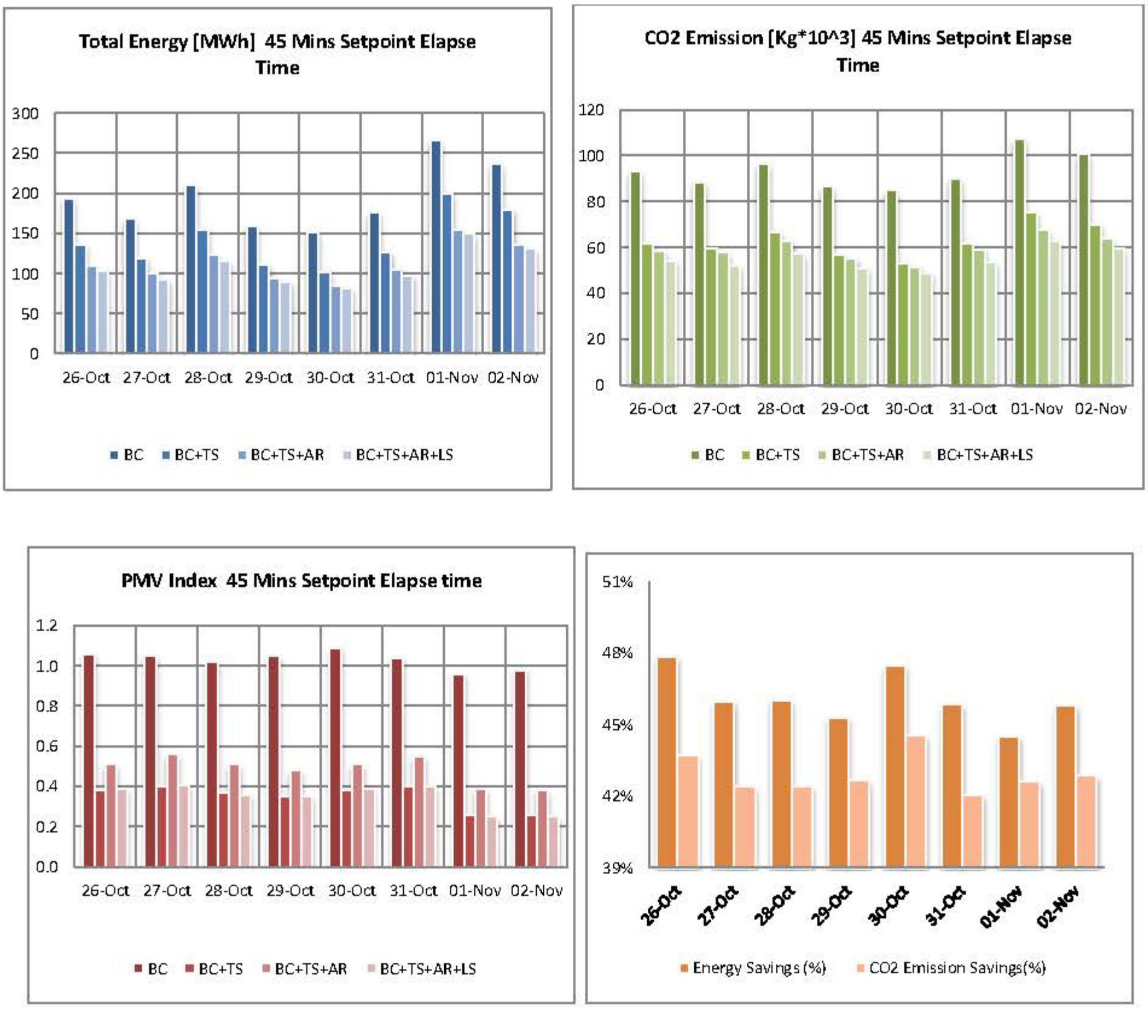

FIGURE 8. RESULTS OF 45 MINUTES SET-POINT ELAPSE TIME

From figure 8, it can be seen due temperature setback during un-occupy period, comfort during occupancy increased from slightly warm to almost neutral, airflow rates setback on the other hand caused an increase in discomfort which was restored by the fall in lighting gains due to lighting control. Comfort level also increase from a PMV value of between 1.1 and 0.9 to between 0.2 and 0.4 for the winter week considered. An indoor thermal environment that has a PPD of less than 10% corresponding to a PMV of about ± 0.50 is considered acceptable [25]. For transitional spaces like the airport a PMV of ± 1 is still acceptable [26, 27]. Energy and CO_2 savings of between 45 to 48% and 42 to 45% respectively can be observed for this scenario.

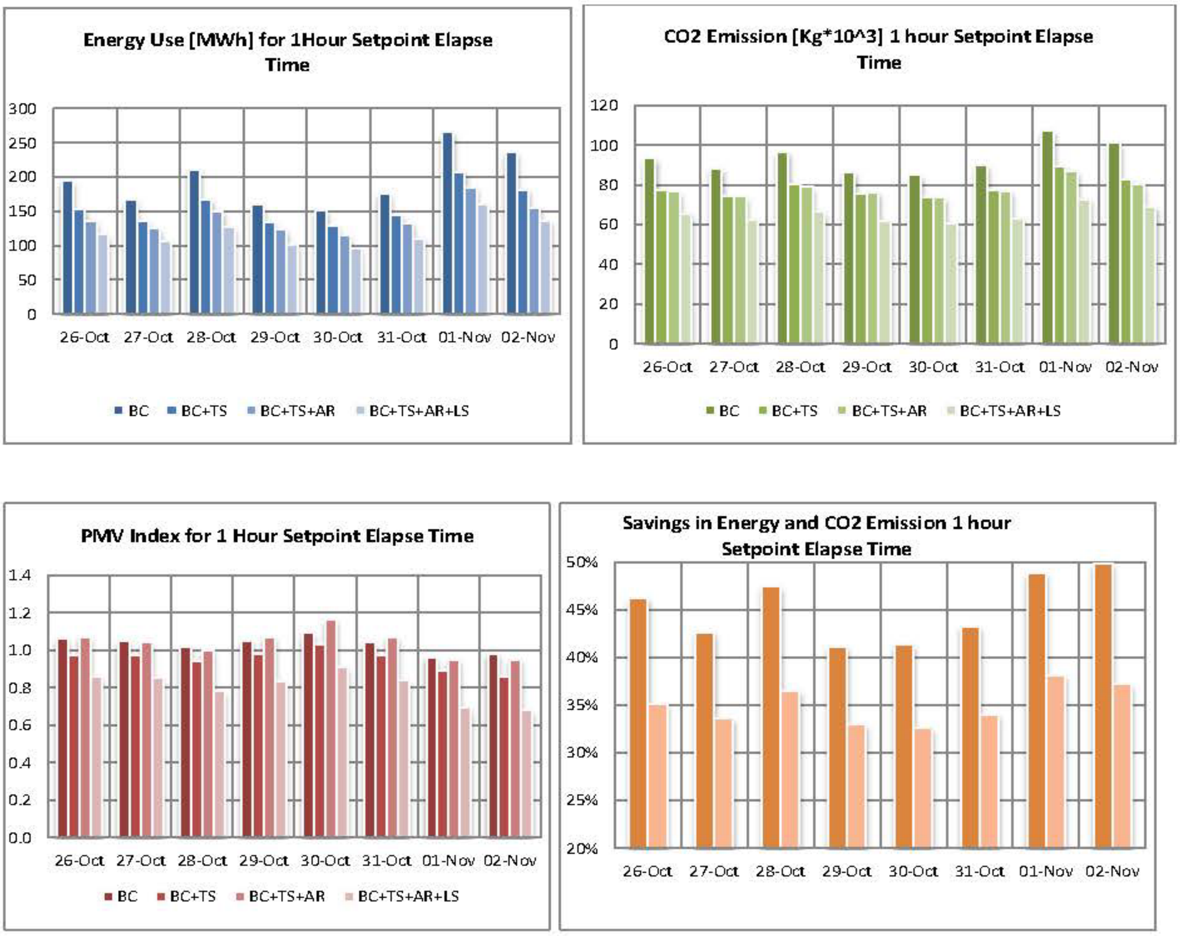

FIGURE 9. RESULTS OF 1 HOUR SET-POINTS ELAPSE TIME

From *figure 9* and is the case with the previous scenario in Figure 8, temperature setback, improves comfort rating, scheduled airflow rates degrade comfort but lighting schedules improve comfort the most. The comfort level also increased from a PMV value of between 1.1 and 0.9 to between 0.8 and 1 for the winter week considered. Also energy and CO_2 savings of between 41 to 50% and 33 to 37% respectively can be observed for this scenario. These results shows a reduction in savings and degradation in comfort level compare to the 45 minutes elapse time.

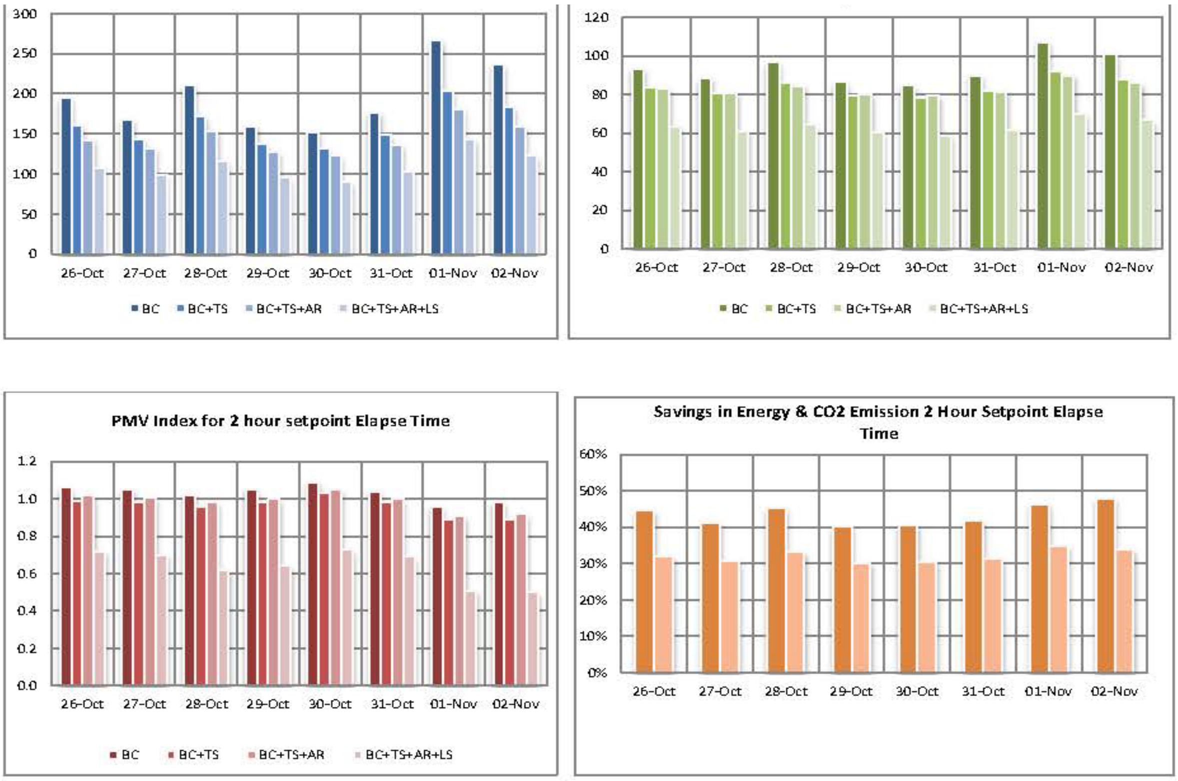

FIGURE 10. RESULTS OF 2 HOUR SET-POINTS ELAPSE TIME

From figure 10, because of the longer set-point elapse time, energy and CO_2 savings of between 41 to 48% and 30 to 34% respectively can be observed for this scenario. The comfort level also increased from a PMV value of between 1.1 and 0.9 to between 0.5 and 0.7 for the winter week considered. Although the savings in energy and carbon emission is less compare to the previous scenarios, comfort is better compare to the 1 hour elapse time.

12. Conclusions

This paper presents the design of a fuzzy supervisory controller in MATLAB/SIMULINK. Its performance is analysed using the thermal model of an existing airport terminal building as a case study. With professional building software, various set-point elapse time and setback operations were investigated. Specifically, the setback operation based on the real time flight schedule, and comfort set-points were applied for both HVAC and lighting in airport terminal building during expected occupancy periods. Simulation results in MATLAB investigating these variable set-points elapse/setback time, passenger numbers and external conditions produces optimised set-points for lighting, heating and airflow rates. Through integrated dynamic simulation in DesignBuilder, these optimised building HVAC and lighting control systems set-points were rated in terms of energy and CO_2 emission savings and comfort vote. The result shows that setback operations based on passengers' occupancy profile could save up to 48% of energy and 45% of carbon emission while still maintaining comfort compare to the baseline scenario.

13. Acknowledgement

The authors gratefully acknowledge the support of Tim Walmsley, Andy Sheridan and Chris Paling of the Environment Group, Manchester Airport for facilitating the effort on data collection. We also acknowledge the financial support provided by the Engineering and Physical Sciences Research Council, UK in its Airport Sandpits Programme and Petroleum Technology Development fund (PTDF) Nigeria.

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EVALUATION OF HVAC SYSTEM OPERATIONAL STRATEGY FOR AIRPORT BUILDINGS

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ABSTRACT

Airport terminals are mostly thought to operate on a 24/7 scale and so indoor environment systems run on full schedules and do not have fine control based on detailed passenger flow information. While this assumption of the round-the-clock operation may be true for the public areas of the airport building and so opportunity for complete shut-down of HVAC and lighting systems are limited especially in a busy airport terminals, there are many passenger exclusive area within the airport in which occupancy varies strictly with passenger flow schedules. This paper analyse the results of indoor environment measurement and flight schedules to identify such opportunities to implement energy conservation measure in passenger exclusive areas of the airport building. It also uses professional building software to rate the benefits of such energy saving interventions in terms of provision of comfort, energy and carbon emission savings.

KEYWORDS

Airport Terminal Building, Energy Conservation in Airport Terminal, Flight Schedule, Thermal Comfort in Airports

1.1 INTRODUCTION

Airports are major magnets of economic growth and development and because only about 5% of the population of the world have ever flown (1), it is an area with huge capacity for further growth. However, like all human activities, airports have great impact on the environment. These impacts includes water and air pollution, waste generation, noise pollution, extensive use of land resources and direct relation with this paper, the use of fossil energy which has been identified as a major culprit for climate change (2-4).

Every year about 200 million people transit through UK's airport (5) which has resulted in demands for huge amount of energy and created an equally huge amount of carbon emission. A large airport can consume more energy than a city of 50,000 households; for example, In 2008 UK's largest airport, Heathrow Airport, consumed over 1000 GWh of energy (6) compared to an average of about 20 MWh (7) for UK's dwellings. Therefore, any little energy saving effort in the way airports terminals are built and operated can have tremendous impact.

It was surprising that; given the stated importance and uniqueness of the airport terminal buildings, published studies on airport built environment energy performances are quite few. Galliers and Booth in a publication by BSRIA carried out a physical and a public's perception survey of some six public transport buildings including an airport terminal. The conclusion was that *public transport buildings have a fair way to go in order to provide the ideal environment for the travelling public* (8). Balaras *et al* (2003) analysed using thermal simulations and collected site data, some specific measures aimed at reducing energy use without compromising comfort in Hellenic airports. By exploring various design options, it was concluded that that potential energy savings of 15-35% exist (9). Babu (2008) proffer design alternatives by varying building fabrics and HVAC configuration (10). Liu *et al* (2009) used CFD thermal simulations, indoor environment monitoring and thermal comfort surveys based on the PMV at Chengdu Shuangliu International Air-port. The result of the study shows that 95.8% of the passengers were satisfied with their thermal environment (11). Griffith et al (2003) actually used the earliest form of EnergyPlus (Ver-sion 1.0.3) to study the influence of advanced building technologies such as optimised envelope systems and schedules for a proposed Air Rescue and Fire Fighting Administration Building at Teterboro airport and found that the results obtained compare well with those obtained using DOE-2.1E (12).

This paper discusses the indoor environmental systems' comfort performance of a UK airport terminal and compares it with the standard comfort requirement for such spaces using Chartered Institute of Building Services Engineers (CIBSE) standards for indoor temperature, relative humidity and lighting levels (13) and Occupational Health and Safety Administration (OHSA) for indoor CO_2 Level. It also analyses the flight schedules to identify the Opportunities for implementing energy conservation strategy such as setbacks and switch offs.

1.2 Site Indoor Monitoring Results

This study was conducted in the Terminal 2 of Manchester Airport. An indoor site monitoring was carried out for winter period from about 26 October 2011 to the 2nd November 2011 and for summer period 22 August 2012 to 29 August 2012. This site monitoring involves mounting HOBO U12 Data logger and CO_2 sensors for a week to measure temperature, relative humidity, lighting levels and CO_2 levels in four separate areas of the airport.

The places monitored include baggage reclaim area, a Duty-Free shop, a departure gate, and the arrival hall. The reason for the choice of these places is to focus on the airside of the terminal where passenger occupancy varies directly with flight schedules as against the landside where the structure occupancy pattern is complex and is not entirely based on passenger flow pattern and so difficult to predict. Some pictures of these places are shown in Figure 1A-D; the position of the sensors is indicated with a red arrow. The more expensive CO_2 sensors have to be hidden from view in some places in order to protect the equipment from theft since the airport is a public place.

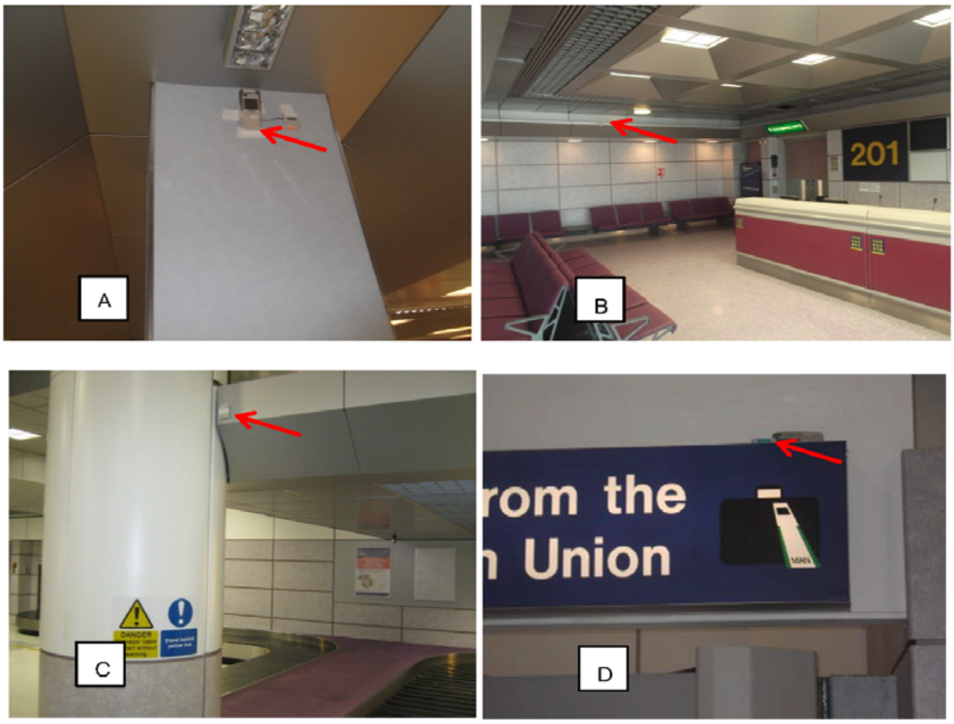

FIGURE 1: (A) PASSPORT CONTROL (B) DEPARTURE GATE (C) BAGGAGE RECLAIM (D) ARRIVAL HALL

1.2.1 WINTER

The indoor temperature of the spaces was monitored and the external temperature derived from the archives of *freemeteo.com* for the same period was recorded. This was because there is a strong correlation between external and internal weather data. It is known that external temperature influence solar heat gains, temperature of ventilation air and the convective and conductive heat exchange across the building fabrics. Therefore, when external temperature profile is compared with the indoor temperature profile it can give an indication of heating or cooling effort needed to achieve the indoor comfort. It can also indicate the opportunities available from the outside environment to meet indoor thermal requirement either purely through passive means and/or with active means. The outside temperature recorded varies from about 2°C on the night of the 28th to the highest day temperature of about 16°C on the 30th and 31st.

1.2.2 INDOOR THERMAL COMFORT VARIABLES

The results for indoor temperature for the monitored spaces are as shown in Figure 2A and this shows that indoor temperature range for Arrival Hall (21 – 22.5°C), Baggage Reclaim (20 - 22.5), Departure Gate (22 - 23°C) and Duty-Free Shop (24 - 26°C) throughout the week as against the CIBSE recommended temperature of 19 – 21°C for Arrival Hall, Departure Gate, Duty-Free Shop and

12-19°C for baggage reclaim area. The variability in the measured indoor temperature among the spaces could have been influenced by many factors. Such factors could include the use of space, adjacency to external building fabrics, heat gains, ceiling to floor height, and positions of the measuring device (sensors) etc.

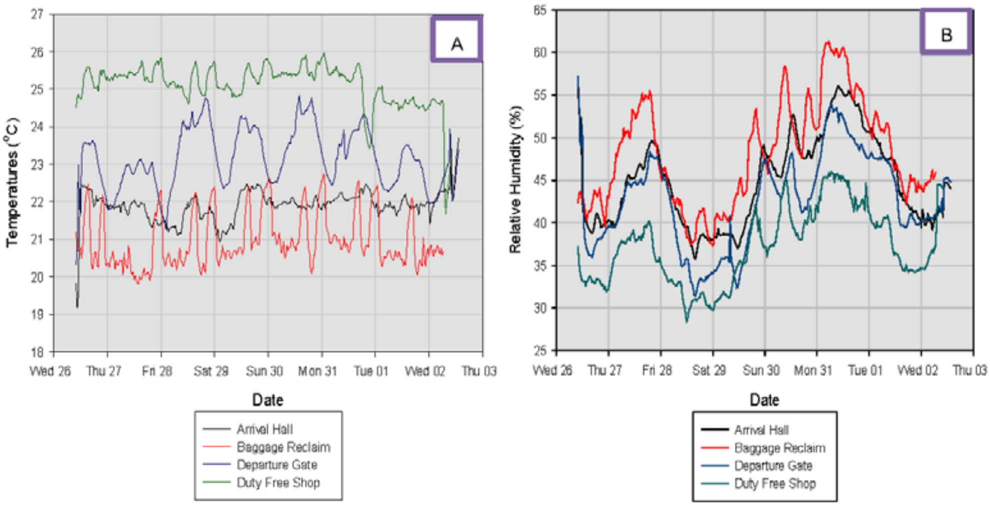

FIGURE 2: INDOOR TEMPERATURE PROFILES

Also, Figure 2B shows the relative humidity profile for the same spaces. The range of values for Arrival Hall, Baggage Reclaim, Departure Gate and Duty-Free Shop is 36-55%, 38-60%, 32-55% and 28-46% respectively as against the 40-70% as the CIBSE recommended values for all kinds indoor spaces. However, CIBSE Guide A also mentioned that a relative humidity lower than 30% is acceptable where risk of static electricity is low and above 70% where risk of microbial growth is minimal as such it is not uncommon to see practitioners quoting 20 - 80% as the acceptable range for comfort. Additionally and more important to the passenger exclusive areas of the airport, lower relative humidity is acceptable in areas of short duration of occupancy. In this context, therefore, the relative humidity values recorded for all the indoor space except the Duty-Free Shop are acceptable. In the shops, attendants remain in the space for a long duration of time, so while it may not matter to the passenger, 28% relative humidity may be not be acceptable to the staff but then this level was only reached briefly on a Friday afternoon, otherwise, it has been within acceptable level for the rest of the times.

By plotting the measured indoor temperature and relative humidity represented by the yellow shade and the CIBSE recommended setpoints for the same variables depicted with the blue shade on the psychometric chart shown in Figure 3; it can be seen that the indoor environments are warmer than they should be. In terms of relative humidity however and in virtually all the space monitored, the level is within the acceptable limits (20-80%).

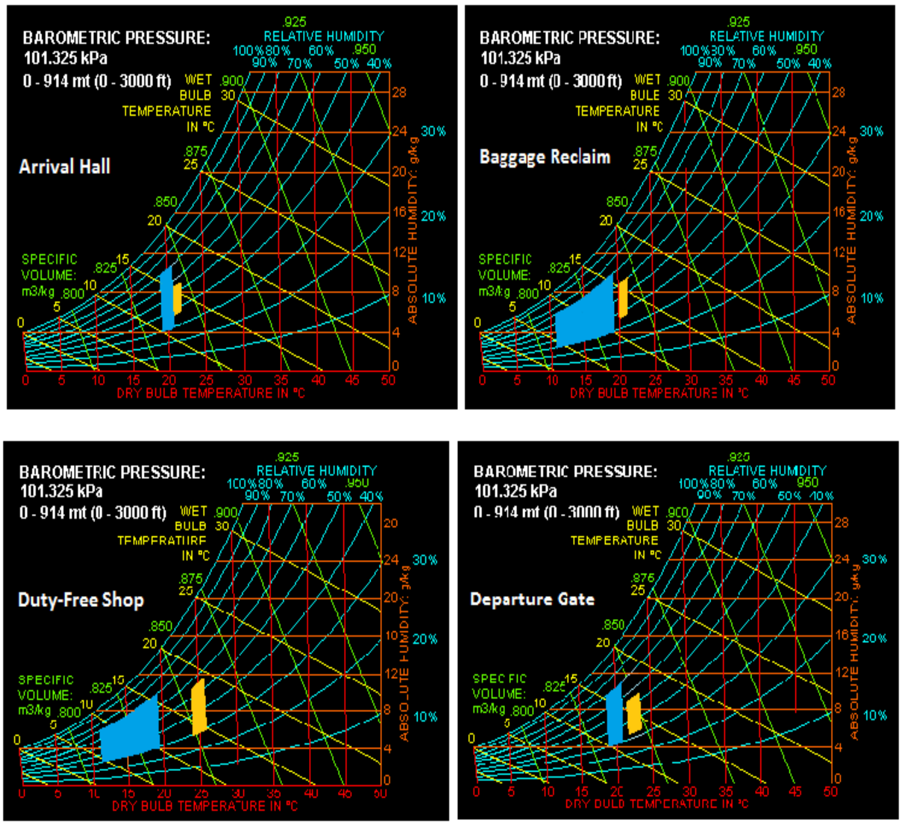

FIGURE 8: MEASURED VS. RECOMMENDED COMFORT VARIABLE

1.2.3 INDOOR CO_2 LEVELS

CO_2 is a surrogate gas in indoor spaces that can indicate human occupancy. It is also an indication of the amount of fresh air injected into the space to dilute pollutants and provides oxygen necessary for respiration. So, elevated CO_2 is a likely indicator of the presence of other air pollutants and a pointer to inadequate ventilation. Although, ANSI/ASHRAE Standard 62-2007 (a very conservative standard for transient spaces) specified that an indoor concentration of no more than 700 ppm above the outdoor concentration will satisfy majority (80%) of building occupants and NIOSH recommends that a concentration of over 1000 ppm was a marker for inadequate ventilation. European standards however limit carbon dioxide to 3500 ppm and Occupational Health and Safety Administration (OHSA) limits carbon dioxide concentration in the workplace to 5,000 ppm for prolonged periods, and 35,000 ppm for 15 minutes.

The CO_2 Levels recorded in virtually all the places monitored was less than 900 ppm during peak occupancy. Comparing this with the standards quoted above, it suggests that these spaces may have been over ventilated.

1.2.4 INDOOR ILLUMINANCE LEVELS

As can be seen from Figure 4, the indoor illuminance level for Arrival Hall, Baggage Reclaim, Departure Gate and Duty-Free Shop is 250-400 Lux, 310-370 Lux, 320-600 Lux and over 310 Lux respectively. These levels are higher than the recommended 200 lux (the brown line in Figure 4) with for these spaces. The indoor illuminance level depends on whether the space in question is exposed to direct daylight and that is the reasons for the high illuminance spikes during the day time in the Departure Gate Area. This made this space suitable for Dayligthing control. During site assessment tour, it was noticed that virtually all the artificial lights are on even in spaces where the daylight illuminance was very high such as the departure gates and departure concourses generally. The reason being that the airport does not have lighting control as at the time this monitoring was done, however new lighting control system was already being considered.

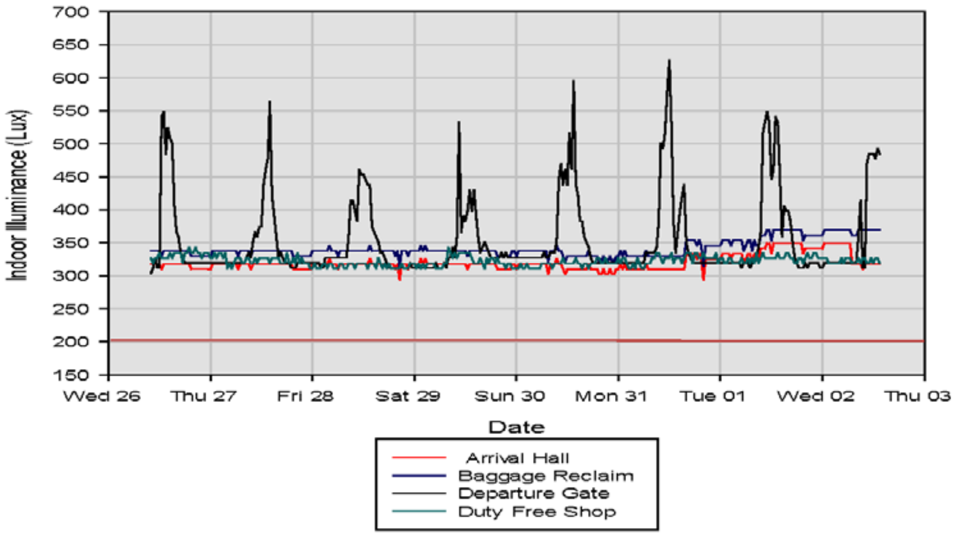

FIGURE 4: INDOOR ILLUMINANCE

It is clear from the analysis of the winter monitored results of the environmental system's performance that the lighting, temperature and ventilation setpoints for winter has exceeded the recommended CIBSE and NIOSH values respectively. This alone will lead to substantial loss in energy. Also, it can be seen from the temperature profile that there was no indication that setback operation is being implemented in the space during unoccupied times. The setback temperature during unoccupied hours will be dictated by the external temperature and occupancy. Also, although relative humidity level is not controlled as part of the airport's HVAC control strategy, the level recorded was about right for comfort in all the spaces monitored except for a short time in the shop.

1.3 SUMMER

External temperature and indoor temperature was measured. The temperature variation was of about 11^{o}C for some nights to about 19^{o}C on some days.

1.4 Indoor Thermal Comfort Variables

This indoor temperature profile in Figure 5A showed a week long temperature range of 22-25°C for Arrival Hall, 24-26.5°C for Baggage Reclaim, 22-23°C for Departure Gate, 22.5-23.5°C Duty-Free as against the CIBSE recommended range of 21-25°C for all the spaces. There was no adjustment of setpoint during unoccupied hours to reduce energy consumption in the airport terminal. So although, the recommended setpoints is the same for all the spaces, recorded temperature shows considerable variation with the Baggage Reclaim area, a deep plan space with no connection to the outside was much warmer. However, the Departure Gate, the only space with an external wall had the lowest temperature.

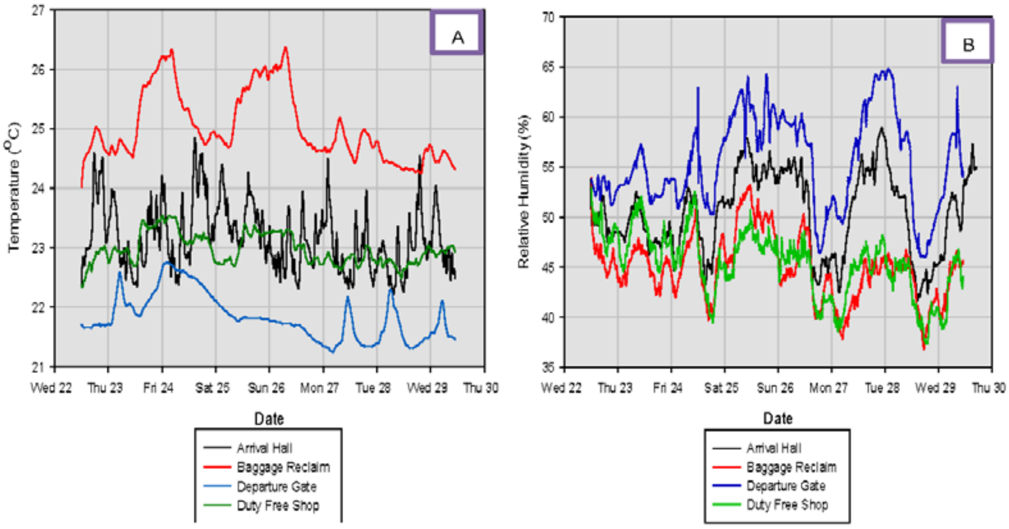

FIGURE 5: SUMMER INDOOR TEMPERATURE

Similarly, the indoor relative humidity value for the indoor places shows considerable variation (Figure 5B). For example, the range of values measured for the Arrival Hall, Baggage Reclaim, Departure Gate and the Duty-Free Shop was 43-58%, 37-53%, 46-65% and 37-53% respectively. In spite of this variability, the range in all the spaces monitored fell within the acceptable level for comfort.

By juxtaposing the plotted measured indoor relative humidity and temperature (Yellow shade) with the acceptable values (Blue shade) for these variables on the psychometric chart as shown in Figure 6, it can be seen that the indoor spaces are a bit warmer than they should be. Space temperature control for comfort usually has a deadband (interval between higher and lower comfort setpoint) of several degrees for most indoor spaces, in fact ASHRAE Standard 90 requires a deadband of about 5 degrees over which controls can modulate (14). What can be deduced from the indoor data collected for both winter and summer operation was that the HVAC is applying tight control (small area covered by yellow compare to the large area covered by the blue shade) of the variables compare to what is acceptable. Although, this is typical of many air conditioned space, it results in high energy cost (15).

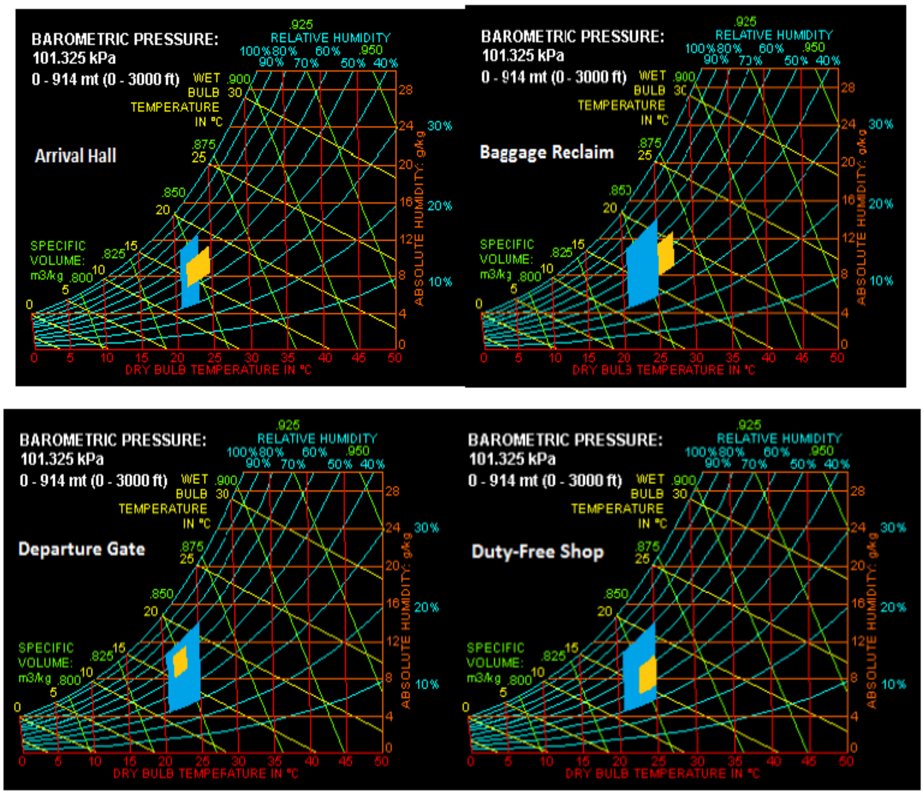

FIGURE 6: MEASURED VS. RECOMMENDED COMFORT VARIABLE

1.5 INDOOR CO_2 LEVELS

The measured CO_2 at peak occupancy is about 1150 ppm. While this is just about fails the requirement for ASRAE Standard 62 and NIOSH recommendations considering an atmospheric concentration of about 400 ppm, it still appears over-ventilated for European and OHSA Standards for transient occupancy.

1.6 INDOOR ILLUMINANCE LEVELS

Also, a look at the indoor illuminance values for the indoor spaces in Figure 7 shows a range of over 250 Lux for Arrival Hall, 300 lux for Baggage Reclaim, 250 Lux for the Departure Gate and 280 lux for Duty-Free Shop as against the recommended 200 Lux (Brown line in Figure 7) for most of these spaces. The difference in the illuminance level between winter (2011) and summer (2012) periods especially in arrival and departure areas are due to upgrade of the terminals luminaires from the metal Halides to TiLite High Bay. According to the installer company, Philips, this has already resulted in about 50% energy savings but the fact that these high illuminance levels were sustained throughout the experimental week shows that there is still room for more energy conservation if the artificial lights can be automatically dimmed or switched off during period of unoccupancy (15). Because the Departure Gate is a day lit space, Daylighting availability ranges from 240 lux to a daily peak of between 300-1000 lux. This was more than sufficient for the requirement of this space, so, incorporating a Daylighting control in this area and similar areas within the terminals will lead to additional energy savings. The difference in illuminance levels among all the spaces monitored in the departure and arrival area might be due to the positioning of the lighting sensors. Illuminance levels will depends on the distance between the sensors and the luminaire and for the security of the equipment and airport operational needs we were not able to place them at the working plane (about 0.85 m above the floor level) as required.

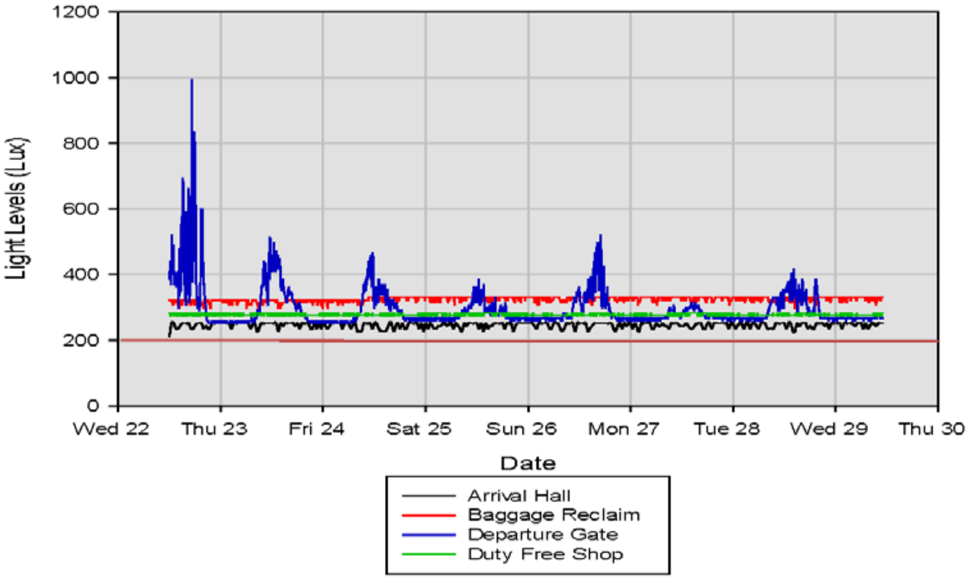

FIGURE 7: SUMMER INDOOR ILLUMINANCE

From the summer and winter results it is clear that opportunities for energy savings abounds within this airport building services. The energy conservation strategy will include providing the right set-points for indoor air quality, thermal and visual comfort during occupancy and setback to energy saving mode during unoccupancy. Relative humidity level was generally OK and so to save energy used in humidification or dehumidification, such intervention may not be necessary for comfort in transient areas.

1.7 Winter Arrival & Departure Times And Intervals Between Flights

Figure 8A below shows plane arrival times plotted against the time-interval between any two consecutive arrivals for the period 26th October to 3rd (8 days) November 2011. If we assume that it takes one hour for passenger to clear from disembarkation to baggage collection as depicted by the area above the blues line in the figure, Up to 51.16 hours opportunity exist for the period under review to implement energy saving strategies. The one hour provision is the ICAO recommended standard period (actually 45 minutes) for passenger processing in an airport (16).

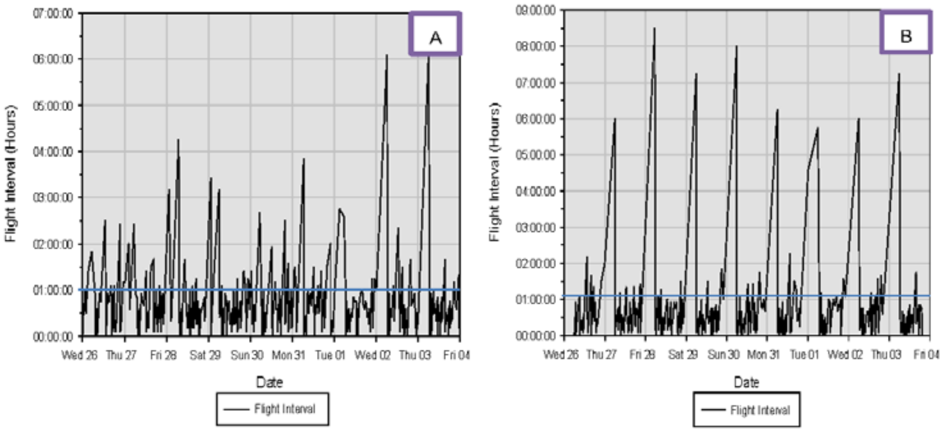

FIGURE 8: (A) PLANE ARRIVAL'S; (B) DEPARTURE'S TIME VERSUS ARRIVAL'S TIME INTERVALS

Figure 8B also shows real time plane departure times plotted against the time-interval between any two consecutive departures for 8 days. By using the 1 hour assumption, Up to 69.05 hours opportunity exist for the period under review to implement energy conservation measures.

1.8 Summer Arrival & Departure Times And Intervals Between Flights

Similarly, Figure 9A below shows plane arrival time-interval between any two consecutive arrivals for the period 22nd to 29th (8 days) August 2012. Based on the one hour clearing time, Up to 21 hours (0.9 days) opportunity exist for the week under review to switch to energy saving mode.

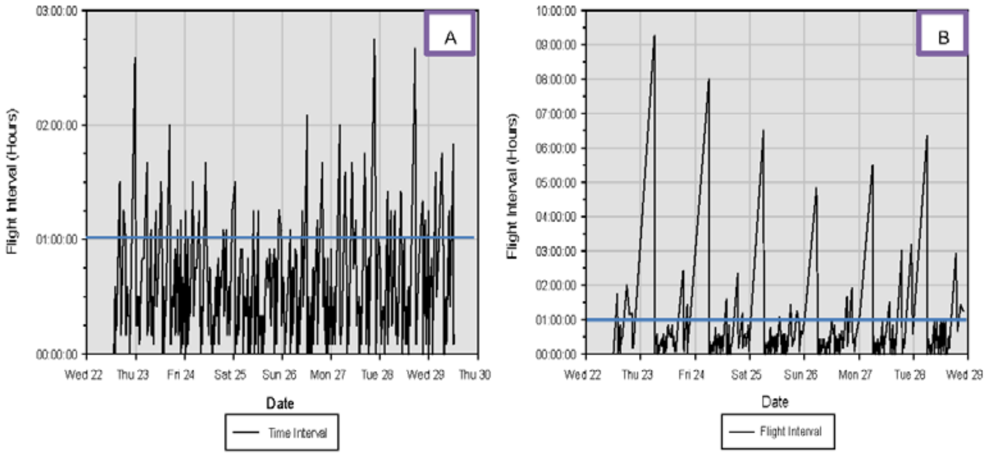

FIGURE 9: A PLOT OF PLANE ARRIVAL'S TIME VERSUS ARRIVAL'S TIME INTERVALS

Figure 9B shows departures for the period 22nd to 29th (about 8 days) August 2012 and has Up to 50.667 hours (2.11 days) worth opportunity existed for energy conservation.

From the winter and summer arrival and departure schedules and as summarised in Table 1, it can be seen that there are more flights in summer time than in winter period (less time interval between flights for the same number of days) and also there are more arriving than departing flights in both seasons.

TABLE 1: SETBACK OPPORTUNITIES IN 8 DAYS MONITORING

Spaces	Winter (Hours)	Summer (Hours)
Arrival	51.10	**21.5**
Departure	**69.05**	**50.67**

A close look at the histographs in Figure 10 showing the distribution of the interval duration for the week under review shows that 70% of the time intervals is in the range of over 1 hour duration in the Winter Arrival, about 82% of the time for the winter departure and about 85% of the time for summer departure. This shows that the time available to implement energy conservation measure for duration of over an hour is in the majority. The distribution in summer arrival however shows that this is a particularly busy period for the airport and so the intervals are tighter and the duration shorter (0-1 forms 70% of the range). The entire distribution shows that there are more arrivals than departure flights for both winter and summer.

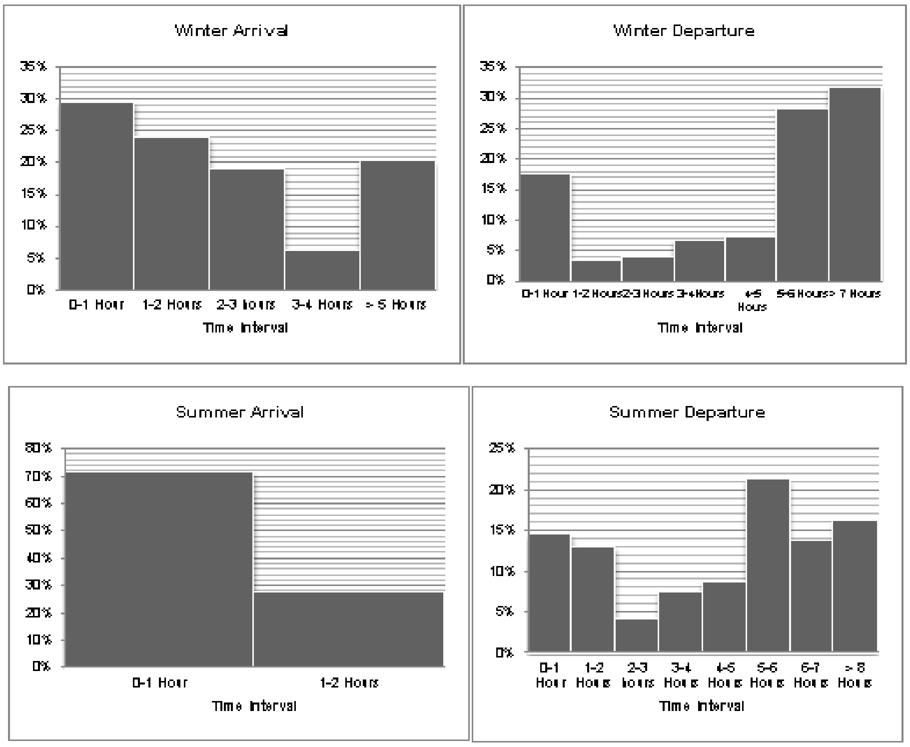

FIGURE 10: DISTRIBUTION OF FLIGHT INTERVAL

When all these energy conservation opportunities are extrapolated across the whole airport terminals and for a whole year, the savings in energy will be significant.

This results shows the need to develop an airport environment management system capable of providing the required comfort setpoint during occupancy and implementing energy conservation measure during unoccupancy by taking into account passenger flow pattern and external conditions.

1.9 Description of Case Study Airport Terminal

Our case study airport is the busiest airport in the UK outside London with an annual turnover of 21 million air passengers transiting through it and about 16,250 employees on site (17). It has two runways operated in two ways depending on the wind directions.

Terminal 2 of the airport was the terminal of interest because although it is the farthest of the three from the runaways the indoor environment systems are currently being upgraded. This makes it a suitable candidate for low energy refurbishing study. This terminal was constructed in 1992 on the North-West part of the airport site. It is made up of five-floor central building covering a gross floor area of about 18,000 m^2 and has two piers of four floor levels measuring about 5,400 m^2 spanning to the left and right direction of the central building. The ground and the first floor contain the arrivals halls, the third floor, the departure halls, and the fourth floor is made up of lounges, offices and the control room on the central building it mainly housed the plant rooms on the piers. The fifth floor is mainly plant rooms. So the airport building's function is already well segregated.

The terminal is heated by gas boilers located in the central and eastside of the terminal. There are air-cooled chillers externally located on steelwork frames in the main plant rooms. The air handling units comprises of Inlet damper, mixing box, HPHW Frost Coil, Panel Filter, Bag Filter, Carbon Filter, Cooling Coil, HPHW Re-heat Coil, Supply Fan, Extract Fan. The building has no lighting and Dayligthing control. However, the luminaires was upgraded, and the introduction of lighting control is being considered.

1.10 MODELLING OF BUILDING GEOMETRY AND HVAC SYSTEMS

The first step in building modelling in DesignBuilder is the definition of location and choice of weather data to match the location. Weather data for Manchester Airport used in this modelling was the hourly ASHRAE International Weather for Energy Calculation (IWEC) GBR Manchester Ringway MN6 data based on thirty years average in EnergyPlus Weather format (.epw) available for free in the EnergyPlus user forum portal.

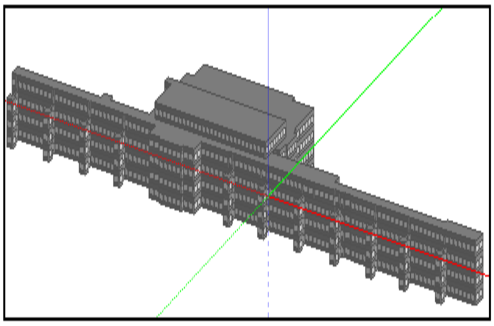

FIGURE 11: MANCHESTER AIRPORT TERMINAL TWO

The building geometry was modelled fresh by importing the 2D AutoCAD drawings of the airport building using the dxf import facility. The model was assembled by positioning blocks in the 3D space to define the external walls based on the CAD drawings. Figure 11 shows the resultant 3D geometric form of the building.

Thermal zones (internal partition walls) were defined based on the functions of the space and type of the HVAC system in the indoor space for each of the floors according to the description obtained from Jacobs Engineering's HVAC system physical survey report and CAD drawings on terminal 2.

For this case study, there are twenty-two thermal zones in the building. However, these zones are further sub-grouped into six zone groups according to the HVAC system type. In EnergyPlus, A "zone" is different from a geometric form; it is an air volume of uniform temperature and all the heat transfer and heat storage surfaces surrounding or internal to the air volume. The building model was zoned according to passenger flow such that the areas accessible to the public were separated from the areas that were restricted to only passengers and staff. Occupancy in the restricted areas such as the Check-in, Customs, Security, passport control and baggage reclaim areas can easily be linked to arriving/departing passenger planes. However, in the public spaces such as the booking hall, some retail areas and some offices, the flow of people needs to be estimated and therefore more complicated to control.

The building construction data, lighting and opening types was chosen from the template to satisfy the Part L Building Regulation for commercial buildings in England and Wales (1990-1994) since according to the report; the building was constructed in 1992 and the details of the airport building material was not available.

The HVAC modelling was done using a recently approved Version 3 which allows access to a wide range of EnergyPlus HVAC systems through an easy to use diagrammatic interface and satisfied compliance rating for LEED, BREEAM and Green Star. The HVAC system specification was also based on the airport's HVAC system survey report.

The HVAC model includes the boilers, chillers, condenser, air handling units (AHU) and the zone groups as described previously. The activity template was based on the BRE National Calculation method specifications for passenger terminal spaces contained in the DesignBuilder activity templates. This template covers occupancy profiles, internal gain data, equipment usage and plant schedules, design indoor temperature, illuminance levels and ventilation rates per person. To create the base case scenario, occupancy schedules, internal gain data and setpoints were adjusted to simulate the as measured scenario.

For the energy saving scenario, compact schedules interface was utilised to supply CIBSE thermal setpoints, lighting setpoints and air flow rates which varies with the passenger flow data. The model was checked by ensuring that occupancy data was inherited correctly so that changes at block and building level produce the needed effect.

The summer and winter week simulation dates was chosen to reflect the monitoring period i.e. 26/10/2011 to 2nd/11/2012 for winter operations and 22-29/08/2012 for summer operations.

The output of the simulation was the total electricity and gas usage in kWh combined to give the total energy usage in kWh, total carbon dioxide emission in kg of CO_2 and Fanger PMV rating. These results were plotted for both the base case and the low energy test cases in bar charts to allow for easy comparison.

1.11 Results and Discussion

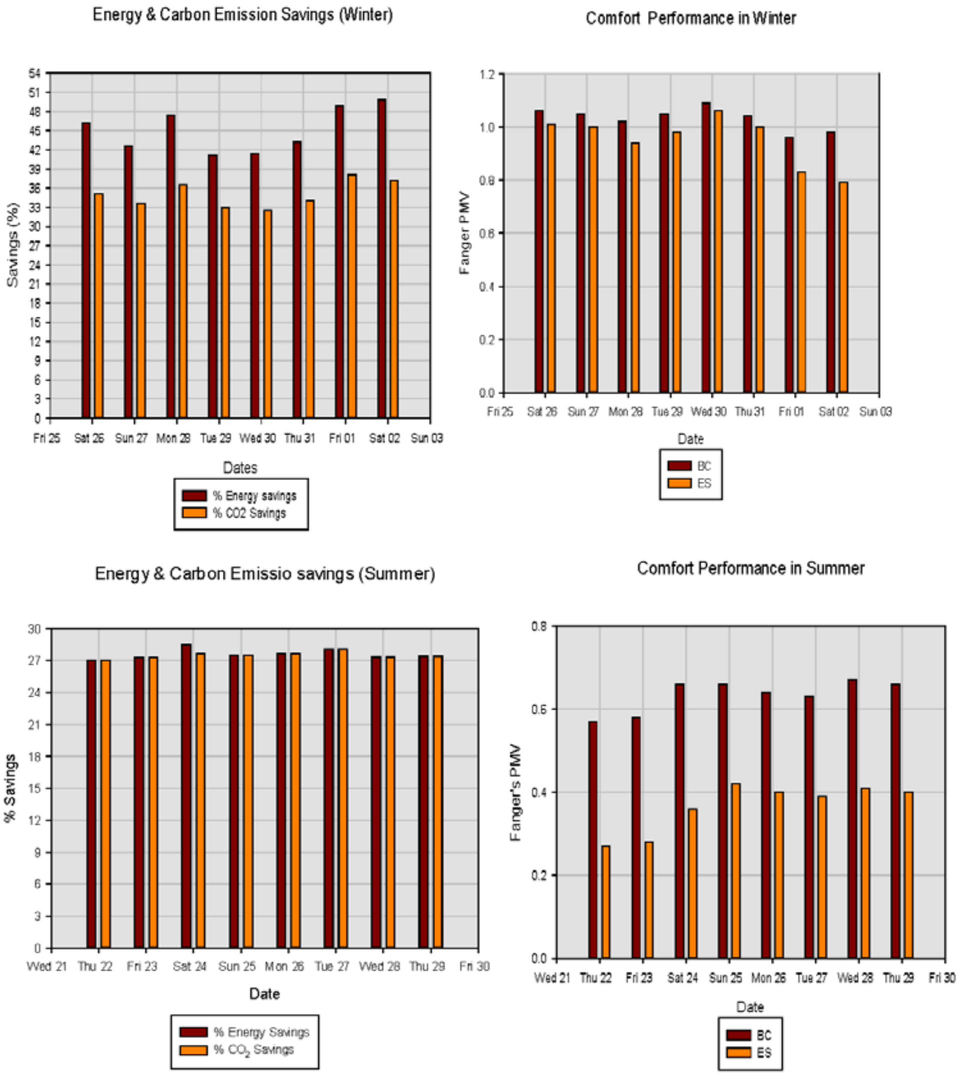

FIGURE 12: ENERGY, CO_2 EMISSION AND COMFORT RATING FROM ENERGY CONSERVATION

From Figure 12 it can be seen that the energy savings of 21 to 27% was achieved for the summer case was less than the 40 to 50% recorded for the winter time. This is because summer times are busier for the airports as such there are less time available to implement energy conservation measure other than just applying the right comfort setpoints. Also, the need for active cooling or heating is generally less considering the prevailing external weather data.

1.12 CONCLUSIONS

This paper presented the analysis of the primary data collected for both the arrival and departure indoor spaces in Manchester airport during winter and summer scenarios. From the comfort variables data analysed, it was seen that that the indoor spaces' temperature, lighting and ventilation was higher than the stipulation in the standards and although relative humidity is not being control, the threshold recorded satisfy the acceptable level for comfort. Tight controls were also noticed in the regulation of temperature; a situation that may lead to higher energy consumption compared to if an adequate deadband is implemented. Also, analysis of the flight schedules reveals that there are sufficient opportunities to implement energy conservation measures especially in the passenger exclusive spaces. This Paper considers varying indoor environment comfort setpoints according to passenger information and this energy conservation could lead to between 20–50% energy savings while at the same time improving comfort.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of Environment Group, Manchester Airport for facilitating the effort on data collection. We also acknowledge the financial support provided by the Engineering and Physical Sciences Research Council, UK in its Airport Sandpits Programme and Petroleum Technology Development fund (PTDF) Nigeria.

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Appendix 6: Paper Published as a Book Chapter in Smart Innovation, Systems and Technologies Series vol. 22, Springer-Verlag

Occupancy-driven supervisory control strategies to minimise energy consumption of airport terminal building

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Abstract

The most cost-effective way to improve the energy efficiency of a building is often achieved through efficient control strategy. Such strategies may include shutting down plant or setting back/up setpoints of indoor environment systems as the case may be during period of un-occupancy and providing optimal setpoints for comfort during occupancy. In most cases airport terminal indoor environment systems run on full schedules and do not have fine control based on detailed passenger flow information. While opportunity for complete shutdown of HVAC and lighting systems are limited in a busy airport terminals due to round-the-clock operation, this paper uses a professional building software to examines the potentials of applying appropriate setpoints during occupancy and setback operation during un-occupancy as an energy saving strategy for the airport terminal indoor spaces. Based on acquired site information, existing HVAC and lighting control system, a thermal model of the terminal 2 building, Manchester Airport was constructed, this base model was upgraded to a more energy efficient model based on real-time passenger flow. Results showing improved energy and CO_2 savings are presented.

Keywords

Building Control, Indoor Comfort, Airport Terminal Building, Building Energy Consumption, Building CO_2 emission savings

Introduction

HVAC and lighting systems in buildings must be augmented with a good control scheme to provide comfort under any varying load conditions. Efficient control is often the most cost effective way to improve the energy efficiency of a building. Airport buildings contain many spaces that are different in functions and structure and the operations within these buildings are round-the-clock. These leads to a complicated building system such as heating, ventilation, air-conditioning, electric lighting and hot water systems that is difficult to predict. This complexity is further compounded by the non-linear and time-varying nature of the variables inside and outside of the building affecting these systems as a result the HVAC and Lighting system are ran on full schedules thereby leading to a substantial waste in energy. This paper examines the potentials of applying CIBSE specified setpoints for visual and thermal comfort with setback operation in the terminal 2 building of Manchester airport.

Comparison and Selection of Simulation tools

Computer based building design and development is beneficial in studying complex buildings such as the airports but the fragmentations within the building industry has reflected in the development of these tools, such that whole-building simulation is still an open issue (Salsbury 2005). For example simulating advanced controller is still limited in most state-of-art building simulation tools. Some are better at specifying local controllers such as TRNSYS and ESP-r while EnergyPlus offer ease in specifying supervisory control (Pan et al 2011). Although domain independent simulation platforms such as MATLAB/SIMULINK, LABVIEW, SIMBAD and Dymola are efficient in design and testing of controllers but they do not have all the models to accurately simulate buildings forms and systems (Marija & Jan 2010).

The complex nature of airport terminal building and systems made us experiment with several building modelling tools in order to develop an accurate model. Since our research thrust is on supervisory control, EnergyPlus was our choice. This is a new generation building energy analysis tool that is suitable for analysing building performances with unusual building systems (Yiqun et al 2011) such as airport. Indeed Griffith et al (2003) used the earliest form of energy plus (Version 1.0.3) to study the influence of advanced building technologies such as optimised envelop system and schedules for a proposed Air Rescue and Fire Fighting Administration Building at Teterboro airport and find that the results obtained compare well with those obtained using DOE-2.1E. Ellis and Torcellini (2005) confirmed the reliability and accuracy of energy plus in simulating tall buildings.

Standard control tools within EnergyPlus includes low level control, high level control and the Energy Management System (EMS) based on the EnergyPlus runtime language (Ellis et al 2007). The low level control simulates a particular closed-loop hardware controls that have a specific task to accomplish. They are usually found in the input of an EnergyPlus object. High level (Supervisory control) operates at a higher level than the local loop in control hierarchy. This type of control affects the operation of local control and can jump across system boundaries and can be used to manage and control the running of other component objects, part of or the entire system.

The major short-coming of EnergyPlus is that it does not have a friendly user interface. To overcome this problem, DesignBuilder was used for our modelling process. DesignBuilder is the first and most comprehensive user interface to the EnergyPlus dynamic thermal simulation engine. It combines rapid building geometry, HVAC and lighting modelling and ease of use with state of the art dynamic energy simulation based on EnergyPlus. Through the DesignBuilder (DB 2011) and for the first time, the advanced HVAC and Dayligthing features in EnergyPlus are now accessible in a user-friendly graphical environment. The latest DesignBuilder v3 now provides a powerful and flexible new way to model both air and water sides together in full detail with a good range of components including all ASHRAE 90.1 baseline HVAC systems.

Results of HVAC Probe

According to a recent physical survey report on terminal 2 of Manchester Airport, it was recommended that energy efficiency improvements across the terminal should include *improving controls and metering in the buildings to allow the setting back of temperatures and the operation of systems outside of occupied hours for the terminal.* From indoor temperature monitoring we conducted of the same building from 26th October to 2nd November, 2011 as shown below, *figure 1* is from the baggage reclaim area of the arrival concourse. It can be seen that the indoor temperature for this area hovers between 20-22 ^{0}C throughout the week under review instead of the 12 – 19 ^{0}C recommended in CIBSE guide A. The same situation was observed for all the spaces monitored in the terminal.

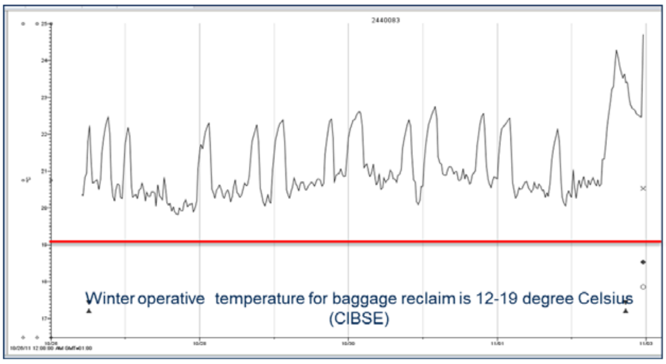

Figure 1. Temperature and lighting setpoint for the baggage reclaim

For example in figure 2 for the departure hall on the airside the temperature band is between 21-24 instead of the CIBSE recommended 19-20^{0}C and the temperature swings for all the spaces monitored does not tally with passenger flow information for the period under review.

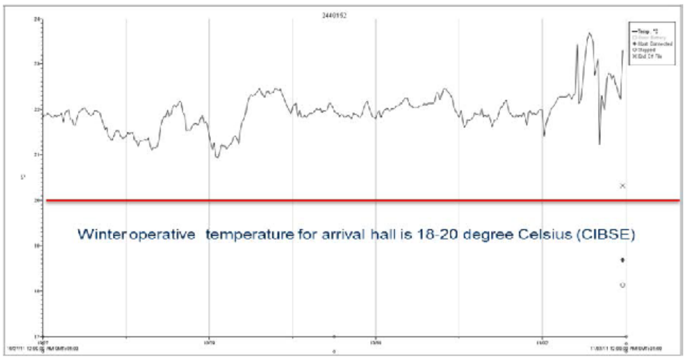

Figure 2. Temperature and lighting setpoint for the Departure hall (Airside)

Real-time Flight Schedules

Also figure 4 below shows real time plane arrival times plotted against the time interval between any 2 consecutive arrivals for the period between 26th October and 3rd November 2011. Here, it is assumed that it takes 2 hours to complete processing of arriving passenger to accommodate any delays, although the actual time recommended by International Civil Aviation Organisation (ICAO) was 45 minutes for international arrival passenger processing from disembarkation to completion of last clearance process (ICAO 2005). For domestic passenger, it is much less. Using the very conservative 2 hours benchmark, Up to 40 hours opportunity exist for the week under review to implement setback operation. When this is extrapolated across the airport and for a whole year, the savings in energy will be significant.

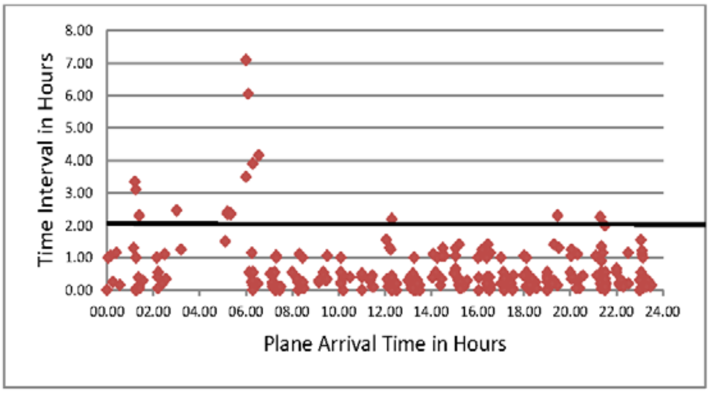

Figure 3. A plot of plane arrival time versus arrival time intervals

Figure 5 shows a similar opportunity to save energy using efficient controls exists in the departure areas of the terminal especially in the airside where only boarding passengers were allowed. 4 hours minimum was selected to accommodates the up to 3 hours check-in time allowed for international flight and delays even though ICAO recommends only 1 hour from presentation at first processing point to the scheduled time of flight departure. About 50 hours (2 days of the week) opportunity exists to implement energy saving strategy. It can also be clearly seen that there are only 2 departures flights between 22.00 hours to 6.00 hours and no flight at all between 0.00 hours and 6.00 hours for the entire week.

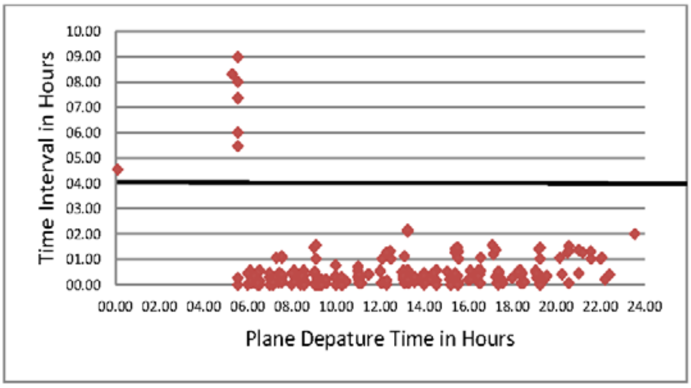

Figure 4. A plot of plane Departure time versus Departure time intervals

Building Layout

Manchester Airport is composed of three terminals (Terminal 1, 2 and 3). Our case study is terminal2. This terminal was constructed in 1992 on the North-West part of the airport site.

The terminal is made up of five floor central building covering a gross floor area of about 18,000 m^2 and has two piers of four floor levels measuring about 5,400 m^2 spanning to the left and right direction of the central building. The ground and the first floor contain the arrivals halls, the third floor, the departure halls, and the fourth floor is made up of lounges, offices and the control room on the central building it mainly housed the plant rooms on the piers. The fifth floor is mainly plant rooms.

The terminal is heated by gas boilers located in the central and eastside of the terminal. There are air cooled chillers externally located on steel-work frames in the main plant rooms. The air handling units comprises of Inlet damper, mixing box, HPHW Frost Coil, Panel Filter, Bag Filter, Carbon Filter, Cooling Coil, HPHW Re-heat Coil, Supply Fan, Extract Fan. The building has no lighting and Dayligthing control but the luminaries are currently being upgraded and introducing lighting control is also being considered and so for the purpose of this research, lighting control will be introduced into the energy efficiency model.

Modelling of building geometry and HVAC systems

The building geometry was modelled in DesignBuilder by importing the 2D AutoCAD drawings in the dxf format and tracing the external walls and defining the zones based on the functions and type of the HVAC system in the indoor space for each of the floors. Figure 7 provides 3D geometric form of the building.

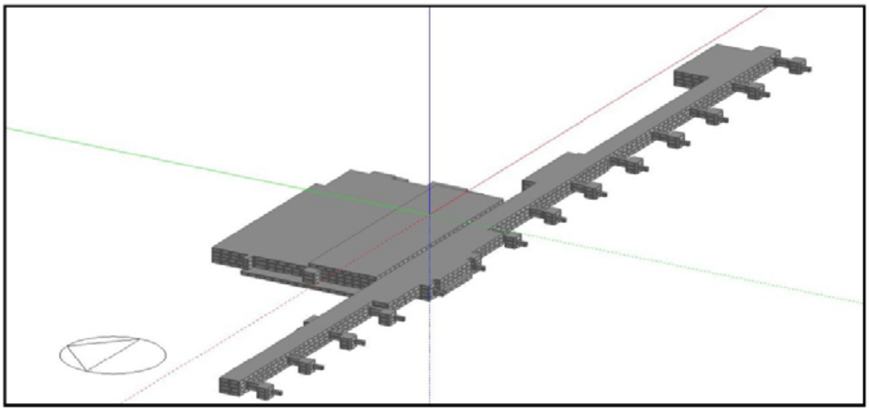

Figure 5. 3D view of the designed model

The HVAC and Dayligthing modelling was done using a recently approved Version 3 which allows access to a wide range of EnergyPlus HVAC systems through an easy to use diagrammatic interface and calculations with integrated graphical daylight distribution contour plots and reports for LEED, BREEAM and Green Star.

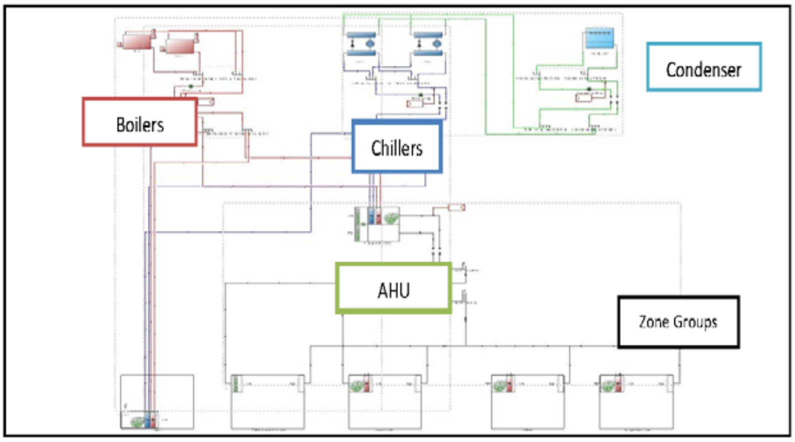

Figure 6 Schematics of the HVAC system

The building was zoned such that the landside area accessible to the general public is separated from the areas that are accessible to only passengers and staff with relevant entry documents. While is easier to schedule environmental systems according to passenger flow in the latter, it is not so for the former. Generally, terminal arrival process is also less complicated as passengers are mostly interested in picking their baggage and checking-out quickly to attend to their travel purpose. The departing process takes longer time and requires more facilities. These explanations are summarised in figure 9 and 10 below.

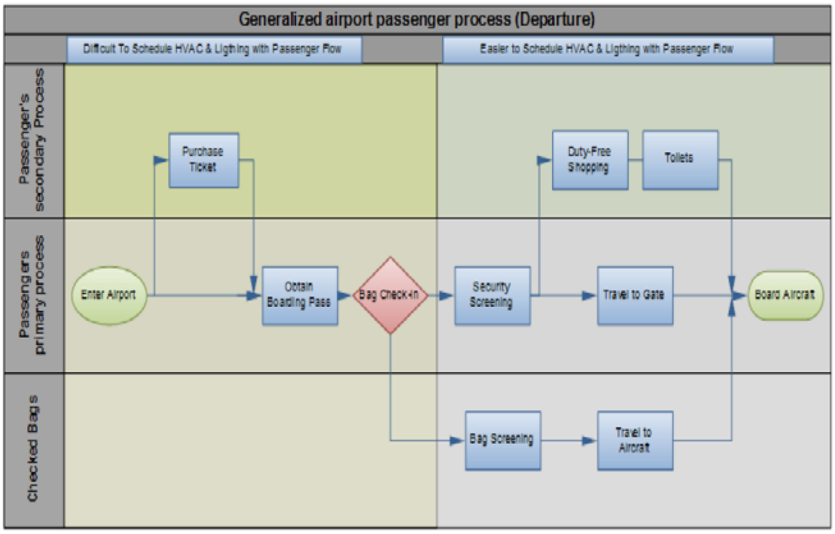

Figure 7. A generalised airport passenger departure process

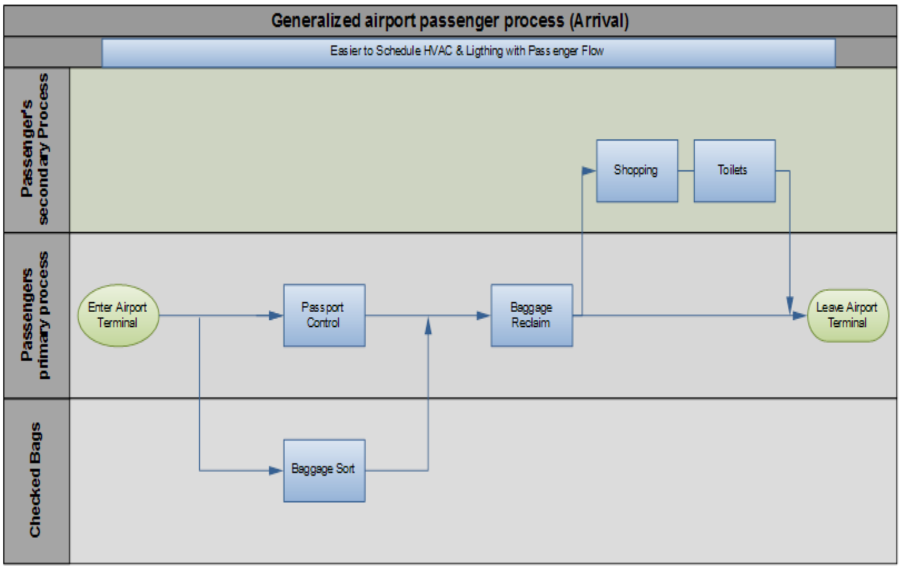

Figure 8. A generalised airport passenger arrival process

The model was checked by ensuring that data occupancy data was inherited correctly so that changes at block and building level produce the needed effect.

Simulations

The base model of the terminal was constructed using the details listed above. For the entire week under review, HVAC and lighting systems was scheduled to run for 24 hours and Temperature setpoint of between 22 - 23 degree Celsius was applied to all the indoor space of the terminal building to simulate what we observed from our indoor monitoring as explained earlier. In the energy saving model, CIBSE guide recommended setpoints was applied to the various indoor spaces. HVAC and lighting systems were scheduled to vary with arriving and departing flight time in the airside (Check-in, Customs, Security, passport control and baggage reclaim areas) areas of the terminal building while the offices and booking hall were scheduled to run for 24 hours. During un-occupancy the heating energy is reduce and indoor temperature is allowed to fall back to 12 degree Celsius and general indoor lights are in energy saving mode. Figure 9 shows how the internal gains vary correspondingly with passenger flow.

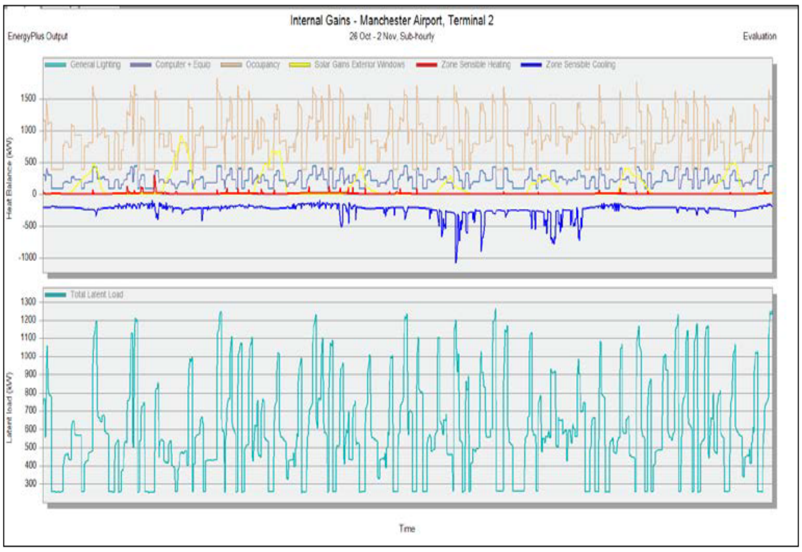

Figure 9. Internal gains for the week under review

Results

The results are summarised in the charts below in figure 10, 11, 12 and 13. It can be seen that selectively relieving HVAC and lighting setpoints to energy saving mode during passenger un-occupancy period has great potentials in saving energy and reducing carbon emission in airport buildings. Up to 60% energy savings and about 70% carbon emission savings results was achieved for our case study in the period under review. Providing the right setpoints as recommended by CIBSE for the various indoor spaces in the terminal is responsible for about 40% energy savings and 30% CO_2 emission savings.

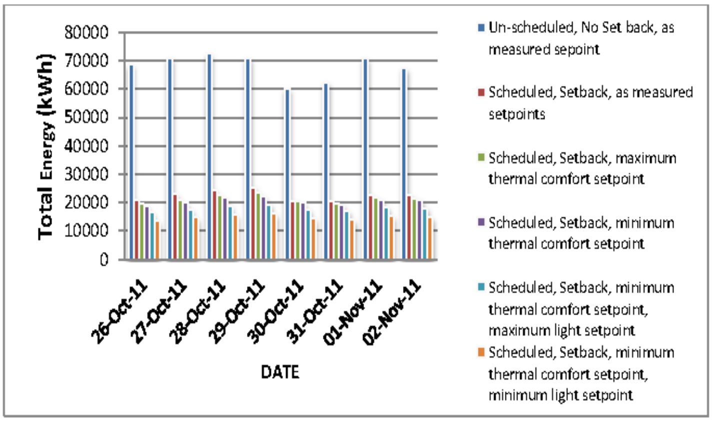

Figure 10. Comparison of energy consumptions

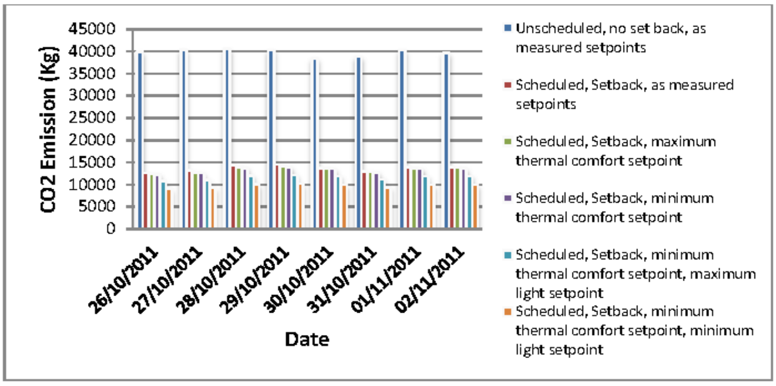

Figure 11. Comparisons of Co2 Emissions from Energy Use

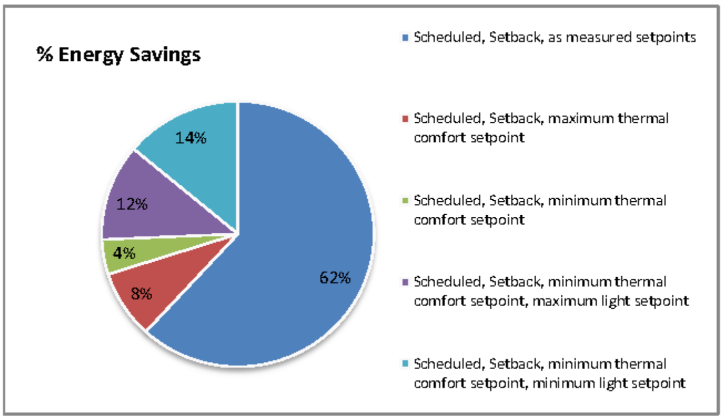

Figure 12. energy saving potentials of retrofit options

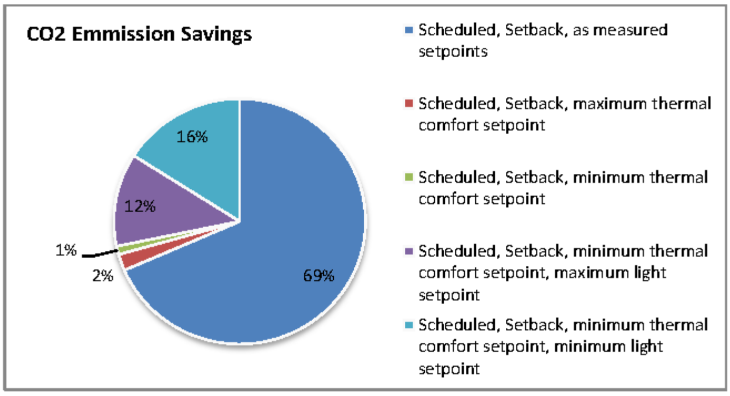

Figure 9. CO_2 emission saving potentials of retrofit options

Conclusions

This paper presented a case study of a Manchester airport terminal building aimed at developing HVAC and lighting control strategies the ensures sufficient comfort and optimal energy use. Through the use of professional building software various supervisory control retrofit options were examined. These options include; setback operation based on real time flight schedule and minimum comfort setpoint application for both HVAC and lighting in airport terminal building. Through integrated simulation of the building HVAC, lighting and control systems were optimised and rated in terms of energy and CO2 emission savings. The result shows that setback operations based on realtime passenger occupancy profile has a huge potential in reducing energy used and carbon emission from the airport terminal building investigated. This investigation is a precursor proof for the design of an intelligent indoor environment control system for airport building which is already being undertaken by us.

Acknowledgement

The authors gratefully acknowledge the financial support provided by the Engineering and Physical Sciences Research Council, UK in its Airport Sandpits Programme (EP/H004181/1) and Petroleum Technology Development fund (PTDF) Nigeria.

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Appendix 7: Paper Published as a Book Chapter in Smart Innovation, Systems and Technologies Series Vol. 12, Springer-Verlag

SUPERVISORY CONTROL OF INDOOR ENVIRONMENT SYSTEMS TO MINIMISE THE CARBON FOOTPRINT OF AIRPORT TERMINAL BUILDINGS – A REVIEW

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ABSTRACT

The issues surrounding the need to cut carbon emissions in buildings include climate change, increasing energy cost, and the need for energy security due to increasing instability in major world supply sources of fossil fuels. The awareness on accruing evidence of environmental degradation from the use of energy has resulted in renewed economic and political pressure which has forced the aviation industries and its infrastructures to be reset within the concept of reducing the effect of global warming and to reduce maintenance and operating cost. Buildings are responsible for 40% of global energy consumption/carbon emission and systems, such as HVAC and lighting, linked to building energy management are responsible for more than half the energy use/carbon emission in buildings. Airport terminal buildings, different in contents and functions to other commercial buildings, are among the energy most consuming centres per square meters on our planet. While energy saving techniques exists for new airport buildings, most of the airport terminal buildings for the next 50 years are already on ground. The engineering response being considered in this research to the problems of carbon emission is the control and integration of active and passive indoor environment systems of the airport terminal building in response to external conditions, passenger flow and occupancy levels. This paper discusses the unique nature, the comfort criteria, the control set-points and control strategy for the indoor micro-climates of the airport terminal building. The initial approach of designing a supervisory controller as a retrofitting part-way to improve the intelligence and sensitivity of the existing indoor environment control infrastructure in a UK Airport will also be presented.

KEYWORDS

Building Control, Indoor Comfort, Airport Terminal Building, Building Energy Consumption, Fuzzy Logic

INTRODUCTION

The answer to what constitute an indoor comfortable environment is very relevant to the way we design and operate buildings also of growing importance is the question of how much energy is consumed to provide a comfortable indoor environment. Interest in energy consumption to provide thermal and visual comfort in work and living spaces was spurred initially by the increase in the cost of fossil fuel and recently, by the accruing evidence of environmental degradation resulting from the use of energy. The UK in 2008 became the first country to sets an ambitious and legally binding target for overall CO_2 reductions of 80% by 2050 relative to 1990 level (DEFRA 2008) as part of the global effort to combat global warming and climate change. Since more than 70% of 2050 buildings are already on ground (Boardman 2007), something has to be done on their carbon emission to achieve this target. While building engineers may not influence fuel or engine technology causing carbon emission in airports, they can help to significantly reduce or eliminate carbon emissions associated with designing, adapting and using of airport buildings. The engineering responses to these concerns include, among other things, optimal use of sustainable technologies such as passive designs and exercising control over the active building components. The amount of heat, air and light introduced to an indoor space will depends on several internal and external dynamics such as the make-up of the building fabrics, the nature of occupants, use of the space and weather (Nikolopoulou 2001). Therefore, overall building energy efficiency will depend more on defining the space comfort requirements and appropriate selection of the climate control system (Piechowski 2007) by taking proper account of the indoor dynamics. Although guidance documents on energy saving retrofit exists of shopping centres, office buildings, convention places and other large scale commercial development, such guidance are not transferable to the airport terminals because of its unique functions and round-the-clock operation (USDE, 2003). USDE (2003) also noted in its report that, based upon the comparison of energy use in airports, building and systems design seems to exert greater influence on energy consumption than the climate or geographical location of the airport terminals. Due to the often large size of the building, even a small improvement could translate to huge savings in energy.

Airport Terminal building

Air transport infrastructure is made up of three components; the airspace, airfield and the passenger terminal. The airspace is occupied by aircraft in flight and the airfield by aircraft on the ground; stationary and in motion. The airport passenger terminals are buildings in airports where passengers transfer from other ground mode of transportation to the facility that allows them to embark or disembark from an aircraft. It divides the airside from the landside and provides facilities that make this transition possible. Passenger terminal is an essential unit of the airport estate. The reputation of an airport depends greatly on the quality of its terminal building. Although the air transport industry is of little stability, the passenger terminal is one of its permanent features. The average life of the airport terminal is about 50 years. This is often more than the life of the airline company and about two to three times the life of an aircraft (Edwards, 1998).

Depending on its capacity, the airport terminal, process millions of passengers per year. Within the airport terminals, passengers purchase tickets, move luggage and go through security checks. Also, in order to maximise marketing and rental opportunities, modern airport terminals are known to contain several commercial spaces. They have extensive restaurants, retail shops and leisure facilities. These have lead to increase in the demand for higher thermal and visual comfort conditions; in fact, airport terminals are among the greatest energy consuming centres per kilometres on our planet (Edwards, 1998). Although energy use within the terminal building is not the highest source of greenhouse emission within the airport infrastructure as shown in Figure 1, it constitutes an important block and system linked to building energy management (BMS) constitute about 75% of total carbon emission due to energy use in the terminal building as shown in Figure 2 (Knowles 2006).

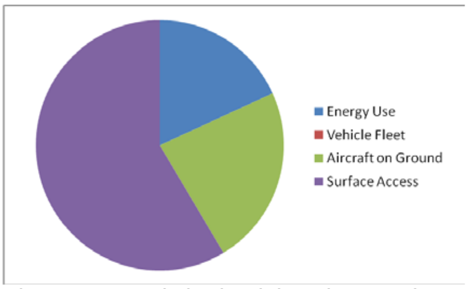

Figure 1 CO_2 Emission breakdown in a UK airport

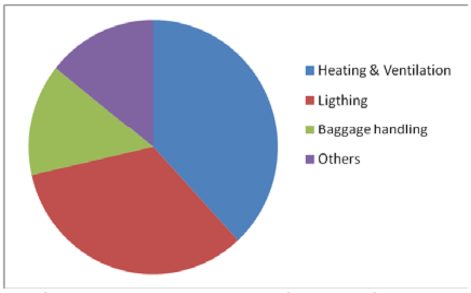

Figure 2 Energy use pattern in a UK airport

Airports terminals are characterised by their large open spaces and high ceilings with not only diverse transient population but the space occupied by people in relation to the total volume of the enclosure is small (Piechowski 2007, Murakami, 1992). The high ceilings result in large vertical temperature distribution and stratification. Also, as in most large enclosures such as the airport terminals, it is difficult to arrange exhaust and inlet openings in a suitable place. Furthermore, the interior heat sources are often distributed very unevenly causing large distribution in temperature and air velocity in both vertical and horizontal direction (Murakami, 1992). The office and shopping spaces are often open to large scale indoor spaces. All these make the control of indoor environment more difficult (Murakami, 1992). For aesthetic gains glass panels and transparent walls are used extensively to form the walls and roof facade. Thermal environments like this experience rapid deterioration due to radiant heat and the outer thermal conditions (Kim et al 2001). This severely subject the indoor enclosures to the vagaries of the outdoor conditions and make fine control of the indoor climate difficult (Murakami, 1992). Terminal operations is highly dynamic and the interplay between the passengers and the airport terminal processes; check-in, customs, shopping, eating and drinking, waiting, baggage reclaim, is difficult to control and predict because the passengers have freewill and so behave sometimes contrary to expectation (Verbraeck 2002). Peak passenger occupancy in airport terminals is mostly transient and concentric. That is, the passengers occupied the same area for short periods. There is usually a surge in activity and occupancy shortly before the departure or after the arrival of a passenger aircraft. The passengers are mostly engaged in standing on queues, brisk walking, strolling or even occasionally running in the transitional spaces. In the departure lounge there may be some sitting by passengers since most international airlines allows up to three hours check-in times. Sitting is less at the arrival lounge as passengers are mostly interested in getting quickly to their destination.

Both the outbound and the inbound passengers are often dressed or have within reach dress to suite the prevailing outside temperature while passing through the processes at the airport terminal buildings. All these are relevant to how energy is used.

Comfort criteria for Airport Terminal

Comfort condition in indoor spaces is affected by thermal, visual and air quality. In agreement with ASHRAE Standard 55-56, comfort is a 'state of mind which expresses satisfaction with the indoor environment'. It is a subjective response which although may be influenced to some extent by contextual, cultural, physiological, psychological and behavioural factors (Brager & de-Dear, 1996), it is primarily of a strong relation with balance between the body and the environment (Fanger, 1973).

Thermal comfort is measured using the PMV (Predictive mean vote) index (Fanger, 1973). This index is an average rating of a group of people exposed to a particular thermal condition of interest on the following scale: -3 (cold), -2(cool), -1 (slightly cool), 0 (neutral), +1 (slightly warm), +2 (warm), and +3 (hot). An indoor thermal environment that has a PPD of less than 10% corresponding to a PMV of about ± 0.5 is considered acceptable (Oughton & Hodkinson, 2008). The requirement prescribed in the ISO-7730:1994, suggests that for certain indoor spaces the level of thermal acceptability of 80% (PMV of ± 0.73) could be considered acceptable (Olesen 2001). Thermal conditions in airports are met mainly by air conditioners.

Visual comfort depends on the adequacy of lighting. Visual comfort is measured by indoor illuminance level at working plane. Lighting is responsible for up to 30% of electricity use in commercial buildings and offices (Oakley 2000) and up to 40% of energy bill for retail outlets (BRE 2004). Artificial lighting should be used as a supplement rather than a replacement for day lighting. Bordat (2001) reported energy savings from electricity of between 50 – 80% due to integrating day lighting with artificial lighting. Other gains of day lighting in indoor spaces could be to provide; outside view, enough light to work with, enhanced colour rendering and enhanced appearance of place. These improvements have also been shown to be capable of increasing retail sales (Heschong *et al* 2002). Effective integration of artificial lighting and day lighting is achieved when artificial lighting can be switch on, off or dimmed as a function of day lighting levels reaching the work surface. It involves switching on and off light based on occupancy and timers (Salsbury, 2005).

Ventilation is the means through which outside air is deliberately introduced indoors but this strategy comes with energy burden, as such only adequate amount of air should be used. Poor external air condition of airport terminals due to concentrated burning of fossil fuels and noise impacts negatively on the indoor space. These externalities coupled with security issues forces these buildings to rely almost entirely on mechanical ventilation. Mechanical ventilation consumes energy because the outdoor air is often conditioned (heated, cooled, humidified or dehumidified) and cleaned before being introduced indoor and energy is needed to drive fans and modulate dampers. Increase in mechanical ventilation rates will result in energy waste and increase carbon dioxide emissions. Reduction in ventilation rates will save energy but indoor air quality will deteriorate. Demand Controlled Ventilation (DCV) is the method used to reduce heating and cooling needs by adjusting ventilation rates in response to occupancy (Lawrence 2007). DCV is mostly used in buildings with highly variable and sometimes dense occupancy such as airport terminal buildings. Seppanen (2008) stated that between 20-60% energy can be saved when DCV is deployed in airport buildings.

Comfort set-points

The choice of operating thermal set-points such as relative humidity, air and radiant temperatures and air velocity affects occupant's comforts and building energy consumptions (Simmonds, 1993 & Olsen 2000). It is surprising that; given the stated importance and uniqueness of the airport terminal, published studies on thermal and visual comfort of airport terminals are few. Kim et al (2001) described, using numerical simulations, the effect of vertical air circulation on the thermal environment in an airport passenger terminal with induced flow by jet fans. They submitted that comfort in the terminal investigated improves from "slightly warm" to "neutral" due to vertical air circulation. Galliers and Booth in a publication by BSRIA carried out a physical and a public's perception survey of some 6 public transport buildings including an airport terminal. Comparison was made between the physical data, the questionnaire data and relevant standards and guide. The conclusion was that, among other things, *public transport buildings have a fair way to go in order to provide the ideal environment for the travelling public.* Table 1 summarised the result in their work as it relate to the some physical parameters of interest for the airport terminal.

Table 1: Physical and environmental parameters

Parameters	Standards	Standard level	Measured level
Air Velocity	CIBSE Guide A, 2006		0.1 – 0.5 m.s^{-1}
Relative Humidity	CIBSE Guide A, 2006	40% - 70%	30 – 50%
Air temperature	CIBSE Guide A, 2006	Departure lounge Winter: 19 – 21^{0}C Summer: 22 – 24^{0}C	Departure lounge Winter: 13 – 27^{0}C Summer:18 – 27^{0}C
Carbon dioxide	HSE EH40/2000	Average time:15 minutes Concentration: 15000ppm Average time:8 hours Concentration: 5000ppm	400 – 1200 ppm
Light level	BS 8206 PT 1: 1985	200 – 500 Lux	190 – 520 lux

According to Yik et al (1994), it is reasonable to expend huge amount on energy to provide comfort for office buildings and shopping malls, similar expenditure is not justifiable for a queuing enclosures in the terminus. The criteria to be adopted for design should be established on the basis of tolerable limits for passengers rather than thermal comfort consideration. Achieving a PPD of 15 % (EN ISO 7730: 2005) for baggage claim area, concourses and check-in should be acceptable. Table 2 shows the comfort set points for personal and environmental parameters of the airport terminal as in CIBSE Guide A. These studies suggest that the airport terminal environment is indeed a lot different from other indoor spaces and as such does not require the mechanistic application of comfort set-points. In airport terminal each micro space has a separate comfort need.

Table 2: Airport terminal building's environmental parameters

Area	AT [1] (°C)		RH[1] (%)	AV[1] (m/s)	Co_2L[2] (ppm)	LL[1] (lux)	ASR[1] (m/s/p)	CI[1] (clo)		MR[1] (met)
	W	S						W	S	
Baggage claim	12-19	21-25	40-70	0.1-0.3	5000	200	10	1.15	0.65	1.8
Check in	18-20	21-23	40-70	0.1-0.3	5000	500	10	1.15	0.65	1.4
Concourses	19-24	21-25	40-70	0.1-0.3	5000	200	10	1.15	0.65	1.8
Custom	18-20	21-23	40-70	0.1-0.3	5000	500	10	1.15	0.65	1.4
Departure lounge	19-21	22-24	40-70	0.1-0.3	5000	200	10	1.15	0.65	1.3
Shops	19-21	21-23	40-70	0.1-0.3	5000	500	10	1.15	0.65	1.4
Offices	21-23	22-24	40-70	0.1-0.3	5000	300-500	10	1.15	0.65	1.2

AT= Air temperature, RH = Relative humidity, AV= Air velocity, Co_2L= Co_2 levels, LL= Lighting levels, ASR= Air supply rates, CI= Clothing insulation, MR= Metabolic rates, S = summer, W= winter, 1 = CIBSE Guide 2006 A, 2 = HSE

The preceding paragraphs showed that integrated control of indoor comfort in an airport terminal is complex and multivariable and this is due to different activity levels, occupancy schedules, and different microclimates within the same building leading to different set point definition. It is also possible that a good control strategy will present great opportunity to save more energy.

METHODS

Control objective and strategy for the Airport terminal

The control objectives being considered here are:

- To adjust and maintain thermal and visual comfort variables in response, changes in indoor condition, external condition and passenger and staff occupancy.
- To give preference to passive techniques where appropriate because aesthetics, security, noise and high outdoor air pollutants could limit the use of some passive options such as natural ventilation and the use of external shading to reduce overheating in summer.
- To ensure that more energy is saved compare to the conventional systems in use without sacrificing comfort.

To achieve these objectives, this research uses intelligent supervisory control technique to ensure that local controllers regulate:

- Fan speed and damper opening to regulate air in the occupied space in response to the expected level of occupancy made available from flight information.

- Artificial lighting in response to availability of day lighting and occupancy indoor. In visual comfort the input variable of concern is indoor daylight illuminance level at the working surfaces. This is measured by illuminance sensors and compared against the threshold set-point for that space of interest. Although glare also affects perception of visual comfort it is difficult to measure and for transitional space like the airport terminal where occupancy is transient it may not be very important. External shading and blinds are used to control glare, again for aesthetic reasons to allow the outside view such devices are mostly not used in the airport terminal.
- Auxiliary heating and cooling in response to external condition and occupancy. Air temperature, radiant temperature, air velocity and relative humidity are the measurable PMV variables and serves as the input variables for most thermal comfort control. Although activity level and clothing insulation also affects comfort but they are highly variable and often immeasurable and so are often considered as constants.

Fuzzy Supervisory Control

This supervisory controller is to augment the function of an existing low level controller by adjusting its parameters so that control objectives are attained. By this means, the behaviour of the low level controller is tuned to cope with non-linearity and changes in operational and environmental set points. The supervisor can use any data from the control system to describe the system's current behaviour so as to change the controller and eventually achieve the required specifications. In addition, the supervisor can be used to integrate other information into the control decision-making process. So the supervisor being considered in this study will take part of the role of the human operator and so is laced in hierarchy between the field controllers and the human operator (Figure3).

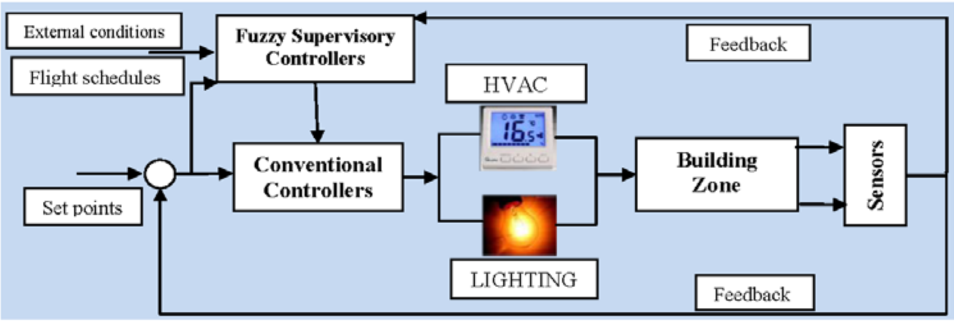

Figure 3 Schematics of the fuzzy- PID control framework

Our choice of focus on supervisory control was a result of field observations and interaction with the BMS engineers based in our airport of interest. Because of the sheer size of the building, there are hundreds of field controllers for thermal conditions and indoor air quality but the robustness of these controllers is contestable. Lighting is still been controlled manually and the BMS system operation was not synchronised with passenger flow. Indoor environment conditions monitored within the airport terminal for three days (from 2.00 pm on 21[st] to 4.00pm on the 24[th] December 2010) as shown in Figure 4 clearly showed that while indoor lighting levels and relative humidity are off the radar of the BMS, the operative temperature ranges between 15 -23 °C without any regards for the time of the day.

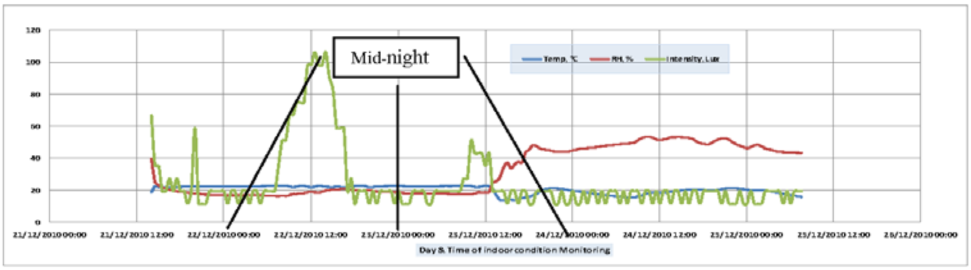

Figure 4 A graph of Temperature, Relative Humidity and light Intensity monitored in a UK airport terminal

Since most airport buildings in the UK already have conventional control systems, supervisory control architecture is a cost effective way to improve the performance of the local controllers. Also, since the control of lighting, ventilation and thermal comfort will require different control strategies; this structure allows the implementation of several control strategies in a single controller. Lastly, to address the industry's apathy to a replacement for the PID, supervisory controller of the type intended here, although an expert system, will simply be an add-on to the conventional PID control elements making it easier to be accepted.

There are other methods for the design of supervisory control (Wang 2008) to solve highly non-linear control problems with promising results such as predictive control, neural network and genetic algorithm. Important researches were conducted on these control strategies, and some have been used successfully in other industries, it is yet to make impact in the building industry mainly due to implementation problems (Dounis 2009). The major shortcoming which they share with the classical control systems is the requirement for accurate model of the system to control and this is difficult for many real systems especially buildings where there exist interplay of several complex variables.

The alternative to these controllers is fuzzy logic controller (FLC). FLC do not require accurate information about plant dynamics and are capable of approximating any real function on a compact fuzzy set (Singh 2006). Human sensation of thermal comfort is not crispy but fuzzy and subjective, as such; classical adaptive controllers requiring crisp comfort inputs compared poorly to fuzzy logic controllers which are robust and are well adapted to regulate fuzzy items (Dounis et al 1995, Hamdi 1998).

The main component of a fuzzy controller as shown in Figure 5 includes the *Fuzzification interface* in which crisp inputs are converted to fuzzy sets, *the knowledge/rule base* which contains knowledge/rule of the application domain, *the inference engine*, a method that interprets the values in the input vector and, based on user-defined rules, assigns values to the output vector and *the defuzzification interface* which converts fuzzy set (Zadeh 1965) defined by the inference engine into a crisp value (Jantzen 1999).

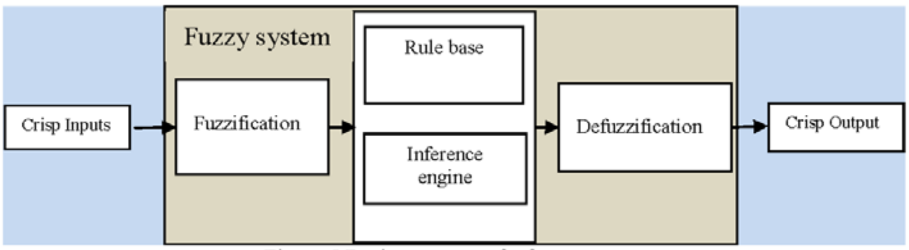

Figure 5 Basic structure of a fuzzy system

It was Professor EH mamdani who pioneered the development of the first fuzzy controller in 1974. Dounis et al (1995) presented the design of fuzzy expert system for the achievement of thermal comfort in buildings. The system was to decide the actuator(s) to trigger consequent upon environmental measurement made in real time. Hamdi & Lachiver (1998) proposed a fuzzy logic system for the control of HVAC based on human sensation of thermal comfort. The fuzzy system evaluates the indoor thermal comfort level based on the inputs of the personal and environmental parameters it received. Kolokotsa *et al* (2001) evaluated different control strategies for thermal and visual comfort, indoor air quality and energy consumption in buildings. The simulation was performed using in MATLAB. From simulation results it was found that adaptive fuzzy PD gave optimum responses and also less energy was consumed because the controller experienced lower overshoot. It was concluded that adaptive fuzzy PD controller minimized thermal energy consumption but for visual comfort the non-adaptive controller is sufficient. Gauda *et al* (2001) uses the PMV index of zero as the threshold for indoor thermal comfort control. This controller is free from set-up and tuning problems of conventional HVAC control strategy. Simulations results of this control strategy maximises indoor comfort and reported a 20% energy savings compare the conventional strategy with less overshoot.

Marjanovic *et al* (2004) discussed the supervisory control for a test room. The controllers were designed for a single sided natural ventilation test room and were based on fuzzy logics. The input data to these controllers were outside wind speed, inside and outside air temperature. Validation was performed using SIMULINK. It was found that the controllers responded well to inputs and were capable of controlling window opening. Calvino *et al* (2004) described fuzzy control of a HVAC system focussed on the application of an adaptive fuzzy controller that avoids modelling of indoor and outdoor environment. Simulation and then experimental validation of this controller was done in a university room. It was also suggested that this method could be used for controlling solar radiations entering the room. Soyguder *et al* (2009a) designed a HVAC system to serve two zones. In this research fan motor speed was controlled using PID controller. Adaptive network based fuzzy inference system (ANFIS) was used. They found that values used to predict fan speed using ANFIS were accurate. Soyguder *et al* (2009b) obtained PID parameters using fuzzy sets. In multipurpose buildings, desired indoor air temperatures may be different depending on the use of the area. For this type of building, flexible HVAC system has to be designed in order to decrease initial and operational costs. This study was aimed to decrease design cost and design process by using modelling and simulation process. A HVAC system with variable flow rate was modelled using SIMULINK. Kp, Ki and Kd (parameters of PID) were determined by using self tuning PID fuzzy adaptive controller. This controller was compared with classical PID and fuzzy PD type controllers. It was found that there were no steady state error and the adaptive controller also has minimum settling time. It was also found that self tuning PID type fuzzy adaptive controller was the best as compared to other two controllers.

What is clear from most of the studies is the absent of rigorous online validation of these controllers in real time and non have been tested for airport buildings. Real time validation is necessary not just to fill the gap in literature but to also shore-up confidence in the controllers and prove the veracity of their astuteness for subsequent adoption in the building industries. Most of these controllers are implemented at local level and very few at the supervisory level. Supervisory control still remains a very open area for research.

This research is using the SIMBAD (Simulator for Building and Devices) toolbox; a commercial software in MATLAB to model the terminal building, the HVAC systems and its conventional control systems (sensors and PID controller) while the fuzzy logic toolbox also in MATLAB is used to model the supervisory control system. The simulation results will be validated by converting the control strategy in to a physical device which will interact with the building and HVAC emulators in SIMBAD via a data acquisition interface.

CONCLUSIONS

This work has reviewed the environmental characteristic of the airport terminal to prove its uniqueness. It touched on the criteria for thermal comfort, visual comfort and indoor air quality and provides the environmental set-points for thermal, visual and ventilation control. It justified the need for supervisory control system for the management of indoor environment of the airport terminal building. Conventional, model predictive and fuzzy logic control strategy were briefly discussed and literature suggesting the superior performance of fuzzy logic in comparison to other control systems was presented. Initial designs of a fuzzy logic supervisory control were also presented. It is hoped that this work will help in reducing energy use in airport building and would provide a cost effective real-time way of gauging the control strategy for an airport building

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by the Engineering and Physical Sciences Research Council, UK in its Airport Sandpits Programme (EP/H004181/1) and our project partner, the Manchester International Airports.

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APPENDIX 8: PUBLISHED AS A CONFERENCE PAPER (ICAC 2012) IN IEEE XPLORE

Fuzzy Supervisory Control Strategies to Minimise Energy Use of Airport Terminal Buildings

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***Abstract*— Airport terminal buildings are among energy most consuming buildings and this presents huge opportunities for implementing energy saving strategies. Achieving satisfactory control of these buildings using classical controllers alone is difficult because they contain components that are complex, non-linear but dynamically related. Therefore, this paper presents and appraises fuzzy control strategies for reducing energy consumptions while simultaneously providing comfort for passengers in an airport terminal building. The inputs into this fuzzy supervisory controller are the time schedule for arrival and departure of passenger planes as well as the expected number of passengers during each flight, zone illuminance and external temperature. The controller outputs optimised temperature, airflow rates and lighting setpoints for the conventional controllers. Simulation studies in MATLAB/SIMULINK confirmed the capacity of this control strategy to provide comfort setpoints for the passengers at reduced energy.**

Keywords- Fuzzy Logic Control, Building Energy Management, Airport Terminal, Carbon Emission, Supervisory Control

I. INTRODUCTION

The problem of carbon emission has made the aviation industry and its infrastructure to be reorganised within the idea of low carbon, energy saving and reduced operating cost. One of the most effective ways of saving energy in large buildings generally is efficient control system based on realistic control strategy for that building. A control strategy described how the achievement of some selected objectives could be realised under the constraints imposed by the process itself, the quality of the available information, and the mathematical tools and support available [1].

PID control and other advanced model-based techniques are typical examples of algorithmic-based control. In order to design these controllers, the mathematical model of the system to be controlled must also be modelled. Building environmental systems are known for their non-linear dynamic behaviours, uncertain and time varying parameters; these characteristics make the mathematical modelling of such systems from first principles very difficult or sometimes impossible. Because they are built on the assumption of a linear system, classical controllers of these systems do not respond well to disturbances and modification [2].

Professor Lotfi Zadeh, an expert of Systems Theory at the University of California, Berkeley, theoretically developed fuzzy logic principle during the first half of the 1960s and for the first time used the word "fuzzy" to describe the logic [3]. However, it was Ebrahim Mamdani who first built a fuzzy logic controller during the early 1970's to control the operation of a steam generator that was difficult to control using the conventional control techniques [4].

Since then, Fuzzy logic theory is now applied to problems in several fields of engineering, business, medical and related health sciences, and the natural sciences.

In line with this development, recently, the use of logic rules in emulating operator thinking, also known as heuristic control based on different techniques has been implemented for the control of building systems and fuzzy logic has featured in many of them. Studies in building artificial intelligence has proved that smart control techniques such as fuzzy control can bring about reduction in energy use while still maintaining comfort [5].

Fuzzy logic control is especially suited for resolving control ambiguity in modelling nonlinear and multi-variable relationships using every day language [6]. Fuzzy modelling has the ability to combine different kinds of information obtained from an experienced operator, measurements and first principle modelling, thus, it employs as much of the available information as needed. Even with vague or imprecise knowledge of those systems, it is still possible for them to be described by an expert in human language, or in nonmathematical terms, using the so-called fuzzy IF-THEN rules [7].

Kolonkotsa et al (2002) used optimisation method based on genetic algorithm to provide optimal comfort settings, which are applied directly on fuzzy logic controllers [8]. Also Dounis et al (2007) developed an intelligent coordinator, which uses fuzzy inference mechanism based on 3D fuzzy sets to produce signal that change setpoints of the primary controllers [9, 10]. Soyguder et al, (2009) applied a self-tuning proportional-integral-derivative (PID)-type fuzzy supervisor to tune the parameters of classical PID controllers with successful results [11]. A more comprehensive literature review on this topic is found in [12].

In most building control applications, a human operator must determine the setpoints for numerous PID controllers and periodically adjust the setpoints to adapt to changing process conditions [13]. Because comfort setpoints changes many times daily, annually and diurnally, updating it manually is a herculean task for operators of large buildings such as the airport terminals. In addition, airport building control operation assumed a 24/7 operations, a study conducted in Manchester airport summarised in another paper [14] found that there are many hours' opportunities in the week investigated to operate energy saving setback strategies. Our approach therefore uses high-level fuzzy logic module to perform set point regulation and supervision for the classical controllers in response to variation in passenger occupancy, external temperature and zone illuminance.

The remainder of this paper was organised as follows; supervisory control strategy was first briefly introduced followed by discussions on the structure of the fuzzy controller, determination of the membership function and construction of the fuzzy rules for the supervisory controller. In the last section, a case study simulation results based on some input data from Manchester Airport was presented.

II. SUPERVISORY CONTROL STRATEGY

This control strategy was developed for zones that are exclusive to the passengers and staff of the airport; such that the occupancy flow pattern can be mapped directly to flight schedules. Airport buildings are often zoned such that the landside areas accessible to the public is separated from the airside areas that are accessible to only passengers and staff with relevant entry documents. The usual practice for transit passengers in many airports is that they are allowed in the general areas such as the shops or other leisure area not covered in this strategy until few hours before their departure when they can move to a particular gate, which is covered in the strategy. This differentiation is necessary in order to capture areas within the terminal in which occupancy varies strictly with arriving and departing planes. In general, terminal arrival process is less complicated as passengers are mostly interested in picking their baggage and checking-out quickly to attend to their travel purpose. The departing process takes longer time. International Civil Aviation Organisation (ICAO) recommends forty-five minutes for international arrival passenger processing from disembarkation to completion of the last clearance process and one hour for the departing passenger from clearance to embarkation [15]. To account for delays in the environmental systems, we are assumed that arriving and departing passenger processing takes one hour each. The additional fifteen minutes to the arrival processing is the time taken to bring the building to the new comfort-setting regime before occupation and this was about the time taken between landing of aircraft and passengers entering airport building.

This fuzzy controller is supervision on top of the conventional control system and its main goal is to increase the operating availability of the process under control based on the functionality of the control space (fig. 1). To achieve this, the controller coordinates the actions of the distributed controllers according to the evolution of the passenger flows and external conditions. The heuristic tools in this strategy are based on operator knowledge obtained from building operation and in-situ measurements of control variable carried in the building.

This supervisory controller is schematically modelled after Yokogawa Electric's temperature controller [13] where the fuzzy supervisory module leads the PID controller along a temperature trajectory that can quickly reach the actual setpoints without overshoot. The difference is that Yokogawa controller is a close-loop system while the one described here is an open-loop system.

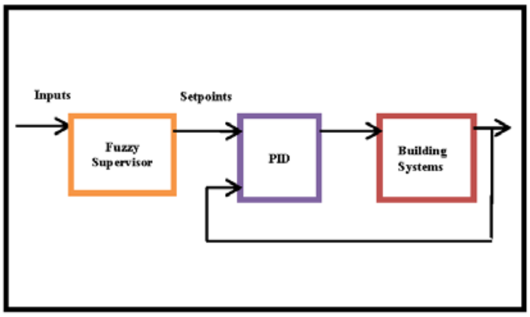

Figure 1. Architecture of control strategy

Contributions to improve the overall performance of the supervised systems is achieved mainly from mapping availability of operating setpoints for identified zones and coordination and management of local control based on passenger flows and variation in external condition. The overall architecture of this control strategy for a zone in the airport building is shown in fig. 1 above.

The controller designed using SIMULINK [16] and Fuzzy Logic Tool box [17] (fig. 2) in MATLAB [18] was fed with information on when a plane is to land/take-up and the number of people on board estimated form the aircraft type. This information can be acquired from the passengers' information desk up-to a week before the actual flight. The controller also receives as input the real-time external temperature and zone illuminance data from the outside temperature sensors and inside lighting sensors respectively. The controller will then provide the required thermal, lighting and indoor air-quality comfort setpoints to the identified zones in the terminal where the passengers will be transiting. These setpoints are available at the landing time of the aircraft allowing the systems to raise or lower the indoor conditions as the case may be to the required comfort range before occupation about fifteen minutes later.

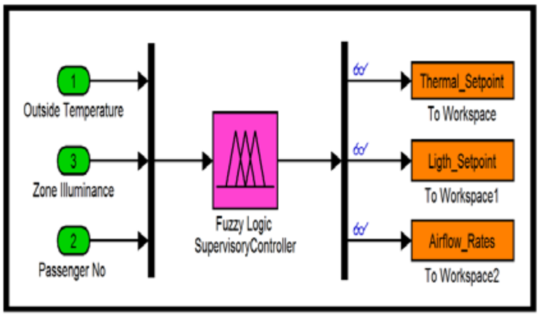

Figure 2. SIMULINK Model of the Supervisory Controller

III. STRUCTURE OF FUZZY CONTROLLER

Fuzzy logic provides a convenient way to map an input space to an output space. Specifically, a fuzzy inference system interprets the values in the input vector and, based on some set of rules, assigns values to the output vector. The mapping then provides a basis from which decisions are made, or patterns discerned [20].

In general fuzzy controller comprises the *fuzzifier* which determines the membership degrees of the controller *crisps* input values in the antecedent fuzzy sets, the *inference mechanism* which combines this information with the knowledge stored in the rules and determines what the *output* of the *rule-based* system should be. The output is a fuzzy set but for control purposes, a *crisp* control signal is required. The *defuzzifier* calculates the value of this *crisp* signal from the fuzzy controller outputs [19].

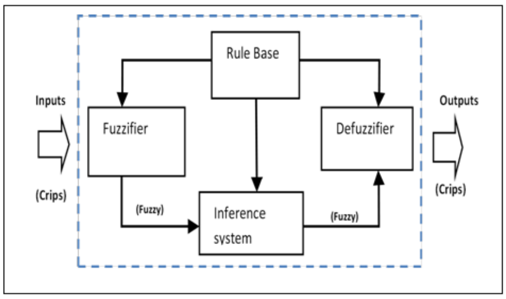

Figure 3. Basic Configuration of a Fuzzy System

IV. Determination of Membership Functions

The controller takes Outdoor Temperature (OT), Zone Illuminance (ZI), Passenger Numbers (PN) at a given flight time as inputs and outputs indoor Lighting Levels (LL), Temperature Setpoint (TS) and Airflow Rates (AR) for the zones. The varying range of OT, ZI, PN, LL, TS and AR are described using linguistic terms. The discourse domains in the fuzzy set are between *(-10 to 35)* degree Celsius for OT, *(0 to 500)* for PN, *(0 to 30)* degree Celsius for TS, *(0 to 400)* lux for ZI, *(0 to 250)* lux for LL and *(0 to 50000)* litres per seconds for AR. Fuzzification was done using the triangular membership function. Defuzzification was achieved using the centroid of area method.

V. Construction of Fuzzy Rules

The heuristic rules mapping inputs to outputs was defined using linguistic terms (Table 1) such as if ***Outside Temperature*** is **Cold**, ***Zone Illuminance*** is ***Dark*** and the ***Passenger Number*** is ***Many*** then provide ***Winter*** temperature setpoints, lighting is ***Bright*** and ***Airflow Rates*** is ***Many***. An in-occupancy scenario might read if ***Outside Temperature*** is ***Cold, Passenger Number*** is ***None*** and ***Zone Illuminance*** is ***Dark*** then provide Winter-un-occupied temperature setpoint, ***Light Levels*** is ***Off*** and ***Airflow Rate*** is ***Un-occupied.***

The thirty-six fuzzy rules for this controller were defined using Mamdani [20] Fuzzy Modeling. That is, the antecedent and the consequent proposition were expressed linguistically.

TABLE 1. LINGUISTIC TERMS FOR INPUT AND OUTPUT VARIABLES

Parameters	Type	Linguistic Expression
OT	Input	Cold, Medium and Hot
ZI	Input	Dark, Dim and Adequate
PN	Input	None, Few, Average and Many
TS	Output	Winter-Unoccupied, Winter, Medium, Summer and Summer-Unoccupied
LL	Output	Off, Dim and Bright
AR	Output	Unoccupied, Few, Average and Many

VI. Case Study of Manchester Airport Building

Terminal 2 is a jet only terminal with Low Cost, Charter and Long Haul carriers. Smallest regular aircraft type is the B737-300 with 148 seats. Largest is Virgin's B747-400 with 456 seats. This information was used to estimates the passenger number per giving flight time. The flight arrival and departure data was collected from Airport information desk. The external temperature data was retrieved from the British Atmospheric Data Centre (BADC). The airport building has extensive use of glass window and wall façade making several places suitable candidate for Daylighting. Available illuminance for the period of October 26th to November 2nd was estimated from global and diffuse horizontal illuminance variation based on ten years of measurements by the Building Research Establishment (BRE) [21].

VII. Simulation Results and Discussion

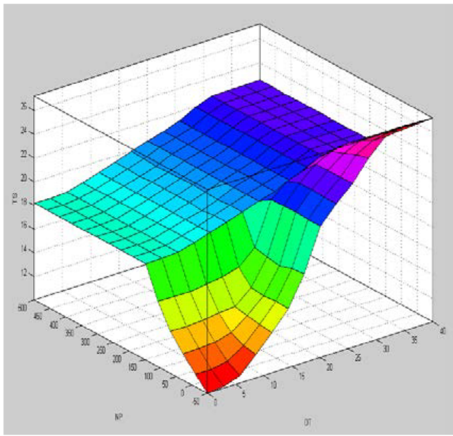

Figure 4. Surface view results mapping inputs NP, OT & output TS

Fig 4 shows how temperature setpoints changes in relation to passenger numbers and external temperature. For example; when the zone was un-occupied, (passenger number was zero) and external temperature was less 10^{0}C as could be the case in

Winter or over 20^0C as may be the case in Summer; the controller relapses the setpoint to its setback temperature of about 10^0C or above 23^0C for Winter and Summer unoccupied scenario respectively. However, when the place becomes occupied the controller provides comfort setpoints commensurate with the comfort requirement for that zone based on whether outside condition is winter, midseason or summer. Therefore, temperature setpoints are varied due to occupancy and change in external condition.

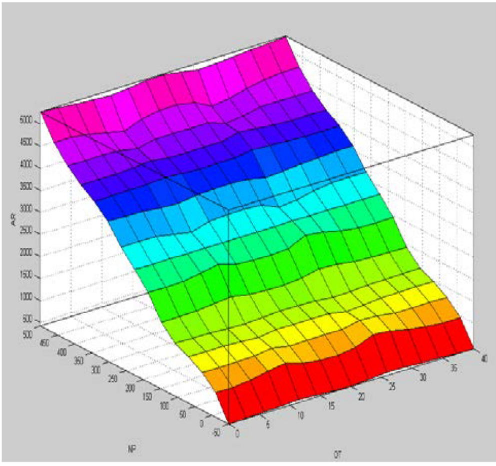

Figure 5. Surface view results of mapping between inputs and outputs for

Air Flow rates as in figure 5 on the other hand varies directly with the estimated arriving or departing passengers at a giving time. This explained the rise in airflow rates as the passenger numbers increases. Ten litres per second per person was provided for each passenger being the minimum fresh air requirement recommended by CIBSE [22] for such place.

During period of inoccupancy, up to 1000 litres per second is still provided to support non-passenger activities.

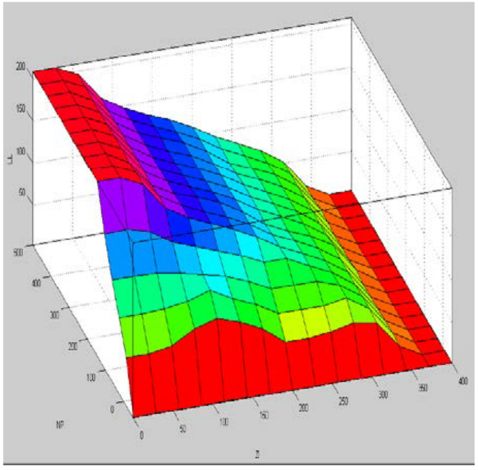

Figure 6. Surface view results of mapping between inputs and outputs for Arrival hall

Lighting setpoints of 200 lux was provided when occupancy was predicted to occur and it is off when the zone was unoccupied as shown in figure 6. This was because according to CIBSE Guide A [22] 200 lux is recommended for most indoor spaces within the terminal except offices and shop areas. Dayligthing control was also included as the lights are dimed or switched-off depending on the adequacy of the daylight illuminance within the zone. This lighting control does not include security and a task light that may be used by the staff if higher illuminance values are required at the desk for passenger processing.

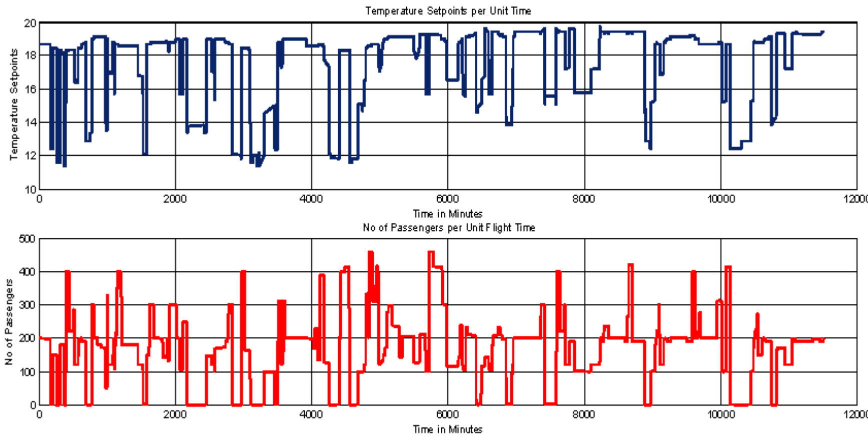

Figure 7. Temperature Setpoint output from the controller

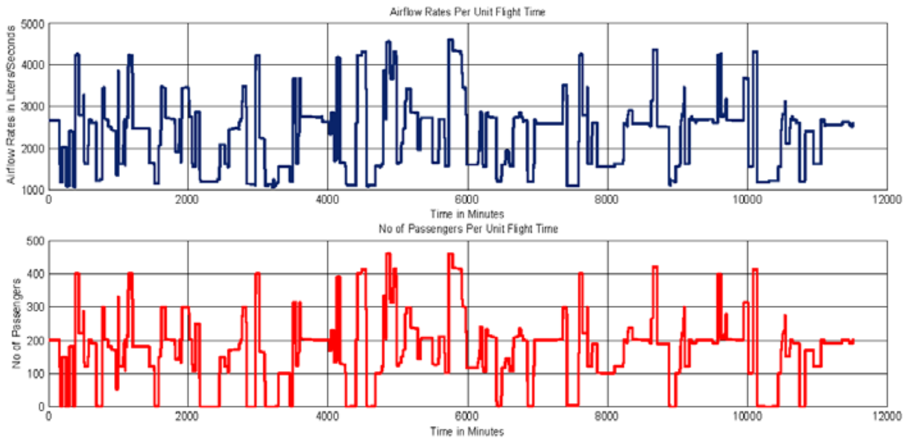

Figure 8. Airflow rate output of the fuzzy controller

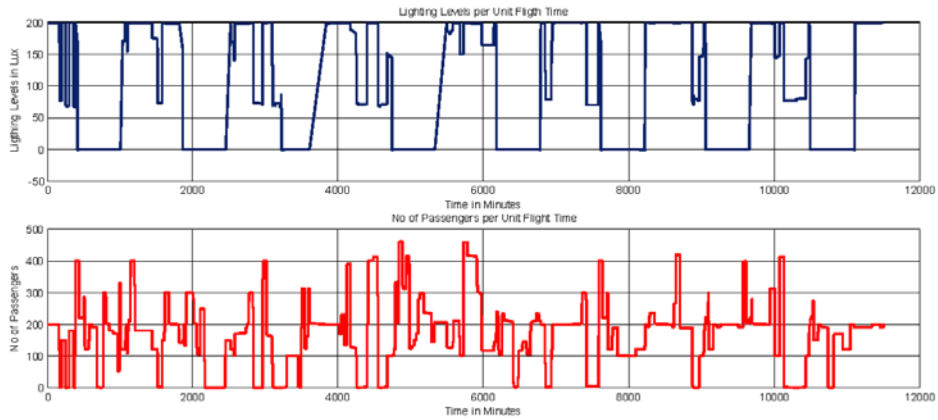

Figure 9. Illuminance output of the fuzzy controller

One-week simulation results for winter using Manchester Airport external weather data, flight arrival time for T2 and estimated available zone illuminance from 26 October to 2nd November 2011 shown in figure 7,8 and 9. These figures clearly showed that the comfort setpoint based on CIBSE recommendations for arrival area of the airport in winter is being provided and they vary with passengers' occupancy schedule. Fig. 7 shows a temperature setpoint of about 19^{0}C during occupancy and less than 12^{0}C during period of inoccupancy. Fig. 8 shows that about a 1000 litres per second minimum fresh air was provided during inoccupancy while the ventilation rates during occupancy varies with the number of passengers. Fig. 9 shows that about 200 lux setpoint of artificial lighting was provided for the zone during occupancy and when available natural daylight was inadequate while the artificial lighting remained switched-off during inoccupancy and when there is adequate daylight within the zone.

VIII. Summary & Conclusion

This paper shows that fuzzy rule systems do not require any process model and that heuristic rules could be used to model a controller. Fuzzy supervisory controller strategy and design process was presented. Also, using 3D surface view and output results from the fuzzy supervisory control system, the controller performance was analysed. This paper has demonstrated the capacity of the designed system to optimise indoor thermal, visual and air flow setpoints for airport terminal buildings, which will lead to reduction in energy use. Another contribution of the paper is that thermal and visual comfort and indoor air quality setpoints were derived from fuzzy controller rather than from operator's manipulations.

Acknowledgement

The authors gratefully acknowledged the financial support provided by the Engineering and Physical Sciences Research Council, UK in its Airport Sandpits Programme (EP/H004181/1) and Petroleum Technology Development fund (PTDF) Nigeria.

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