Implementing Productivity Based Demand Response in Office Buildings Using Building Automation Standards

KARA, DENIZ

Implementing Productivity Based Demand Response in Office Buildings Using Building Automation Standards

Deniz Kara

2014

Abstract

Demand response is an effective method that can solve known issues in electrical power systems caused by peak power demand and intermittent supply from renewable sources. Office buildings are good candidates for implementing demand response because they usually incorporate building management systems which are able to control and monitor various electrical devices, from lighting to HVAC, security to power management.

In order to study the feasibility of using an existing office building management system to implement demand response, a simulator for a typical office building has been built which models the energy consumption characteristics of the building. With the help of this simulator, an Indoor Environment Quality based control algorithm is developed whose aim is to minimise reduction in productivity in an office building during a demand response application. This research revealed two key elements of automatic demand response: lighting loads need to be utilised in every demand response scenario along with HVAC, and the control system needs to be able to operate rapidly because of changing conditions.

A multi-agent based demand response control algorithm for lighting is then developed and used to test the suitability of two communication protocols currently widely used in office buildings: KNX and LonWorks. The results show that excessive overload of the communication channel and the lag caused by slow communication speeds using these protocols present serious problems for the implementation of real time agent based communication in office buildings. A solution to these problems is proposed.

Implementing Productivity Based Demand Response in Office Buildings Using Building Automation Standards

Deniz Kara

Durham University
School of Engineering and Computing Sciences

A thesis submitted in partial fulfilment of the requirements of the Council of the University of Durham for the Degree of Doctor of Philosophy (PhD)

2014

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ACH	: Air change per hour
ACL	: Agent communication language
ACT	: Auction completion time
ADR	: Automatic demand response
AFS	: Auction buffer frame size
AFS	: Auction buffer frame size
ANSI	: American national standards institute
APR	: Achieved power reduction for a load level
AQT	: Agent query bit time
ASHRAE	: American Society of Heating, Refrigerating and Air Conditioning Engineers
BACnet	: Building automation and control network
BAS	: Building automation system
BL	: Bus load adjustment factor
BMS	: Basic metabolic rate
BR	: Baud rate
BST	: Bid submit time
BST	: Bid submit time
BW	: Buffer worth
CAV	: Constant air volume
CFL	: Compact fluorescent lamp
CIBSE	: Chartered institute of building services engineers
CNDSR	: Contract net based demand side response
CNET	: Contract net
CPP	: Critical peak pricing
CRT	: Cathode ray tube
CSMA/CA	: Carrier sense multiple access with collission avoidance
CSP	: Comfort, satisfaction and performance
DA	: Day ahead
DALI	: Digital addressable lighting controller
DC	: Direct current
DF	: Directory facilitator
DO	: Day of
DR	: Demand response
DSM	: Demand side management
DSR	: Demand side response

EAS	: Expected auction size
EB	: Expected numbe of bidders
EB	: Expected number of bids
EBS	: Expected bid size
EDRP	: Emergency demand response
EU	: European union
FAN	: Field area network
FIPA	: Foundation for Intelligent Physical Agents
FO	: Fiberoptic
FSx	: Expected number of messages for stage x
FSx	: Frame size for stage x
FT	: Fixed time
GJ	: Gigajoules
HVAC	: Heating ventilation and air conditioning
I/CLT	: Interruptable curtailable load tarriff
IAQ	: Indoor air quality
IEA	: International energy association
IEQ	: Indoor environment quality
IT	: Information technology
KNX	: Konnex
KS	: Knowledge source
LCD	: Liquid crystal display
LED	: Light emitting diode
LSA	: Lighting system agent
LZA	: Lighting zone agent
MAS	: Multi agent system
MFD	: Multi-function device
NAC	: Number of auctions covered
NAx	: Number of interventions for stage x
NBAR	: Non bidding agent reply bit time
NBC	: Number of bids collected
NM	: Number of messages
NMT	: Number of messages for each intervention
NSx	: Bit time to complete bidding stages 1-3.
OECD	: Organisation of economid development and cooperation
OFGEM	: Office of gas and electricity markets
OSI	: Open systems interconnection

PB	: Probability of an agent having a better bid
PB	: Probability of bidding to a full buffer
PBx	: Probability of an agent willing to bid to an auction at stage x
PIR	: Passive infra-red
PL	: Powerline
PMV	: Predicted mean vote
PP	: Peak pricing
PPD	: Percentage people dissatisfied
PRR	: Power reduction request for a load level
PV	: Photovoltaic
QFS	: Query frame size
RF	: Radio frequency
RFS	: Reply frame size
RTP	: Real time pricing
RVP	: Relative visual performance
SA	: Simple auction
SSM	: Supply Side Management
TAPR	: Total achieved power reduction
TCT	: Token circulation bit time
TFS	: Token frame size
TNA	: Total number of agents
TNA	: Total number of agents
TOU	: Time of use
TP	: Twisted pair
TPRR	: Total power reduction request
UAC	: Unit auction time
UART	: Universal asynchronous receiver transmitter
UPS	: Uninterruptible power supply
VAV	: Variable air volume
VTA	: Virtual token based auction

Declaration

I hereby declare that this thesis is a record of work undertaken by myself, that it has not been the subject of any previous application for a degree, and that all sources of information have been duly acknowledged.

Acknowledgements

This study took five years to complete and during this time period, numerous people have contributed to it.

I would like to thank my supervisor Mr. Peter Baxendale whose support in almost all aspects of my study has been invaluable. It wouldn't have been possible to complete this thesis without his encouragement and efforts.

I would like to thank Mr John Wright for his understanding and support during the five years in which I had to balance work and this demanding study. I would also like to thank my current employer Legrand and previous employer Electrak and their employees who had helped with various technical aspects of this study.

My friends from Durham University Engineering and Computing Sciences, Dr Omar Shaneb for his kind support during the initial phases, Ms. Barbara Alimisi and Dr. Sam Drake for their friendships which made me enjoy my student life in Durham, thank you to all.

I would like to thank Professor Philip Taylor for his help and Professor Yener Altunbas, who has supported me and kindly provided reference for me in the beginning of this study.

To my parents who have committed most of their lives trying to raise and prepare me for the challenges of life. You have done a great job, thank you!

Another great thank you to my brother Dr. Alper Kara who was with me from day one since I stepped in the UK. His moral support have helped me go through the most difficult hurdles of this study. Thank you Müdür!

Finally to my lovely wife who has patiently waited for 5 years for me to complete my studies so that we can get together again. Your smiling face on the web cam every night gave me the encouragement to continue and finish my work. Thank you for your patience and support. Now it's time to enjoy life together!

Dedicated to my parents, brother,

and beautiful wife...

1. Introduction

In electricity grids, Demand Side Management (DSM) is a term used to describe methods which are about controlling loads to maintain the health of the generation and distribution system. In the recent years, DSM has started to draw more attention from scholars because it offers a swift solution to many of the problems that cannot be solved with traditional methods like supply side management (SSM). These problems not only arise from ageing transmission infrastructure or increasing energy demand but also from introduction of renewable generation systems which are unpredictable and inflexible when it comes to control.

DSM can be achieved in various ways and Demand Side Response (DSR) is one of them. In DSR, consumers voluntarily reduce their consumption as a result of commercial arrangements between them and the suppliers. It is a beneficial arrangement for both parties where the customers benefit from generous financial incentives and suppliers can avoid building extra infrastructure to cover very short periods of peak consumption.

Office buildings are major consumers in cities and they are good candidates for DSR for several reasons. Firstly, they are commercially driven hence are easier to incentivise. Secondly, they are more likely to have controllable loads that are of similar nature. Thirdly, they are also more likely to have automation infrastructure in place to enable DSR methods.

On the other hand, DSR in office buildings comes with a monetary cost because all of the loads in an office building serve the needs of humans that produce work therefore there are limitations on how much load can be shed. In order to carry out DSR effectively and minimize disruption to workers, an automatic control system is required. To develop such a system, the relationship between work and amount of energy consumed needs to be established. This is a difficult problem because it has multidisciplinary elements. Figure 2.1 shows the factors that are involved when the loads in an office building are assessed from DSR perspective.

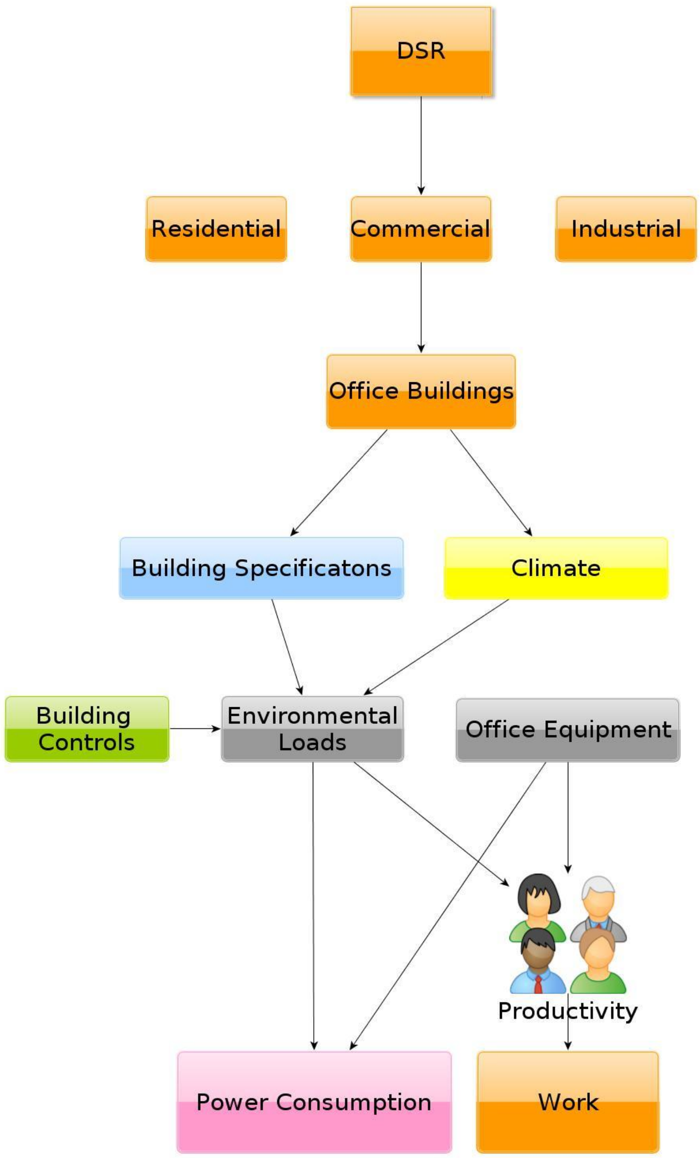


Figure 1: Relationship between DSR, work and power consumption

As can be seen from the figure, the specification of office buildings and the climate determine the loads that control the environmental conditions within the office. Building controls are used to automate the control process of these loads. Together with the office equipment they allow office workers to produce work at the expense of energy consumption.

Research Objective

The purpose of this study is to propose a valid automatic control method for DSR in office buildings and assess the capability of existing building automation systems in achieving this control method.

To achieve this objective, major elements shown in Figure 1 are investigated thoroughly and the relationship between them is established in this research. These are as follows:

- **Identifying Suitable Loads for DSR**

There are numerous types of loads in office buildings and not all of these are suitable for controlling during a DSR scenario. Some loads might not have facilities to be controlled automatically whereas others would not be worth controlling for DSR because of the little contribution they make to overall power consumption. For this reason, the loads that are suitable for controlling during a DSR scenario are identified.

- **Productivity Aspects of Major Consumers**

Turning off a load for DSR will have implications on the productivity of office workers.

A *valid control method* needs to take these productivity implications into account. Therefore, productivity aspects of major consumers are investigated before proposing such a control method.

- **Proposing a Control Method Based on Productivity**

Once productivity aspects of loads are determined, an algorithm that can relate productivity to power consumption is proposed.

- **Solving Distributed Load Control Problem**

Office buildings are large structures and controllable loads might be physically distributed in the building. The nature of certain loads and their spatial distribution make it necessary to develop novel distributed control methods where these loads would be required to communicate with their counterparts to coordinate their actions.

- **Assessment of Building Automation Standards and Systems from DSR Control Perspective**

Distributed control can only be achieved with a reliable communication system. Such communication systems are already available and they are mature enough to be utilised for DSR control. However, the nature of DSR control might overload the resources of these systems. For this reason, whether or not existing communication standards are capable of handling the distributed control requirements that are specific to DSR is investigated.

The rest of the thesis is organised as follows:

Chapter 2 is the background research and literature review that lays the foundations of the following chapters. Three main subjects are covered; office buildings and loads within them, productivity aspect of various environmental parameters and building automation standards that are dominant in office building automation.

Chapter 3 explains the development of a building energy consumption simulator that is built as part of this research to predict the outcome of load reduction strategies and to test the effectiveness of productivity based load reduction algorithm presented in Chapter 5.

Chapter 4 is about IEQ which is a parameter that can be used to indicate productivity cost in office buildings.

Chapter 5 presents a control method that is based on indoor environmental quality. Building energy consumption simulator described in Chapter 3 is used to test the effectiveness of this control method and the results are presented in this chapter.

Chapter 6 is about implementation of the control method described in chapter 5. In this chapter, lighting loads are identified as the loads that would require a distributed control approach and an agent based control scheme called CNDSR is proposed. The effectiveness of this scheme is tested with MATLAB simulation and the results are presented.

Chapter 7 discusses whether or not existing commonly found building automation standards can handle CNDSR protocol. Research carried out to estimate the network load is presented together with experiments showing the consequences of excessive communication load caused by CNDSR algorithm. A solution to avoid this is also presented in this chapter.

Chapter 8 summarises the conclusions of this research.

2. Literature Review and Background Research

Because of the complexity of the subject, only a multi-disciplinary approach can bring an answer to DSR related questions like 'How much load can be shed in a building for a given amount of time?' or 'How can we design a control system that manages to reduce consumption while ensuring that productivity is kept at its maximum level?' For this reason, in order to carry out research on DSR and to develop control methods that can maximise the benefits of DSR, all of the relevant topics in Figure 1 need to be taken into account. Hence, the purpose of this chapter is to cover these subjects. The chapter will start with an overall review of Demand Side Management. Later, the properties of office buildings and the loads that consume the most power will be explained. Productivity aspects of the variables that effect humans working in office environments will be reviewed afterwards. Finally, the control requirements of major loads in office buildings will be covered. The foundations laid in this chapter will serve as guidance for the subsequent chapters.

2.1. Demand Side Management

The terms Demand Side Management, Load Management, Load Response, and Demand Response have existed for some time and are being used as synonyms in most of the literature [1]. Demand Side Management is a broad term that spans individual techniques for changing consumption of loads for the benefit of either the energy supplier or the consumer.

Demand side management techniques have been discussed mainly to solve problems in the utility scale. The old way to satisfy increasing energy demand by the utilities was to increase supply capacity by building more power generation plants, which is called Supply-Side Management (SSM). However, problems with the centralized grid have become more apparent in the last decade, raising questions about the sustainability of this approach. Therefore new techniques have been developed to manage the demand side. The motivation behind this can be listed as follows [2]:

- Reducing generation margin.
- Improving transmission grid investment and operation efficiency.
- Improving distribution network investment and operation efficiency.

On top of the above, DSM methods started to offer an even greater benefit. As the penetration of renewable energy has increased in the recent years, questions arose about how the variations in the supply will be handled. This problem is one of the main obstacles in front of the adoption of renewable generation. DSM technologies provide promising solutions to problems that intermittent supply will cause [3].

DSM techniques are not strictly defined by any standard and researchers consider different actions taken by the demand side as DSM methods. Some of them even include switching to distributed generation as a DSM method [1]. For the interest of this research, methods that change load shape in a relatively short time will be investigated such as load management and demand side response.

2.1.1. Demand Side Response

Demand side response (DSR) and load management are similar strategies. They are both used to modify demand shape in order to avoid issues with the supply. From the utility perspective, the purpose is to avoid peaks. The difference between load management and DSR is that DSR is not a planned action. It is initiated from the consumer side if the circumstances make it necessary [1].

Direct load control (DLC), interruptible curtailable load tariff (I/CLT) and emergency demand response programme (EDRP) are counted as DSR techniques. In the case of DLC, customers sign up for a DLC programme to allow utilities to shed customer loads unilaterally by directly switching different equipment on or off with short or no notice ahead. Usually domestic consumers are more suitable for DLC. I/CLT is similar to DLC though it is targeted at medium to large capacity customers (above 100 kW). The load that is involved in curtailment is much larger as well, typically a major portion of the load of the facility. EDRP's are load shedding programs where customers are voluntarily shedding loads when emergency conditions occur. Participating customers are paid incentives for load reductions during emergency conditions [4].

DSR has numerous benefits which are summarised by a U.S. Department of Energy report prepared by Lawrence Berkeley National Laboratory [5]:

- Financial benefits for participants: These are bill savings and incentive payments to customers participating in DSR schemes.
- Market-wide financial benefits: Lower wholesale market prices because of fewer requirements for costly high demand generation plants.
- Reliability benefits: Operational and adequacy savings because of the prevention of forced blackouts.

2.1.2. DSR Methods

The methods for DSR can be investigated in two groups, Tariff based and Program Based.

Tariff Based DSR

These are indirect methods to initiate DSR on the customer side by varying electricity prices.

Time of Use (TOU): Different electricity unit prices for different blocks of time which are defined in a 24 hour day. It is based on the average cost of generating and delivering power during those periods.

Real Time Pricing (RTP): Electricity unit prices change hourly reflecting the wholesale prices. These prices are released to customers beforehand (by the day or the hour) to allow preparation on the customer side.

Critical Peak Pricing (CPP): There is a pre-specified high rate for usage at times designated by the grid operator as critical peak period. The projection of prices depends on various circumstances such as wholesale market price.

Program Based DSR

These are prearranged load reduction programs that pay incentives to customers for shedding certain loads.

Direct Load Control: A program where the utility operator is allowed to shut down a customer's electrical equipment on short notice. Customers that are in this program receive a participation payment. Some programs allow the customer to opt-out which causes the incentive to be reduced.

Interruptible/Curtailable Service: Programs integrated with the customer tariff that provide a rate discount or bill credit for agreeing to reduce load, typically to a predefined service level. Customers that do not reduce their load at these times pay a penalty.

Emergency Demand Response Programs: Programs that provide incentive payments to customers for measured load reductions during reliability triggered events.

2.1.3. Application of DSR In Commercial Sector

Application of DSR varies depending on the building type. There are three categories that are distinct; commercial, residential and industrial. This research is aimed at commercial sector, particularly office buildings.

The report [6] gives the status of demand response programs in the U.S. Participation to DSR programs and actions during a DSR event are determined by the customers. For participation, the customers initially determine an energy budget based on their average electricity prices (both current and future). They then evaluate factors such as the notice of events, expected duration and the frequency of the events, expected benefits and penalties. If the customers believe that they will be able to respond to these events and that they can afford the cost of DSR enabling technologies, they sign up.

Customers may respond to the DSR events in several ways. They may forego (reduce consumption totally) or shift (carry out tasks at a different time) their consumption. They may also use their on site generation facilities to supply their loads in order to reduce their energy draw from the grid.

Although not well quantified, the participants face two types of costs when they join DSR programs. These are initial costs and event specific costs. Initial costs involve enabling technologies and planning for DR events. Event specific costs involve comfort/inconvenience, lost business, rescheduling business and (in the case of on site generation), fuel and maintenance costs.

The report has recommendations for fostering both price and incentive based DSR. The suggestions for large commercial customers include making RTP as the default service (in states that allow retail regulation), improving technologies (control, communications and monitoring) and enhancing payment strategies (such as pay for performance) by implementing methods that measure and verify demand reductions.

The report also advises that adopting DSR enabling technologies will increase demand response offerings and make DSR more attractive and cost effective for both the utilities and the customers. HVAC and lighting controls, smart thermostats, distributed energy generators (such as wind turbines), CHP, energy storage solutions, photovoltaic generators are all counted as enabling technologies. Building automation systems are also mentioned as integrating technologies that are essential to controlling both the loads and the generators for the purpose of DSR.

Another report [7] examines the automated response of small and medium (whose ratings are smaller than 200 kW) commercial sites in the California region to DR events that are communicated via the Internet. The goal of the report is to determine how well small and medium commercial buildings could respond to DR signals using available technologies. Hence the report was intended to help equipment manufacturers modify or improve their products so that their products can be more suitable to the needs of the customers.

The results of DR tests that have been performed by Pacific Gas and Electric Company (PG&E) are given in the report. The results have shown that:

- Demand reduction was limited in sites where HVAC was not controlled automatically.
- In sites where HVAC controls were used, the reduction in demand was visible though this could not be sustained for the required amount of time. This is thought to have been due to site specific limitations such as poor HVAC equipment sizing.

DSR programs are more primitive in the UK compared to the U.S. As discussed in the report for OFGEM [8]. However, it is being realized that in order to accommodate the renewable generation plants and solve the problems with the incapacity of the existing grid, DSR technologies will have to be more widely adopted.

The report distinguishes the non-domestic (or commercial sector) from the industrial and domestic sector where it constitutes around 30% of the peak demand. The three sub-sectors that contribute most to peak demands are listed as Retail, Education and Commercial Offices. The technical potential of the non-domestic sector to reduce its peak demand is estimated to be between 8% - 30%. Figure 2 shows electricity demand profile for non-domestic sector.

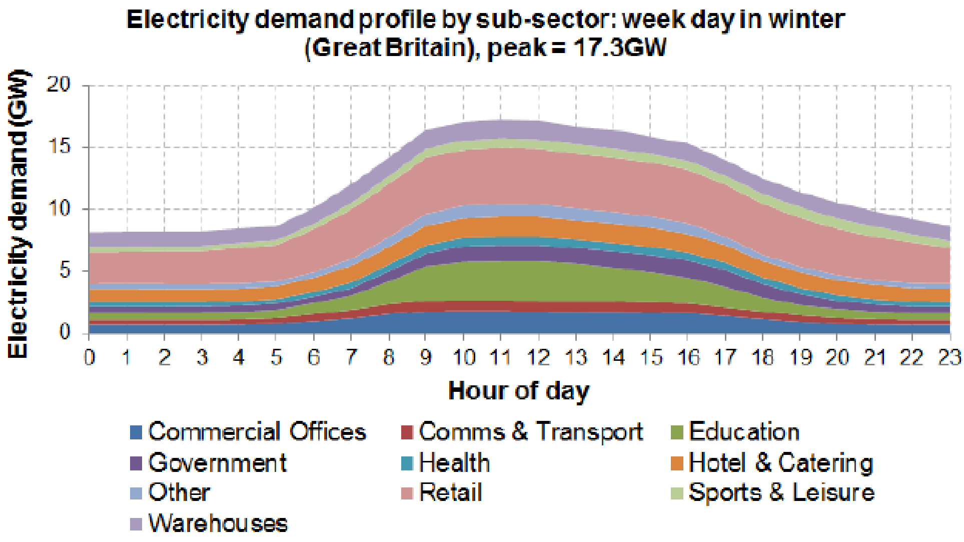


Figure 2: Hourly electricity demand profile by sub sector in the UK [8].

The report lists the barriers that restrict the adoption of DSR in the UK. These barriers are derived from consultation which took the form of telephone interviews with 16 organisations such as management companies, demand aggregators, and retailers. The frequency and type of barriers cited by the interviewed institutions are shown in Figure 3.

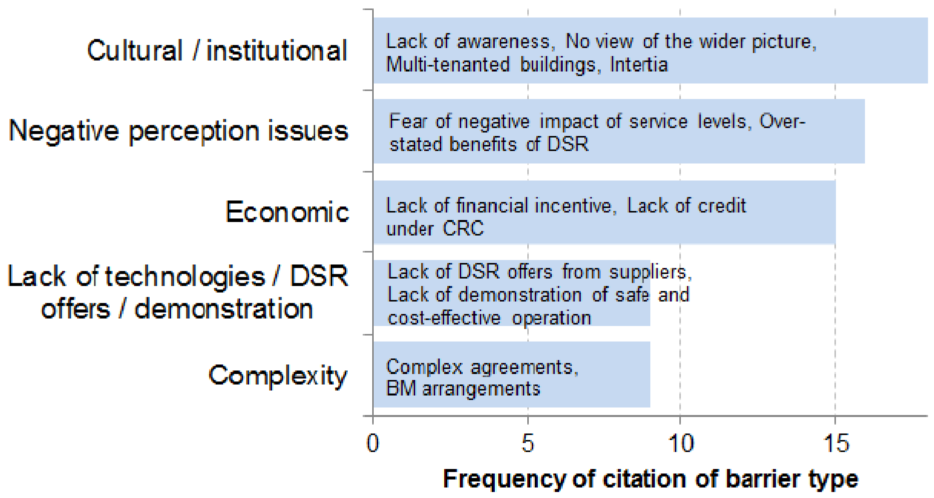


Figure 3: Frequency of citation for different barriers to adopting DSR [8].

The barriers are summarised as follows:

- DSR is not the focus of most organisations because energy bills are a very small proportion of the costs.
- There is widespread concern that DSR measures could lead to reduced levels of service by building occupiers. This becomes a greater challenge for multi-tenanted buildings.
- Low and uncertain financial incentives that are not adequate to encourage the potential customers.

The report also lists the suitability of end usage to DSR. These are described as follows:

Space cooling and ventilation: It is stated that these can be interrupted for up to 30 minutes with no significant impact on the environment in the building.

Heating: It is stated that electric heating may have the potential to be reduced for short periods of time (15 minutes) and that extended reduction is not likely without impact on temperatures. No reference study is given for this statement.

Computing: The potential for shifting loads in this category is stated to be very limited.

Lighting: The report gives mixed views on the potential of load reduction in the lighting category. This sub-category is the greatest contributor to peak demands. There is also sufficient technology such as dimming and electronic controls that allow precise control of lighting. The problem with load reduction in lighting is that this category is not seen as viable by the interviewed companies because of its potential effects on productivity. Moreover, lighting technology requires significant supervision and control which needs automated building management systems. This increases the investment required to achieve DSR. On the other hand, the report suggests that load reduction in lighting can be achieved in areas of buildings where occupancy is intermittent.

Catering: Ovens, electric hobs, grills, microwaves and extraction fans are given as examples of devices that are in the catering sub-category. It is reported that limited reduction is possible in catering.

Another UK report by Pöyry [9] which conducted work to understand the potential role of DSR in helping deliver a secure and economic energy sector by 2050 have found that in order to make DSR work for the grid, suppliers should be able to give the desired price signals far more readily given the scale of potential benefits such as investment avoidance and operational cost reductions. The report also concludes that for DSR services that are of highest value to networks, the requirements for reliability and the consequences of failure to deliver are such that commercial price signals may need to be augmented by mandatory approaches.

2.1.4. Discussion

The review above shows that DSR is going to play an ever increasing role in the future of electricity distribution and generation. Energy Policy Act of 2005 established demand response as an official policy of the US government. The US report on the benefits of DSR indicate that DSR tariffs should be the default tariff for large customers. From these and the other reports, it can be concluded that;

- DSR, will become part of the future electricity grid.
- Because of the importance of DSR in not just the profitability but also the reliability of the grid, it is very likely that DSR will be mandatory for certain types of electricity customers.

In such conditions, the requirements of DSR will establish a unique relationship between the customers and the suppliers of electricity such that the customers will play a functional part in the reliable operation of the grid. This will require the integration of the loads into the control structure of the grid. The control structure will either be price based or incentive based. Price based controls will allow more flexibility for the customers in deciding when and how to respond to DSR events. Incentive based programs will be more absolute and will also bring in more responsibility though their benefits to customers will be known in advance. In either way, the DSR programs will have the following features;

- Customers will be informed of when the DSR events will take place.
- Customers will be informed of the length of time that the DSR events will have.
- Customers will know how much load should be reduced in order to satisfy the requirements of the DSR program.
- Customers will know how much penalty they will pay for not complying with the requirements of the DSR event.

It is evident that DSR programs will have to be tailored to specific types of customers which can be divided in three: commercial, residential and industrial. Even though commercial customers constitute a significant percentage of peak demand, their energy consumption flexibility is more limited compared to industrial and domestic customers. It can be deduced from the reports that lack of awareness is a major obstacle in adopting DSR among commercial customers. However, there are other major obstacles;

- The concerns over the potential effects of DSR on productivity.
- The technical challenges such as controlling the loads effectively so that the reduction is adequate to satisfy the DSR contract.

The reports and papers show that office buildings have the potential to contribute to DSR. As this research is about developing control methods, assessing their potential and investigating whether or not they could be implemented to existing office buildings, the complex nature of office buildings need to be fully understood. The next section will describe many aspects of office buildings starting from their passive components (envelope and the structure) and active components (environmental equipment such as lighting and HVAC), as well as office equipment that is used by office workers.

2.2. Office Buildings

The word office originates from Latin 'officium' which means 'performance of a task', based on 'opus' which is 'work' and 'facere' which is 'do'. Oxford dictionary gives the definition as 'a room, set of rooms, or building used as a place of business for non-manual work'. Although offices are a common part of many people's lives today, modern offices originated fairly recently, in the late 19'th century in the United States. With the advances in communications such as telephone and telegraph, clerical jobs which were used to be close to the manufacturing facilities could be moved to more urban areas. Moreover the requirements for the usage of new devices such as typewriters and calculation machines needed a more educated work force to be employed which required large buildings in the cities that employ literate 'white collar' workers. Altogether with the advances in the services sectors (such as banks and insurance companies) to support this complex manufacturing organisations gave birth to a new type building called the office building. Hence office buildings resulted from both the necessity of the industrial era and the availability of new technologies from the industrial era.

From the numerous developments in technologies that changed peoples' lives; lighting, heating, air conditioning and communications affected the office environment the most. Although these technologies increased work efficiency in buildings', energy consumption started to emerge as the new problem. Therefore there have been numerous improvements in these fields to bring down the mounting operating costs of buildings.

2.2.1. Thermodynamics of Buildings

The heating or cooling requirements of a building depend on the mechanisms that enable the transfer of heat to and from the conditioned environment. This is closely related to the thermodynamic and construction properties of the buildings which cause heat energy to be exchanged with the outer environment by conduction, convection and radiation [10].

Conduction affects the direct heat transfer between the building and the outside medium. For example in winter when the indoor temperatures are higher than outside, heat is transferred through the walls to the outside air by conduction. Also, some heat is lost through the foundation of the building into the earth. Because outdoor temperatures during the day fluctuate, the heat capacity of a building determines the extent of the temperature swings.

Convection has multiple affects on heat transfer in buildings. Air is the primary transfer medium in a building. Heated air in winter leaks outside the building carrying its energy with it. It is displaced with colder air from outside. This unwanted displacement of air is called infiltration and is a major source of energy waste. Another problem which is caused by convection is because of buoyancy properties of air. Warm air is more buoyant, it tends to stack up in the roof of buildings causing temperature differences between higher and lower floors. This not only causes energy to escape more rapidly through the roof (because temperature difference is higher), but also causes inconveniences due to heat build-up in upper floors which can only be dealt by forced ventilation. Convection becomes a useful physical property when air is to be conditioned in remote parts of a building. Air conditioning units operate using convection principles where heat is carried to and from the conditioned environment.

When it comes to radiation, its effects work in two ways in buildings. Diffuse and solar radiation from the sun heats up the envelope of the building which is passed to the interiors through conduction. Radiation also goes through the windows and directly increases the temperature of the interior surfaces and space. At night time and especially in winter the opposite happens. Warm building envelope and windows radiate energy to the outside environment causing the building to cool down.

2.2.2. Energy Consumption and Control of Equipment in Offices

Energy consumption of an office building depends on the size, complexity and climate of the building. Therefore typical consumption of office buildings vary across the countries.

Energy consumption guide [11] gives valuable information on energy consumption categories for office buildings in the UK. According to the guide, office buildings can be separated into four distinct categories depending on their ventilation type (naturally ventilated and air conditioned) and size. Table 1, extracted from the report, shows annual energy consumption per square metre for each category of building.

Table 1: Energy consumption of various category of loads in office buildings [11]

Load Category	**Naturally Ventilated Small**	**Naturally Ventilated Medium**	**Air Conditioned Medium**	**Air Conditioned Large (with server room)**
Gas (kWh/m^2)	151	151	178	210
Elec. (kWh/m^2)	54	85	208	253
Heating / Catering	100% (Gas)	100% (Gas)	100% (Gas)	100%(Gas)
Cooling	0	2% (Elect.)	23% (Elect.)	25% (Elect.)
Fans and pumps	11% (Elect.)	10% (Elect.)	29% (Elect.)	26% (Elect.)
Lighting	43% (Elect.)	46% (Elect.)	26% (Elect.)	24% (Elect.)
Office and IT Equipment	34% (Elect.)	27% (Elect.)	15% (Elect.)	13% (Elect.)
Other	12% (Elect.)	15% (Elect.)	7% (Elect.)	11% (Elect.)

According to the table, air conditioned offices consume more than twice as much electrical energy compared to naturally ventilated offices. Large air conditioned offices consume more energy because of the size of cooling equipment. In all of the categories, the most prominent electricity consumers are HVAC, lighting and office equipment. The type of services that these load categories provide are highly distinct from one another therefore a deeper understanding of how these loads operate in office buildings is required.

2.2.3. Heating, Ventilation and Air Conditioning

HVAC is necessary in order to maintain the air in buildings fresh and within certain temperatures that are comfortable for humans to live and work efficiently [12]. Temperature control is particularly important and challenging in modern buildings because heat gains from sunlight, lighting and various business machines accumulate within the envelope and cause indoor temperatures to increase quickly to uncomfortable levels. Even if outside air temperature is adequate, ventilation with windows might not be possible in tall buildings where wind speeds are likely to cause draughts. For buildings with few floors, open windows can cause inconveniences such as dust and noise. Also, because natural air flow is effective for a depth of six metres, most deep plan offices cannot benefit from windows.

Air conditioning requires that the air supplied to the conditioned zone is pure with a comfortable temperature, humidity and speed. This means that air conditioning almost always requires cooling [12]. For this reason, air conditioning is a major consumer of energy. Energy use for heating and air conditioning accounts for more than 25% of the primary energy consumed in commercial buildings in the U.S. where offices have the largest share. 27% percent of energy consumed for cooling is due to office floor space.

2.2.3.1. Evolution of HVAC in Offices

Air conditioning existed as early as 1850's with devices that utilised fan-forced heating systems. Cooling of air had to wait until late 1880's where the advances in the refrigeration technologies made them applicable to buildings. The efforts to develop a proper cooling methodology however, brought in the necessity of approaching the idea in a more scientific perspective. How to cool the air to a given temperature and remove the moisture from air for a desired result in humidity was not as easy as heating the air to the specified temperature with burning of some fuel. These breakthroughs came at early 1920's to theatres and other buildings where large crowds usually gathered ([13] and [14]).

In 1930's, offices had already become a distinct category of buildings. Skyscrapers had already started to appear at this time but they did not benefit from air conditioning technology. For example Woolworth and Chrysler buildings in New York reached unprecedented heights but their principal ventilation was dependent on nature with operational windows. It took some time before air conditioning principles were applied to office buildings. The first building that is fully sealed, air conditioned, open plan and that has been a model to modern office architecture was the Lever House built in 1952. Air conditioning in this building was so fundamental to the design that the building could not operate without it ([13] and [14] .).

Air conditioning until 1970's were done with constant volume systems which were inefficient. 1970's saw the ascent of VAV (variable air volume) systems. Variable air volume systems that carried constant temperature air allowed less energy consumption by utilising outside air. This system also allowed less plant load because not all parts of the building required the same amount of cooling. Today, VAV remains the dominant air conditioning technology incorporated in large office buildings ([13] and [14]).

2.2.3.2. Primary Duties of Air Conditioning Systems

Air conditioning systems have two main duties, to supply fresh air to the building and to maintain the indoor air at a comfortable temperature and humidity [10].

Air supply Requirements

Supplying fresh air to an office zone is the primary function of an air conditioning system. The amount of fresh air to keep a human being alive varies from 0.1 litres/second to 1.2 litres/second. However, enough air from outside must be supplied to reduce the accumulation of body odours. According to [15], outdoor air supply rate for an office should be 8 litres/second per person when it is occupied. To supply this air, some systems incorporate complex control mechanisms that provide air based on the number of occupants in the building. However, most systems work on constant operation regimes where the amount of ventilation is fixed based on the operating schedules of the building. For example in working days and office hours, the building is ventilated more rapidly compared to non-working days and out of office hours.

Temperature Requirements

Comfortable indoor air temperature for humans is 22-24° C [10]. The air is either heated or cooled to maintain its temperature within these limits. If the air is warm, a compressor operates to supply a cooling agent to cooling coils. If it is cool, a heating element operates to supply the heating coils. In basic systems, operation of the compressor or the heater is usually controlled by a thermostat which determines whether the zone requires cooling or heating.

2.2.3.3. Types of Air Conditioning Systems

Based on the cooling technology implemented, air conditioning systems in commercial buildings are usually broadly categorised into three: central, packaged and individual systems [12].

Central systems are systems where a central cooling plant (a chiller) is used to deliver cool water to air handling units or fan coil units that treat the air and that are located in proximity to conditioned zones. Packaged systems are systems where cooling and heat rejection is carried out in the same unit. These systems utilise direct expansion coils for cooling. Cooling is delivered directly to the supply air in a refrigerant evaporator coil. Individual systems can be considered as small capacity packaged units. They operate like packaged systems but deliver the air directly from the outside environment to inside through a hole in the envelope of the building. According to [12], packaged systems have been the main choice for cooling among contractors and designers in the past two decades due to their reduced equipment cost and installation time (Figure 4).

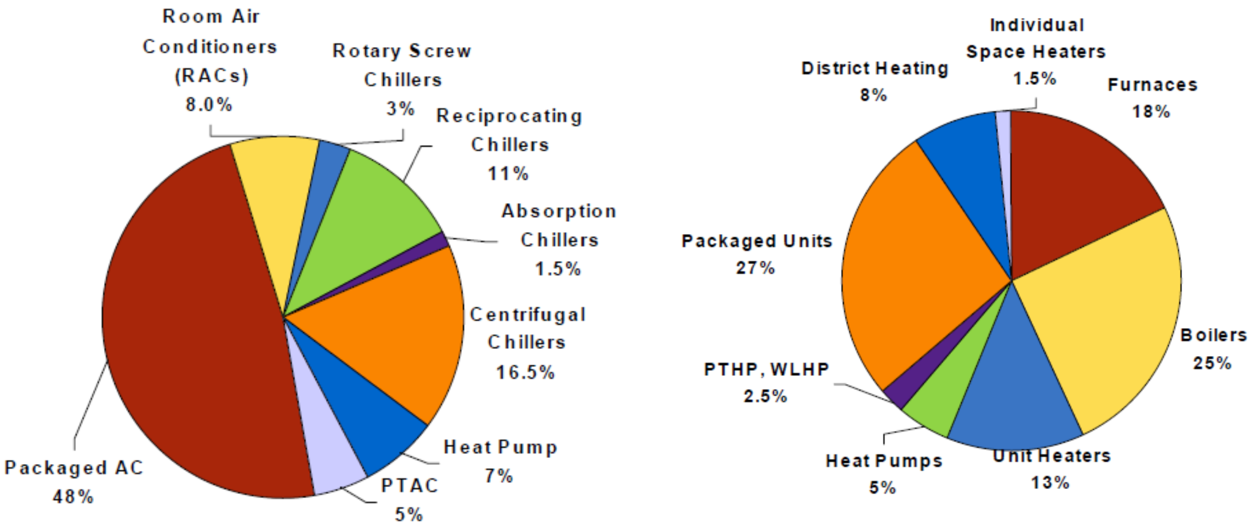


Figure 4: HVAC equipment distribution in the U.S. for cooled floor space (left) and heated floor space (right) [14].

They are used to cool 48% of cooled floor space in offices in the US and this percentage is increasing. As they are the most dominant HVAC type, packaged systems will be described in more detail in the following section.

2.2.3.4. Structure of a packaged HVAC Unit

Packaged units can be classified into two types; split and rooftop. Split units consist of separate devices for humidifying and heat rejection. Rooftop units which are more common in larger installations operate as single entities. These units have cooling capacities that vary between 10kW – 850kW and air flow rates ranging between 400 l/s to 38000 l/s [15].

A packaged system has four major energy consuming parts; compressor, heating coil, fans and pumps [12]. In a rooftop system (Figure 5) in which the air is circulated between the conditioned zone and the unit, these elements work at different intervals.

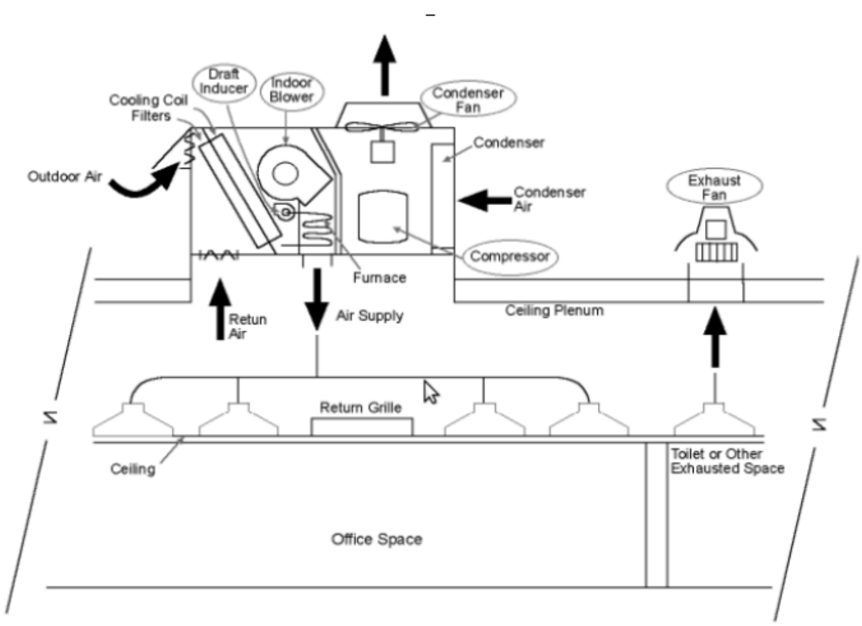


Figure 5: Schematic of a Packaged System. Power-Using components are circled [12].

The air first enters to a filter through an inlet duct (or return fan if it is circulated), then to a cooling coil where the compressor cools it(or furnace coil if heating is required instead) and finally the supply fan that supplies the conditioned air to the conditioned environment. Cooling is delivered directly to the supply air and heat is rejected in a condenser coil to the outside air. Extract or exhaust fans operate continuously to discharge the contaminated air to the outside environment.

2.2.3.5. Control of an Air Conditioning System

Air temperature control and ventilation in a conditioned environment can be carried out in several ways [16]. One of the most economical ways of maintaining the temperature is circulating the conditioned air and mixing it with the outside air to maintain freshness. Figure 6 shows the schematic of a simple but common ventilation system that recycles the return air that is sourced from the conditioned environment.

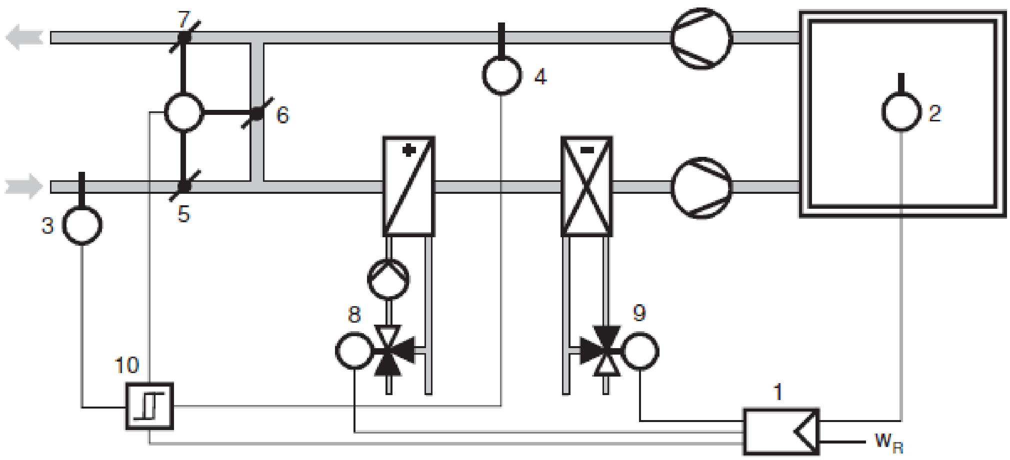


Figure 6: Control schematic for a typical ventilation system

In this figure, elements of the control system are marked as follows:

1) Temperature controller
2) Room temperature sensor
3) Outside air temperature sensor
4) Extract air temperature sensor
5) Outside air damper
6) Circulated air damper
7) Exhaust air damper
8) Motorized heating valve
9) Motorized cooling valve
10) Hysteresis control depending on the outside and circulating air temperatures.

In this control scheme, the temperature controller (1) reads the room temperature sensor(2). If the temperature falls below the given temperature set point, the controller minimises the intake of fresh air and circulates most of the exhaust air by closing the circulation dampers (5, 6 and 7). It also opens the heating valve (8) to enable heating of the supply air. When the indoor temperature starts to increase, the heating valve is closed. Also, more outside air is allowed to assist cooling. If the temperature (or enthalpy) of the outside air sensed by the sensor(3) is higher than return air sensor(4), it means that it is no longer economical to use the outside air. Hence the dampers (5, 6 and 7) are closed to circulate most of the indoor air.

Regardless of a central system or a packaged system, the control methodology explained above can be applied to most of the HVAC systems that utilise the return air. As can be observed, the supply and return fans operate continuously to circulate the air for filtration and to bring the air temperature to the desired levels by either heating it or cooling it.

The continuous operation of the fans causes significant energy consumption throughout the year. This is highlighted in the papers published by researchers who investigated the control aspects of HVAC systems. For example, Wang et al [17] evaluate a number of control strategies that can be implemented in a packaged air conditioning controller. They note that in most packaged units, a thermostat controls the operation of the compressor or the gas furnace depending on whether the conditioned space requires heating or cooling. Even though the compressor or the gas furnace is cycled, supply and return fans operate continuously when the building is occupied hence causing inefficiencies.

The observation of Wang et al is in line with the study of Westphalen et al [18]. They indicate that although rated power consumption of supply fans of packaged AC units are less than the compressors', their overall energy consumption is almost equal to compressors' or gas furnaces because they are operated at 100% power when the building is occupied.

2.2.4. Lighting

Visible light is an electromagnetic radiation. Human eye is capable of sensing light that has a wavelength in the range between 370 nanometres to around 740 nanometres. Useful power that is emitted by a light source is measured by luminous flux (*lumens*). The efficiency of a light source is usually measured by the amount of light received divided by the amount of power delivered to it (*lumens/Watt*). Luminous flux can be used to compare different light sources but it is inadequate to describe lighting for human perception because ordinary objects don't emit light and they require an external light source to provide luminance [19].

Many technologies exist for lighting such as Tungsten, Mercury, Fluorescent, Sodium and LED. Among these, the most dominant technology is Fluorescent. Fluorescent lamp elements have medium luminous efficacy varying between 37 – 90 *lm/Watt* though their low cost and low run up time make them suitable for residential and commercial building indoor lighting applications. LED is a very promising technology though it hasn't been competitive in the lighting market yet because of its high costs.

From a global perspective, lighting energy in the commercial sector is consumed by six major categories of buildings. These are; offices, warehouses, education buildings, retail buildings, hotels and healthcare buildings. Among these, offices have the largest share with 19% in OECD countries.

In office buildings, lighting is on par with HVAC when it comes to electricity consumption. Offices in the EU use approximately 50% of their total electricity consumption for lighting. Offices are second after healthcare buildings when energy intensity for lighting is considered. According to IEA, annually 35kWh/m^2 is consumed for lighting in offices [19].

Lighting infrastructure in office buildings have evolved with the lighting technology itself. Fluorescent lamps have been dominant since 1950's. 76.5% of light output in commercial buildings of OECD countries in 2005 were provided by linear fluorescent lamps. Fluorescents have also seen various upgrades particularly in their ballasts. Table 2 shows lamp types used for some of the European countries' office buildings [20]. It can be seen that almost all of the new office lighting consists of fluorescent lamps. However, both T5 and CFL lamps are increasing their share of usage compared to T8 and other lamp types.

Table 2: Fluorescent lamp usage in some European office buildings [20].

	Existing Office Buildings		**New Office Buildings**	
	Fluorescent	**Other**	**Fluorescent**	**Other**
Belgium	80%	20%	95%	5%
Germany	99%	1%	100%	0
Spain	70%	30%	85%	15%

With the improvements in control technologies of the fluorescent lamps, dimming of fluorescent lamps have become possible. This allows dimming up and down of light fittings based on available day light hence saving energy.

2.2.4.1. Lighting Controls in Office Buildings

Control of lighting in office buildings can be done in variety of ways as explained in [21]. For small office buildings, manual controls can be used. For medium to large office buildings, automatic controls are required. This requirement not only arises from the difficulty of managing lighting in such buildings but also from building regulations (such as defined in Building Regulations Part L of the UK) that govern energy efficiency standards.

Control of lighting requires three elements, controllable light fitting, sensors and control gear.

Light fittings can be controlled in a variety of ways. Simple on/off control can be achieved by controlling the power supply that feeds the fitting. With the introduction of dimmable fittings, an additional control line was required to indicate the desired dimming level. This was achieved with DC voltage on a separate cable that is wired to the fitting called 1-10V's dimming. Because of its susceptibility to noise, this 1-10V signal was soon replaced with Digital Signal Interface. In 2000's, it was possible to implement microcontroller based communication to light fittings with little additional cost therefore a communication standard based on bus topology was brought out. This system is called DALI which stands for Digital Addressable Lighting Interface [22]. It allows up to 64 DALI light fittings to be controlled with a single pair of wires. DALI not only reduces control cabling but also enables lighting controllers to receive digital diagnostics feedback from light fittings.

Another element in automatic lighting control is the sensor [23]. Sensors have two varieties, passive infrared (PIR) and ultrasonic. PIR sensors are sensitive to light in the infrared spectrum that is emitted by human beings. Whenever the sensor detects a spatial movement on this spectrum, it sets the 'on' signal. Ultrasonic sensors emit high frequency sound which is above human audible range and look for changes on the sound that is reflected from objects around them. If the frequency changes, it means that an object is moving in the radial direction of the sensor. Both of these sensor types have their advantages and disadvantages therefore certain manufacturers incorporate both technologies to ensure accurate detection.

The third element in lighting controls in office buildings is the control gear that commands individual or groups of light fittings. This element is required for various reasons. First, lighting sensors might not be able to incorporate communication facilities to instruct light fittings individually. Second, light fittings might need to be grouped in a variety of ways which prevent them from being hard wired directly to sensors. Third, the data available from the sensors might be used for other purposes such as security or air conditioning. This is where building automation standards are useful. Sensors communicate with lighting controllers via building automation networks. Controllers then instruct their light fittings accordingly.

2.2.5. Office Equipment

Office equipment that can process information by utilising electrical energy existed as early as 1890's [24]. At that time, U.S. Census Bureau sponsored a contest to find out an efficient method to tabulate census data. Herman Hollerith won the contest with his machine that used an electric current to sense holes in punched cards and that also could keep a running total of data. These type of machines soon flourished and a whole new industry that designed, manufactured and marketed computing machines was born.

Soon after this, other types of devices followed such as electric accounting machines, electric writing machines etc.

In the 70's, wide adoption of computers allowed software to become a different industry on its own thanks to the development of programming languages. The availability of thousands of computer programs enhanced the position of computers in work environments even more. 1980's saw the birth of personal computers (PC's). During these years, photocopy machines, fax machines, digital telephony devices all started to change the work environment. These devices became so essential that offices became overly dependent on their functioning.

1990's brought huge technological advances in network infrastructures where large mainframe computers were being used to serve PC's that were now available to nearly every office worker. Internet caused enormous expansion in network equipment market. Today, internet is the driving force in the computing world.

2.2.5.1. Office Equipment and Energy Consumption

In the U.S. non residential office and telecomms equipment accounted for 3% of national electricity consumption in 2000. 9% of electricity consumed in the commercial buildings was because of these [25].

Roth et al [26] have categorised office equipment into eight groups:

- Computer Monitors and Display
- Personal Computers

- Server Computers
- Copy Machines
- Computer Network Equipments
- Telephone Network Equipment
- Printers
- Uninterruptable Power Supplies

These equipment types accounted for 90% of the total annual office equipment energy consumption in the U.S. Their research also shows that five categories which are PC's, monitors, servers, copiers and printers constitute approximately 70% of the overall annual energy consumption of office equipment (Figure 7).

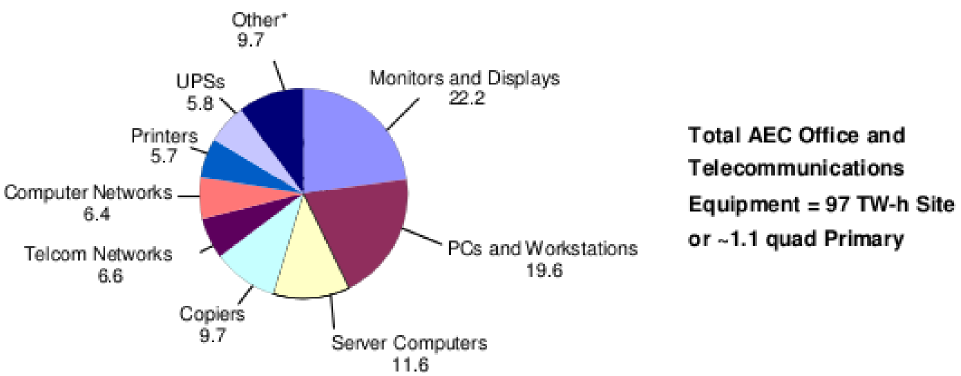


Figure 7: Energy consumption of various office equipment in the U.S. [26]

2.2.5.2. Power consumption of PC's and Monitors

Developments in computing technology allowed laptop computers to overtake desktop computer sales [27]. Nonetheless, office environments still have a combination of both desktop PC's and laptops [28] where desktops are still dominant. When it comes to energy consumption of computers, desktops consume up to three times as much as laptops. The paper [29] lists the studies that were carried out to identify the power consumption of computers. According to the research, desktop computers consume between 50 to 70 watts when active compared to Laptops which consume 10 to 20 watts when active.

Just like PC's themselves, display devices such as monitors and TV's have seen radical changes in the past decade. The introduction of cheap colour Liquid Crystal Displays (LCD's) not only allowed significant space savings but also reduced energy consumption of computers as well. On average, a cathode ray tube (CRT) monitor requires 65W – 135W while working whereas an LCD monitor requires just 30W while working [29].

2.2.5.3. Power consumption of servers

A server is a computer that is dedicated to run specific programs which are designed to serve the requests of other computers. Depending on the type of service that it is designed for, a server can be database server, file server, web server, gaming server etc. Servers provide services to either users across local intranet or to public via internet.

A comprehensive report by Koomey [30] gives valuable information about the global trends in server technologies as well as power consumption of an average server. He indicates that the substantial increase in the usage of internet has caused the number of servers and the data centres (which are dedicated buildings that host many servers) to multiply in the recent years. Also, the energy consumed by servers has doubled between

2000 and 2005 throughout the world. Most of this is caused not by the energy consumption of individual servers themselves but by the increase in the number of servers installed in offices and data centres.

The number of servers is also required to calculate the power consumption caused by servers in an office environment. In [30], the authors have carried out surveys in commercial and public buildings in various cities in the U.S. According to their survey, approximately 89 servers exist for 1453 computers. This shows that the computer/server ratio is approximately 16. Their study also shows the fact that most servers are kept in 'On' status even after hours. Therefore they usually contribute to the base-load of a building's electricity consumption.

2.2.5.4. Power consumption of Copiers, Printers and MFD's

Printers have two dominant technologies that are still in competition today. These are toner based (laser) printers and inkjet printers. Toner based printers use xerography whereas inkjet printers use paper ink. There are two major differences between laser printers and inkjet printers. Laser printers are fast with up to 50 paper per minute print rate. However they consume more power. Inkjet printers are much slower (up to 20 papers per minute print rate) but they consume less power.

According to [31], small power equipment loads for copiers is 850 watts and for printers is 150 watts. However, it is also indicated in this resource that peak power of printing equipment does not give clear indication on the overall energy consumption of these devices since these devices are most likely to be idle.

In this case, printing habits of employees would give a good indication of how and when these devices operate at their rated power. The survey [32] revealed that an average UK office worker prints 45 pages a day. Combining this information with an average of 40 papers per minute speed rate, a printer profile that shows electrical power consumption of a typical printer (or a multi function device) can be obtained.

Finally multifunction devices (MFD's) are usually devices that are capable of printing, scanning, copying and faxing. These devices have become popular in recent years because of their practicality. Their power profiles though, are similar to laser or inkjet printers.

2.2.6. Discussion

Office buildings have evolved in such a way that they grew bigger and more sophisticated in the past decades. These buildings need to incorporate various technologies to allow large numbers of people to work comfortably in them. These technologies provide appropriate environmental conditions (for temperature and lighting) and useful tools to carry out office tasks. For buildings that incorporate a central air conditioning system, the three main consumers of energy are HVAC, lighting and office equipment. Among these the HVAC system and the lighting system constitute a large majority (more than 50%).

2.2.6.1. HVAC

The preferred choice for air conditioning in most office buildings is the packaged systems where heating, cooling and filtration is carried out in the same enclosure. The main energy consuming elements in a packaged system is the compressor, furnace (if heating is carried out by the packaged unit), and the supply and return fans. Unlike the compressor and the heating element, the supply and return fans operate throughout the year because they circulate the air for filtering purposes. When it comes to fuel, it is possible to say that electricity is the main consumer for cooling because of compressors that operate in packaged air conditioning systems. For heating, popularity of boilers and furnaces show that gas is the dominant type of fuel. Control of HVAC systems can be carried out in variety of ways but in a typical control scenario, the central control system utilises temperature sensors to detect the indoor and outdoor temperatures. It then changes the position of dampers that manage external air intake and also operates the heating element or the cooling element to maintain the temperature of the indoor environment at comfortable levels.

Significant share of the HVAC system in overall power consumption of office buildings confirm that this is the most feasible load type when it comes to reducing consumption during a DSR period. Several predictions can be made on the involvement of the HVAC system for DSR activities. Firstly, an approach focusing on a packaged VAV system is likely to cover most of the buildings since this the dominant HVAC type. Secondly, the problem of controlling HVAC for DSR is likely to become more difficult for summer months because the main element that is used during summer is the compressor which consumes electrical energy. Thirdly, the central control nature of the HVAC system shows that it is likely to be easier to integrate it into a central DSR controller.

One difficulty of the HVAC system when it comes to DSR is to predict the resulting temperatures for given amount of power consumption. The thermal exchanges of the building with the outer environment depend on the structural properties of the building as well as outdoor conditions. Hence, the control strategy for DSR should take these circumstances into account when load reduction is to be carried out.

2.2.6.2. Lighting

The majority of lighting systems in office buildings incorporate fluorescent tubes. The advances in digital control gear allow dimming to be carried out. This flexibility provides opportunities for DSR because it enables lighting to be reduced homogeneously in office areas. The direct relationship between energy consumption and the amount of light that is emitted is also an advantage because it makes it easier to for the DSR system to predict the amount of light in an office zone when the power consumption is reduced by a certain amount.

Like the HVAC systems, lighting energy consumption also depends on the outer environment. When there is enough light from the external environment, the artificial lighting in the vicinity of the windows could be reduced for energy saving. However this feature is only limited to office zones that are close to windows. Therefore when it comes to lighting, the variability of the external conditions does not pose a difficulty as much as the HVAC system.

2.2.6.3. Office Equipment

Office equipment can be classed as the third major consumer after HVAC and lighting systems. The share of this category is lower compared to the other two. From a power consumption perspective, the biggest consumers in offices are computers. These are followed by other devices such as servers, MFD's etc.

Control of office equipment is done by individuals working in the environment. For this reason, it is not possible to predict a scenario where the office equipment is turned off by a central DSR system in order to reduce consumption. The only promising technology that can assist DSR is the increase in the number of portable devices. Laptop pc's are replacing desktops. These have the ability to operate on battery power. They also have the means to communicate with a central control system through their computer networks. This might allow a central DSR controller to reduce their consumption provided that they have enough battery power to last throughout the DSR period. If this could be achieved, the majority of the energy consuming loads in an office building could be involved in a DSR control scheme.

2.3. Productivity and the Environment

The primary function of an office building is to provide a comfortable environment to its occupants so that they can carry out collective work. In order to provide this comfort, various systems operate. These systems, particularly HVAC and lighting have fairly fixed operating points that are not only determined by common sense but also various standards. As this research is about reducing the energy consumption of the equipment in the office buildings, it is certain that the conditions in the environment will deviate from regions that are considered comfortable. As loss of comfort will translate to loss of productivity, such a load reduction should be carried out very carefully. This part of the literature review has been carried out to determine the link between productivity and comfort. Therefore individual effects of lighting, air temperature and air freshness on productivity is investigated. As the load reduction in the office might require more than one environmental parameter to deviate at the same time, the combined effects of these environmental parameters are also covered.

2.3.1. Thermal Environment

Humans have mechanisms that take active part in controlling their body temperature [10]. Any change in the temperature of the external environment will cause a change in the thermal state of the body. Moreover, humans constantly generate heat which needs to be dissipated to the exterior environment. Biological processes that are involved in these heat exchanges influence the comfort of humans and hence their productivity.

Body reactions to outside temperature: Human core body temperature is found to be 36.7° C. The skin temperature which is lower than the core temperature varies depending on the part of the body and the activity that the person is carrying out. The skin temperature determines the perception of outside temperature therefore it is more important than the core body temperature when it comes to assessing how comfortable the environment is.

A nude resting man who sits comfortably in a 28° C environment has a skin temperature of 34° C. At this temperature if the ambient temperature is lowered, the body reacts by reducing its skin conductance. Further decrease produces shivering which also causes increase in body metabolic rate. If the temperature is increased, more blood is moved to the skin surface which enables more rapid cooling of the blood. Above an air temperature of 30° C sweating starts which enhances the ability of the skin to cool even further. Sweating and shivering are natural reactions that allow the body to maintain its thermal balance though they are not desirable in modern work environments.

Body reactions to activity: The human body requires constant generation of heat in order to keep itself alive. This minimum rate of energy production is called basic metabolic rate (BMR). BMR changes from person to person. It also changes depending on the activity that the person is carrying out. This is because physical activities require extra energy and this extra energy has to be produced by the metabolism. The BMR of office workers is considered low because their activities involve cognitive tasks rather than excessive physical activity.

Affects of clothing: Heat loss to the environment occurs both through respiration and the skin. However as respiration is dependent on the level of activity, it is the skin that acts as the primary thermo-regulatory organ when the person is not carrying out excessive physical activity like in office environments. Clothing provides a thermal resistance over the skin to prevent excessive heat loss in cold environments. The measure of clothing is clo where one clo is equal to $0.155 m^2 K/W$.

2.3.1.1. Feeling of Comfort

Clothing and activity are the two factors that depend on the individuals. The other comfort factors are; air speed, temperature, mean radiant temperature and humidity which are all dependent on the environment. Fanger has derived a comfort index that is based on these variables and is widely accepted and explained in [33]. His equation can be used to determine the environmental conditions which would produce optimum comfort. One problem with this equation is that it does not allow the measurement of how uncomfortable an environmental condition is. Therefore he developed an index which predicts thermal sensation for any given combination of the environmental variables. This index is called Predicted Mean Vote (PMV). PMV is the mean vote on a seven point scale, which one would expect to get by averaging the thermal sensation votes of a large group of people in a given environment. PMV as a function of ambient temperature is well established for lightly clad people working in office environments.

2.3.1.2. Ergonomics of the Thermal Environment: ISO 7730

ISO 7730 is the standard that is referred by many researchers that investigate the effects of temperature on office productivity [33]. It is used to evaluate moderate thermal environments such as offices using the concept of PMV which is explained in the previous section.

According to the standard, PMV can only be applied to steady-state conditions which are sustained in the previous one hour period. Non-steady-state thermal environments are identified as temperature cycles, drifts and ramps. Temperature cycles are variations in temperature in a given environment where peak to peak temperature difference is greater than 1 K. Temperature drifts and ramps are the rate of change in the temperature of an environment where if it is higher than 2 K/h, it is considered as a temperature drift or ramp. Transients are sudden change in thermal conditions due to step change in temperature, humidity, activity or clothing. Although the definition of these non-steady-state conditions are made, their affects on the perception of comfort in the office is not quantified.

Local thermal discomfort is also defined in the standard. Draught, vertical air temperature difference, warm and cool floors and radiant asymmetry are all factors that affect local temperature sensation. Draught is identified as the most common cause of local discomfort. It is also noted that people at light sedentary activity (like office work) are more sensitive to local discomfort.

The standard defines three categories of thermal environment (Table 3). For each category, the PPD, PMV, draught rate and other local discomfort is specified. The selection of the category in which the building would comply is left to the designers. For an office building, (clo value of 1.0 and activity level of 70 W/m^2) the operative temperatures for summer and winter are also given in the table.

Table 3: Allowed PMV values for the three classes of offices defined in [33].

Category	**Thermal State of the Body**		**Summer (Cooling Season) Celsius**	**Winter (Heating Season) Celsius**
	PPD %	PMV		
A	<6	-0.2<PMV<+0.2	24.5 +- 1.0	22.0 +-1.0
B	<10	-0.5<PMV<+0.5	24.5 +- 1.5	22.0 +-2.0
C	<15	-0.7<PMV<+0.7	24.5 +- 2.5	22.0 +-3.0

The standard allows the temperature of an environment to be linked to PPD/PMV. This is a valuable correlation because PPD/PMV is a single parameter that can be used for a group of people that work in an environment which can be defined with six parameters (temperature, humidity, clothing etc.) This makes it easier to define productivity-thermal environment relationships. The following section is the literature review of the research carried out to determine the relationship between temperature, PPD/PMV and productivity.

2.3.1.3. Effects of Temperature on Productivity

Quantitative research that investigates the effects of indoor thermal environment on the productivity of workers has been carried out for industrial environments and offices.

In his book Indoor Climate [10], McIntyre gives a summary of early work that has been carried out and which investigates how the temperatures affect the performance of manual labour workers. A series of reports issued to the Industrial Fatigue Board in the early 1900's in Britain showed that in hot industries such as tin-plate manufacturing, plant output was related to the outdoor temperature such that as the temperature increased (e.g. in summer season), the plant output dropped. Studies in coal mines also showed that accidents increased as the temperatures rose. Data from munitions factories that operated in World War 2 in Britain show that relative accident frequency increases as the temperature falls below the acceptable room temperature levels.

When it comes to tasks that are more dependent on cognitive performance, McIntyre identified that performance is related to the type of task and the arousal level of the person carrying out the task. He summarizes the study of Wilkinson et al. [34] who have found that vigilance tasks that require workers to respond to external stimulation that is unexpected (such as monitoring radars) are performed poorly when the body temperature was at a level considered to be optimum. Slight arousal (such as higher or lower temperature) caused improvements in the response time of the subjects. Although vigilance is improved with slight arousal, Griffiths and Boyce [35] have found that complex cognitive tasks like tracking moving dots while listening to triplets of numbers through earphones and responding with foot pedals according to the laid down criteria was performed best when the temperatures were close to the comfort level.

Early studies that investigate the effects of temperature on tasks such as learning and offices type work are also summarized in McIntyre. The studies of Mayo [36], Wyon

[37] and Langkilde [38] are presented. From these, he concludes that there is no evidence to suggest that a temperature other than that found comfortable by the majority will produce more work output for such tasks. He also notes that, the effects of arousal depend on the type of task being carried out. For monotone and continuous tasks, slight arousal such as higher or lower temperature improves performance. For tasks requiring great effort, best performance is observed in optimum comfort conditions.

Recent studies have also been carried out to determine the effects of temperature on human productivity. Seppanen et al. [39] reviewed 24 other studies that investigated the affects of temperature on performance at office work. These studies have taken performance indicators that are relevant in office work (such as calculation, text processing, length of telephone customer service time) as a criteria. They have concluded that performance increases with temperature of up to 21° - 22° C and decreases above 23-24° C. They also confirm their previous work reporting that the temperature range between 21° – 25° C has no effect in performance of office workers.

One of the pieces of research that has been reviewed in Seppanen et al.'s study is Niemela et al. [40]. They have monitored two call centres where both observation and intervention techniques were used for assessment. On one call centre, the performance of workers working in different thermal zones was observed. On the other call centre, the performance of workers before and after an intervention (cooling unit installation in the centre) was recorded. The number of calls was used as performance criteria. They found that productivity decreased by 5-7% when the temperatures exceeded 25° C and that cooling the environment to optimum temperatures had positive effect on the performance of the workers.

Some researchers used PMV rather than direct temperature measurements to investigate the effects of thermal environment on human productivity. Lan et al [41] recruited twelve volunteers that performed arithmetic and typing tasks similar to the ones in offices. They established a quantitative relationship between thermal sensation votes (PMV) and task performance such that the subjects were thermally neutral at 22° C and performed poorly as the temperatures increased above this value. They compared their results with Seppanen et al's and found similar relationship between temperature and productivity. Kosonen et al [42] assessed the productivity loss in air conditioned office buildings using PMV index. They compared the findings based on other research (Wyon) and report that task related performance is correlated with the human perception of thermal environment and thus PMV.

2.3.2. Air Quality

Air quality in enclosed environments depends on not only the temperature and humidity but also other factors such as:

- Oxygen,
- Carbon dioxide,
- Odour
- Contaminant level.

The minimum amount of fresh air required for breathing purposes is small (0.2 litre/second per person) though this amount is not adequate to satisfy the various requirements listed above [10].

Fanger has proposed equations that enable determination of both the necessary supply air in an environment and percentage of people dissatisfied because of the levels of pollutants in the air. The concepts of Olf and Decipol are used in these equations. These are defined as:

Olf: Pollution generated by a standard, sedentary, non-smoking person in a state of thermal neutrality.

Decipol: Percieved quality of air in a space wherein the pollution source strength is one olf and the ventilation rate with clean outdoor air is 10 litres per second.

Because CO2 is the most abundant pollutant produced by people, it is often used as an indicator of pollution and odour from other sources as well [43].

2.3.2.1. Effects of Air Quality on Productivity

Yaglou et al [44] were among the first to study the methods that are necessary to reduce odours in closed environments. They found that the quantity of outside air needed to give a satisfactory reduction of odours depended on the number of people present in the environment and advised 3 to 12 litres per second of fresh air for sedentary adults.

Munch et al.'s [45] research is what influenced the ASHRAE standard for ventilation. In their research 79 judges (equal number of men and women) evaluated the intensity and acceptance of body odour by entering an auditorium occupied by 106 people. They found that steady state ventilation rate of around 8 l/sec is required to satisfy 80% of people entering the space.

Worgocki et al.s studies [46] also investigated the effects of air quality on well being and satisfaction in the office. In the first research, they introduced a pollution source to an environment which was occupied by five groups of six female subjects. The subjects were exposed to the environment both when the pollutant was present and absent. The result of the assessment of the perceived air quality and SBS (Sick Building Syndrome) symptoms while performing simulated work was that subjects worked significantly slower when the pollution source was present and the number of people dissatisfied was 7% higher compared to the environment when the pollutant was absent (15%). In the second research, they used the same setup but this time used three different ventilation rates without any pollutant present in the environment. The result was that on average, performance improved by 1.7% for each two fold increase in ventilation rate.

The research carried out by Kosonen and Tan not only summarize the previous work on relationship between air quality and productivity but also propose quantitative formulas to relate the two concepts. In [47], they use published findings of Wargocki to create a productivity loss model using PPD and airflow rate as a criteria. In the relationship between airflow rate and productivity loss, it is stated that the contaminant removal effectiveness of the HVAC system greatly affects the productivity loss percentage.

2.3.3. Lighting

Visual performance and the effects of lighting on productivity has been a central topic of research mostly because it is driven by commercial interests. Rea remarks that "Visual performance has been a central topic of research and discussion in illuminating engineering for many years. This interest is driven by practitioners who want to know how lighting affects the performance of workers in industrial and commercial environments.” [48]. However developing a direct relationship between performance (or productivity) and lighting is not a trivial task. The main reason for this is that every task consists of various components that may or may not require visual feedback. Therefore improving the visual aspects of a task does not necessarily mean that the overall task performance will improve the same amount. Hence the productivity aspect of lighting prevents a global visual performance versus lighting relationship to be developed [49].

Figure 8 shows the relationship between task, light and human performance [50]. As seen in the graph, a task might have components that are directly related to lighting (visual size, contrast, color, image quality). However, there are other aspects such as mood and circadian system which are indirectly related to visual performance but directly related to task performance. Although not shown on the graph, safety can be counted as an indirect aspect of lighting as well. These indirect aspects of lighting that affect task performance are reviewed in the following section before moving on to reviewing the literature about direct visual performance of humans under varying light conditions.

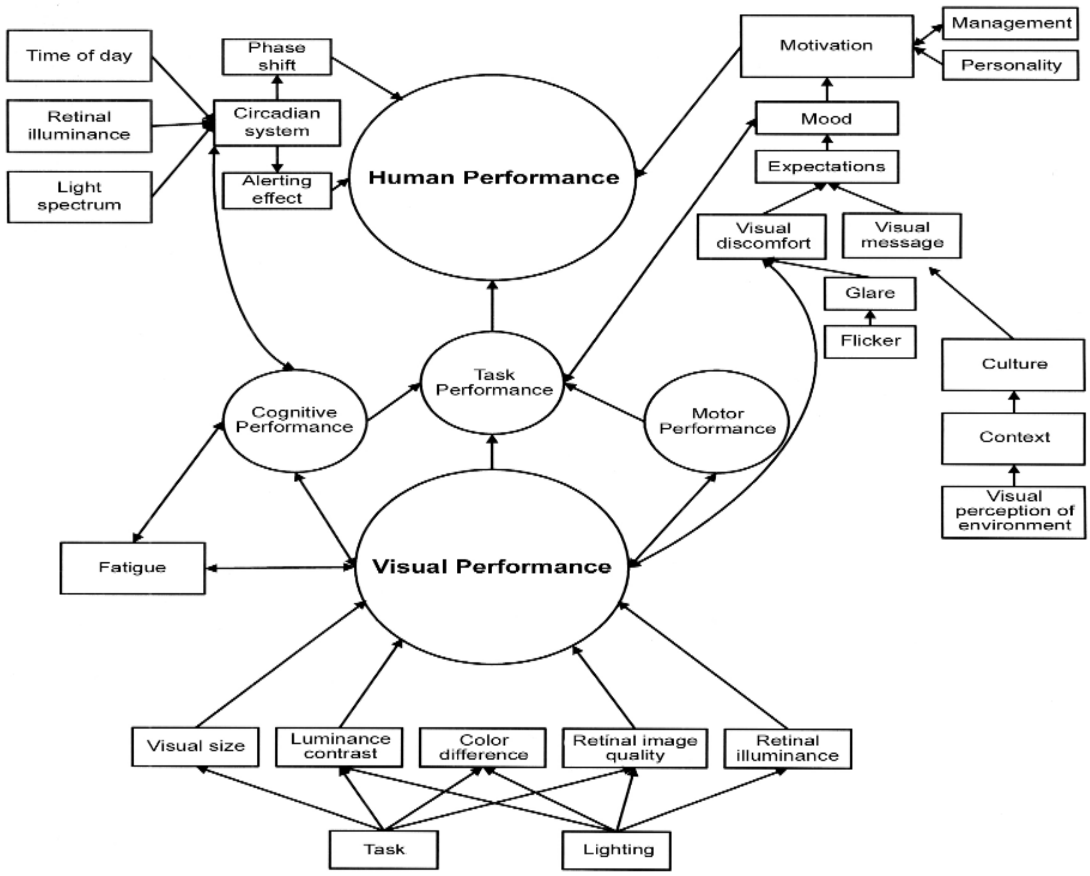


Figure 8 : Relationship between human performance and lighting [50]

2.3.3.1. Biological Effects of Lighting

Biological mechanisms associated with vision not only affect the way humans see but also their psychologies as well. This has complex consequences in the way humans interact and perceive their environments.

Light controls various biochemical processes in the human body [51]. Among these, biological clock and hormone regulation are considered to be the most important effects of lighting. Human biological clock is driven by signals from photoreceptor cells. These regulate the daily and seasonal variations of unique body processes such as hormone regulation (Figure 9). The hormones Cortisol and melatonin play an important role in the alertness and sleep of the body. Cortisol controls the increase in blood sugar levels therefore it is high early in the morning so that the body can be prepared for the daily activities. Melatonin hormone controls the sleep. It drops to minimum early in the morning to keep the body awake and increases at night to prepare the body for the sleep period.

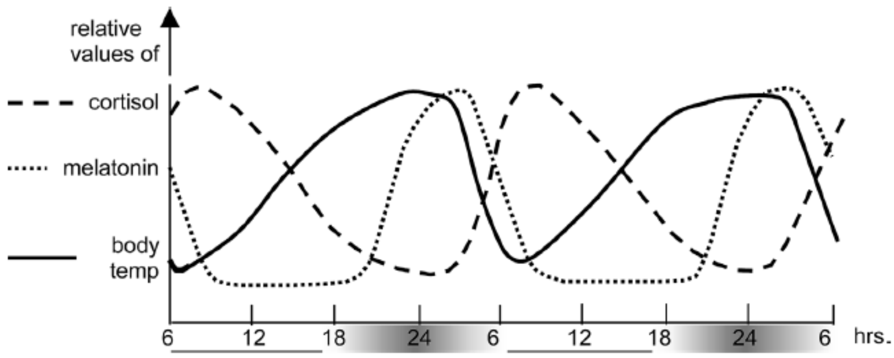


Figure 9: Hormone regulation of lighting [50]

Without the exposure to natural light, the body clock deviates by 15 – 30 minutes every day. This deviation causes the person to feel sleepy during the day and be alert during the night. As a result, not being exposed to natural light cycle causes symptoms that affects the productivity and well being of humans.

Lighting also affects the alertness of humans. Laboratory studies carried out by Küller and Wetterberg [52] indicate that higher lighting level has an alerting influence on the central nervous system. The alertness affect of light is more apparent in night shift workers. A study by Boyce et al [53] shows that arousal levels for workers working during night shifts are higher for workers working in bright light conditions (2800 lux) compared to the workers in low light conditions (250 lux). Other studies show that stress levels for people working in buildings are higher when daylight penetration is low during summer time.

2.3.3.2. Safety Aspect of Lighting

Low light conditions are likely to increase hazards in work environments. According to H&S (Health and Safety) Executive of the UK [54], lighting hazards are caused by factors such as insufficient light on the task, uneven lighting, luminaires being too bright, natural light being too bright and other factors that are related to the quality of lighting. Among these, insufficient lighting on the task is relevant for offices where artificial lighting is the primary source of illuminance. The H&S Executive has good practice guidelines for different types of buildings and sites. The lighting levels in offices should be as shown in Table 4:

Table 4: H&S lighting requirements for offices [54].

	Average illuminance (lux)	**Minimum measured illuminance (lux)**
Work requiring perception of detail (Standard offices)	200	100
Work requiring perception of fine detail (Drawing offices)	500	200

2.3.3.3. Artistic Aspect of Lighting

According to CIBSE, brightness and colour of a work environment determines the perception of people working in there. For example, natural lighting is considered valuable by users and gives a roomy impression. This impression can also be created with artificial lighting in buildings where natural light is not available. Apart from the general impression, accent lighting gives depth and shade to certain areas or objects that are aesthetically pleasing. Paintings, display objects or anything that is suitable can be highlighted with proper lighting which in turn would increase the quality of the environment.

2.3.3.4. Effects of Lighting on Productivity

CIBSE provides a brief summary of how lighting affects task performance [55]. They state that performance due to lighting depends on the type of task and it is determined by size, contrast and the viewer's vision. CIBSE provides a graph where performance score vs. illuminance is depicted (Figure 10).

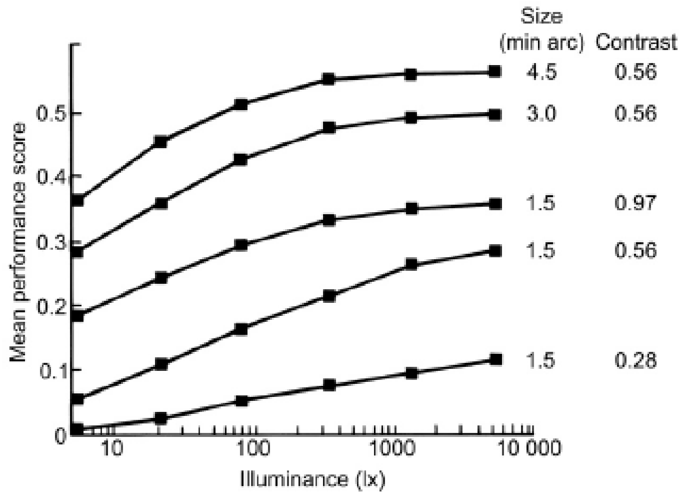


Figure 10: Performance versus Illuminance from CIBSE

Three key facts are pointed:

- Increase in illuminance increases performance.
- Performance effects of illuminance depend on the size and contrast of the task.
- Increasing the illuminance cannot bring a hard task to the level of an easy task.

The performance data provided by CIBSE and many other researchers mostly rely on the work of Rea who has delivered many papers about the productivity aspects of lighting. As discussed earlier, Rea underlines the fact that task performance is not the same as visual performance, hence any effort to develop a global productivity model for lighting is impossible because of the complicated nature of cognitive performance. He then presents a calculation procedure (or a model) that establishes the relationship between visual productivity and light level.

The model presented by Rea requires two inputs to calculate Relative Visual Performance (RVP) of a task; these are contrast and luminance. Rea's 3D plot of relative visual performance, luminance and contrast can be seen in Figure 11:

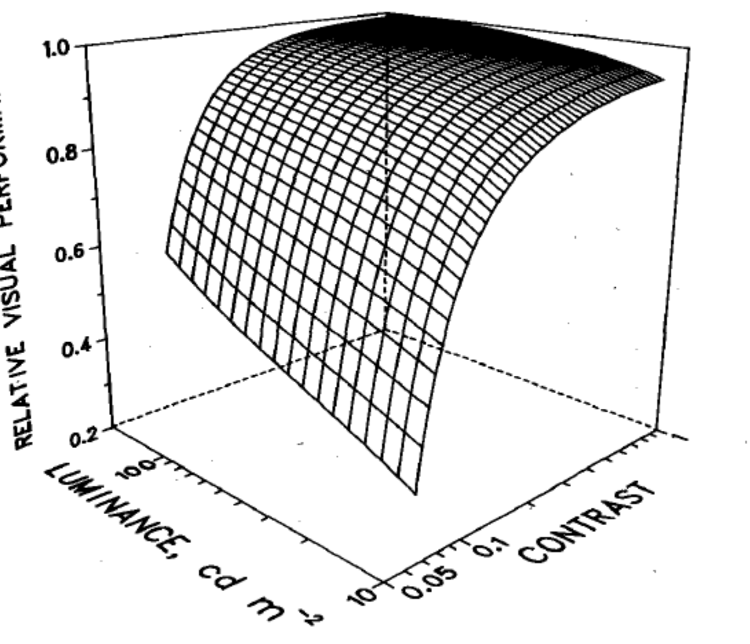


Figure 11: Rea's Visual performance, illuminance and contrast relationship

The results of Rea show that luminance in a work environment is only part of the performance equation the other one being contrast. Moreover, it is evident that performance is more sensitive to contrast rather than luminance. Even at low luminance levels, RVP could reach 90% provided that contrast is sufficiently high. The opposite of this argument is not true; at low contrast levels, increasing luminance does not increase performance the same amount.

Rea's equations make it more difficult to predict performance loss in an office environment when lighting is reduced; not only performance of a task is partly related to visual performance but also visual performance depends on contrast which is a task specific entity. For this reason, researchers have carried out studies to determine the change in productivity indicators in real work environments. For example, studies carried out in factory environments have looked into increase in product output or decrease in product rejects. Surveys carried out in offices looked for worker satisfaction.

Juslen et al [56] provides a good review on lighting and performance. They depict the result of previous studies (Figure 12) that investigate the increase in output and the decrease in rejects in factory environments that have increased the quality of lighting.

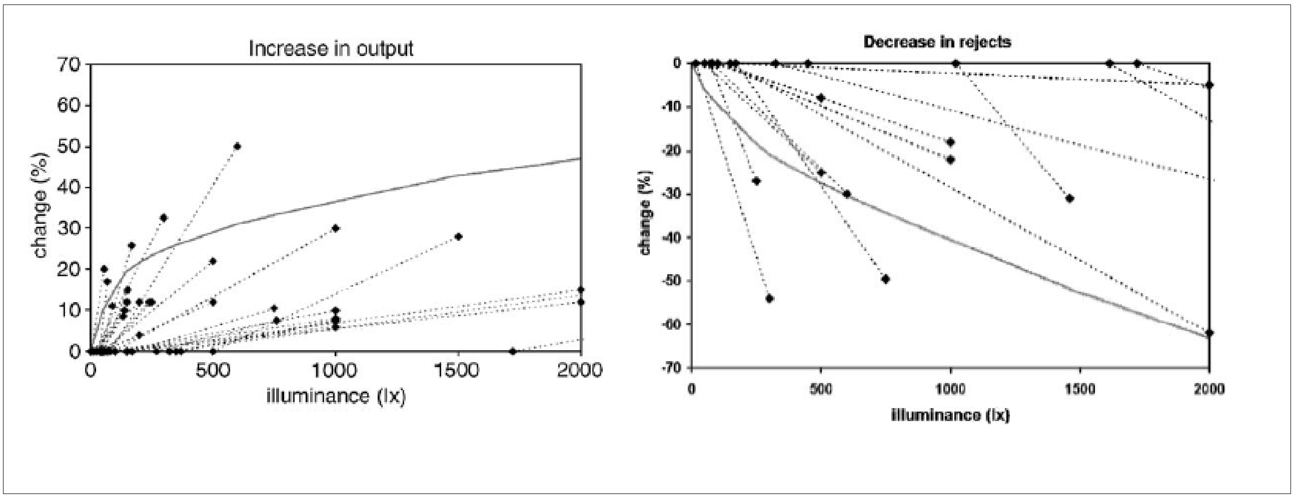


Figure 12: Summary of various papers that investigate affects of lighting on productivity [56]

Their graphs show that performance in manual work environments increases rapidly with increased lighting. However this increase slows down after a threshold which most likely depends on the task being carried out.

In another work, Juslen et al. [57] have carried out a study for a period of 16 months in a luminaire factory in Finland. They found that the test group that worked in an enhanced lighting environment performed better by 4.5%. This is thought to be caused by either better visual performance, biological effects or psychological improvement caused by task lighting. They also discuss the importance of these mechanisms by reviewing the field studies carried out by other researchers.

Hemphälä et al. [58] have looked into the effects of visual environment in mail sorting facilities. They carried pre intervention surveys to reveal the existing status in the workers' perception of lighting conditions, health and musculoskeletal symptoms. It was revealed with pre-intervention surveys that workers who suffered from eye strain had a higher prevalence of musculoskeletal disorders and their sorting performance was slower. After the intervention in the work place by improving the illuminance and uniformity, the workers' performance has improved and they reported less work related stress.

Saunders et al. [59] have investigated the role of the level and intensity of lighting on a simple office task. They carried out their experiments in a medium sized office environment where the observers were first allowed to adapt and then read a paragraph written on a paper. The observers were then asked to rate the visual environment on a 10 point scale. 33 observers participated in the experiment. The experimenters did not distinguish between different light layouts (appearance of the room) but appreciated the level of lighting. Their acceptance ratings increased rapidly to 400 lux where after this value, the level of appreciation was limited.

Chung [60] et al have carried out surveys to assess the validity of a lighting quality index called CSP (comfort, satisfaction and performance) in office premises in Hong Kong. As a result, they found no correlation between subjective assessment and any of the parameters of the CSP index. In the survey that was carried out after the retrofit which increased the working plane illumination from 462 lux to 766 lux, 72% of the occupants agreed that they were satisfied with the new office lighting compared to 40% before the retrofit.

Mui et al. [61] examined the acceptable illumination levels in an office environment by interviewing 293 occupants about the visual environment that is being perceived. The average illumination levels in the offices were found to be 650 lux with a standard deviation of 300 lux. The surveys have shown that the subjects found illumination levels higher than 500 lux more comfortable where the acceptance level was 86%. The acceptance level reached 96% when the illumination level reached 750 lux.

Some research has delivered contradictory results about the quantity of lighting and productivity in an office. Baron at al. [62] examined the effects of indoor lighting on the performance of tasks that involve visual processing. They found that low light conditions enhanced the mood of female subjects that they assigned higher performance appraisals to a fictitious employee presented by the experimenters.

2.3.4. Combined Effects of Environmental Variables and IEQ

The research that is reviewed in the previous section was focused on finding the best environmental conditions for office tasks. Therefore the parameters other than the ones that were being investigated were assumed to be optimum. When DSR is considered, the productivity of an environment needs to be quantified when more than one environmental variable is suboptimal.

IEQ (Indoor Environmental Quality) is the term used to describe the quality of temperature, humidity, lighting, noise and any other environmental variable that affects humans living in an indoor space. It is a global term that is used to summarize 'how well' an environment is. For DSR research, IEQ is the closest parameter to productivity if more than one environmental variable is considered.

In their paper, Fisk et al [63] summarises all the aspects of IEQ and quantifies the benefits from better IEQ in monetary terms. According to their papers, estimated productivity gains from thermal and lighting improvements had potential annual savings of between $US 20 billion and $US 160 Billion in the year 1996. They argue that the benefit to cost ratio for improving IEQ in workplaces is very high. For example, they have estimated that improving ventilation in work environments has a benefit to cost ratio of 14 for the lifetime of the building.

Until recently, IEQ has been considered to be a definition rather than a numerical value. In order to quantify IEQ, not only the effects of individual environmental variables on humans have to be known, but their combined effects should be determined as well. This is a difficult task as explained by Jin et al [64] in their paper:

“Several researchers have investigated quantitative relationships between individual IEQ aspects and occupant productivity. The main limitation of these studies is that they only consider single IEQ aspects, and the combinatorial effects of varying two or more IEQ aspects are overlooked. As a result, the predicted occupant productivity is only valid when other IEQ aspects are identical to the original experiments. Extrapolating to other conditions may therefore lead to errors."

Regardless of the difficulty, there have been efforts to quantify the combined effects of environmental variables on human productivity. One such research was carried out by Kawamura et al. [65] who reported the results of a subjective experiment that was carried out in a climatic chamber which was controlled for temperature, illuminance and noise. The employed subjects performed multiplication and voted their satisfaction levels with the environment which was controlled with different combinations of the environmental variables. The results of their study showed that the subjects gave priority to improved thermal and acoustic environment rather than lighting and that the best results were achieved when all the environmental variables were optimum.

Wong et al [66] have proposed expressions to approximate IEQ acceptance of an office environment using Temperature, Carbon Dioxide, noise level and illumination level with a regression model. They then interviewed 293 office occupants which evaluated the IEQ based on subjective criteria. The correlation between the responses of the occupants and the overall IEQ has been established by a statistic test. Their results from the proposed IEQ acceptance model show that IEQ acceptance is very sensitive to the operative temperature but less sensitive to CO^2. Also, the acceptance remains relatively steady for illumination levels above 500 lux.

Ncube et al [67] also describe a new model for the assessment of IEQ in air conditioned office buildings. They developed an IEQ index where the weighting factors for temperature, air quality, lighting and noise are derived by using a regression model that is based on the questionnaire data obtained from 68 occupants and measurements from two case study buildings in the UK.

Zhu et al [68] have carried out questionnaires to determine the satisfaction levels of subjects who assessed the environmental parameters (lighting, temperature and noise) in a controlled area. They developed charts that show the satisfaction level of the subjects where each one of the variables were kept constant while the satisfaction for the other two were displayed in a four point scale. Their results show that acceptable temperature ranges were between 20.9° C and 30.4° C and the illumination level above 400 lux.

2.3.5. Discussion

Productivity of humans not only depends on the typical environmental parameters but also other factors such as the activity being carried out, psychology and motivation of the worker. Even measuring the productivity of factory workers or workers carrying out manual work which seems trivial because of the quantifiable outputs available from this type of work has proven to be difficult.

When it comes to office type of work where the majority of the tasks are cognitive rather than physical, the difficulty becomes greater. The sensory inputs of humans are only part of the complex environment that effects the processing inside the brain. It is not exactly known how other factors influence the cognitive tasks like thinking and communicating with others. The research that has been reviewed in this work shows that various methods such as collecting survey data and observation of real work environments or measuring performance before and after an intervention on artificial environments has only proven the optimum and/or most adverse environmental conditions for cognitive tasks. The area between maximum productivity and no productivity needs more research.

2.3.5.1. HVAC

From HVAC perspective, it is clear that temperature has an immense affect on productivity. However, the ability of humans to changing temperatures allows some flexibility which can be utilised for DSR. For example, Category C buildings can have a temperature range between 19° C and 25° C according to [33]. Further deviation in temperatures for short periods of time could still be accommodated by office workers provided that they are prepared for such changes. This preparation might be in the form of more suitable clothing or less activity.

When it comes to air freshness, humans need very little oxygen to carry out everyday tasks. Provided that office buildings are not completely sealed and they are not over crowded, it is unlikely that there will be lack of oxygen in the environment during the DSR period. If there is a negative effect caused by unavailability of the HVAC system, this will likely come in the form of pollutants causing undesirable odours. However, considering the limited amount of time that DSR is to be carried out, air freshness is unlikely to have negative impact on occupant productivity.

2.3.5.2. Lighting

As Rea has indicated, it is impossible to develop a formula that relates the amount of lighting level to the amount of productivity of a human being. Visual productivity depends on many factors (as shown in Figure 8). The formulas that are available can only measure productivity for visual tasks that have specific contrast ratios and illuminance levels.

The literature review shows that it is possible to define the boundaries of the allowed light levels. H&S recommendation can be considered as minimum (which is 200 lux). 600 lux is a value that can be considered as maximum since there is no research that indicates observable increase in productivity if the light level is increased further. The effect of light levels between these values is not well defined though both the experimental results and the surveys show that Rea's graph would deliver results that are not far off from reality.

2.3.5.3. Combined effects of Lighting and HVAC

Most of the research carried out in the literature isolates one environmental variable that is being investigated and assumes that the other environmental parameters are optimum. As discussed in Section 2.3.4, researchers interested in the combined effects of several variables on productivity can only do so by looking into research that has been carried out on isolated parameters and by building combined models based on statistical methods which might not be accurate. This adds to the difficulty of estimating the productivity output of office workers where multiple environmental parameters are suboptimal.

A handful of researchers have looked into the area of defining accurate IEQ models. The experimental approach of these researchers are encouraging and the results of their approach could be useful in developing control algorithms that can pick the best environmental variables for given amount of power during a DSR scenario. These are discussed in more detail in the following chapters.

2.4. Building Automation Standards

Building automation standards are vital in controlling loads in an office building for the purpose of DSR. In this section, the fundamentals of building automation standards are explained.

Kastner et al. [69] explain in their review paper that key elements in a building automation system can be categorized into three; field level, automation level and supervision level. At field level, sensors interact with the building environment to collect data and actuators are instructed to carry out actions based on this data. The processing between sensors and actuators happen at the automation level. This is where logical connections are made for enabling numerous elements to be controlled in variety of ways. Kastner et al correctly identifies the interaction between automation level and field level as horizontal because most of this interaction occur among devices that are in similar application areas. On the other hand, at supervision level, vertical communication takes place where all of the equipment from every application in the field and automation levels can be supervised. Supervision level is not meant to carry out control actions for automation but it usually has the facilities to intervene to other levels.

Communication standards might define all or part of the communication stack. Strict standards such as KNX define every aspect of a node starting from the application all the way to the physical level. Others such as BACnet only define layers down to network layer and use other standards' physical and link layers to transport their packages.

In building automation, components on a network are represented as data points. These are logical representation of the application or process that the nodes facilitate. The application developer for the network connects the datapoints using a commissioning program which later loads this information to the nodes. This way, logical links are created between the outputs of sensors and inputs of actuators. Parameters related to the behaviour or functioning of the nodes which host the datapoints can also be set using similar commissioning tools. For example in a lighting application, a sensor is represented as a 1 Bit on/off object. This output of the sensor can be linked to 1 Bit on/off object of a lighting actuator. Eventually, when the sensor sets its output value to 'on' all of the actuators that are linked to this sensor receive the 'on' command and switch on their lights. Being able to create virtual circuits with a configuration tool is one of the greatest benefits of using a standardised building automation network.

Standard bodies have emerged particularly in the U.S. and Europe to promote interoperability among manufacturers, systems and applications. BACNet, LonWorks and KNX are open systems that are popular in the US. and Europe therefore these will be introduced in the next section.

2.4.1. BACNet

BACNet stands for Building Automation and Control Networking Protocol which began its development in 1987 in the US [70]. The first standard was published in 1995 which was adopted by CEN and ISO. There are more than 30000 installations in 82 countries that use BACNet. Use of BACnet is license free.

BACnet is intended for supervision and automation level therefore it does not specify a proprietary physical and datalink layer for communications. Various physical and datalink layers that are already available are standardized for BACnet. The most commonly used ones are Ethernet, and LonTalk. Hence, features like bus topology and speed are irrelevant to BACnet. For this reason, the base element in the BACnet network topology is the segment. To form a network, the segments are coupled with bridges and repeaters. Different media types can be linked with routers to form BACnet internetworks. Data link layers for the networks supported by BACnet is shown in Figure 13.

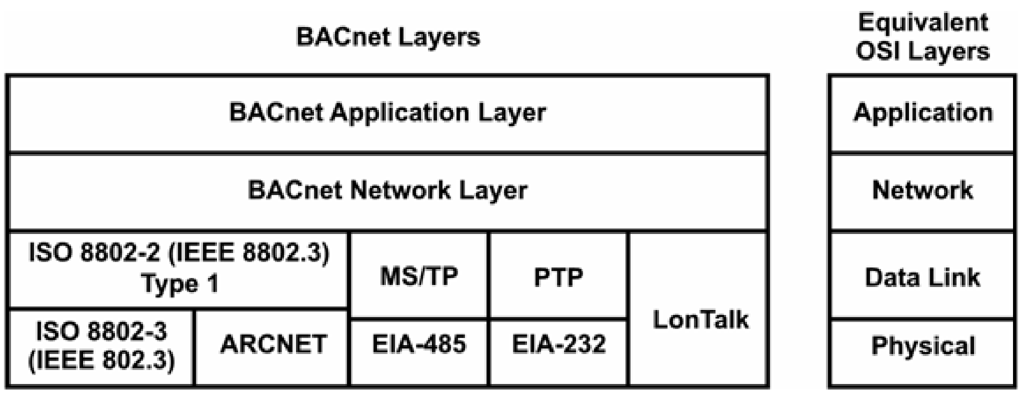


Figure 13: Layers of BACnet

For data link layers, PTP stands for point to point direct communication. It allows nodes to be queried and controlled either through EIA-232 (RS-232) or phone lines. MS/TP stands for master slave token passing. It utilises EIA-485 and uses a token passing scheme for communications. IEEE 802.3 is Ethernet. Under Ethernet datalink layer, ARCNET can be used though this is an obsolete bus standard based on token passing.

Finally LonTalk can be used for both datalink and physical layers.

All of the information in a BACnet system is represented as objects. An object might represent information about an input or output. It may represent logical grouping of points that perform a similar function. Objects have identifiers that allow the network to identify them. In this respect, an object is different compared to a data point because data points represent a single value whereas objects might contain a set of values and properties. For example, a room temperature can be represented as an analog input object in a BACnet system. Apart from the current temperature, the object might include other information such as temperature unit, resolution, description etc.

All of the objects are controlled through their properties. Three mandatory properties need to be included in every object; identifier, name and type. BACnet specification might require additional properties to be mandatorily included into an object. There are two classes of properties, mandatory properties and optional properties. The properties might also have read and write restrictions.

The interactions between devices are carried out by a mechanism called service. A command to read data or instruct an action is defined as a service in the devices that are part of the communication medium. BACnet specifies the services that devices need to provide as part of their specifications.

2.4.2. Lon Works

LonWorks was initially developed by a commercial company called Echelon Corp. It is a bundle of standards and services which consist of LonTalk protocol, neuron chip and a network management tool. The LonTalk protocol has been standardised in 1999 under the name EIA-709 [71].

All of the OSI layers are specified in LonTalk except the presentation and session layers. For physical layer, LonWorks supports twisted pair (TP), powerline (PL), fiberoptic (FO) and radio (RF). The most popular medium is TP which has 78.1 kb/s baud rate. TP medium uses a medium access mechanism based on CSMA which is specifically designed for this protocol and reduces collisions compared to similar systems.

At the heart of a LonWorks node is the semiconductor called the neuron chip. The neuron chip contains the application, communication stack and the facilities to access the physical bus (Figure 14). A derivative of ANSI C language called the Neuron C can be used to program neuron chip.

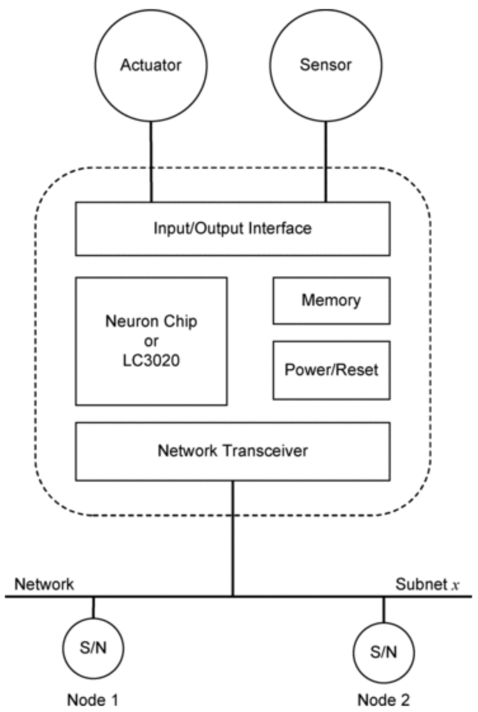
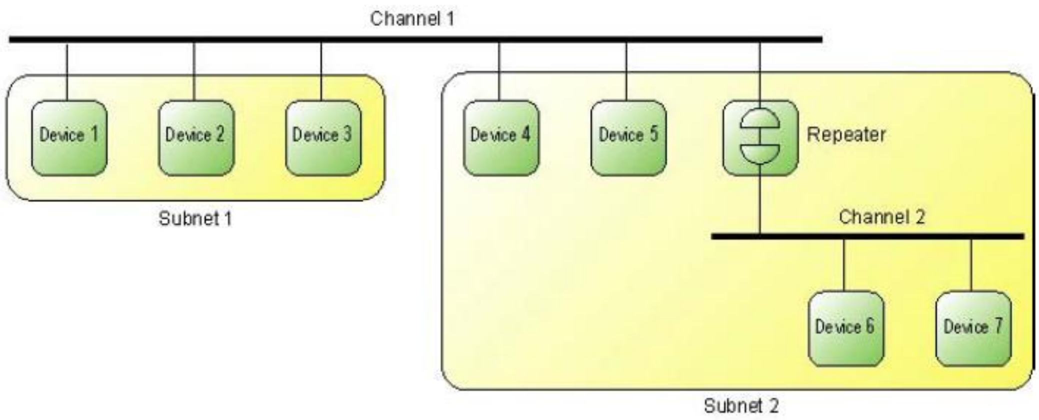


Figure 14: Neuron Chip Functions

Lonwork domain is a logical collection of devices on one or more physical channels (such as TP). Communication can only take place among devices configured in a common domain and can be achieved with broadcast, multicast and individual addressing. A subnet is a logical collection of devices within a domain (Figure 15). Each LonWorks domain can hold up to 255 subnets each having 127 nodes. Similar to a subnet, a group is defined as logical collection of nodes. However, groups do not need to be on the same channel. Group addressing is used for multicast communication. 256 group addresses can be defined in every domain. For peer to peer communication, 48 bit address called the node id or the 9 byte neuron id can be used.



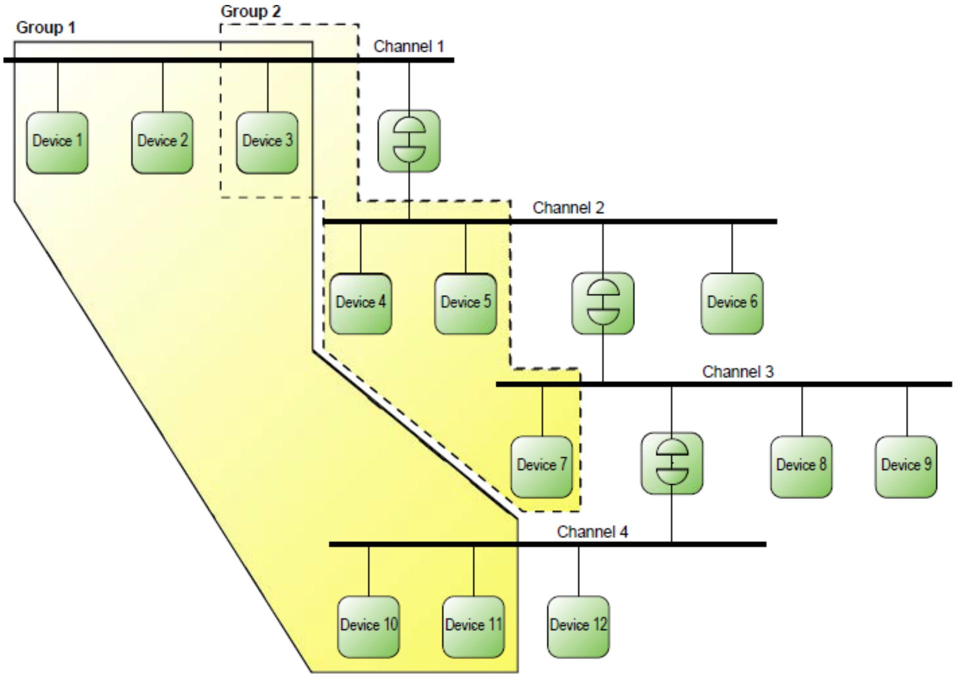


Figure 15: Various addressing options for Lonworks

There are five addressing formats defined in LonWorks. These are; domain wide broadcast, subnet wide broadcast, multicast, unicast (using node id), and neuron id. Each node contains an address table that contains addressing information which can be managed by a network management tool in a network. The application can specify an address for an outgoing message by referencing an entry in the address table (which is called implicit addressing). Alternatively, the node can specify the full address of the destination (which is called explicit addressing). To program addresses and configure nodes, LonWorks provide a variety of management tools that is based on middleware developed by Echelon.

Finally, a typical frame of a LonWorks system is seen in Figure 16. The header contains information about bus protocol version, packet format, address format and address length. The address size is variable depending on the addressing scheme. If domain is defined, domain address can also be defined. The rest of the packet consists of transport and application layer data.

msb			lsb
Version	Packet Format	Addr Format	Length
Address (3 to 9 bytes)			
Domain (0, 1, 3, or 6 bytes)			
Packet			

Figure 16: Data frame sizes of a Lonworks packet

2.4.3. KNX

KNX is founded in 2002 with the merger of three fieldbus standards that were dominant in Europe; EIB, EHS and BatiBus. It is managed by a non-profit organisation called Konnex Association which is based in Germany [72]. According to Konnex, more than 10 million KNX devices operate across the globe and there are more than 20000 qualified KNX installers and engineers. Various standard bodies have accepted KNX standard such as ISO 14543 and CENELEC 13321-1.

Like LonWorks, KNX also defines all but two of the OSI layers. For physical layer, there are various options available; twisted pair, powerline, radio frequency (RF) and IP. Among these, the most popular physical layer is the twisted pair bus which supports speeds up to 9600 bps. The TP uses CSMA/CA mechanism that is controlled by a transceiver chip called TP-UART. Unlike LonWorks, a single chip is not promoted for application development. Instead, the specification is available to KNX member companies who can develop their own software stacks. However, the transceiver chip which manages the data link layer is a monopoly of a single company which puts KNX into a similar position to LonWorks.

KNX TP bus is structured as lines. Lines are separated from one another with devices called Line Couplers. The largest line is called the backbone. A backbone might have up to 15 main lines attached to it. Similarly, each mainline can contain up to 15 lines. A main line together with its lines and nodes constitute an Area (Figure 17). Each line can contain up to 256 KNX nodes. As a result, the total number of devices that can exist on a KNX system is 65536.

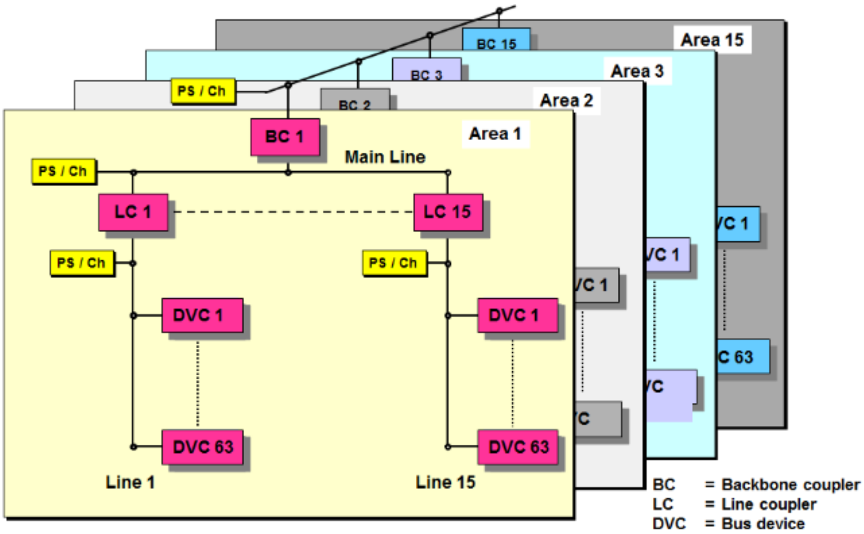


Figure 17: KNX Line structure

Addressing in KNX can be done as broadcast, multicast and individual addressing. Individual addressing utilises the two byte individual address of a KNX node and is used for configuring the node during the commissioning process. All of the application on the automation level is done through multicast messaging which depends on a group address. There can be up to 65536 group addresses on a KNX bus. Each node contains a group address table and an association table which links the addresses to the datapoints on the node. When a multicast message arrives to a node, the node checks its address table. If it finds the address, it passes the packet to the datapoint using its association table.

Figure 18 shows a KNX data frame. It consists of a control field, destination and source address field, routing and length (RL) field, data field and parity field. Unlike LonWorks, address field sizes on KNX are not variable. The extra bit in the destination field is used to indicate whether the address in the destination field is a multicast or individual address. In the basic frame format, only 16 bytes is allowed for data field though KNX defines an extended frame format which allows up to 245 bytes in the data field.

C field (8 bit)	Source field (16 bit)	Destination field (17 bit)	RL field (7 bit)	Data field (1-16 Byte)	P field (8 bit)

Figure 18: Typical KNX frame

As shown in Figure 18, a standard frame that only carries simple information (such as a switch on/off command) consists of 8 bytes which are allocated as follows.

1 Bytes Header

2 Bytes Source Address

2 Bytes Destination Address

1 Byte Package Information

2 Bytes Command Information

Frame size information will be used in the following chapters to predict the capability of this bus standard in handling DSR specific applications.

3. Energy Consumption Simulation Model for DSR

3.1. Introduction

Office buildings are large and complex structures. It is not easy (and practical) to develop DSR methods for office buildings using real set-ups in real buildings. This makes computer models the only available option to carry out experiments that yield applicable results. However, in order to have valid results, a computer model that is used for the purpose of DSR study needs to be designed specifically for this purpose.

This chapter is about design, implementation and validation of a building energy consumption simulator that has been used as a test bed for this study.

3.2. The Scope of a DSR Simulator

One of the objectives of this thesis is to propose an automatic DSR control system for office buildings. This control system needs to utilise all of the controllable loads at its disposal to ensure that load reduction is carried out while maintaining the productivity levels of the occupants at maximum. However, each load type has a different effect on productivity. Chapter 2 has shown that two load types, HVAC and lighting cause the greatest energy consumption in an office building. HVAC maintains the building at given temperature set-points whereas the lighting system maintains the lighting at optimum levels. The productivity aspect of these two loads require a simulator that can calculate the resulting temperature and lux level values in the office environment during a DSR event. For this reason, the scope of a DSR simulator covers thermal and lighting aspects of a typical office building. Among these two elements, thermal simulation is the most complex part. Energy consumption of an HVAC system depends on many parameters that are specific to the environment and the building.

Researchers who investigated the utilisation of building heat capacities for DSR needed to answer a similar question: How do the temperatures inside a building deviate when power to the air conditioning system is reduced? The following literature review has been useful in understanding how they tackled this problem and what tools they have used.

3.3. Demand Response and Building Heat Storage

One of the most comprehensive papers on heat capacity utilisation is authored by Yin et al [73]. They have used Demand Response Quick Assessment tool to assess the potential impact of DR strategies on office and retail buildings in California. They use a standard building specification and test the effectiveness of various strategies that can reduce peak power demand caused by the HVAC system. The main focus is to observe the effectiveness of the thermal mass of a building on temperature variation when the climate is warm and when pre-cooling strategies are used. Their results show that high thermal mass is an effective element in reducing thermal loads by up to 30%.

In a another work, Xu studies the potential of pre-cooling in office buildings under very hot climates [74]. The study was carried out as a form of field tests where two buildings in the California region were monitored intensively. It is found that the effectiveness of night pre-cooling in a typical office is very limited if the building has adequate HVAC capacity.

In another study, Braun et al. developed a tool that allows evaluation of thermal mass control strategies in buildings. They represent the behaviour of the building, cooling plant and air distribution system and train the model using measured data. Based on this model, they propose thermal mass control strategies which result in up to 40% reduction in total cooling costs compared to night setup control [75].

In Lee et al's paper, a demand limiting strategy for commercial building cooling loads is presented [76]. They first describe the development and evaluation of the model that they use as a test bed for their studies. Their model is based on a thermal network of a building that has been developed by Chatuverdi and Braun. The internal capacitances and resistances that are present in the model are found by training the model with a data set. The trained model is then used to investigate the impact of different control variables on demand reduction and to determine an appropriate strategy that is to be used in the modelled building. The strategy results in 30% reduction in peak cooling loads compared to the existing cooling strategies.

An experimental study by Xu et al has been carried out to demonstrate the potential for reducing peak-period electrical demand in moderate weight commercial buildings by modifying the control of the HVAC system [77]. The study was carried out on an 80000 ft^2 office building where the performance of the HVAC system was monitored by using temperature sensors as well as power meters that were connected to the components of the system such as fans and compressors. It was found that a simple demand limiting strategy where the building is pre-cooled to the lower temperature comfort limits prior to peak period and then allowed to float to the upper limits worked well. The effects of night pre-cooling on load reduction were found to be unclear.

Even though the results of these studies report varying effectiveness of preconditioning buildings for the purpose of DSR, they all show that it is possible to reduce consumption for short periods of time without causing discomfort. When it comes to modelling, two categories become apparent: simple models that are trained for specific buildings and complex tools that are intended for more complex simulation but utilised for DSR. For example, Lee [76] use a model that utilise an electrical representation of building thermal loads. The specific values for the resistances and capacitances of the model are determined by training it with real data. On the other hand, Yin et al utilise the 'Demand Response Quick Assessment Tool' to achieve a similar objective. This is a comprehensive tool that utilises a much more complex simulation engine.

Based on this information, it becomes apparent that it is possible to construct a DSR simulator by utilising the tools that are already developed for the purposes mentioned above. In the following section, some of these tools are reviewed from their suitability to DSR perspective.

3.4. Existing Simulation Tools

The difficulty in constructing a DSR simulator from scratch makes it mandatory to utilise the existing simulation models. In this section, the tools or simulators that have the potential to be utilised for the purpose of this study are reviewed.

3.4.1. Simple Tools Based on Models

Simple tools to simulate various aspects of building energy consumption can be investigated in two broad categories; tools that focus on thermal requirements and tools that focus on electrical demand.

Tools that are developed for assessing the HVAC aspect of a building consist of basic models or tabulated data. In his paper [78], Balaras reviews a significant number of tools that are developed for predicting the HVAC requirements of office buildings. He classifies these based on their inputs, outputs and limitations. He describes 16 of the simplified tools in his discussion and explains their pros and cons.

Balaras's assessment shows that simple tools require few input parameters such as building geometry, ambient temperatures, internal loads, external loads and infiltration to deliver their outputs. The outputs are generally centred around either indoor temperatures or cooling loads; monthly or hourly.

Tools that are developed to investigate electrical demand are explained in several papers ([79] , [80], [81], [82], [83]). In [79], the tool that is developed can produce demand simulators for individual dwellings. This tool serves the purpose of quantifying the affects of low carbon measures on the power grid.

Although in a minority, some researchers investigated electricity consumption simulators for office buildings [84] though their efforts are made for understanding the influence of user behaviour on demand.

3.4.2. Complex Simulation Tools

Complex simulators are developed to carry out detailed energy consumption analysis of buildings. A study that compares available aggregate building energy simulation programs has been carried out by Crawley et al [85]. Their study confirms that most of the simulators are dominated by thermal performance of buildings. Daylight and solar performance are also included in many of the simulators but these are included because of their influence on thermal performance. Electrical consumption is calculated by using the thermal simulation results to find out HVAC consumption (pumps and compressors) which is then added to the consumption of other conventional loads. Conventional loads are usually predefined by users in the beginning of the simulation.

3.4.3. Assessment of Tool Types

The major advantage of simple tools is that they require few input parameters which make them easy to use and understand. Their disadvantage is, because they are developed for a specific purpose, the outputs that they deliver are less likely to be suitable for simulations that have a different purpose. Hence if a simple tool is to be utilised, it needs to be modified for the purpose of the study that is being carried out and this process might be cumbersome.

Complex tools have lots of options to deliver DSR specific results. They have the flexibility to model almost any type of building and climate. However they usually require numerous inputs to deliver even simple results. Moreover, most of the simulators are not flexible in implementing various electrical loads in detail. The greatest problem of using complex simulation tools though is the difficulty in adapting them to other purposes. For example, most of the simulation engines carry out complex functions to include all aspects of building design. Isolating the parameters or procedures that are unnecessary for a specific purpose is difficult. Also, developing the results based on the individual simulation requirements might not be possible due to the integrated nature of various functions.

3.5. Methodology Followed for Developing a DSR Model

In this study, a DSR model is constructed by building various elements around a simple but proven thermal model. In order to construct the model, the following approach has been taken:

- Identification of the electrical loads that will be controlled for DSR
- Determination of the thermal simulation model..
- Implementation of the various elements of the DSR Model which include:
    - Thermal Simulation Block
    - Electrical Simulation Block
    - DSR Simulation Block
- Verifying the model
- Determination of the building size, shape and construction properties to be modelled
- Identifying climate data to be used in the model
- Calculation of the HVAC size, capacity and duct work.
- Validation of the Model using a complex simulator.
- Validation of the model by sensitivity analysis
- Comparing results with data available from the literature

Development Platform

Matlab has been selected as the development platform for the DSR model because it allows enough flexibility to carry out mathematical equations necessary to solve thermodynamic problems and also allows implementation of bespoke functions. The ability of Matlab to produce the results in various forms is also an advantage.

3.6. Determining the Controllable Loads

The variety of loads can vary significantly from building to building and not all of these are suitable for controlling. Moreover, as DSR is related to the energy consumption of a load, it is unnecessary to implement loads that consume little energy and therefore whose removal will have negligible effect on the total consumption of the building.

For this reason, the loads that will be involved in the control algorithm development need to be selected. The evaluation criteria for this selection are determined as follows:

Average energy consumption: It has been shown in Chapter 2 that DSR can only be carried out for short periods of time (e.g. 2 hours). This means that the control methods should focus on the loads that contribute to the average power consumption during this time frame. Because DSR can be required any time during the work day, loads that have high average consumption throughout the year are likely to be more suitable for DSR.

Technical potential for controllability: The loads that are candidate for DSR control should have the necessary computing power to carry out the DSR algorithms and should be able to communicate with other loads.

Power reduction flexibility of the loads: Loads that are critical in the functioning of a business or whose sudden removal are likely to cause negative impact on the occupants are not suitable for DSR applications. From this perspective, energy storage becomes an important feature. If the load offers a direct or indirect storage option for its functions, then its sudden removal would have minimum or no impact on the occupants until the storage runs out. For this reason, the capability of energy storage becomes an important feature for DSR.

Based on these criteria, the load categories are evaluated as follows:

HVAC: Air conditioning and heating systems are the primary contributors to peak energy demand. Because of the physical location of the HVAC plants and the sensors, automation industry is well established in controlling of the HVAC units. The heat storage capability of the buildings, which can be considered as an indirect storage, allows these devices to be shed for short periods of time without significant changes in the temperature and the air quality of the environment.

Lighting: Lighting is on par with HVAC when it comes to peak demand contribution. Recent technologies allow new generation fittings to be precision controlled as well. The possibility of dimming in more advanced light fittings allows their power to be reduced without causing significant reduction in productivity levels.

Computers: Computers make up most of the IT equipment when it comes to power consumption. These devices are networked therefore they are relatively easy to interface into the building automation systems. Until recently, personal computers had limited storage availability making them vulnerable in black out situations. However, with the advances in portable device technologies, many computers have their own batteries making them suitable for temporary load shedding applications.

Servers: Servers are critical to the operation of computer networks. They consume significant amounts of energy (though the total is lower than computers). Their operation is considered to be vital to the operation of the IT facilities therefore their interruption cannot be considered. On the other hand, the UPS systems on these devices allow some load shedding though it is unknown whether or not the UPS systems that are designed to supply power in the event of a power outage would be suitable for load shedding purposes.

MFD: Multi-function devices, particularly laser printers, require high power momentarily. Because they are not in operation all the time, most of these devices consume little energy on average. They might have network access that make them suitable for DSR commands though their lack of storage is a disadvantage.

Catering Devices: Catering appliances have little impact on the overall energy consumption in a typical office environment. They are shared among the users and have limited communications capability.

A summary of the above observations is given in Table 5.

Table 5: Assessment of the loads from DSR control perspective

Device	**Total Energy Consumption**	**Controllability**	**Battery or Storage Option**
HVAC	High	Yes	Yes
Lighting	High	Yes	No
Computers	High	Possible	Yes
Servers	Medium	Possible	Yes
MFD	Low	Possible	No
Catering	Low	No	No

The three categories; HVAC, lighting and computers have high energy consumption and they offer the possibility of being controlled. Portable computers and HVAC offer storage capability as well. Among the high consumers, only lighting does not have battery or storage option. If load reduction in lighting is considered possible, then it can be assumed that all of the three major consumers are suitable for DSR. This means that a majority of the total load can be shed for short periods of time.

The following sections will present the functions that are used to implement the simulator.

3.7. Implementation of the DSR Simulator

Figure 19 shows the graph that depicts the main elements of the DSR simulator that has been implemented. The inputs are shown in green boxes and outputs in yellow boxes. Blue boxes represent the main simulation blocks.

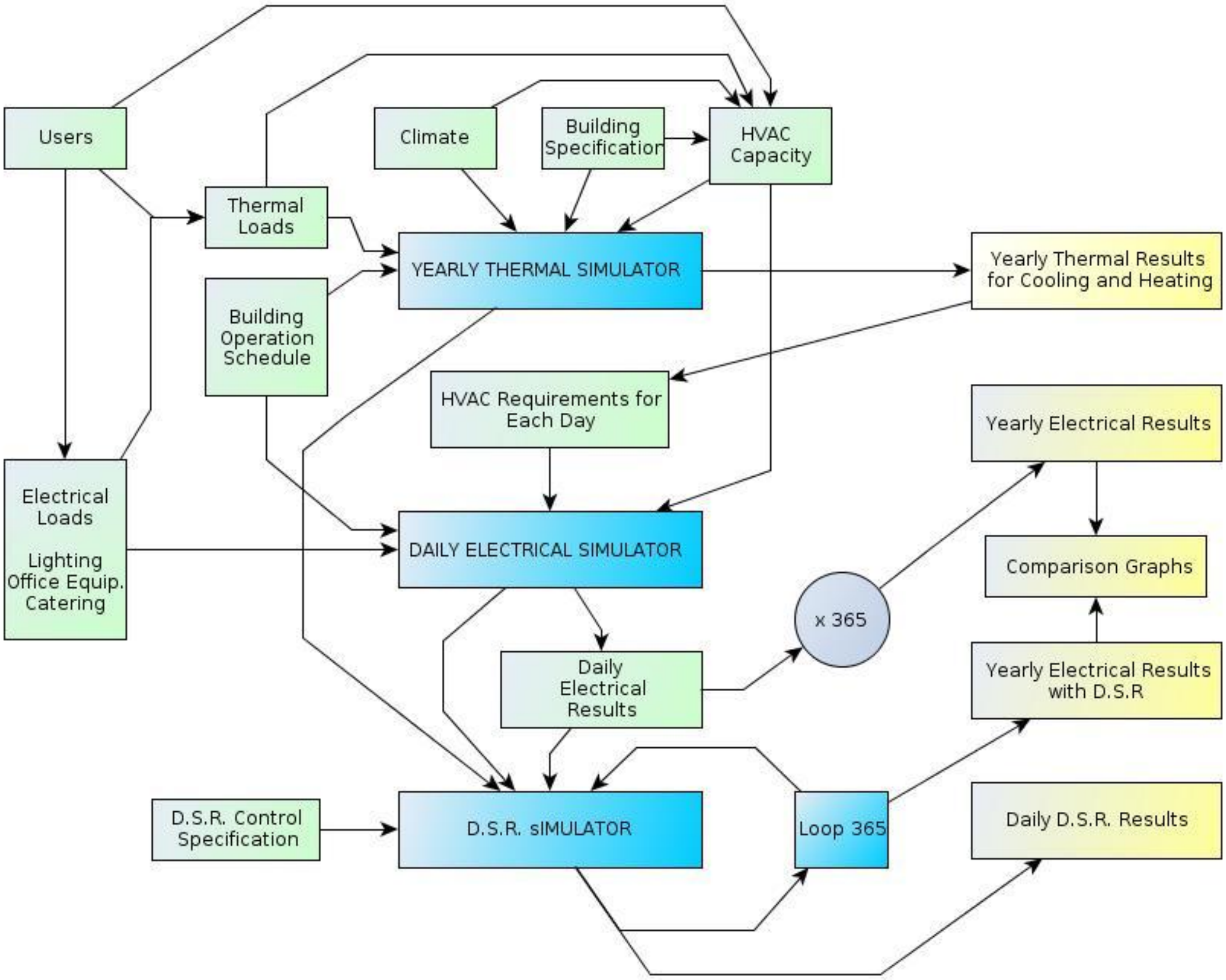


Figure 19: General Schematic of the DSR Simulator

The simulator has three main blocks that carry out distinct operations. These are; thermal simulator, electrical simulator and DSR simulator. The thermal simulator runs the thermal model of the building to determine the heating and cooling requirements. From the heating and cooling requirements, the consumption patterns for electrical loads of the HVAC system (such as the compressor and the fans) are determined. These are passed on to the electrical simulator which runs a daily simulator to determine the daily electrical consumption of the building. The daily results are used to predict the yearly electrical results. Both the yearly thermal and electrical results serve for two purposes:

- To ensure that the overall energy consumption of the building that is simulated is accurate.
- To serve as a baseline to compare the DSR case with non-DSR case.

The results of the thermal model and electrical model are passed on to the DSR model. The DSR model carries out the same thermal and electrical simulation using the exact parameters that the yearly thermal model and electrical model has used to develop their results. However, the DSR simulator changes the consumption pattern of one or more controllable loads so that the deviation in productivity could be compared with non-DSR case. It then develops the results for the DSR case. The DSR simulator needs to loop for the number of days it has to simulate.

The model then develops the yearly DSR results as well as daily DSR results if a specific day is to be analysed. Graphs depicting the DSR and non DSR case are produced for comparison.

The following sections will describe the implementation and verification of the three simulation blocks.

3.7.1. Thermal Simulation Block

The task of the thermal simulator is to determine the thermal energy to maintain the building in suitable environmental conditions. In order to do this, the thermal simulator needs to model the heat exchanges between the outside and the inside of the building envelope. The implementation process has been carried out as follows: 1) Selection of the thermal model algorithm. 2) Determining the inputs to the algorithm. 3) Implementing the functions to carry out the simulation that uses the algorithm. 4) Implementing the functions that deliver outputs.

3.7.1.1. Selecting a Building Thermal Simulation Model

BuildingCalc simulation model that has been developed by Nielsen [86] for building thermal research and that has been validated by comparison with at least one of the sophisticated models has been the basis of the thermal part of the simulation model developed for this study.

The basis of BuildingCalc is WinSim which is explained in Schultz et al. [87]'s paper. Schultz et al. argue that precise information for detailed building analysis might not be available at the beginning stages of building design. Therefore they identify that a model that can estimate the overall energy consumption with minimum parameters should be useful. They also argue that fundamental information related to the heat loss coefficient and thermal capacity of the building can be estimated from the design. Most transmitted solar radiation will be absorbed by surfaces having very low thermal capacitance hence this will cause solar radiation to be quickly reflected to indoor temperatures. Therefore the internal capacitances, thermal conductance parameters and contribution of heat sources (external and internal) should be adequate to calculate energy performance.

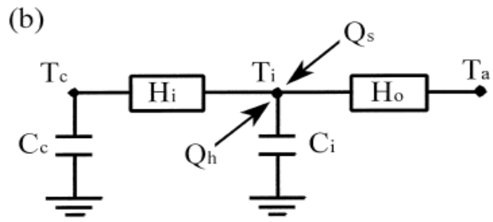


Figure 20: Simple model of Schultz et al.

Figure 20 shows the basic model used by Schultz et al. In this model, H_i and H_o are the heat transfer coefficients from internal construction to indoors and indoors to outdoors respectively. C_c is the heat stored by the construction of the building and C_i is the heat stored by the internal mass such as the air and the furniture. Both the Sun (Q_s) and other loads (Q_h) contribute to internal heat storage of the building.

In order to make it a more useful tool, Nielsen has improved WinSim by including a more comprehensive HVAC system operation, variable *UA* for heat loss to the external environment, shading factor from external objects, and also adding heat transfer coefficient from internal construction surface to the air (Figure 21). They called this model BuildingCalc.

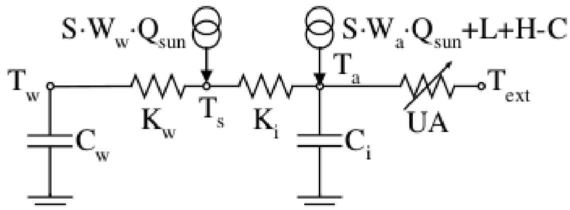


Figure 21: Model of Nielsen et al.called BuildingCalc

In BuildingCalc, energy from solar radiation is absorbed by both the wall surfaces and the internal mass (air and furniture). The heat transfer between the two is determined by the heat transfer coefficient K_i. Internal loads L, air conditioning heating and cooling H and C all affect the internal mass. Shading factor S is the coefficient that represents the decrease in solar heat transfer due to outside obstructions.

The equations necessary to solve the model are:

$$
\begin{aligned}
&C_{\mathrm{i}} \frac{\mathrm{d}T_{\mathrm{a}}}{\mathrm{d}t} = UA \cdot (T_{\mathrm{ext}} - T_{\mathrm{a}}) + K_{\mathrm{i}} \cdot (T_{\mathrm{s}} - T_{\mathrm{a}}) \\
&\quad + S \cdot w_{\mathrm{a}} \cdot Q_{\mathrm{sun}} + L + H - C \\
&C_{\mathrm{w}} \frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} = K_{\mathrm{w}} \cdot (T_{\mathrm{s}} - T_{\mathrm{w}}) \\
&0 = K_{\mathrm{w}} \cdot (T_{\mathrm{w}} - T_{\mathrm{s}}) + K_{\mathrm{i}} \cdot (T_{\mathrm{a}} - T_{\mathrm{s}}) + S \cdot w_{\mathrm{w}} \cdot Q_{\mathrm{sun}}
\end{aligned}
$$

(1)

Where;

T_{ext}: External temperature

T_a : Indoor air temperature

T_s : Temperature on Indoor Surfaces

T_w : Temperature in thermal mass

C_i : Internal air heat capacity

C_w: Heat capacity of construction

K_w: Conductance between internal surfaces and construction

K_i : Conductance between internal surfaces and indoor air

UA: Conductance to the external environment

w_a : Solar Energy fraction absorbed by indoor air

w_w: Solar energy fraction absorbed by internal surfaces

Q_{sun}: Solar energy transmitted

S : Shading factor from variable shading devices

L : Internal loads

H : Heating load

C : Cooling load

t : Time

For each time step, the computer model calculates solar gains, ventilation requirements and the temperatures by solving the equation.

The total thermal conductance is calculated with the following equation:

$$UA = \sum U \cdot A + \sum \Psi \cdot l + c_{\mathrm{a}} \cdot V \cdot (n_{\mathrm{vent}} + n_{\mathrm{inf}} + n_{\mathrm{mec}} \cdot (1 - \varepsilon))$$

(2)

Where the total *UA* of the building is equal to the sum of the *UA* of windows, the thermal conductance of the building envelope and the heat carried out by convection through the ventilation processes and as well as the infiltration. As the ventilation rates are time dependent, *UA* value has to be calculated in every time step.

Heat capacity of the construction material is calculated by summing up the product of specific heat capacity (*cw)* and area (*A*) of each surface *i*.

$$C_{\mathrm{w}} = \sum_i c_{\mathrm{w},i} \cdot A_i$$

(3)

The conductance K_w between the construction material and the internal surfaces is found from:

$$K_{\mathrm{w}} = \sum_{i=1}^{N} \frac{A_i}{r_{\mathrm{eq},i}}$$

(4)

Where *req* is the thermal resistance of the surface.

The operation of the systems is as follows: if the temperature of the air at the end of each time step exceeds the set-point temperature, outdoor ventilation is activated. If it still exceeds, cooling system is fully activated. If the step value of cooling is too high an intermediate value is calculated by using the following linear dependency equation:

$$x_{\mathrm{set}} = x_{\mathrm{min}} + (x_{\mathrm{max}} - x_{\mathrm{min}}) \cdot \frac{T_{\mathrm{set}} - T_1}{T_2 - T_1}$$

(5)

Similar calculation is done for heating as well.

This way, the indoor temperatures are kept within boundaries defined in the system operation schedule. The solution to this equation gives the heating and cooling that is necessary to maintain the building within given temperature set-points. This way, power consumption of the air conditioning system is calculated.

3.7.1.2. Inputs to the Thermal Algorithm

The equations show that the thermal algorithm requires inputs in the following categories: Climate, Building Specification, HVAC Capacities, Building Schedule and Thermal Loads.

Climate and Geographical Location

Q_{sun}, T_{ext} and H are the parameters that depend on climate. Q_{sun} is the energy brought in by solar radiation. Solar radiation depends not only on the latitude of the building but also on the status of the momentary weather conditions (e.g. clouds). Similarly, T_{ext} (external temperature) depends on the specific location of the building. The outdoor weather conditions also influence H which is affected by the enthalpy of the outdoor air. All of the parameters of climate are time dependent and therefore require a time series data of the weather conditions of the building.

Building Specification

Conductance's (K_i, K_w, UA), heat capacities (C_a, C_i), solar energy transmitted (Q_{sun}) are all determined by the building specification. Materials that are used in the building determine the heat capacity of the building. The conductance to the outside environment depends on the conductance of the materials but also the geometry of the building. The size of the windows contributes to the conductance and also determine the amount of solar radiation that is transmitted to indoors.

HVAC Capacities

H and C are the heating and cooling delivered by the HVAC system. The maximum allowed H and C depend on the capacity of the HVAC system. This capacity is determined at the design stages of buildings and various calculations are made to cover the worst case scenarios to ensure that indoor temperatures of the building are maintained between the designated boundaries. The calculations depend on the climate, building specifications and the expected maximum thermal loads.

Building Operating Schedule

The building that is modelled will not be kept at the same indoor temperatures throughout the day (and the year). Holidays and out of office hours will have different indoor temperatures. This affects the target T_a of the building (hence the H and C provided by the HVAC system). The ventilation levels are also influenced by occupancy. Thermal loads which are determined by the usage of appliances and the presence of people inside the building depend on the operating schedule as well.

Thermal Loads

Thermal loads are uncontrolled heat sources which are caused by the electrical equipment and the humans present in the environment. These are determined by the number of people and the type of equipment that they use.

3.7.1.3. Implementation of the Thermal Simulation Block

The core functions of the thermal model have been implemented in Matlab (Figure 22). This simulation block runs a yearly thermal simulation of the building using Nielsen's equations and derives the indoor temperatures given the amount of thermal heating and cooling power. The timestep in the thermal simulation block is selected as one hour because the main purpose of this simulation block is to find out the necessary power to maintain the indoor temperatures at given set-points. These power levels are then used to compare the results derived from the DSR block (explained later) which run with a finer resolution for a given DSR period (2 hours). This way, the internal temperatures can be compared between the normal state (no DSR) and the DSR state. The coding of the thermal simulation block consists of three stages; preprocessing, running and post processing.

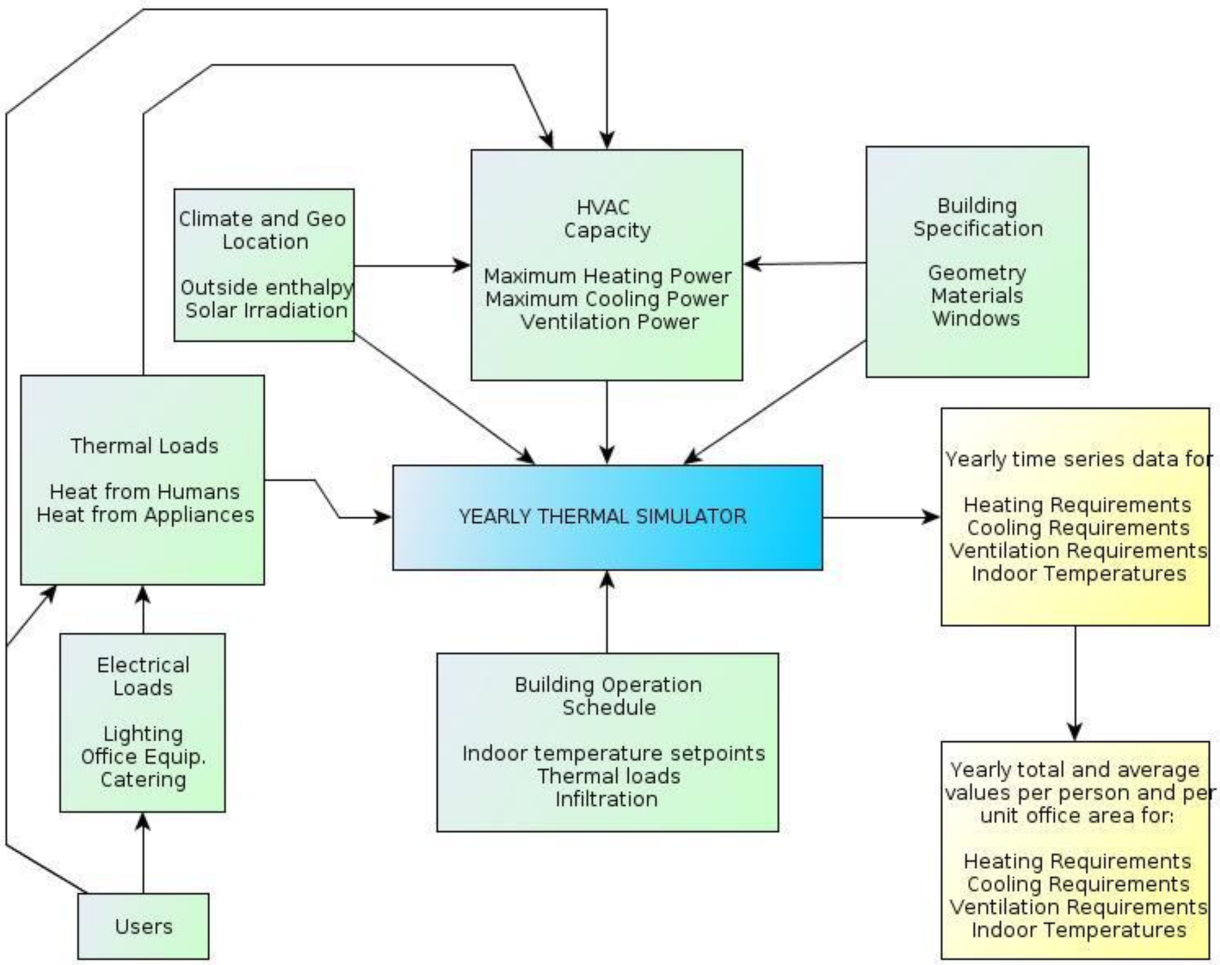


Figure 22: Thermal Simulation Block

In the preprocessing stage, the inputs are converted to time series data. For example, the thermal schedules that are given for the HVAC system are used to generate hourly time series data for HVAC inputs. Similarly, every time dependent input is converted to hourly time series data to be fed into the model. In the running stage, the code runs 8760 steps (which represent the whole year in hourly time steps). The results from each time step such as hourly indoor temperatures, heating and cooling requirements are recorded in time series arrays.

3.7.1.4. Implementation of the Post Processing Functions

The arrays produced by the model need to be converted to valid and understandable results. For example, the heat required to maintain the building at given indoor temperatures are produced in an array. In order to check the validity of these values, the aggregate sum of yearly heat energy consumption needs to be divided into the total usable area of the building. Another example can be given for indoor temperatures. The indoor temperatures during office hours need to be checked to ensure that the temperatures don't fall below the given set-points. In order to do this, a function is needed to calculate the average office hour temperatures for each working day. Developing the necessary graphical outputs for inspection is also required. All of these functions are implemented as the post processing part of the simulation model.

3.7.2. Electrical Simulation Block

The task of the electrical simulation block is to determine the daily and yearly electricity consumption of the office building so that the power consumption during a DSR period can be compared with normal operating conditions. In order to do this, the electrical model needs to simulate how the loads are controlled in the building. Even though the majority of the loads that consume most of the energy are controlled automatically (such as lighting and HVAC), there are other loads that depend on humans. For this reason, the electrical simulation block needs to simulate not only the consumption patterns of the loads but also simulate user behaviour to a certain level. The following steps have been followed in order to implement the electrical simulation block: 1) Modelling the individual electricity consumers. 2) Determining the Input Parameters. 3) Implementing the main simulation block. 4) Implementing the output stage of the block. Figure 23 shows the electrical simulation block.

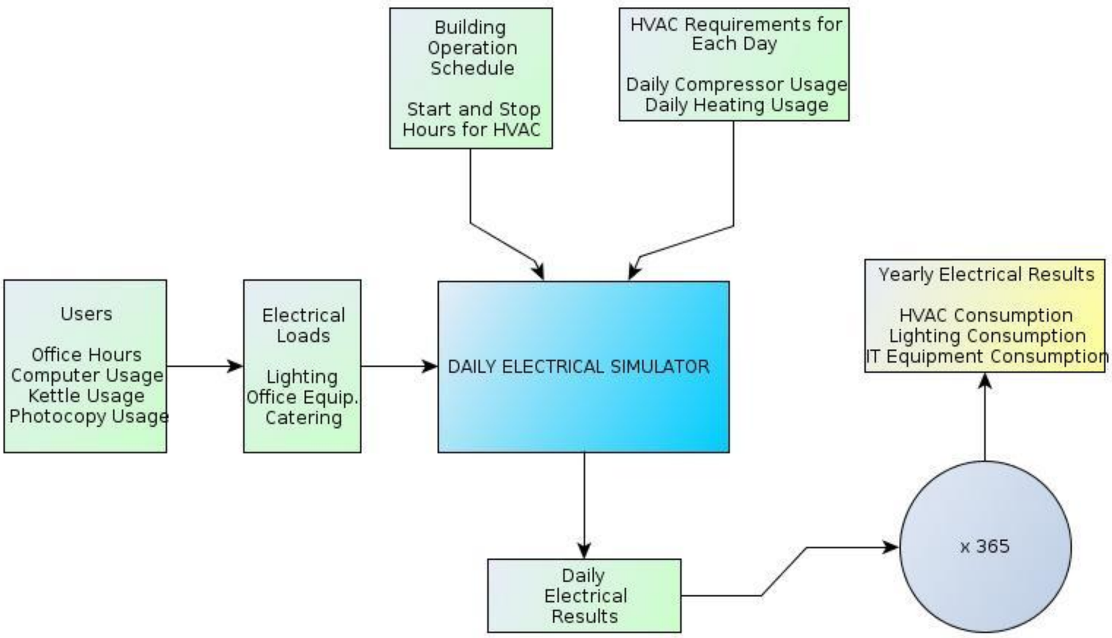


Figure 23: Schematic of the electrical simulation block

3.7.2.1. Modelling automatic electrical loads

HVAC

HVAC system's operation depends on the thermal and ventilation requirements of the building. Electrical consumption of the HVAC system consists of supply and return fans, extract fan and the compressor. Supply and return fans operate for two purposes; to supply fresh air to occupants and to deliver cool or warm air to the environment. When the building is occupied, all of the fans (supply, return and extract) operate at their rated power. When the building is not occupied and the building requires heating or cooling, the supply and return fans operate proportional to the heating or cooling requirements. The compressor which delivers the cooling operates when there is a need for cooling power (Figure 24).

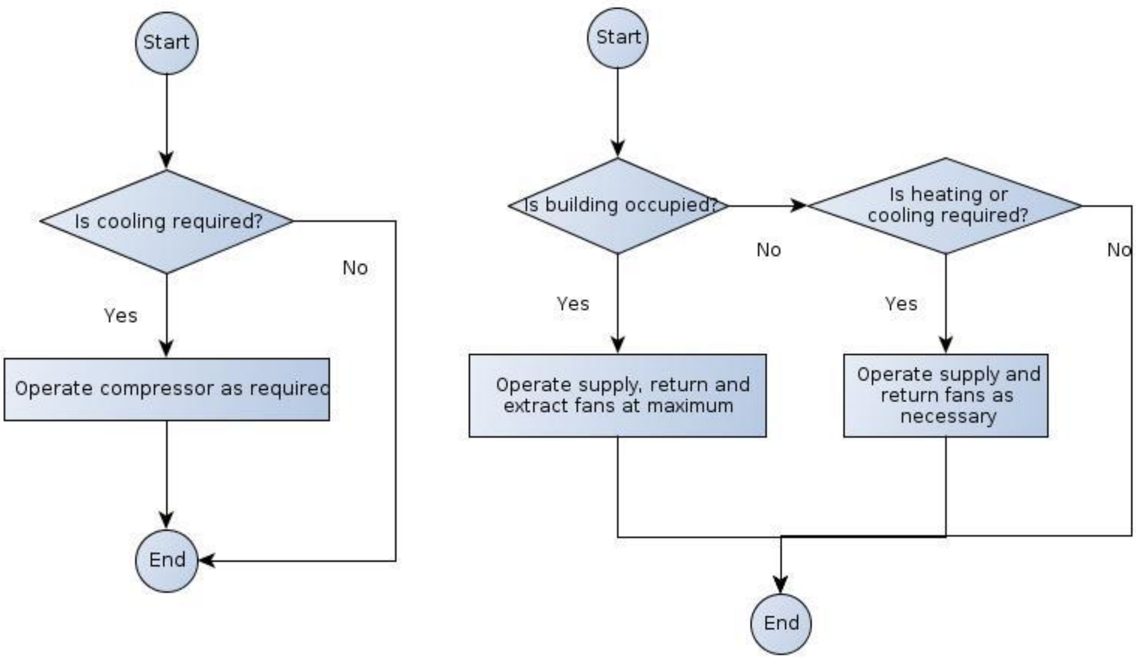


Figure 24: Algorithms for HVAC compressor (left) and fan (right) operation.

Lighting

Operation of the lighting system depends on the occupation status of the building. If the building is occupied, the lighting system is considered to be at maximum. If it is not, the lighting system is considered to consume very small amount of power (for perimeter lighting).

Refrigerator

Operation of the refrigerator is considered to be cyclic and independent of any of the variables. When the model starts, refrigerators randomly start operation from any point in their duty cycle regimes. If the refrigerator reaches its on time, it turns its compressor on for a fixed period of time. After this, the refrigerator is off.

3.7.2.2. Modelling human controlled loads

Office Workers

Only the energy consuming aspects of office workers are modelled. These are; office arrival and departure times, number of times a photocopier is used and the catering equipment usage.

Arrival and departure to the office: This parameter defines the time period when human triggered consumption occurs.

Number of times a photocopier is used: This parameter defines the usages of photocopier machine by the worker. A parameter randomly assigns the number of pages the person is to print in a day for that specific day. These are then randomly distributed throughout the work day as photocopy tasks where at each task, random number of pages are photocopied by the worker.

Kettle Usage: Kettles for coffee are assumed to be the only catering equipment. The number of times a kettle is used is defined by a parameter that sets the number of times an office worker has coffee. These times are randomly distributed throughout the day with minimum time differences between coffee breaks to avoid successive coffee breaks very close to each other.

Computers

All of the computers in the modelled building are assumed to be laptops. Laptops have the ability to operate on battery power. For this reason, laptops have three consumption characteristics while they are operating; mains operation when not charging, mains operation when charging and battery operation.

In all of the conditions, the laptop is assumed to draw constant power. If the laptop operates on battery power, its charge will decrease. When the laptop is brought back online, its power draw from the mains will be more than the case when it is not charging and its charge levels will increase.

Photocopy Machines

A photocopier consumes the most energy when it is carrying out the copying process. For this reason, the photocopier in this study is assumed to draw peak power when it receives a copy command. At other times, the photocopier is assumed to consume standby power.

Catering Equipment

Kettles are considered to be the only catering equipment. These are assumed to consume power only when they are operating.

Other Loads

Loads that are unspecified but assumed to exist are modelled as other loads. The operation schedule of these are assumed to be synchronous with lighting.

3.7.2.3. Implementing the Main Electrical Simulation Block

For every office day, the simulator creates an array of 86400 elements (representing one second time step) for all of the electricity consumers. For user controlled items, consumption arrays are generated by combining usage data and load consumption profiles. Usage of heating or cooling elements in the HVAC system differs throughout the year. Therefore the electrical simulator is run for the whole year to simulate the yearly overall consumption.

3.7.2.4. Implementing the Output Stage of the Electrical Block

Once the arrays are generated, they are added to calculate the aggregate sums for; heating, cooling, parasitic power (fans for HVAC), lighting, computers, IT equipment and others (catering).

3.7.3. DSR Block

The duty of the DSR block is to simulate DSR conditions so that electrical consumption and thermal status of the building can be compared with non-DSR case. In order to achieve this, the DSR block carries out the same thermal and electrical simulations as discussed in the earlier sections. The difference is that because DSR is carried out in much shorter time frames, the simulation step for the thermal simulation needs to be decreased. Also, for lighting and computers, the changes in operation states should be reflected in the outputs (e.g. decrease in lux levels for lighting and charge levels for laptops). Comparisons between DSR case and non-DSR case should also be made so these functions need to be implemented as the output of the DSR block (Figure 25).

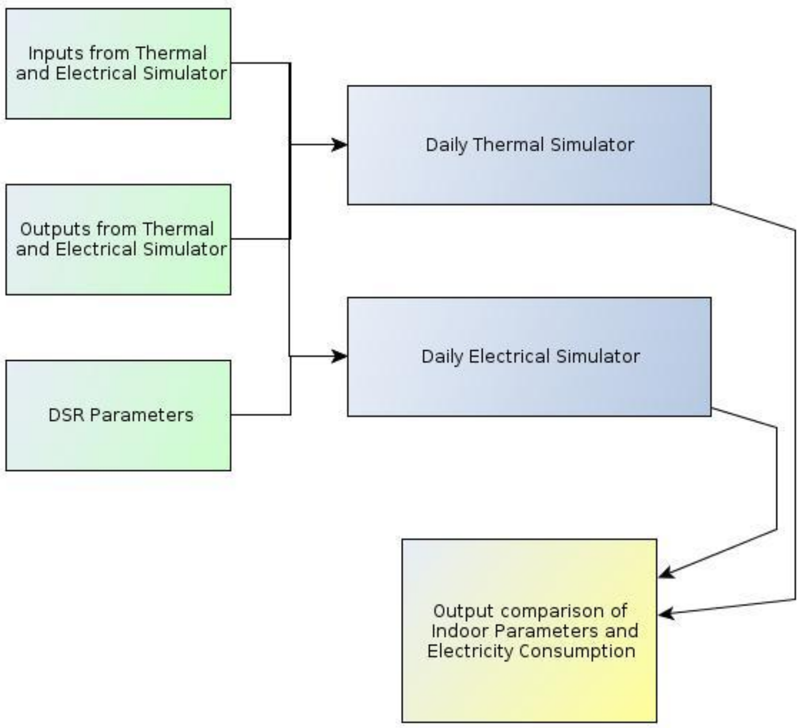


Figure 25: Operation of the DSR Block

The implementation of the DSR block consists of the following steps; 1) Determining the Requirements of the DSR Simulator. 2) Implementation of the Daily Thermal Simulator. 3) Implementation of the Electrical Simulator that carries out DSR. 4) Implementation of the Output Generators.

3.7.3.1. Determining the Requirements of the DSR Simulator

The main purpose of the DSR model is to compare the case of normal conditions with DSR conditions. For the DSR case, controllable loads in the building were identified as; HVAC, lighting and laptops. Therefore the DSR simulator block needs to simulate the conditions in the building when these loads are off.

DSR requirements for office buildings show that DSR actions will be carried out during office hours and for short periods of time. In order to simulate the conditions in these periods, the DSR simulator needs to carry out thermal and electrical simulations identical to the ones carried out in other simulation blocks. For this reason, most of the inputs necessary for the DSR block come from thermal and electrical blocks. This leaves the following inputs for DSR block; DSR time, DSR period, and the amount of load reduction that is to be carried out for each of the loads that are controlled.

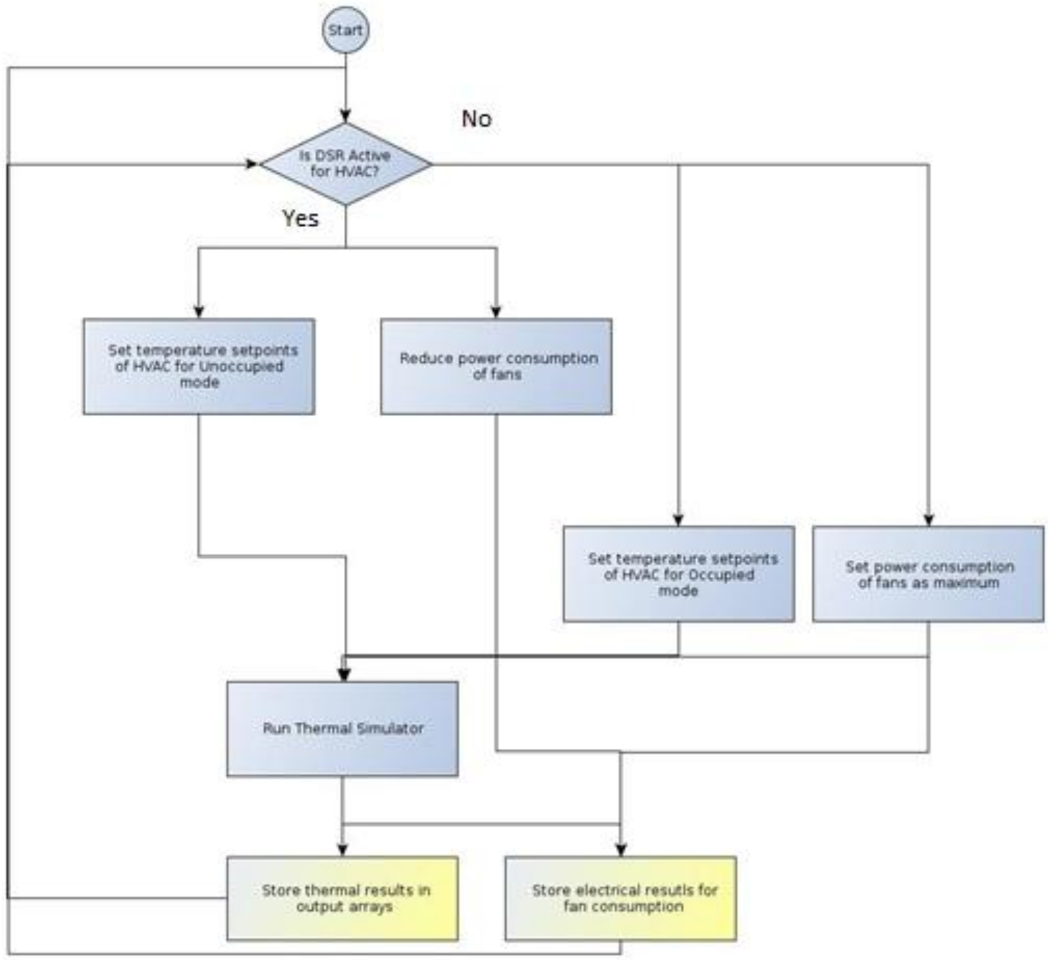
3.7.3.2. Implementation of the DSR Block

The same algorithms that are used for electrical and thermal simulation blocks are used in the DSR block. Also, the input and output parameters of the yearly thermal and electrical simulation block is taken as inputs for the DSR block. The main part of the DSR simulator runs thermal and electrical models simultaneously. It then calculates the resulting indoor environmental conditions and records these as outputs. The specific implementation of the HVAC, lighting and laptop control algorithms are as follows:

3.7.3.3. Implementation of DSR control for HVAC

Standard operation modes for HVAC are; occupied mode and unoccupied mode. If DSR is required during the occupied mode, the HVAC is switched to unoccupied mode which reduces the power consumption of the fans and sets the thermostats to different set-points that are expected to cut power to the compressors or heating elements (Figure 26).

When the temperature set-points change, the thermal simulator cuts off the thermal supply. This causes the energy consumed by the thermal or cooling elements to be cut off. Once this happens, depending on the outdoor conditions, the temperature inside the office is expected to deviate. This deviation is observed at the output arrays that store DSR case thermal conditions in the building



.

Figure 26: Operation of the HVAC System during DSR

3.7.3.4. Implementation of DSR control for Lighting

DSR control for lighting is straight forward. When the input power is reduced, average lux levels inside the building drop (Figure 27). Lux levels are proportional to the available power for light fittings.

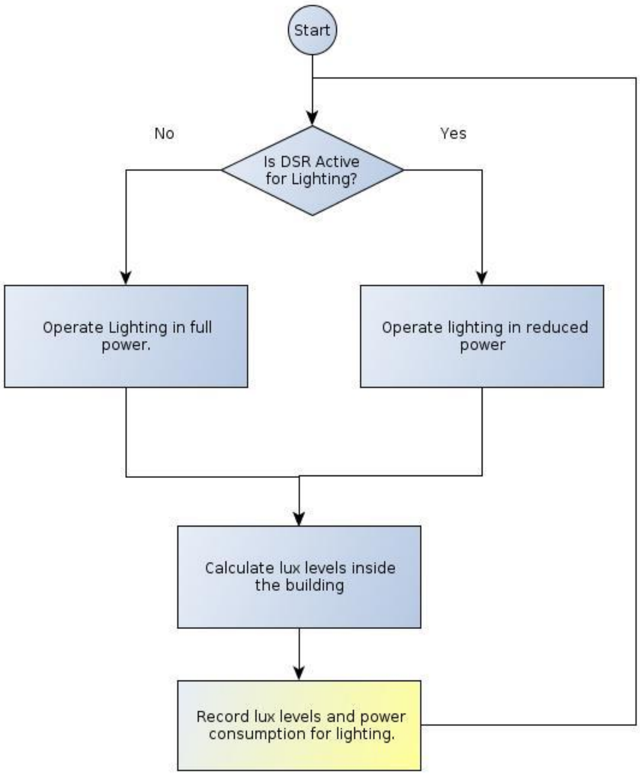


Figure 27: Operation of the Lighting system during DSR

3.7.3.5. Implementation of DSR control for Computers

All of the laptops are assumed to operate simultaneously. Load reduction in laptops depend on their charge status. For each laptop, if load reduction is required, charge status is checked. If the charge status is greater than zero, the laptop operates on battery. If not, the laptop does not enter into DSR mode. If the laptop is not in DSR mode, its power consumption depends on whether it is charging or not. If charge status of the laptop is lower than 100%, the laptop consumes more power compared to non charging state. The algorithm is shown in Figure 28.

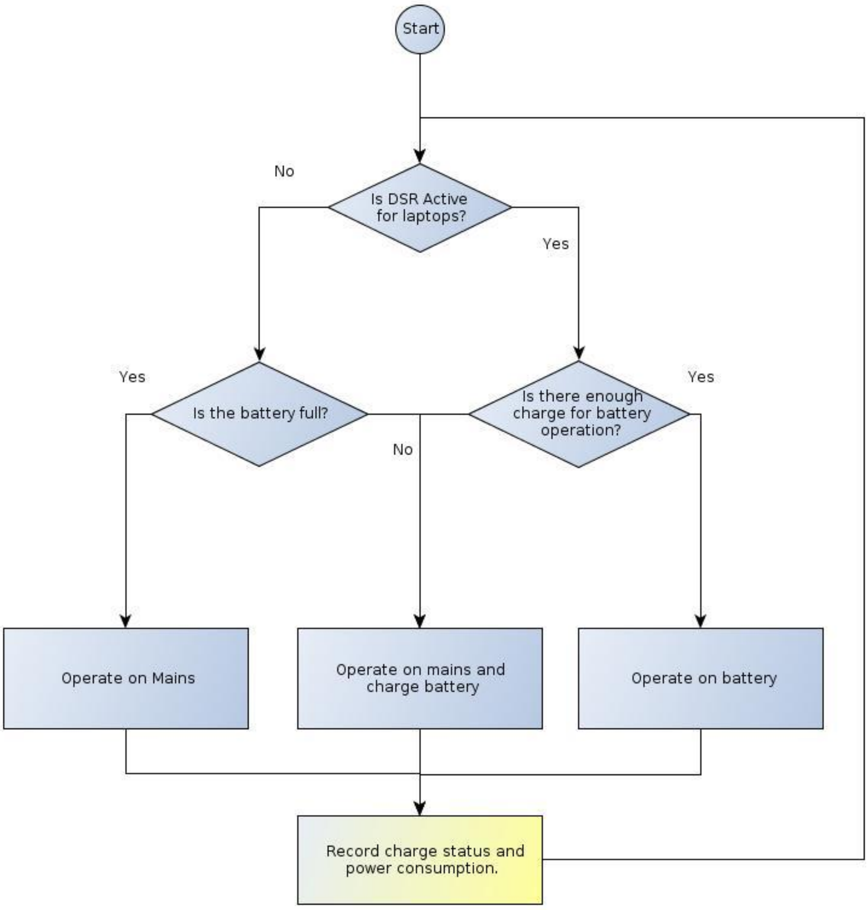


Figure 28: Controlling computers for DSR

3.7.3.6. Implementation of the Output Generators.

Outputs generated by the DSR simulator consist of arrays that contain various information such as; controlled loads, indoor temperatures, lux levels and charge status of batteries. In order to compare the DSR states with non DSR states, graphs depicting the temperature swings, lux level changes, charge statuses are produced. Also, numerical values that show average indoor temperatures and lux levels during DSR conditions are generated for comparison. The DSR simulator produces the following as outputs:

- Graphs for comparing the thermal states in the building with DSR and non-DSR cases.

- Graphs for comparing the total electricity consumption of the building.
- Numerical outputs that show the average temperatures during DSR periods. Numerical outputs that compare the change in electricity consumption during DSR stage with non DSR stage as a percentage.

3.8. Verifying the Simulator

In order to verify the model, a standard office building has been simulated for a whole year in a warm and cold climate. The following has been carried out to ensure that the results of the thermal model and the sizing of the heating and cooling elements are valid:

- Outputs of the simulator are compared with widely used and sophisticated building energy consumption software.
- For standard HVAC sizing, office indoor temperatures are checked to ensure that they are within the boundaries of set-point temperatures.
- Overall energy consumption of various end uses is compared with data from literature.

The determination of the inputs to the model are essential because these are used not only to simulate thermal model but also electrical and DSR models as well. In the following section, these inputs are explained in detail.

3.8.1. Preparing the Inputs

3.8.1.1. Building Construction Properties

The specification of the building depends on the design preferences. In this study, a building design that can be related to existing buildings has been sought to ensure that the results are relevant. For this reason, the specification of the building that is used in the model has been based on [88]. In this paper, the authors have introduced standard test models that span the U.S. commercial building stock. The purpose of their study is to develop standard or reference building energy models for most common commercial building types so that these can serve as a starting point for the analysis related to energy efficiency research. The study encompasses 16 building types in 16 locations and the goal is to represent 70% of all U.S. buildings.

Based on this study, some basic office building parameters are as follows (Table 6).

Table 6: Building forms in [88]

Form Type	**Floor Area(m^2)**	**Aspect Ratio**	**Floor Num.**	**Ceiling Height (m)**	**Glazing Frac.**
Small	511	1.5	1	3	0.21
Medium	4982	1.5	3	2.75	0.33
Large	46320	1.5	12	2.75	0.38

For this research, Medium office form type has been selected for DSR simulation trials so that there is a greater chance to apply the results to other form types.

Other characteristic of Medium sized offices are *[88]*:

Occupancy : 18 m^2/person

Fresh Air Supply : 9.45 L/person

Wall Construction : Steel Frame

Heating : Gas Furnace

Cooling : Packaged AC

Air Distribution : Constant Air Volume

Lighting ([8]) : 11 W/m^2

Loads : 11W/m^2

The reference building is considered to be simple with windows on single side. The unit office section and the complete building is as shown in Figure 29 and Figure 30.

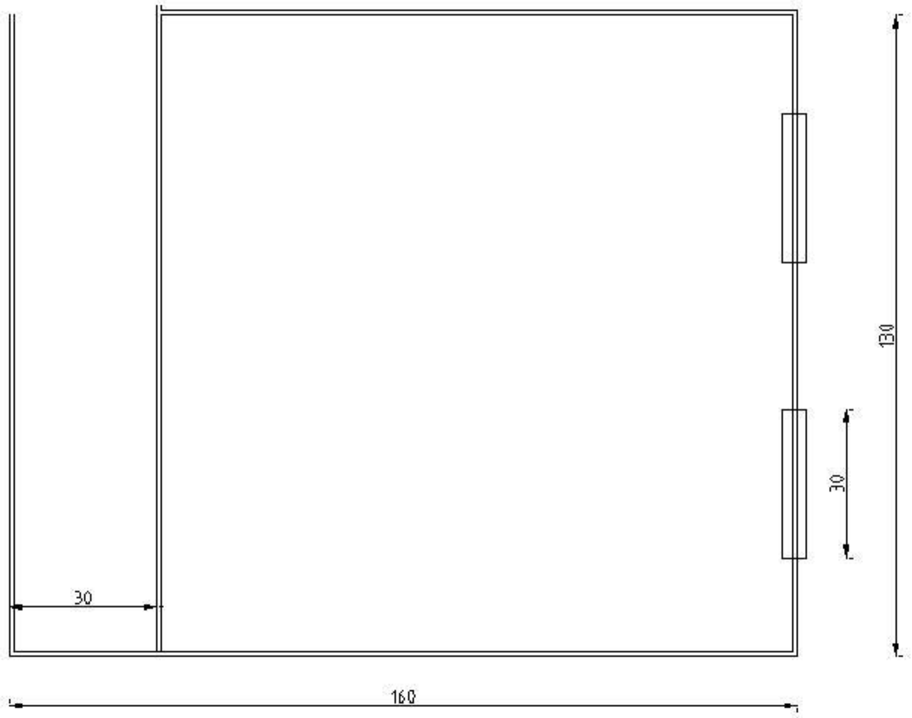


Figure 29: Unit office section in decimeters

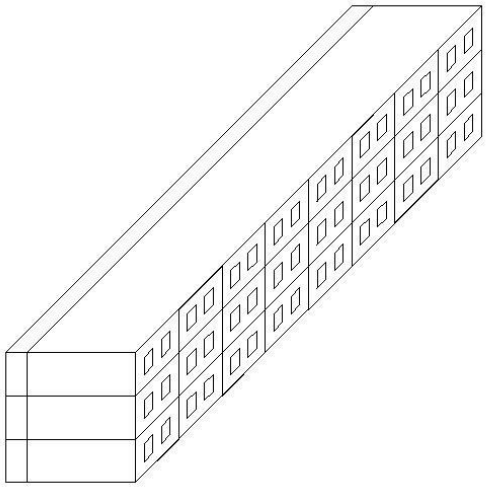


Figure 30: Overall building design

Unit Office Area	: 169 m^2
Number of Offices in each Floor	: 8
Total Building Area	: 5000 m^2

Thermal Loads

Cooling Load from Glazing (max)	: 333 W/m^2
Cooling Load from Humans	: 100 W/person
Cooling Load from Equipment	: Total consumption of devices within the office

3.8.1.2. Building Location and Climate

Heating and cooling in a building depends on the climatic conditions that are specific to the location of the building. Buildings in warm climates require more cooling hence the operation of the compressors are more frequent in these locations. Buildings in cold climates require heating elements to be used frequently. For this reason, the simulations in this study are carried out for both the hot climate and cold climate.

For cold climate, Copenhagen (Denmark) weather data has been selected. For warm climate, the weather data of Izmir (Turkey) has been selected. The weather data has been gathered from Energyplus energy simulation weather data source [89].

Copenhagen Weather Data

Copenhagen is considered to be in the oceanic climate which causes low temperature swings throughout the year (Figure 5). Dry bulb temperatures get below zero and summer months don't see temperatures much above the comfortable room temperatures. The humidity in Copenhagen can be considered as high because of its vicinity to the sea.

Copenhagen Weather Data Summary:

Average yearly mean temperature : 8° C

Average yearly humidity : 79%

Izmir Weather Data

Izmir is a Mediterranean city in the west coast of Turkey. The average yearly temperatures are high as well as the humidity because it is a coastal city.

Izmir Weather Data Summary:

Average yearly mean temperature : 18° C

Average yearly humidity : 60%

3.8.1.3. Sizing and Operation of the HVAC System

As explained in Chapter 2, air conditioning consists of 3 main components which contribute to the overall energy consumption and which are designed specifically for the building and the environment. These are; the compressor, heating element and system fans.

Air Conditioning Sizing Calculations

Air conditioning sizing is carried out based on the worst case conditions of a building. The calculations for the sample building mentioned above are based on [43] and [90].

Compressor and Furnace Capacity

The compressor and the furnace capacity is determined by the amount of air that will be supplied to the building, and the outside weather conditions such as dry bulb temperature and relative humidity.

The sizing calculations are based on [90] and explained in Appendix A.1. The results of these calculations are as follows:

<u>Copenhagen</u>

Compressor Capacity	: 190 kW Output (55kW Input @ 10 EER)
Heating Element Capacity	: 202 kW Output (40kW Input @ 14.7 EER)

Izmir

Compressor Capacity : 257 kW Output (74.4 kW Input @ 10 EER)

Heating Element Capacity : 145 kW Output (28.7 kW Input @ 14.7 EER)

Fan Capacities

The supply and return fan capacities depend on the amount of air that will be circulated in the building. These calculations are made based on the air change requirements and building volume. Fan sizing calculations for the building are made in Appendix A.2.

Supply and Return Fan Size : 22.6 kW

3.8.1.4. Building Schedules

Standard operation of a CAV system requires the air volume to be constant whereas the supply air temperature is varied. This system is widely adopted for packaged systems.

The reference building that is modelled is assumed to have identical office modules facing the same direction. Therefore it is assumed that air volume requirements are identical in all the offices. Because the supply air temperature is the same as well, the energy consumption variation depending on the outside conditions only occurs at the compressor or the heating element and fans are expected to operate in their scheduled operation power which depend on the office air change rates.

HVAC Operation is programmed to have two modes.

Mode 1: Office Hours (Weekdays 8 – 18 hours)

Office Air Change	: 4.6 1/h
Infiltration	: 0.75 ACH
Fresh Air	: 9.44 l/s (per occupant)
Heating Temperature Set-point	: 22° C
Cooling Temperature Set-point	: 24° C

Mode 2: Unoccupied (Weekends and Weekdays 1 – 7 and 19 – 24 hours)

Office Air Change	: 1.15 1/h
Infiltration	: 0.75 ACH
Fresh Air	: 0
Heating Temperature Set-point	: 18° C
Cooling Temperature Set-point	: 29° C

3.8.1.5. Determining the Inputs for the Electrical Block

Lighting

The parameters for lighting is straight forward, the model building dictates that 11W/sq.m^2 is required for lighting. The area of the building is 5000m^2. Therefore the maximum consumption for lighting is:

$5000m^2 * 11W/m^2$: 55kW

<u>Other Loads</u>

Determination of plug loads is similar to lighting. The maximum consumption for these are:

$5000m^2 * 11W/m^2$: 55 kW

3.8.2. Verifying the Indoor Temperatures

The DSR simulator is run for both Copenhagen and Izmir to ensure that the HVAC capacities are able to maintain indoor conditions of the building at given temperature set-point boundaries.

3.8.2.1. Average Monthly Office Hour Temperatures for Copenhagen

When the model is run for a whole year, average monthly office hour indoor temperatures versus outdoor temperatures are shown in Figure 31. Figure on the left shows average indoor temperatures (blue) during office hours versus average outdoor temperatures (red) for each simulated day of the month. Figure on the right shows the amount of hourly thermal power required to maintain the building at given temperatures. Red bars indicate hourly thermal power generated for heating whereas blue lines indicate thermal power removed for cooling the office the environment.

It can be seen that indoor temperatures were within the given range of 22° and 24° Celsius throughout the year. About 1% of office hours (26 out of 2300) were outside set-point temperatures.

“

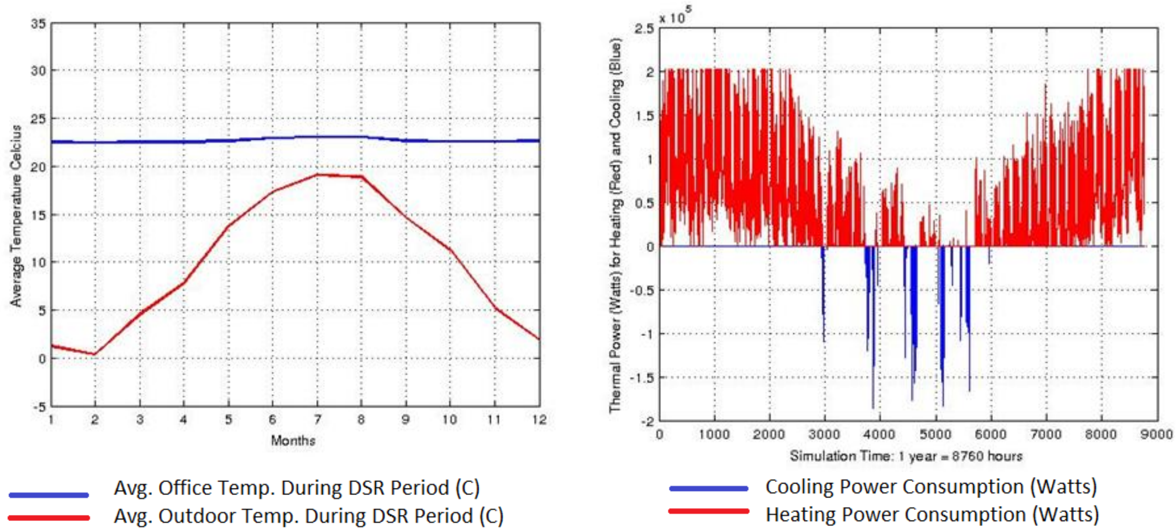


Figure 31: Results of yearly thermal simulation of Copenhagen.

Model Reaction to Changing Capacities and Outdoor Conditions

To validate the response of the building to changing indoor and outdoor conditions, heating and cooling capacities were changed to observe the change in average office hour temperatures and the overall energy consumption.

Model Reaction to Changing HVAC Capacities

Table 7 shows average office hour temperatures versus changing heating capacities. The capacities are given as percentage of the initial capacity of 202kW for heating and 190kW for cooling. As the HVAC capacity is dropped, the number of hours in the office that are below operating set points increase significantly during the winter. Although not as obvious as in winter, the number of hours that are above cooling set-point also increases.

Table 7: Changes in temperatures and thermal consumption versus changes in heating and cooling capacities.

	Heating and Cooling Power (Percentage of Calculated Optimum)			
	50%	**75%**	**100%**	**125%**
Below Heating Setpoint Temperature (Hours)	805	275	21	3
Above Cooling Setpoint Temperature (Hours)	64	23	5	5

3.8.2.2. Average Monthly Office Hour Temperatures for Izmir

For Izmir, average monthly office hour indoor temperatures versus outdoor temperatures are shown in Figure 32. It can be seen that indoor temperatures were within the given range of 22° and 24° Celsius throughout the year. 34 out of 2300 office hours were outside set-point temperatures.

Average Monthly Office Hour Temperatures

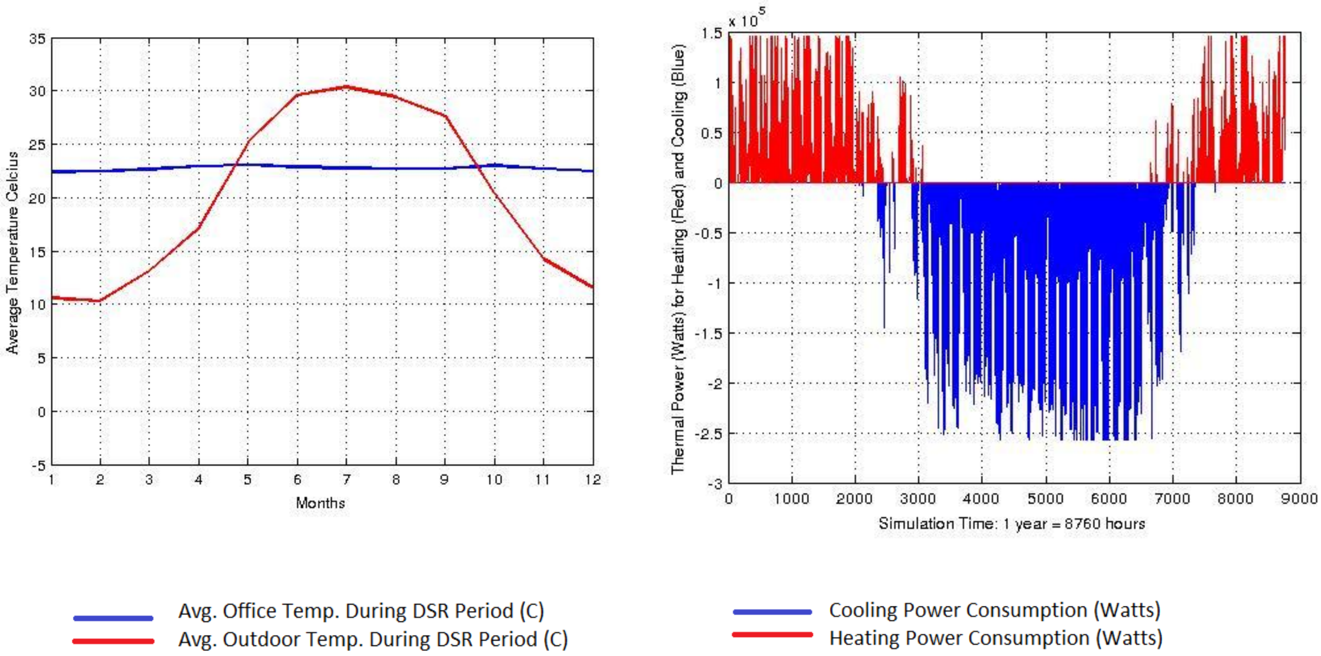


Figure 32: Results of yearly thermal simulation of Izmir.

Model Reaction to Changing HVAC Capacities

Table 8 shows average office hour temperatures versus changing heating capacities. The capacities are given as percentage of the initial capacity of 257kW for heating and 145kW for cooling. Similar to the Copenhagen case, when the HVAC capacity is decreased, the number of hours above cooling set-point increases significantly during the summer because the cooling system capacity becomes inadequate.

Table 8: Changes in Temperature and Thermal Consumption versus changes in heating

and cooling capacities that are calculated for warm climate.

	Heating and Cooling Power (Percentage of Calculated Optimum)			
	50%	**75%**	**100%**	**125%**
Below Setpoint Temperature (Hours)	294	213	13	0
Above Setpoint Temperatrure (Hours)	640	30	21	4

3.8.3. Comparison with Energyplus

Energyplus is a sophisticated simulation program that is designed to simulate thermal loads and carry out energy analysis [91]. It is capable of calculating heating and cooling loads, indoor temperatures and other electrical loads. The program allows a user to simulate all aspects of a building such as size, material, climate, HVAC capacity, and occupancy.

3.8.3.1. Operation of Energyplus

Figure 33 shows how Energyplus operates. The building description is fed into the simulation manager by either third part user interface or a text file. The simulation manager carries out heat and mass balance simulation together with building systems simulation. Various other models can be added to the simulation engine for enhanced functionality. Once a simulation is complete, the results are published which can be displayed by third party user interfaces.

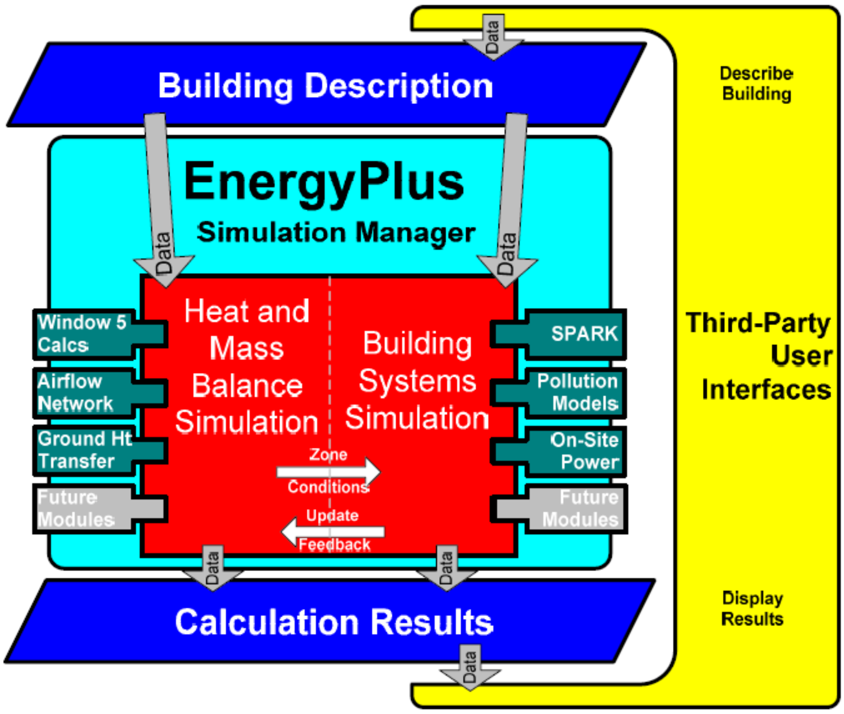


Figure 33: Energyplus Operation Diagram

One feature of the Energyplus simulation program is that it allows auto calculation of various components such as the HVAC system for convenience. These calculations are based on the size and usage of the building as well as its climate and orientation.

The most basic way to operate Energyplus is to define an input definition file (IDF) file for the building that is being simulated. The IDF file should contain all the information about the building and its systems. Another file that is required for simulation is the weather file. When both the definition file and weather file are fed into the Energyplus program, the simulator develops the result files in various forms.

3.8.3.2. Simulating the Model Building with Energyplus

The building that is developed for this study was a standard office building which an Energyplus definition file is available for research purposes. Based on this definition file, two definition files are created to simulate for both Copenhagen and Izmir. Because of the differences between simulation engines, the following modifications were made to the standard definition file to ensure that its inputs are similar to the DSR energy model's inputs.

- Elimination of elevators: Provisions were made for two elevators that would operate in the three floor building. These elevators were removed since they were not simulated in the DSR simulator.
- Modifying loads for usable area: The design of the standard building allowed provisions for all of the floor space whereas the building that is designed for the DSR simulator had corridors.
- Rearranging building schedules: The schedules for the standard building allowed operation during Saturdays and after office hours. These were made similar to the DSR controller.
- Changing design day reference set-points for both Izmir and Copenhagen: The simulator carried out automatic sizing calculations based on reference temperatures. These were changed to suit the two climates; Copenhagen and Izmir.

One difference which was not implemented to the standard definition file was the type of the HVAC system. In the standard definition file, a VAV system had been implemented because the design of the building that is defined in this file consisted of multiple zones that faced different directions. On the other hand, the building defined for DSR simulator consists of a single HVAC zone and therefore a CAV system.

3.8.3.3. Comparing the Results

Copenhagen

When the simulators are run for Copenhagen, the results are as shown in Figure 34. Both of the simulators deliver similar results for all of the consumption categories except fans. The reason for this difference could be attributed to the fact that Energyplus is simulating a VAV system whereas the DSR simulator is simulating a CAV system. The CAV system considers a constantly on operation throughout the occupied periods of the building which increases consumption considerably [92]. The differences in heating system and other elements could be attributed to the energy consumption caused by complex implementation of various other systems that are simulated in Energyplus. However, heating energy consumption which is the main test for the DSR simulator is close to the Energyplus results.

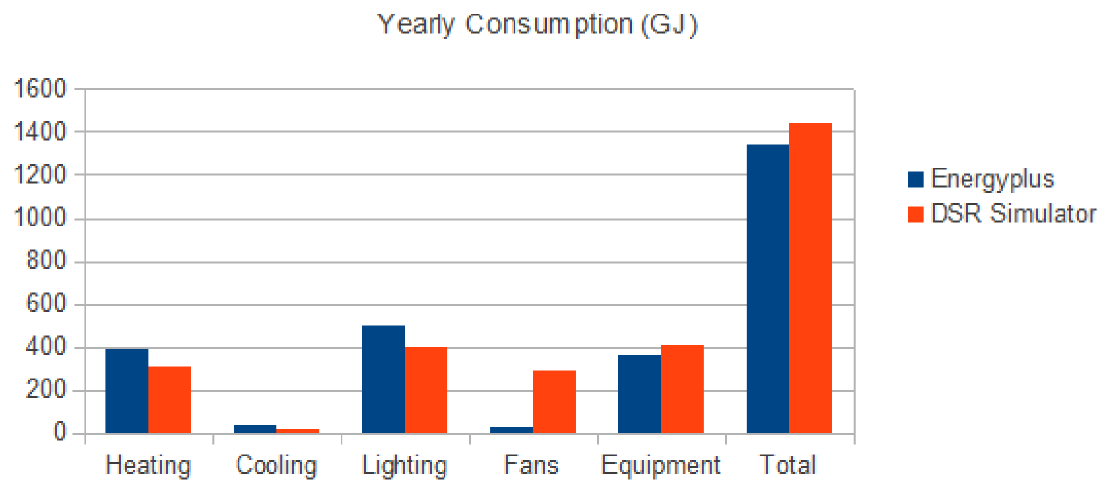


Figure 34: Comparison of Energyplus and DSR Simulator for Copenhagen

Izmir

The comparison for Izmir is shown in Figure 35. Just like Copenhagen, the results for different consumption categories are similar except fans which could be attributed to the CAV system [92]. The difference between Copenhagen and Izmir can be seen in the variation of heating and cooling requirements. The cooling requirement for Izmir is much higher because of its warm climate.

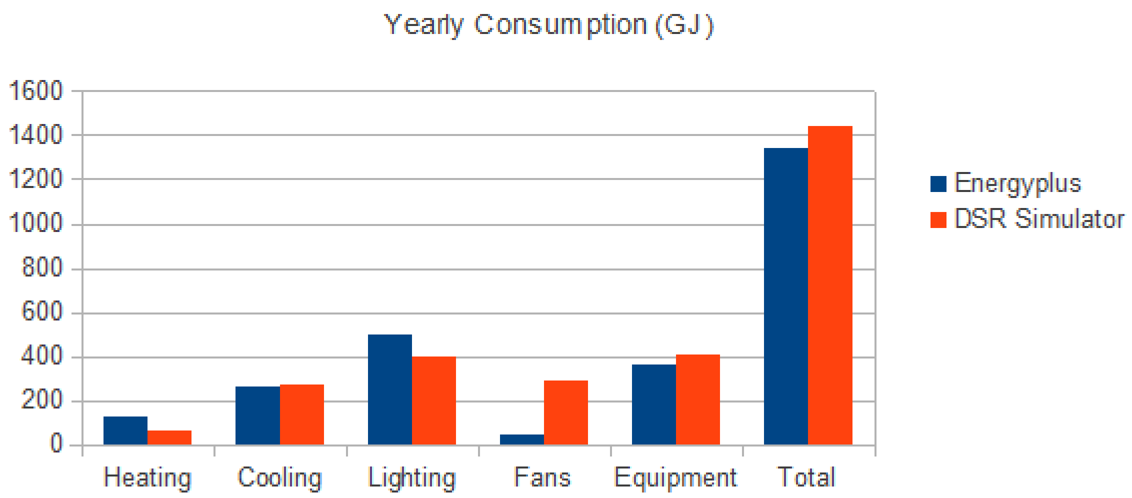


Figure 35: Comparison of Energyplus and DSR Simulator for Izmir

3.8.3.4. Validation of Fan Consumption

To check if the fan consumption and sizing is within reasonable boundaries, the data of U.S. Dept of Energy [17] has been used to compare the results of the DSR simulators outputs. Table 9 shows the comparison of the values in the table with the results obtained from this study.

Table 9: Fan power consumption comparison with US Dept. of Energy [17].

	Study of US Dept. of Energy	**Electrical Simulation Block**
Design Load of Compressor (kW/ft^2)	1.8	1.8
Design Load of Supply/Return Fans (kW/ft^2)	0.6	0.5
Energy Use from Compressor (kWh/ft^2)	1.8	1.4
Energy Use from Supply/Return fans (kWh/ft^2)	1.2	1.5

Energy use from the compressor is 22% lower compared to the average values of US Dept. of Energy. Average power consumption of the fans is 25% higher. These results show that the increased consumption of the fans in the comparison between Energyplus and DSR simulator is not unreasonable.

3.8.4. Verifying the Electrical Simulation Block

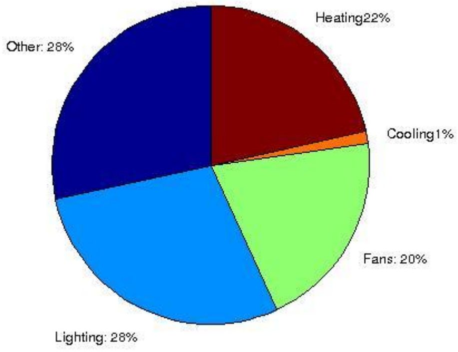
Yearly aggregate electricity consumption per floor area and consumption distribution of the loads are the criteria that has been used to verify the validity of the electrical simulation block (Table 10 and Table 11).

Copenhagen

Total yearly electricity consumption: 1443 GJ.

Table 10: Copenhagen power consumption of electrical loads

	Yearly Consumption GJ	Percentage
Lighting	406	28%
Cooling	25	2%
Heating	310	21%
Fan Power	292	20%
Other	407	28%
Total	1443	100%

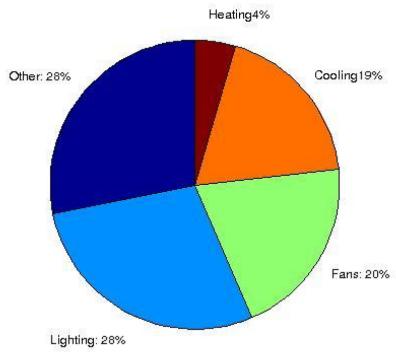


Izmir

Total yearly electricity consumption: 1442 GJ.

Table 11: Izmir power consumption of electrical loads

	Yearly Consum ption GJ	Percentage
Lighting	406	28%
Cooling	271	19%
Heating	64	4%
Fan Power	292	20%
Other	407	28%
Total	1442	100%



The results confirm that HVAC is the most energy consuming component of building. The lighting and equipment follow it. These results are in line with the data available from the literature. For example, data from CIBSE shows that an average UK office building consumes most power HVAC followed by lighting and then plug loads (Figure 36).

The data of CIBSE shows a balanced energy consumption between cooling&fans and heating [93].

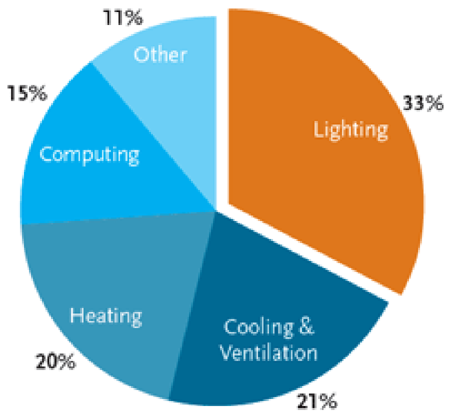


Figure 36: Energy consumption breakdown of end-uses for UK Office Buildings [93]

3.8.5. Assessing the DSR Block

As the primary duty of the DSR simulation block is to simulate the conditions inside the office building when loads are working in suboptimal operation points, it is not possible to validate the output values under these conditions without carrying out real experiments. Particularly the thermal simulation block (which simulates the indoor temperatures when the HVAC is turned off) is the most difficult to validate. As this is beyond the scope of this study, the results are assessed based on the expected behaviour of indoor conditions.

Figure 37 shows the indoor temperature deviation when the power to the HVAC system is cut in the office building located in Copenhagen. The DSR action is carried out at 1.30 pm for 120 minutes. During the DSR action, only HVAC system contributes to load reduction. The graphs in the figures show temperatures of different building parameters. These are as follows:

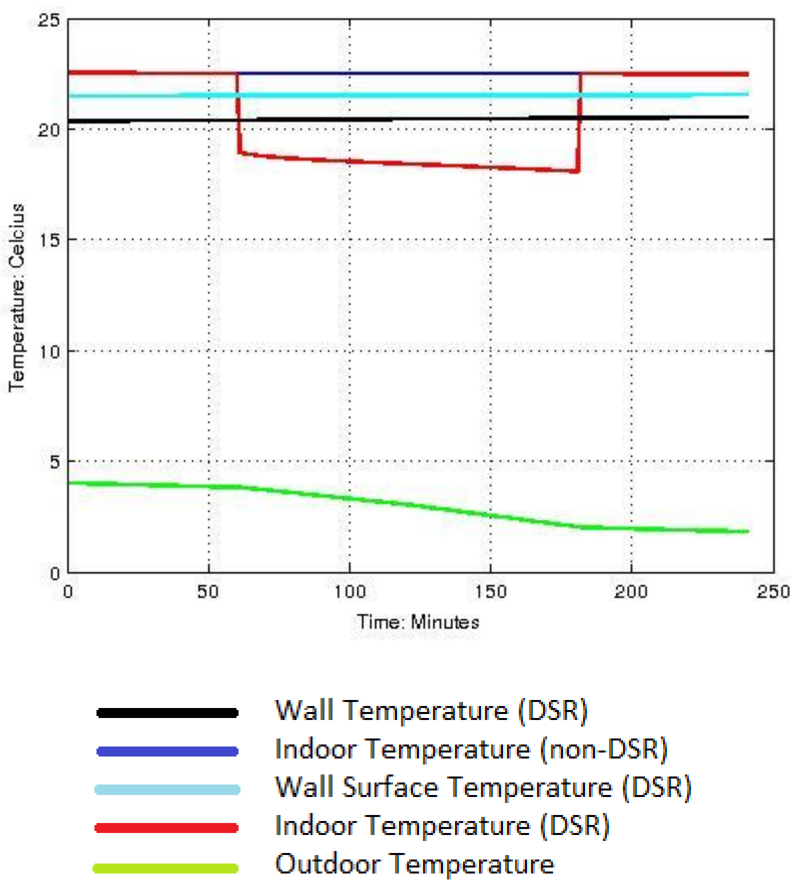


Figure 37: Deviation of temperatures during DSR

When the HVAC system operates in DSR mode, all of the set-point temperatures change to non-occupied state. When this happens, the ambient temperature drops rapidly. However, the drop in temperature slows down soon because of the heat capacity of the building. The black lines which depict the wall temperatures show no sign of deviation during the shutdown of the HVAC system. The same applies to wall surface temperatures as well. Hence, further drop in ambient temperature is prevented by the heat capacity of the building.

The heat capacity of the building does fluctuate if the HVAC system is shut down for sustained periods of time. This is more visible during the transition from Fridays to Saturdays. Figure 38 shows the seven day period comparing the wall temperatures and ambient temperatures of the office in a non-DSR case. The black line which represent the wall temperatures do not fluctuate as much as the ambient temperatures shown with blue line during the first five days of the week (work days). However as the HVAC system is turned off during the weekend, the wall temperatures drop significantly and approach the ambient temperature levels of the building.

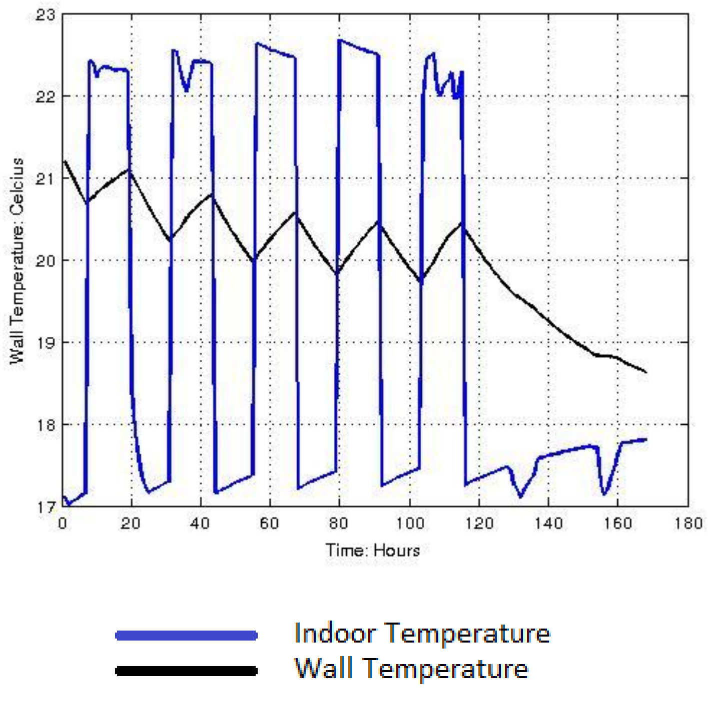


Figure 38: Deviation of wall temperatures in the long term

3.9. Conclusion

The purpose of this chapter has been to develop a building energy consumption simulator that could be used as a test bed to try various control algorithms. Assessment of the available simulation models and tools have shown that the best approach to developing such a model is to utilise a simple building thermal simulator and build other simulation functionalities on top of it.

The DSR simulator has been constructed on Matlab environment. Thermal simulator of Nielsen has been used as the basis to simulate thermal exchanges between the building indoors and outdoors. Electrical simulation blocks and DSR simulation blocks are specifically designed for DSR purpose. The three simulation blocks are integrated together to complete the DSR simulator.

An input file based on a standard office building has been designed to test the performance of the DSR simulator. Initially, sensitivity analysis has been carried out to test the validity of HVAC sizing. Once the results have confirmed that the sizing is valid, comparison between an existing energy simulation program (Energyplus) and DSR Simulator has been made. The standard office building has been simulated both on the DSR simulator and the Energyplus simulation program. The comparison exercise has shown that the DSR simulator delivers results that are close to those given by Energyplus.

The performance of the DSR stage of the simulator is assessed by investigating the reaction of the model for a DSR scenario. The outputs of the simulator show that when the HVAC system is turned off for short periods of time, the reduction in temperatures is limited by the heat capacity of the building. However, sustained periods of HVAC absence causes the heat capacity of the building to diminish. These results, which are in line with the information available from the literature show that the DSR simulator can be used for testing DSR functions. These functions are the subject of the following chapters.

4. DSR Based on Productivity

4.1. Introduction

Establishing a relationship between productivity and energy consumption is vital in the development of DSR methods because such methods will need a measure of productivity in order to determine the extent of load reduction from essential loads that maintain the office environment in a workable condition. This chapter will define and assess a productivity model based on IEQ and will explain the usage of this model to determine the theoretical extent of load reduction in the modelled office building that is described in Chapter 3. This will lay the foundations of a control algorithm that will have to be incorporated in a Building Automation System (BAS). The algorithms will be useful in the evaluation of building automation protocols which will be explained in the following chapters.

4.2. The Problem of Controlling Loads for DSR

Office hours are valuable because of the costs involved in employing workers in a company. For this reason, reduction in the productivity of office workers cannot be tolerated. On the other hand, the difficulties in today's electricity markets show that grid operators are willing to compensate the losses in productivity by offering incentives to customers who can shed their loads for limited amount of periods during peak days.

In such a case, the amount of incentive versus the amount of load reduction is known by the building operators in advance. The duty of the building operators is then to ensure that the load reduction is carried out such that maximum productivity is maintained throughout the office given the amount of available power. Unlike dwellings where device controls can be carried out by the occupants themselves, office buildings that are relatively large have automation systems that will have to be set-up to deal with this problem. Without a parameter that defines productivity, this task becomes impossible. When load reduction is required, should the system turn off air conditioning or lighting? Or should it decrease consumption of both loads? If there is surplus power available during a DSR event, should it increase the lighting or readjust the HVAC for better indoor environment? All of these can only be determined by a productivity function that includes every energy consuming entity as a parameter in its body.

4.3. The Effects of Indoor Environment and Tools on Productivity

For open plan offices where more than one worker share the same conditioned environment, the equipment that contribute to the productivity of workers can be investigated in two categories, environmental equipment and task specific equipment.

Environmental equipment is the equipment which maintains the environment in optimum conditions for the biological needs of humans. The building envelope is the fundamental structure that is essential in having a comfortable environment. In order to enhance this structure, various active systems operate within the building. Among these, lighting and HVAC are the most energy consuming and the most essential equipment though there might be other environmental systems as well (such as water and sewage).

The environment enables humans to gather in the same place (building). This gathering is not adequate to produce work collectively. Task specific equipment (or tools) that are used by modern office workers is essential in producing the necessary work output.

These might consist of communication devices, computers, photocopying devices and so on.

If these arguments are linked to the productivity function discussed in previous section, it can be said that:

$P_{(\%)}$ = *f*(*Indoor Environment*, *Availability of Tools*).

P = 1 when

Indoor Environment = Ideal

Tools = Available

Where P is an abstract variable representing total productivity in an office environment.

This relationship states that under optimum conditions where the environmental variables are ideal and all of the equipment is operational, the productivity (P) of the worker can be assumed to be maximum. The productivity will start to drop if the environmental conditions start to deviate from the optimum or when some of the tools that are necessary for the worker cease to operate. An ideal productivity function should be able to quantify the amount of deviation that is caused by sub-optimal operation of each of the equipment in the building as stated in the equation.

4.4. Assessment of the Loads in the Office from Productivity Perspective

An ideal productivity function is too difficult to model with current knowledge. Developing such a function is not the objective of this research because this research is focused on the energy consuming aspects of productivity. Moreover, the drop in productivity will only be allowed for a short period of time as necessitated by DSR schemes. Therefore the parameters that will be investigated in the productivity function needed to be assessed based on their energy consumption and applicability aspect.

4.4.1. HVAC and Productivity

It has been shown in the literature review that HVAC controls variety of environmental parameters which might influence humans in different ways. These are air temperature, humidity and air freshness.

Dry Bulb Temperature: As the temperature difference between the ambient and the skin is the main entity in the thermo-regulation of human body, air temperature is considered to be the primary parameter when modelling the productivity effects of HVAC.

Humidity: Humans are capable of adapting to various moisture levels. The change in the humidity levels of a building is unlikely to reach uncomfortable levels that will affect the productivity of the workers in the office because of an existing HVAC system. For this reason, humidity aspect of HVAC is dismissed in the productivity equations.

Air freshness: Humans can survive with very little fresh air and the literature review shows that the major purpose of cleaning the air in an environment is not because of Oxygen levels but because of the body odours and particulates. The particulates in the air caused by respiration, body odours and other emitters need to be removed to keep the air fresh. Office environments are places where physical activity is low and the chance of pollution due to equipment is minimal. Also, the natural air change rate of an office building together with the amount of existing fresh air stacked in its volume makes it unlikely that the air freshness of the environment will cause deterioration in productivity when the HVAC system is turned off for limited periods of time.

4.4.2. Lighting and Productivity

Lighting system in the office can have various duties. The literature shows that lighting has safety, aesthetics and functional aspects.

Safety: Health and Safety executives make it mandatory that there should be minimum lighting on a work surface in the office. Therefore, the lighting levels in the environment should not be allowed to drop below a minimum set point (200 lux for the UK) even if the productivity can be sacrificed.

Aesthetics: There is no standard that quantifies how aesthetics of lighting enhance productivity of the environment.

Functional: Functional lighting is the primary contributor to the productivity of office workers.

4.4.3. Office Equipment and Productivity

Office equipment, contribute to the energy consumption of the building significantly. On the other hand, it is very difficult to include office equipment in a productivity function. Some of the reasons for these are as follows:

The productivity aspects of equipment can change depending on the type of office *environment:* It is possible to draw similarities between office buildings from environmental point of view because humans have very similar biological needs. Such a similarity does not exist when it comes to the appliances that are used. The contribution of the equipment to the overall productivity might vary significantly from one office to the other. For example, photocopiers are essential tools in the offices of universities (for producing hand-outs) and that unavailability of these would have a much greater affect than unavailability of photocopy machines in an administrative office.

The productivity aspects of equipment can change with time: The contribution of office equipment on productivity might vary throughout the day or the year. A computer might be used more rigorously in the morning because workers might want to read emails as soon as they arrive. A wending machine might be used more often in summer than winter. Therefore time dependency makes modelling productivity of tools a very complex problem.

The variables of the productivity function are not independent: The productivity loss from unavailability of equipment or from a sub-optimal environmental condition might be exacerbated by another variable. For example if a server is unavailable, the productivity that a computer provides might drop significantly. If lighting is unavailable, productivity from a photocopier might be much lower than with optimum lighting if the photocopiers are operated manually by workers. If the environment is warm, unavailability of a refrigerator might have a much greater effect because workers will need more frequent refreshments. This complex relationship makes it very difficult to implement the productivity aspect of office equipment into the equation.

For these reasons, a relationship between office equipment and productivity is not established in this study.

4.5. Defining the Productivity Function

Productivity function that is developed in this study focuses on temperature and lighting. Defining a numerical link between productivity, lighting and temperature requires experimentation and analysis. Such experimentation has been carried out by researchers in other fields and there is ample data available. However, most of the research that has been carried out has drawbacks that limit their usefulness for this study.

4.5.1. Limitations of Existing Research

Determining a productivity function that relates temperature and lighting to productivity requires the combined effects of these two parameters on productivity to be known. Most of the data available from the literature focuses on the individual aspects of lighting and temperature on productivity (e.g. affects of lighting on productivity when temperature is optimum). Moreover, the data that is available is usually qualitative and reports the acceptance of the environmental variables by the subjects who experience them rather than a direct measurement of their performance.

There is also distinction between the methods that are used, experimental and statistical research. Researchers following the experimental route carried out experiments in isolated environments where the environmental variables were controlled and the subjects were asked to carry out predetermined set of tasks before assessing the environment. Other researchers used statistical methods and carried out surveys in office buildings that have various environmental conditions. Regression models were then developed to link the environmental variables to productivity and acceptance.

4.5.2. Evaluation of IEQ Research Papers

Wong [66] and Ncube [67] et al. have carried out comprehensive studies that investigate the combined effects of lighting and temperature on IEQ (which was explained in Section 2.3.4) and productivity therefore their studies are the most relevant when it comes to developing a productivity function. Hence they are evaluated further in this section.

4.5.2.1. Wong

Wong have carried out surveys at offices in Hong Kong. 293 occupants evaluated the temperature, lighting, CO_2 and noise level of their environment. The results were used to develop a multivariate logistic regression model.

The following formula developed by Wong et al has been used to calculate the overall IEQ acceptance for an office environment perceived by an occupant:

$$\theta = 1 - \frac{1}{1 + \exp\left(k_0 + \sum_{i=1}^{4} k_i \phi_i(\zeta_i)\right)}$$

(6)

The equation has four elements that represent the acceptance of four environmental values; thermal, Carbon-dioxide, noise and illumination. Also, there are four constants from k0-k4 that represent the weighting factors of these variables. The environmental variables are determined as follows:

Thermal Environment: PPD (Φ_1)is used as the acceptance criteria.

$$\phi_1 = 1 - \frac{\text{PPD}}{100}.$$

(7)

CO_2 Level: The acceptance from CO_2 levels (Φ_2) is found by the following equation where ζ_2 represents the CO_2 concentration as PPM

$$\phi_2 = 1 - \frac{1}{2}\left(\frac{1}{1 + \exp(3.118 - 0.00215\zeta_2)} - \frac{1}{1 + \exp(3.230 - 0.00117\zeta_2)}\right); \quad 500 \leqslant \zeta_2 \leqslant 1800,$$

(8)

Noise Level: Acceptance from noise level (Φ_3) is found by the following equation where ζ_3 represents the noise in dB.

$$\phi_3 = 1 - \frac{1}{1 + \exp(9.540 - 0.134\,\zeta_3)}; \quad 45 \leqslant \zeta_3 \leqslant 72,$$

(9)

Light Level: Acceptance from lighting (Φ_4) is found by the following equation where ζ_4 represents light level in Lux.

$$\phi_4 = 1 - \frac{1}{1 + \exp(-1.017 + 0.00558\zeta_4)}; \quad 200 \leqslant \zeta_4 \leqslant 1600.$$

(10)

Wong et al. have carried out their work to find the weighting of these four acceptance values. The constants are based on surveys from 293 occupants who evaluated their environment.

$$k_i = \begin{cases} -15.02 \\ 6.09 \\ 4.88 \\ 4.74 \\ 3.70 \end{cases} ; \quad i = 0, \ldots, 4.$$

(11)

In order to evaluate Wong et al’s model, noise and CO_2 levels are assumed to be optimum since these variables are not considered in the productivity function. Figure 39 shows a 3D graph depicting lighting and temperature versus IEQ (denoted as ‘Performance Index’) relationship. The graph shows that the region between 450 lux and 800 lux for lighting and 21 to 24 degrees Celsius for temperature delivers the maximum IEQ. However, if the temperatures reach beyond 26 degrees, IEQ starts to drop significantly regardless of the lux level. Such a drop is not visible in the cooler region where the acceptance is considerably high.

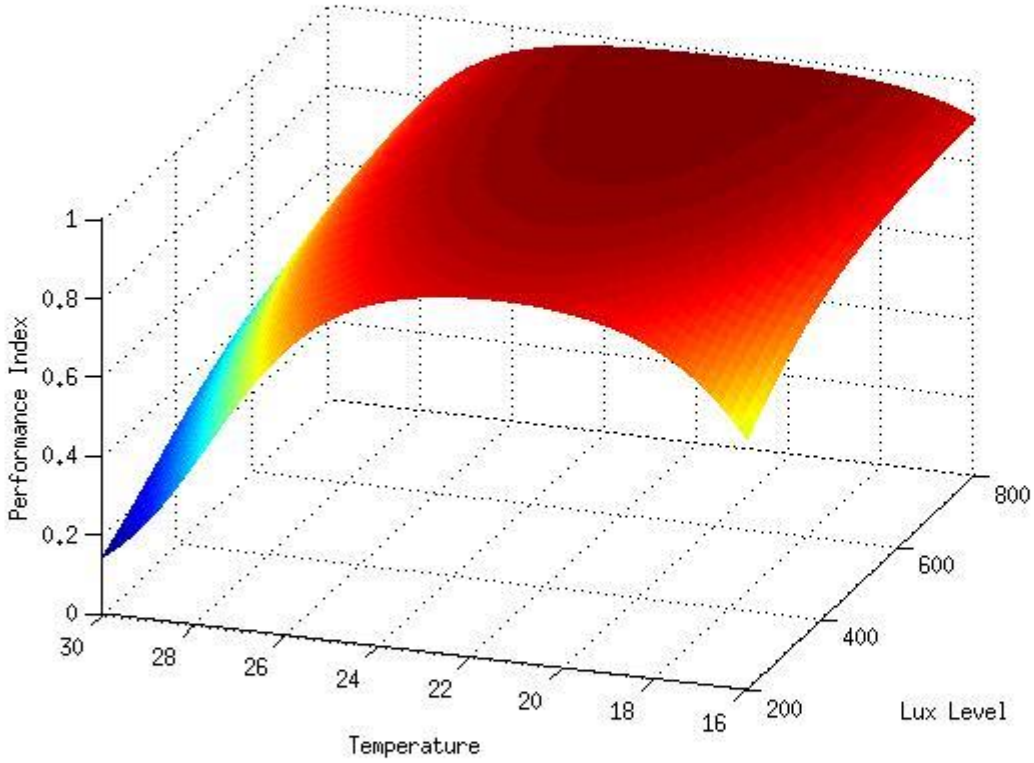


Figure 39: Wong's IEQ equation when CO_2 and noise levels are optimum

4.5.2.2. Ncube

Ncube et al. Have carried out surveys on two office building sites in the UK. They then developed linear regression model to determine the relative importance of lighting, temperature, noise level and CO_2 level on the overall acceptance of the office environment.

Ncube et al's equation is as follows:

$$IEQ_{index} = \beta_1 \times TC_{index} + \beta_2 \times IAQ_{index} + \beta_3 \times ACc_{index} + \beta_4 \times L_{index}$$

(12)

Where *TC* is the temperature, *IAQ* is the air freshness (or CO_2), *AC* is the noise, *L* is the lighting indexes. The values $B_1 - B_4$ represent the weighting factors of these values in the IEQ index. The four different indexes that represent the environmental factors are determined as follows:

Thermal environment: Acceptance of thermal environment is the same as Wong's where PPD is used as the main criteria.

$$TC_{index} = 100 - PPD_{TC}$$

(13)

CO_2 Levels: The acceptance from CO_2 concentration is as follows:

$$IAQ_{index} = 100 - PD_{IAQ}$$

(14)

and,

$$PD_{IAQ} = 395 \times \exp\left(-15.15 C_{CO_2}^{-0.25}\right)$$

(15)

where C is the CO_2 concentration as PPM.

Noise Level: Acceptance of the acoustic environment is found from the following equation:

$$ACc_{index} = 100 - PD_{ACc}$$

(16)

and

$$PD_{ACc} = 2(Actual_{Sound\ Pressure\ level} - Design_{Sound\ Pressure\ level})$$

(17)

where sound pressure level is derived from dB's.

As in Wong's case Acc index and IAQ index are set to 100 since these are assumed to be optimum. Figure 40 shows a 3D plot of Ncube et al's IEQ equation. Their equation gives a curvy area in the regions where lighting and temperature range is considered to be optimum. Moreover, their correlation is more sensitive to the light levels such that the acceptance index can drop significantly when the light level falls below 300 lux. On the other hand, their acceptance is not as sensitive to warm temperatures as Wong's. The acceptance falls to 70% in the worst case scenario.

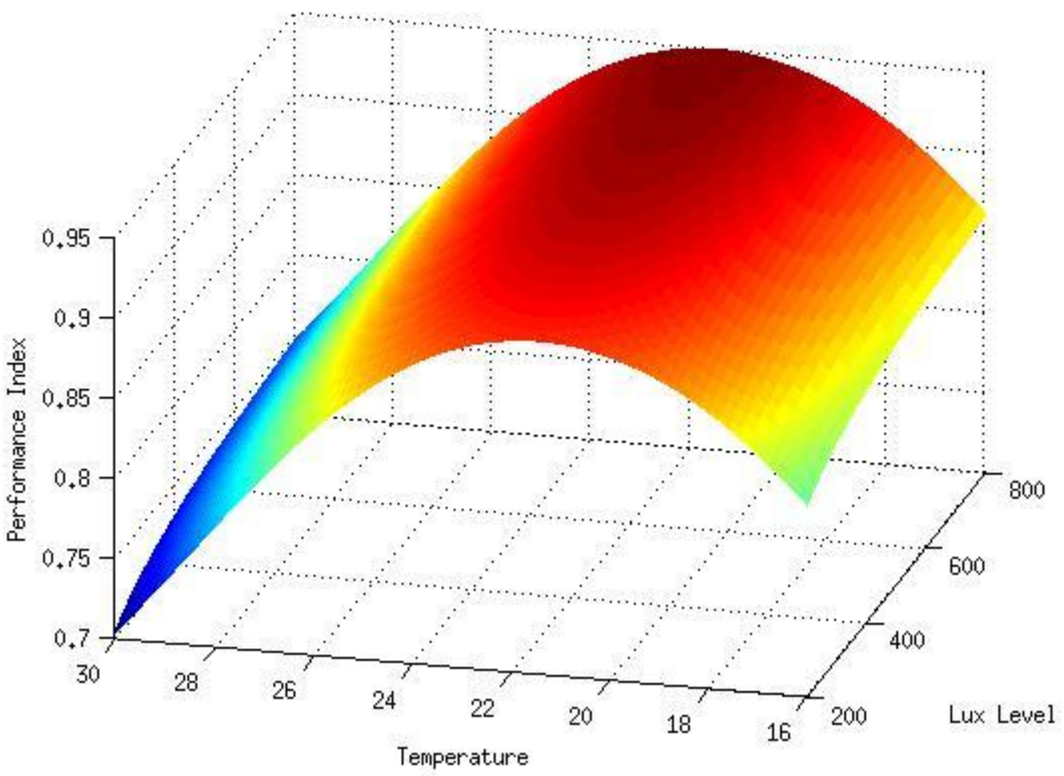


Figure 40: Ncube's IEQ equation when CO2 and noise levels are optimum

4.5.3. Assessment of the IEQ Equations

Both of the IEQ equations derived by Wong and Ncube deliver maximum IEQ values when the lighting and temperature is optimum. However as the buildings in DSR state will operate in non-optimal conditions, the equations will need to deliver accurate IEQ results when the temperature and lighting are out of their expected values. As can be seen from the 3D plots, both of the equations deliver significantly different IEQ values when the temperatures approach 30° C (0.17 for Wong versus 0.7 for Ncube). Because of this noticeable difference, a numerical assessment is carried out to examine the differences between the two equations.

4.5.3.1. Assessment of IEQ Equations from Lighting Perspective

As discussed in the literature review, the relationship between productivity and lighting is highly task dependent. For short term effects, the visual portion of the task is most likely to be influenced by the change in lighting. However, this portion of the task also depends on two parameters, contrast and illuminance of the task environment. It is difficult to define exact conditions for office environments. However, if the following assumptions are made, it is possible to deduce which IEQ relationship is more relevant from productivity point of view:

- Office buildings are environments where cognitive work is more dominant.
- The main equipment used in offices is computers. Computer screens provide constant luminance regardless of the external environment. Hence the majority of the tasks (which are done by computers) that require visual feedback can be assumed to be little affected by external lighting.

When Rea's [48] RVP equation is run for a contrast level of 0.3, the resulting visual productivity graph that produces RVP versus lux level is found as in Figure 41(left). This shows that visual productivity drops to around 92 % when the light level is at its worst (200 lux) and around 98% when light level is at its best (800 lux). Because visual component of tasks carried out by a typical office worker is assumed to be low, this result from Rea is used as a reference to compare Ncube's and Wong's IEQ equations.

The graph on the left in Figure 41 shows Rea's RVP for minimum and maximum lighting conditions. On the right, Ncube's and Wong's IEQ results plotted over Rea's RVP graph.

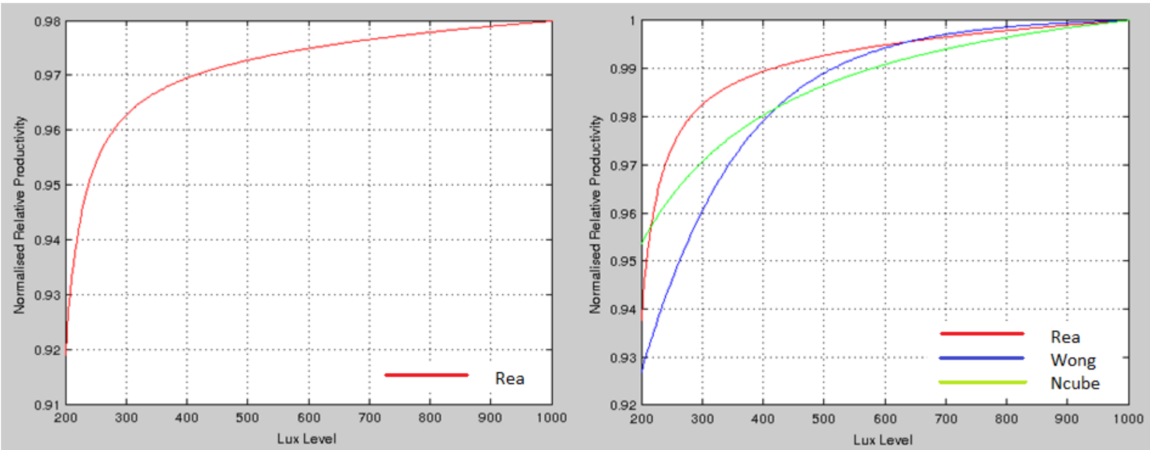


Figure 41: Left: Rea's relative productivity index for a contrast level of 0.3. Right, comparison of Rea with Ncube's and Wong's IEQ equations for indoor temperature of 23° C.

s can be seen in the comparison graph, the three graphs have a similar shape. Hence, it is possible to say that IEQ delivered by acceptance of workers is similar to the RVP index delivered by Rea when the contrast level is low. When lighting is decreased from optimum, both RVP and lighting acceptance drops slowly. As the decrease in lighting increases, the decrease in both RVP and IEQ accelerates.

The following can be deduced from this assessment:

- If the amount of lighting is higher than dictated by H&S executive, then productivity of a worker is expected to be above 90%.
- The productivity increases rapidly as the lighting is increased from this minimum value. The increase in RVP decelerates as light levels are increased.
- Both Ncube and Wong deliver similar results and they are comparable to Rea's relative productivity function for a contrast ratio of 0.3.

4.5.3.2. Assessment Criteria for Temperature

Thermal requirements are effective in all aspects of productivity in an office environment regardless of the task being carried out. Hence, comparison between IEQ and a productivity indicator is more relevant. Seppanen et al.'s [39] review on the performance of office workers in different room temperatures is a good indicator for such a comparison task because it is derived from various other studies.

Figure 42(Left) shows Seppanen et al's Temperature versus Productivity graph derived from their paper. The graph shows that relative performance drops to around 96% at 17° C and 27° C. The peak performance is achieved between 20° and 23.5° C. Figure 42(right) shows Wong's and Ncube's IEQ results when lighting is optimum superimposed on the Seppanen's.

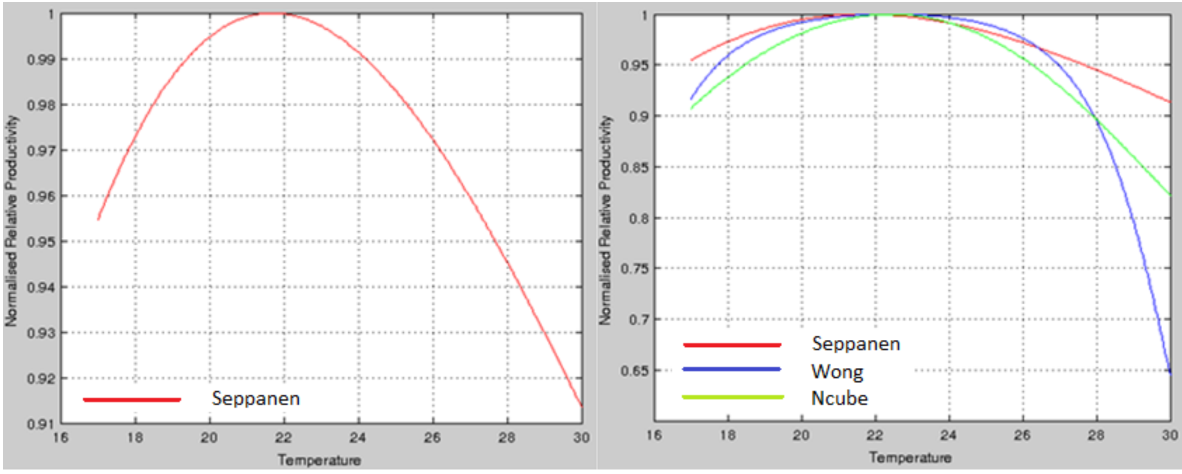


Figure 42:Left: Seppanen's relative productivity function for different indoor temperatures. Right, comparison of Rea with Ncube's and Wong's IEQ equations.

Unlike the situation in lighting, there is a significant difference between Wong's results and the others. At higher temperatures, IEQ index of Wong falls to around 0.65. This is much lower compared to Ncube (0.83) and Seppanen (0.91).

The following can be deduced from these numerical assessments:

- Ncube's IEQ equation delivers closer results to Seppanen's equation. Hence, under current assumptions, it is more suitable for being used as a productivity function.

The comparisons made above highlight the inconsistencies between different IEQ models. These inconsistencies prevent such models to be used as productivity indicators because more work needs to be carried out in this area. However, the studies of Ncube and Wong are the only ones available that present a numerical relationship between temperature, lighting and IEQ. Even though the applicability of their models as a productivity function requires lots more research, it is assumed in this study that they are the state of the art productivity functions that can be applied into a control system for the purpose of DSR. Because of its resemblance to productivity functions developed by Rea and Seppanen, Ncube's IEQ function is selected as the main productivity function that will be used in the following sections.

4.6. Controlling Loads in a Building Using a Productivity Function

As discussed in the literature review, existing load reduction strategies in office buildings are not based on a productivity parameter or any other parameter at all. Without a global productivity indicator, it becomes impossible to carry out the following:

- Distributing load reduction to different types of loads to ensure minimum disruption to occupants. For example, instead of carrying out load reduction using just the HVAC system, distributing it to both HVAC and lighting can achieve the same amount of load reduction while having a more pleasant work environment.

- If a load type is not available for load reduction, using another type of load to compensate its absence provided that productivity loss is kept constant. For example, if HVAC loads cannot be reduced for various reasons (e.g. minimum temperature limitation on a cold day), lighting can take over the load reduction burden provided that productivity loss is kept in check.

In this section, a simple example is given to show that using a productivity indicator to achieve load reduction in a building is more beneficial compared to using existing methods like using HVAC only.

4.6.1. Implementation of IEQ into DSR model

To demonstrate these arguments using the energy consumption model explained in the previous chapter, the following has been carried out:

- Productivity calculation procedure is added to the output stage of DSR simulation block. This is to show the drop in productivity (as a function of temperature and lighting) during the DSR state.
- Simple load control mechanisms are added to adjust temperature and lighting. For example, instead of turning the HVAC system off during the DSR period, it is set to operate in a duty cycle to maintain a given power consumption level.

The outputs are then compared to observe the amount of load reduction to achieve the same productivity value in various control strategies.

4.6.1.1. Implementation of IEQ Calculation

Ncube's productivity function is added as a subroutine to the output stage of the building energy consumption model. The function works as follows:

- For each simulation day, DSR simulation block delivers temperature and lighting recorded for one second intervals in an array. During the simulation, another subroutine that calculates IEQ by using the outputs for temperature and lighting that is derived by the DSR simulator.
- When the simulation is finished, the simulator generates an output graph that compares IEQ for non-DSR state and DSR state.

4.6.2. A Simple Trial with the IEQ Concept

The purpose of the first trial that has been carried out with the IEQ parameter was to observe the difference in the IEQ value of an office building between two load reduction strategies. The first strategy is to use a single energy consumer for load reduction such as the HVAC system. The second strategy is to use both of the energy consumers; lighting and HVAC.

The trial was carried out for the same model office building located in Izmir. A very hot summer day for Izmir is simulated (Table 12. outlines the test parameters). First, the energy simulator is run for Izmir when the indoor operating setpoints are adjusted as optimum (lighting 600 lux and temperature 22.5° C). The resulting IEQ is then taken as reference. Next, the two load reduction strategies are tested. An arbitrary load reduction value of 25% was selected. In the HVAC only strategy, the HVAC system is adjusted to reduce consumption such that the resulting overall consumption was 75%. In the combined strategy, lighting system was set to 400 lux and the remaining load reduction was carried out by the HVAC system.

Table 12: Simulation parameters for DSR Trial

Parameter	**Value**
City	Izmir
Simulation Trial Day	August 25
Average Outdoor Temperature During DSR Period	30
DSR Time	14.00 – 16.00
DSR Control	Hvac only and HVAC/Lighting Combined
Other Parameters Regarding Building and Occupants	Same as explained in Chapter 3

Figure 43 shows the results of the DSR simulator for the HVAC only scenario. In all of the graphs, red lines represent the case during the DSR scenario whereas blue lines represent business as usual scenario. The top left graph shows the indoor temperatures, top right graph shows lux levels, bottom left graph shows the power consumption and bottom right graph shows indoor IEQ. When the HVAC system is asked to reduce consumption, the indoor temperatures rise from their set-point values of 22.5° C to around 25.5° C. Because there is no change in lux levels, the resulting IEQ depends only on the temperature swings.

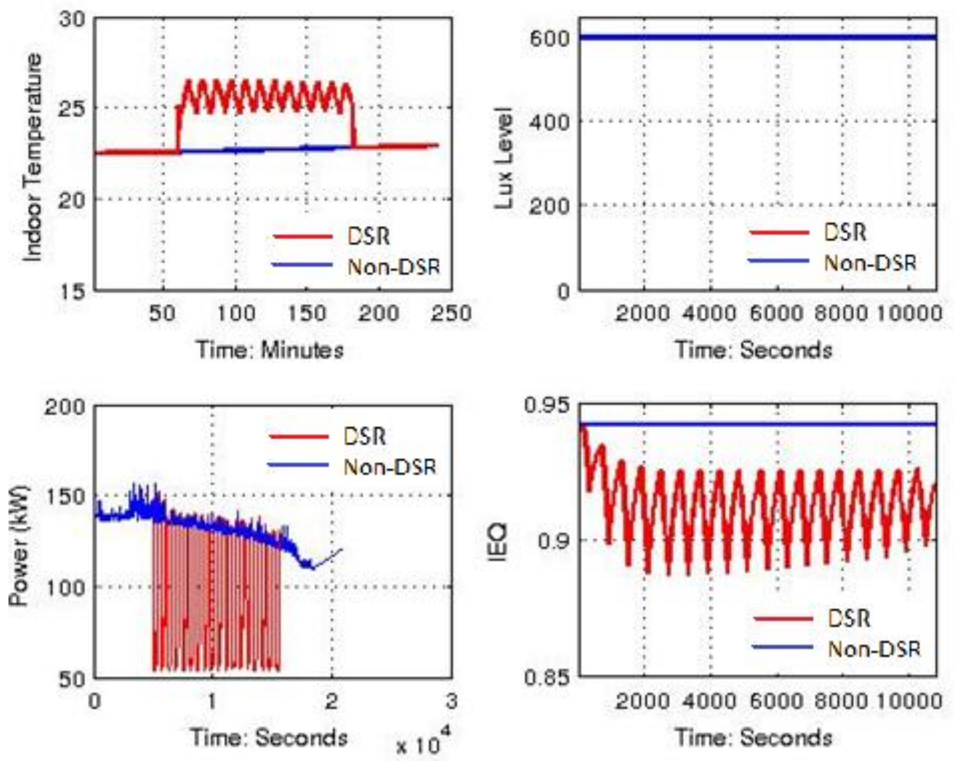


Figure 43: HVAC only load reduction scenario for Izmir

Figure 44 shows the case when both HVAC and lighting is used for load reduction. The average load reduction is equal to the previous case. However, because of the contribution of lighting, the average IEQ drop is much lower compared to the HVAC only scenario.

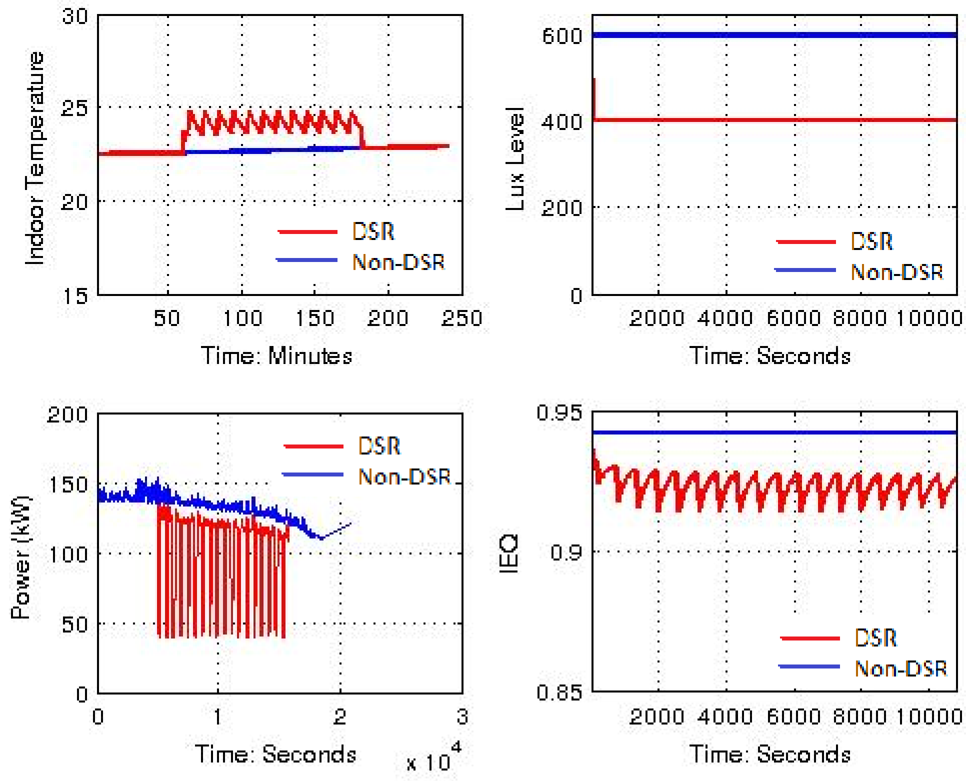


Figure 44: HVAC and Lighting combined load reduction scenario for Izmir

The results are summarised in Table 13. Indoor IEQ is around 1.4 percent higher when both HVAC and lighting is used to reduce power consumption compared to the case where only HVAC is used. Although the percentage value is small, it is significant because IEQ range is defined between 0.88 and 0.95 for the best and worst case indoor scenarios.

Table 13: Simulation results for DSR Trial

	HVAC Only	**HVAC/Lighting**
Average Lux Level	600 lux	400 lux
Average Indoor Temperature	25.57° C	24.12° C
Average IEQ	0.910	0.923
Power Reduction	%74	%74

4.7. Conclusion

The purpose of this chapter has been to establish a relationship between productivity of office workers and the office building. Because of the difficulties involved in including office appliances in a productivity function, the focus has been on environmental parameters. IEQ concept has been identified as the best solution to the problem of relating combined effects of individual environmental variables to human comfort and performance. It has been shown that IEQ equations that are derived by Wong and Ncube are developed to determine the acceptance of environmental conditions by the workers rather than a direct measure for performance. For this reason, these equations are compared with performance data obtained from literature review. Based on this study, Ncube et al.'s equation has been found to show better similarity hence this was selected as a productivity function.

The energy consumption model that has been explained in the previous chapter is modified to include IEQ as a DSR parameter. When a simple load reduction trial is carried out for a hot climate, it has been found that using only one parameter (temperature) as a basis for load reduction might not produce optimum IEQ (and productivity). For this reason, it can be concluded that a building automation system that needs to reduce power consumption for the purpose of DSR needs to be capable of using both the lighting and temperature as a parameter to maintain the maximum productivity in the office.

It should be reminded that the IEQ function tried in this chapter is far off from being a real productivity indicator. For this reason, it is not feasible to use this for calculating productivity loss as well as to evaluate the commercial value of using such a parameter.

The main usage of this indicator is to compare the environmental conditions in an office building during a DSR event and to ensure assess if more power could be shed in environmental conditions that have similar productivity indicators. In the next section, a control algorithm that can be used in an office environment for DSR purposes will be explained. This algorithm will then be tested using the building energy consumption model presented in Chapter 3.

5. Central Control Algorithm for DSR

5.1. Introduction

The loads in an office environment and the existing automated DSR protocols have various properties that limit the options for applying control algorithms in automated DSR control systems. In order to design a working automatic DSR system, these properties need to be taken into consideration. For example, what is the duration and the extent of load reduction that the controller will need to achieve? How will the loads in an office building need to be organised and controlled for maximum load reduction? Moreover, in the previous chapter, the concept of using IEQ as a productivity indicator has been shown to be a valid method to maximise power reduction potential in an office building. If this is the case, how can this concept be implemented into a controller? The purpose of this chapter is to propose a viable control algorithm based on answers to these questions and to determine the benefit of using such an algorithm by comparing it to simple DSR control methods.

5.2. Operation of an Automatic DSR System

The first step in designing an automatic DSR system is to determine its inputs and outputs. Since the subject of this study is office buildings, inputs and outputs are determined by the requirements of the utility operators that arrange commercial DSR schemes. As the literature review has shown, these schemes are based on various methods. Dynamic load control is one of them where certain loads are shut down automatically upon reception of a signal from the utility operator. However, the complex structure of the office environment prohibits direct control of loads without any consideration to the environmental conditions within the building. Therefore, it is evident that not all of these schemes are suitable for office buildings. Office buildings are more suitable to price based or rebate based schemes where the control decision is left to the building operator.

The best way to determine the expected inputs and outputs of a price or rebate based DSR system is to investigate existing communication protocols that are developed for such purpose. In the next section, one of these models called Open Automatic Demand Response (ADR) will be reviewed.

5.2.1. Open ADR

The report [94] written by Ghatikar et al from Lawrence Berkeley National Laboratory gives detailed information on Open ADR which is a web services based open data model that has been used in California utilities. The purpose of this model is to send both price and reliability based demand response information to building control systems and end use control systems (like lighting controls) in order to achieve DSR. The report describes how the Open ADR data model can be used to represent a variety of dynamic electricity price structures. It evaluates these structures and uses the existing Open ADR specification to develop and test data models for a variety of dynamic pricing. Three pricing structures in the information flow are considered, Real Time Pricing (RTP), Peak Pricing (PP) and Time of Use Pricing (TOU). Among these, the pricing information of peak pricing and time of use pricing is known by the customers in advance. Therefore open ADR data structure is developed for RTP which is the most demanding data model.

5.2.2. Example of data that is expected from OpenADR system

Figure 45 shows a sample price schedule that a client system will receive using Open ADR protocol. Open ADR customers can respond to dynamic prices by either using the actual prices or map these prices into “operation modes” which can be used as inputs to control systems. If the client system has enough capability, it can utilise a long data format that shows precise information on how much power will cost for individual time slots. If the client system needs a simple approach, then it can utilise the simple data format which categorises the time slots based on their relative costs. Expensive time slots are marked as 'critical' whereas time slots when the prices are low are marked as 'low'.

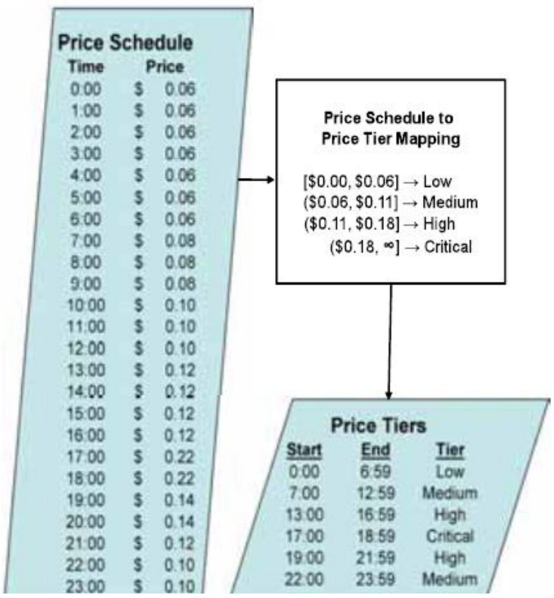


Figure 45: Open ADR Pricing Information

Open ADR system gives good insight on how demand response mechanism is going to work. Clients who are signing up for this will want their building control systems to react to electricity prices that are higher than average prices. In this case, the system will be asked to reduce power consumption in 'critical' periods.

The information provided in the report allows predictions to be made about the inputs that will be supplied to an automated DSR control system. These are related to the timing of the DSR event and the expected amount of load reduction that is to be achieved during a DSR event.

5.2.3. Timing of the DSR Event

The paper [94] suggests Open ADR data model to accommodate various RTP pricing schedules. These are called Day Ahead (DA) and day-of (DO).

In the DA pricing scheme, prices for the next day are published day-ahead. These prices are either provided as hourly chunks or 15 minute chunks depending on the tariff system. In the DO pricing scheme, prices are set directly before they take effect on the same day. Before every hour or x-minute ahead, the prices are set for the next x minute interval. It is indicated in the report that this pricing structure is not used in the retail markets but is common in wholesale markets. The x minute intervals are usually 5 minute or 15 minutes.

5.2.4. Expected Amount of Load Reduction

Since programs that are based on pricing do not dictate the amount of load reduction that is to be achieved, it is difficult to determine how much load reduction is expected in RTP schemes. However, if an automated system in a building is to control the loads, the price information can be used as an indicator therefore it is a good starting point to predict the expected power reduction during a DSR event.

The retail prices that are announced in RTP schemes depend on two factors; market prices or peak days. Peak day tariffs depend on extreme weather conditions and prices for these days are usually set very high to encourage extreme load shedding. An example in the Appendix of the document [94] shows that for extremely hot summer days, the ratio of maximum and minimum prices in a day are as high as 93. On moderate days though, this fluctuation drops to around 4. Price schemes that depend on market prices are also affected by external conditions such as the weather though they are influenced by other factors such as cost increases caused by the drop in supply.

Judging by the increase in prices during peak time periods, it is possible to predict that during a DSR event, drastic load reduction might be required to avoid excessive charges. Therefore in such a case, the band of load required load reduction as a percentage of average power consumption might be between 0 – 100%.

5.3. Description of a Central DSR Controller

5.3.1. Inputs and Outputs of the DSR Controller

Based on the information above, the basic control scheme that specifies the inputs and outputs of a DSR controller can be developed as shown in Figure 46. There are two inputs to the system, pricing information that is received from the utility operator and mapping information from the user. The mapping information determines how the price signals are to be interpreted as load reduction commands. The combination of the mapping information and pricing information allows the controller to issue commands to reduce consumption by the desired amount.

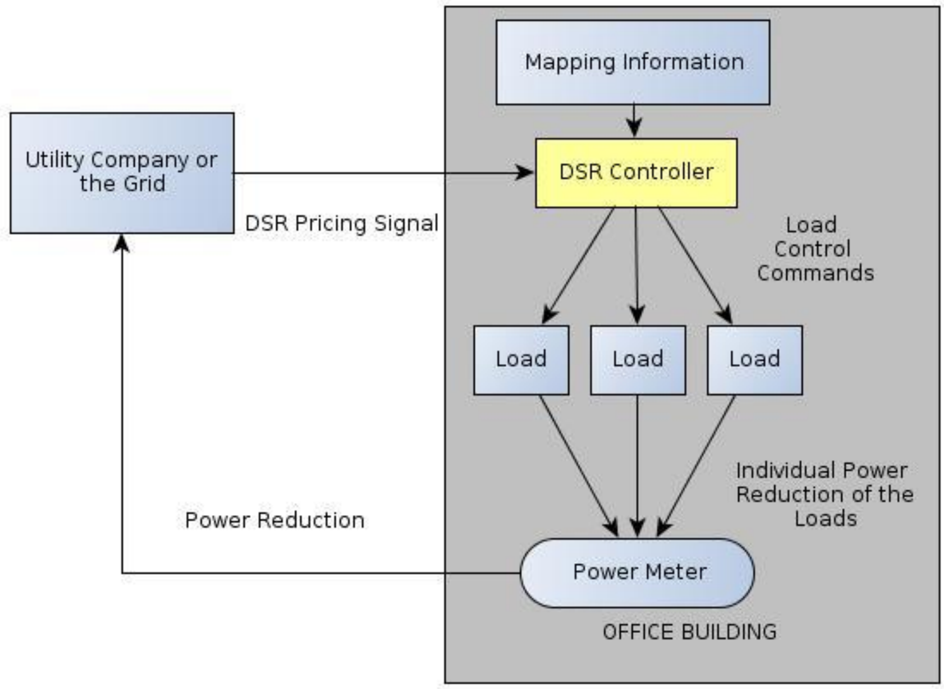


Figure 46: Overview of DSR Control Scheme

Grid Input → Pricing information for the next x minutes.

User Input → Mapping information for the prices

Output from Control System → Commands that reduce consumption by x% during the period x.

Output from the Building → X% Lower consumption during the DSR period.

Communication with the utility and translation of the price signals is beyond the scope of this study as this study is focused on the load reduction activities within the building. The requirements to achieve DSR in the office will be discussed in the following section.

5.3.2. Requirements for enabling Productivity Based DSR Control Strategies in Office Buildings

If productivity was not a consideration, the design of the DSR controller would be less sophisticated. The amount of load reduction required would be distributed to various loads that are under control by a fixed proportion. However, if the decisions that are made are based on productivity, the commands that are issued by the controller should be a function of productivity which in turn is a parameter of environmental variables that each individual load is controlling. Moreover, if productivity is an indicator, loads that are expected to have lower (or no) impact on productivity should be prioritised against the loads that have impact on productivity. These and various other necessities make certain functionalities mandatory to be supported by the elements of a DSR control system which will be discussed as follows.

5.4. Requirements for Automatic DSR Control

An Ideal DSR controller is a single entity where data collection processing and control command generation takes place. It consists of electronic hardware and software that can process inputs from various sources and issue DSR commands to load controllers.

The requirements of certain loads such as the HVAC system or the lighting system are too sophisticated to be implemented into a central DSR controller. For this reason, the controller is expected to communicate with the load controllers (rather than loads themselves) that control these loads. Therefore the communication between the load controllers and the DSR controller is expected to consist of simple information such as operating set-points and average power consumption (Figure 47).

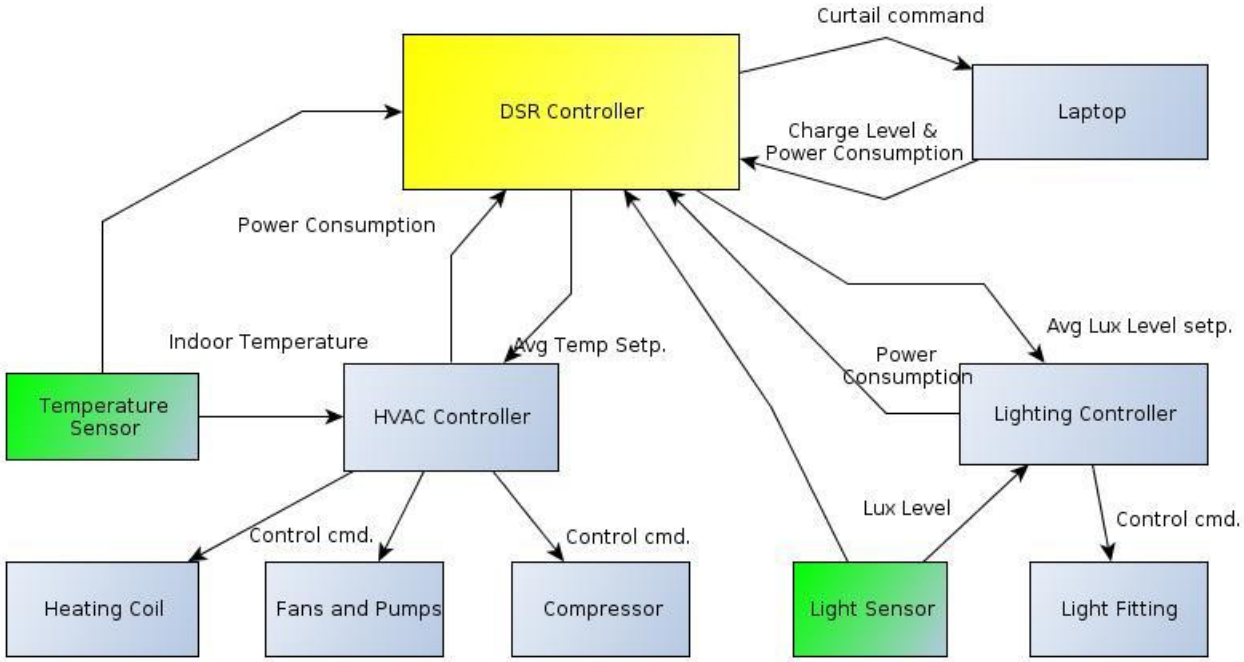


Figure 47: Load Control Command Structure

5.4.1. Requirements of the Load Controllers in the Office Building

In order to support DSR, load controllers should have electronic hardware to support the software requirements for communication and execution of DSR specific control commands. This includes reporting functionality such as current power consumption and power reduction potential. For distributed control to be implemented, the load controllers should be able to communicate with one another as well.

The specific requirements of individual load types can be listed as follows.

5.4.2. Requirements of the HVAC System

As indicated in [7], HVAC system can be controlled in two ways to reduce consumption during a DSR event; zone temperature control and systemic adjustments to HVAC components. In zone temperature control, global temperature adjustment is carried out in all of the conditioned zones. In systemic adjustments to HVAC components, air distribution and cooling components of the HVAC system are adjusted for lower consumption. For example, supply fan can be slowed down or compressor power can be reduced.

The report [7] highlights the difficulties of achieving DSR in an HVAC system by adjusting HVAC components independently. The main drawback is that it is difficult to predict the outcomes of changing various components' operating set points. For example if compressor power is reduced, supply fans will automatically start to operate more speedily to compensate the change in temperature. Hence supply fan speed needs to be controlled (kept constant in such a scenario) as well. Such a decentralised control of a centralised system is difficult to achieve. For these reasons, HVAC system needs to have the capability to achieve zone control in an automated DSR system.

5.4.3. Requirements of the Lighting System

Unlike HVAC systems, lighting systems in buildings are decentralised. The operation of various lighting controllers are independent from one another which allows the possibility for individual control. However, controlling lighting for DSR has its own challenges. For example, homogeneous lighting reduction would be the preferred method to ensure that every occupant is affected from load reduction by the same amount. This requires feedback of current lux levels in the office to the DSR controller. If such feedback is not available, then only absolute control would be possible. In absolute control, every light fitting can be instructed to operate at x% of predetermined value. However, as indicated in report [95], this might result in extra power consumption if the lighting system is already operating below the given value. Therefore the best option for controlling lighting in the office building is to have a feedback based lighting control system.

5.4.4. Requirements of Battery Operated Devices

Battery operated devices are not considered in DSR related literature because of their low contribution to the overall energy consumption therefore information on their controllability in a DSR event is limited. The basic requirements for these loads (if they are to be included in a DSR system) are similar to lighting; they will need to provide communication facilities and they will need to report their statuses (e.g. battery charge levels). However, most conventional battery operated devices need to provide additional functionalities that might not be useful in situations other than DSR. For example, if laptop computers are to be included in a DSR system, they will not only need to communicate and provide feedback but also execute DSR commands such as disconnection from power supply (if it is possible).

5.4.5. Requirements of Other Loads

Loads that are considered to have no storage facility but that are deemed curtailable should have similar features with the loads mentioned above; they should be able to communicate and report the amount of contribution they are achieving during the DSR event.

5.5. Levels of Load Control

Prioritising productivity requires prioritising loads based on their effects on productivity. For this reason, typical loads in an office building are categorised into three; Level 1 being the load type that has the most priority and Level 3 being the load type that has the least priority in a DSR event.

Level 1 Loads: In a DSR scenario, loads that are assumed to have minimum or no effect on productivity during the DSR period will be shed before other loads. In this study, these are called Level 1 loads.

Level 2 Loads: These consist of battery operated devices (like laptops) where the disconnection of the device from the power outlet will have no immediate effect in the productivity of the workers as long as there is enough battery charge.

Level 3 Loads: These are the loads that have indirect storage facility (like HVAC) or have load reduction flexibility (like lighting) and which immediately affect productivity when they are not available.

5.6. DSR Algorithm

Prioritisation of loads requires the DSR controller to run load reduction requests in sequence. The following equations can be used to formulate these.

Total achieved power reduction is a function of total power reduction request.

$TAPR = f(TPRR)$

(18)

where

TAPR = Total Achieved Power Reduction,

TPRR = Total Power Reduction Request

$TAPR \leqslant TPRR$

(19)

If load prioritisation is involved, then we can relate;

$APR(\text{Level}_i) = f(PRR(\text{Level}_i))$

(20)

Where

PRR = Power Reduction Request for a load level

APR = Achieved Power Reduction for a load level

In this case, power reduction request of each load level depends on how much power reduction is achieved on the previous load level.

$PRR(\text{Level}_i) = TPRR - APR(Level_{i-1})$

(21)

where $i>1$ and

$PRR(\text{Level }_1) = TPRR$

These equations show that power reduction request from each category of loads depend on the result of power reduction actions carried out by higher priority loads. This means that a DSR controller needs to operate in sequence to achieve the target load reduction.

If these equations are to be implemented in a DSR controller, the algorithm can be constructed as in Figure 48.

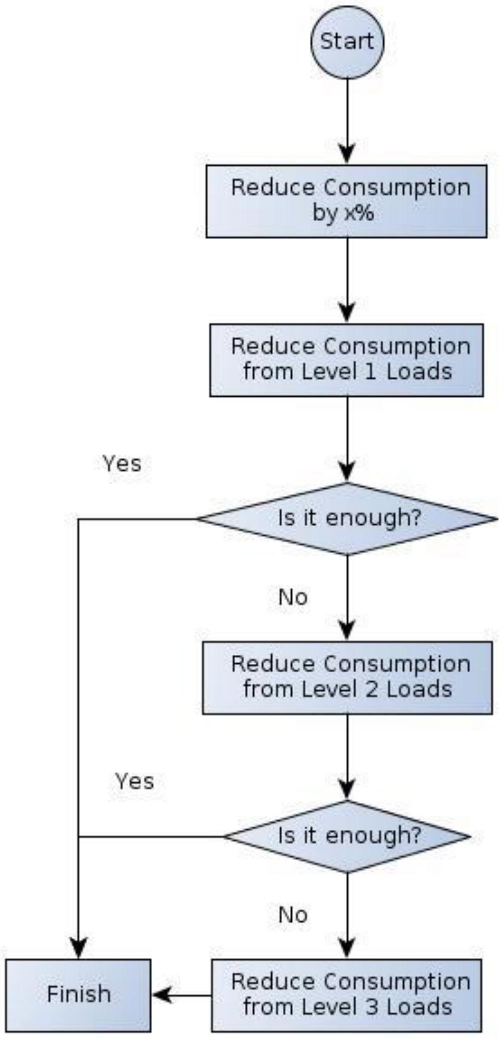


Figure 48: DSR Algorithm Based on Prioritisation

According to this algorithm, when a DSR event starts, the controller will check if the existing total consumption is higher than the requested consumption level. If it is high, it will shed Level 1 loads. If the consumption is still high, it will ask the remaining consumption to be shed from Level 2 loads. Finally if consumption targets are not reached, it will ask Level 3 loads to reduce their consumption.

5.6.1. Load Control Algorithm for Level 3 Loads

Chapters 3 and 4 allow us to be more specific about what loads will be included in various load levels mentioned earlier. Level 1 loads in office buildings will consist of equipment such as elevators or immersion heaters. Being battery operated devices, Level 2 loads will consist of individual laptop computers. As these are assumed to have no immediate productivity affects on occupants, when it comes to these loads, the task of a DSR controller will consist of asking for general load shedding and querying for how much they have achieved. The sophistication of load control can of course be increased but given the small contribution that these loads are expected to make in the overall power reduction, the emphasis will be on Level 3 loads which are the main consumers in office buildings.

The duty of a DSR controller becomes much harder when it comes to Level 3 loads. If productivity is involved, both lighting and HVAC system need to be controlled based on the IEQ parameter. This means that the control parameters passed on to these load controllers should be based on the environmental parameter that they are controlling rather that direct power reduction request. For example;

let

H = Pre-DSR power consumption of the HVAC system

L = Pre-DSR power consumption of the Lighting system

$T = H + L$ = Total pre-DSR power consumption of Level 3 loads

r = load reduction request from Level 3 loads where

$r<T$ and

PH = Power reduction request from HVAC

PL = Power reduction request from Lighting

then a simple control approach would be to reduce consumption by the same amount from both of the load categories.

$PH = r \times H/T$

$PL = r \times L/T$

The problem with this approach is that the IEQ in the building is a parameter of the environmental variables. If;

$Temp$ = Average indoor temperature,

Lux = Average indoor lux level and

IEQ = Average indoor IEQ level then,

$Temp = f(H)$,

$Lux = f(L)$,

$IEQ = \mathrm{f}(Temp, Lux) = f(Temp(H), Lux(L))$

Hence during a DSR event, the resulting IEQ will depend on the load reduction from both category of loads;

max(IEQdsr) != *IEQ(Temp(H-PH), Lux(L-PL))*

The relationship between H,L and IEQ was not linear as has been shown in the previous chapter. For this reason, picking a proportional amount of reduction from both loads will not deliver maximum IEQ during a given DSR scenario.

In this case, the main duty of the DSR controller is to find the best PH and PL to maximise IEQ. In the following section, the algorithms to achieve this objective are explained.

5.6.2. Open Loop versus Closed Loop Control

The methodology for IEQ based control depends on whether the control system has advance information on the resulting environmental conditions given the amount of power consumption from the environmental systems. That is, if the DSR controller can determine the resulting average indoor temperatures given the amount of power reduction from the HVAC system and the resulting indoor lighting conditions given the amount of power reduction from the lighting system, then it can issue direct commands to these systems. This would be an open loop control system. On the other hand, if the system does not have the capability to predict the resulting environmental conditions, a closed loop system would be required.

Figure 49 shows an open loop algorithm where the required power is directly converted to temperature and lux level set points for the HVAC and lighting systems.

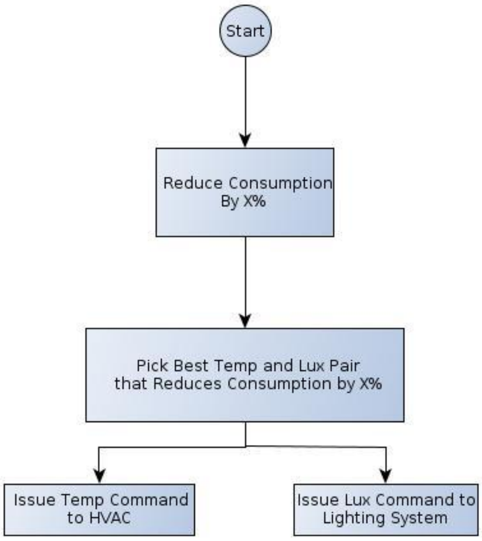


Figure 49: Open Loop Control

In this algorithm, apart from the adjustments that are required because of unpredictable conditions, no immediate feedback is required from the HVAC and lighting system. The controller predicts the optimum operating points for maximum load reduction and IEQ.

Figure 50 shows a closed loop algorithm. If the amount of load reduction is large, it is divided into smaller chunks. Then, this power reduction is asked from HVAC and lighting individually to test which results in a better IEQ level. The reduction is then asked from the load type that has the least disruption on IEQ. The algorithm is completed when all of the required load reduction is achieved.

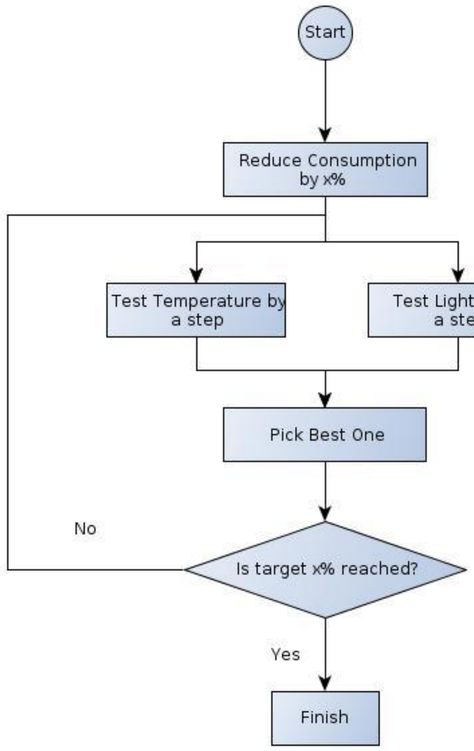


Figure 50: Closed Loop Control

Both of these control strategies have their pros and cons. In an open loop case, predicting the resulting IEQ requires the controller to either carry out model predictive control algorithms or to have a lookup table that is implemented in advance. If a model predictive control is implemented, the algorithm can run this model and determine the resulting temperatures by using the data available from the sensors in the building. If a lookup table is used instead, the calculations for various control scenarios can be carried out before hand to generate a table that can be used for prediction. This table would deliver the resulting indoor temperatures when the HVAC power consumption, load reduction time, outdoor temperatures and other information is given as an input. In both of these open loop solutions, the predictions of the controller might turn out to be inaccurate if there is a change in the building that might affect the environmental parameters. For example, in a winter day, if the air infiltration of the building increases because of openings, the heat lost to the outer environment might cause temperatures to drop more rapidly than predicted by the controller therefore the power reduction that is achieved by the DSR algorithm might not be optimum.

A closed loop control algorithm is difficult to achieve particularly because of the complexities of the HVAC system. The flywheel effect of the building requires some time to pass before the temperatures are settled. This would extend the time that is required to find a solution for a given power reduction request. Considering that demand response time periods are relatively short compared to the daily operation of the building, this solution might turn out to be impractical. Also, this solution requires testing with both of the environmental variables which might be inconvenient to building occupants.

5.7. Implementation of the DSR Control Algorithm

As the DSR controller presented here is an abstract of a real device, specific details related to its operation is not discussed. The focus of this study is to define the fundamental principles of the controller and more importantly show the effectiveness of operating such a controller for DSR purposes. The preceding sections have drawn the outlines of the DSR controller proposed in this study. The rest of this chapter will focus on the benefits of using such a DSR controller. Particularly, the answers to the following questions are sought;

- How effective is using an IEQ based DSR control system?
- How well does using a prioritised DSR approach perform compared to basic

approaches?

- How do the external climatic conditions affect the load reduction potential?

In order to answer these questions, the DSR control algorithm has been implemented into the model office building designed in Chapter 3. Then, the building simulation has been run to compare various DSR control scenarios. In the next section, the implementation of the control algorithm to the building energy consumption model is briefly described.

5.7.1. Operation of the Lighting and Temperature Selection Algorithm

By utilising the energy consumption model explained in Chapter 3, it is possible to derive lookup tables that would allow easy calculation of indoor temperatures for given amount of power. For this reason, an open loop control is selected as the control approach in the simulation model. Figure 51 shows the main algorithm that is implemented.

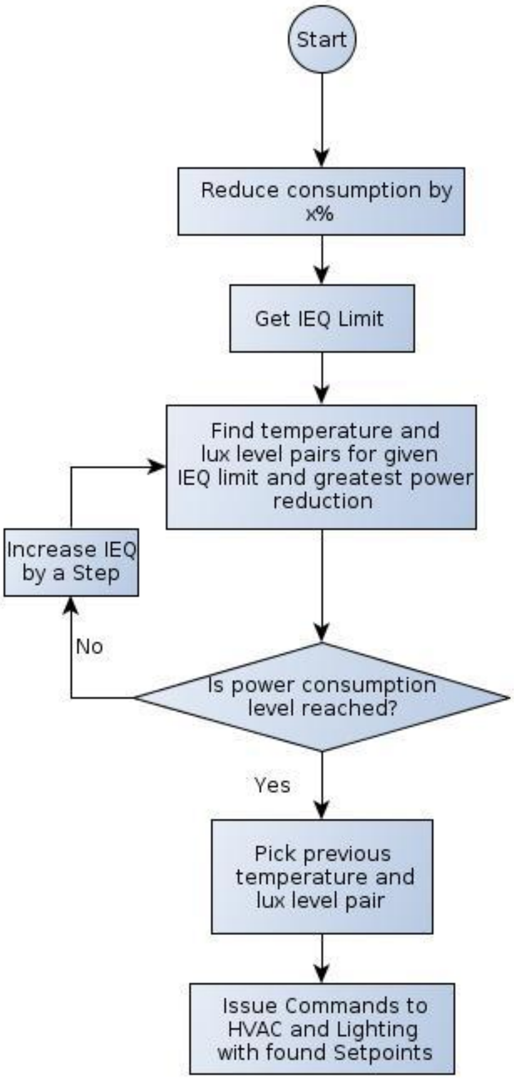


Figure 51: Implementation of IEQ based Load Reduction Algorithm to the DSR Model

In the implementation, it is assumed that the building has a limit based on IEQ (called IEQ limit) on how much productivity can be sacrificed. This limit is necessary because if a given load reduction demand is excessive, it would cause unexpected productivity loss. Therefore whatever the load reduction request, the resulting IEQ is always above or equal to the level determined by the IEQ limit.

The main objective of the algorithm is to achieve best IEQ for a given load reduction request. The operation of the algorithm is bottom up. An IEQ indicator, which is initialised to the IEQ limit is the main loop parameter. Because every IEQ value has multiple temperature and lux level pairs, the first task of the algorithm is to find lux level and temperature set points that corresponds to the IEQ indicator. Next, the power consumption that would result if the building would operate for each of temperature and lux level pairs is calculated. This allows the selection of the best temperature and lux level pair, which is the pair that delivers the greatest amount of load reduction. The resulting load reduction is compared with the load reduction request.

If the resulting load reduction is higher than that is requested, this means that the IEQ indicator could be increased by a step size to find another pair that delivers a value closer to the requested power reduction level.

This loop continues until when the algorithm picks a T and L pair that result in a consumption that is higher than requested. In this case, it picks the previously found T and L pair as the best pair. When the algorithm exits the loop, power consumption is just below that required by the DSR and the IEQ in the building is the highest possible given the amount of load reduction that is requested.

If the algorithm cannot find a T and L pair that meets the power consumption criteria and results an indoor IEQ that is higher or equal to the IEQ limit, it delivers the T and L pair that delivers the maximum load reduction for the given IEQ limit.

The core of the algorithm which is the function that finds the temperature and lux level pairs with greatest amount of power reduction is implemented as follows (Figure 52).

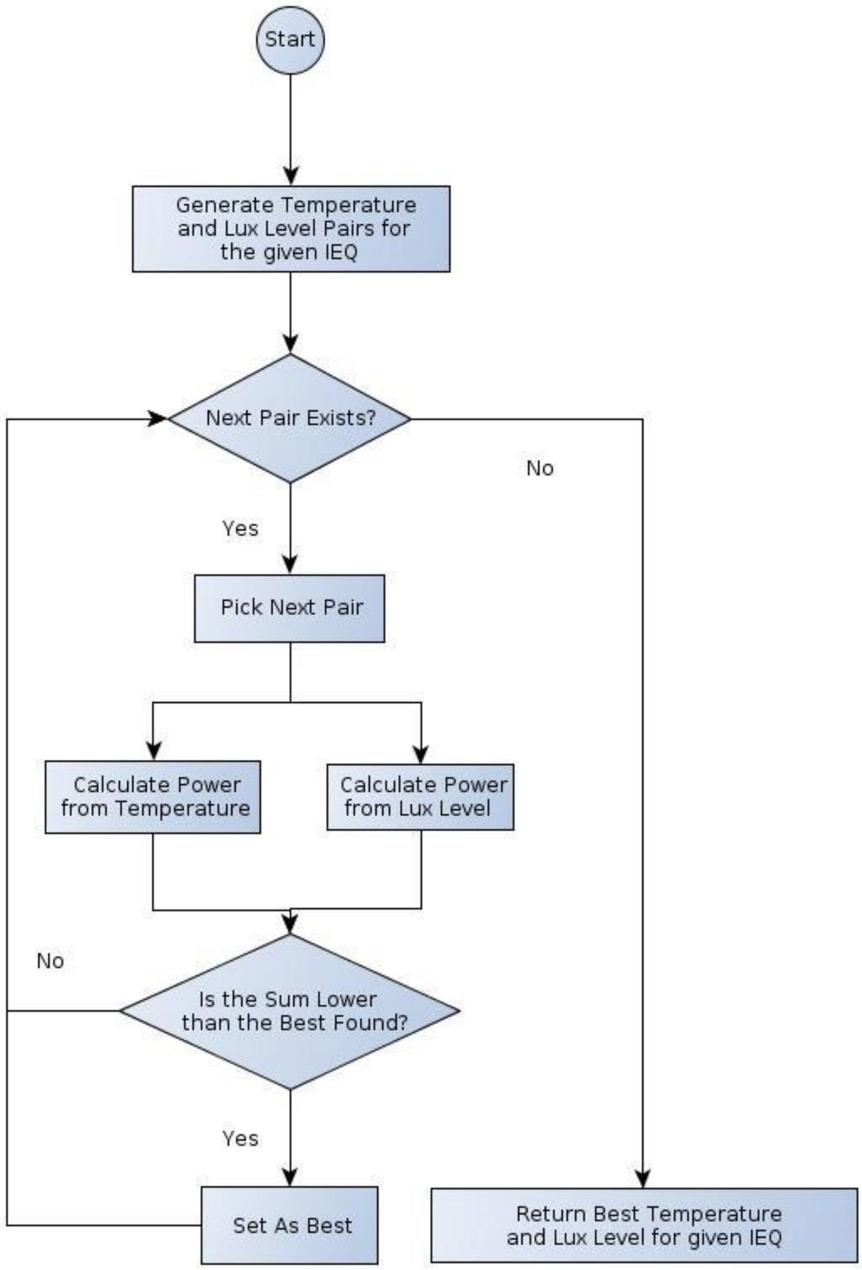


Figure 52: Implementation of Best Temperature and Lux Level Selection Algorithm

The input to this algorithm is the IEQ level. It utilises Ncube et al.'s IEQ equations to deliver the temperature and lux level pairs resulting in the given IEQ level. For each temperature and lux level pair, the algorithm calculates the corresponding power consumption. This consists of two parts; power consumption for given lux level and power consumption for given indoor temperature.

To determine the power consumption for a given indoor temperature, the algorithm utilises a lookup table has been generated using the energy consumption model.

For lux level prediction, it uses a linear lux level/power relationship formula to determine the resulting power consumption for a given lux level.

Once the algorithm calculates the total power consumption, it checks whether this is better than the best power consumption that it has found so far. If so, it records the temperature and lux level pair. If not, it continues with the next pair of temperature and lux level. When all of the temperature and lux level pairs are calculated, the best pair (that delivers the least power consumption or most power reduction) is returned.

5.7.2. Implementation into the DSR Block

The main algorithm is implemented into the DSR simulation block of the building energy consumption model. The input parameters of the algorithm is as follows:

Minimum Allowed IEQ: This value dictates the lowest IEQ level that is allowed in the building.

Amount of power reduction: This is the requested power reduction from the building during the DSR event.

In order to compare with Non-DSR scenario, the following parameters are recorded:

- Average indoor temperature and lux level

- Average indoor IEQ
- Average power consumption

5.8. Experiments with the DSR Algorithm

This section presents various simulation runs that are carried out using the energy consumption model presented in Chapter 3. The purpose of these simulation runs has been to predict the benefit of using IEQ as a central parameter for ensuring maximum power reduction in the office using curtailable loads. In order to achieve this, the building energy consumption model has been run with various combinations of input variables which are explained in this section.

5.8.1. IEQ based control for finding maximum power reduction potential

Since IEQ is the main parameter that indicates productivity, the simulation is run for various levels of allowed IEQ. The purpose of the first trial was to determine the maximum power reduction in the 'business as usual' scenario where productivity in the building is not allowed to drop. The results from this trial have been used as a benchmark when comparing results from other trials where the allowed IEQ level has been lowered. Maximum IEQ is determined by Ncube et al's equation; when indoor temperature is 23.5° C and lux level is 600 lux. Two trials were carried out afterwards; first one setting the IEQ as 97% of maximum and the second one 95% of the maximum.

5.8.1.1. Varying levels of DSR

Three DSR scenarios have been tested. First, 'HVAC only' scenario, where only the

HVAC system is used to achieve given power reduction set-points is tested. This scenario is the basis for comparison with existing DSR practices because it is commonly referred in the literature as the most widely used DSR method. Second, Level 3 loads only (where both lighting and HVAC is allowed to reduce consumption) were tested. Third, a control algorithm that utilises both Level 2 and Level 3 loads is tested.

5.8.1.2. Cold and Warm Climate

As explained in Chapter 3, the difference between these two variables is the usage of cooling system. In warm climates, electricity consumption increases significantly during summer. Therefore the algorithm is run for both climates to observe the differences that are related to outside conditions. Copenhagen and Izmir's weather files are used for these tests. Figure 53 shows the outdoor temperatures for one sample day of each week hence there are 54 samples collected for the year that has been simulated.

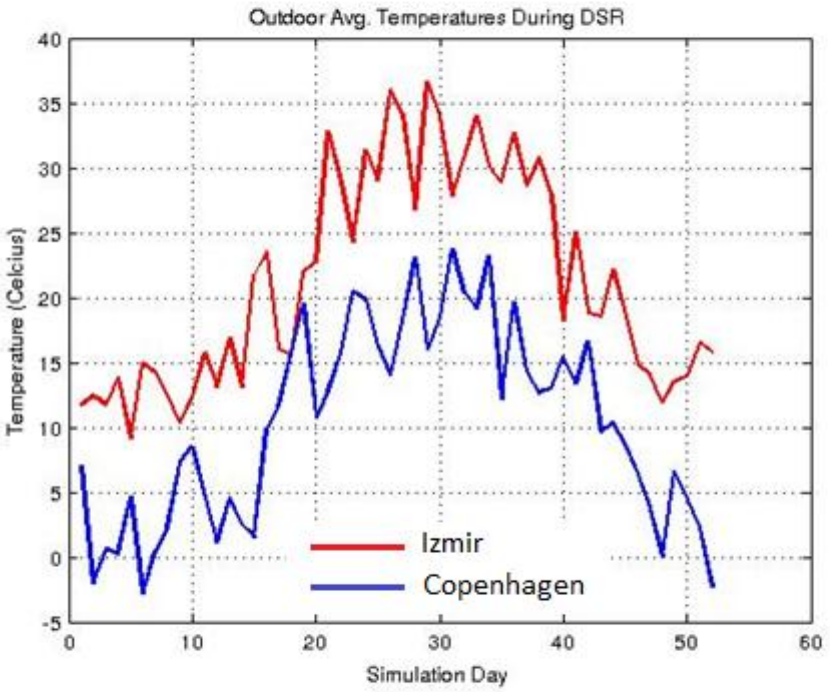


Figure 53: Outdoor temperatures for Izmir (Red) and Copenhagen (Blue) for the simulation period of 52 weeks.

5.8.2. Simulation Run for Copenhagen

5.8.2.1. Copenhagen 99% IEQ

Figure 54 shows two graphs depicting the result of the simulation. On both of the graphs, x axis represents the simulation days (one day for each week in the year).

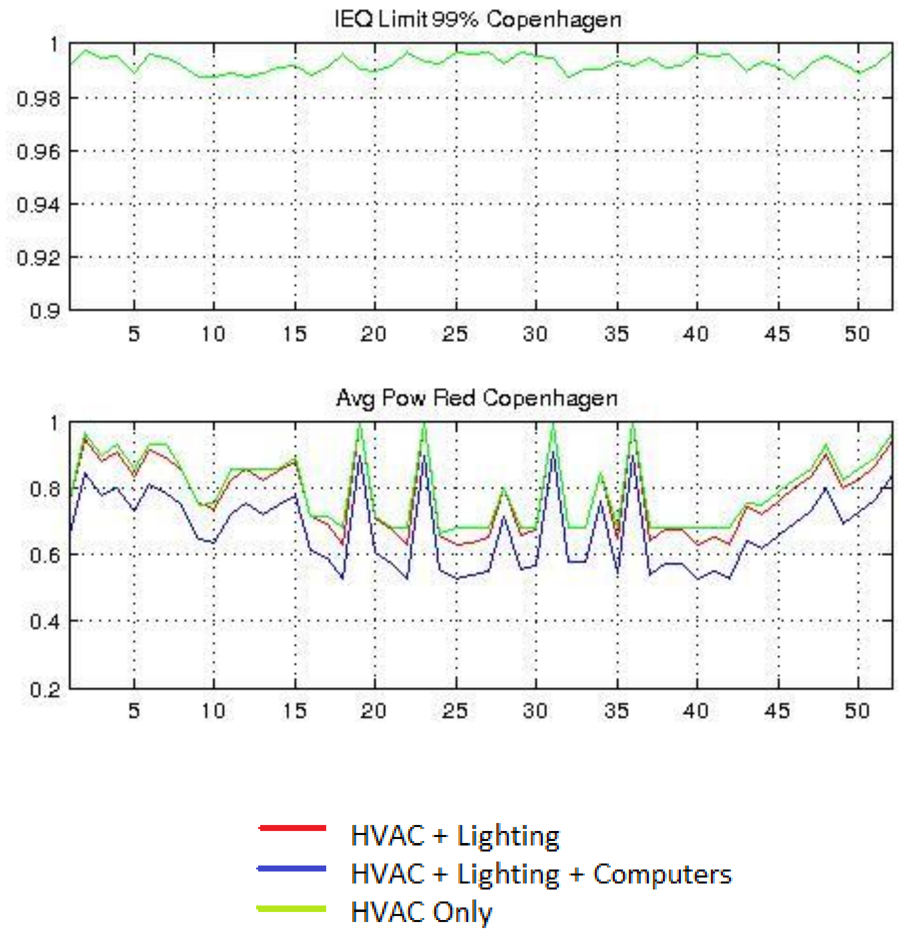


Figure 54: Copenhagen simulation result for 99% IEQ.

On the upper graph, y axis shows the average IEQ level in the office during the DSR period. On the lower graph, average power reduction during the DSR period as a percentage of non-DSR case is depicted. The three colours represent different levels of

DSR control. Green represents HVAC only scenario where only the HVAC system is allowed to reduce consumption. Red represents Level 3 scenario where both lighting and HVAC is allowed to reduce consumption. Blue represents Level 2 + Level 3 scenario where laptop computers are allowed to contribute to the DSR as well. In this simulation run, IEQ is set as 99% therefore the system is not allowed to sacrifice IEQ for power reduction. For this reason, the upper graph shows a line very close to 1. In certain days, the IEQ level in the building drops by up to 1-2% because of the unexpected indoor temperatures during those days. However, the system could achieve indoor temperatures that are very close to 99% IEQ level in most of the days that is simulated. In contrast, the lower graph which depicts the average energy consumption shows lines falling below the 99% mark. The simulation times where the deviation from maximum consumption occurs corresponds to summer times where the outdoor temperatures are moderate in Copenhagen. This causes the HVAC system to operate hence it consumes more power to maintain the indoor temperatures at given set-point levels. Also, values represented by the blue line which depicts Level 2 + Level 3 combined DSR case is always lower than the others.

This simulation run delivers expected results for several reasons. First, setting the IEQ to maximum causes all 3 levels of DSR control to deliver the same IEQ throughout the year therefore there is no difference among the indoor conditions of three levels of control depicted in the upper graph. Second, average power reduction falls below the 99% mark even if the IEQ level is set as 99% because the temperatures inside the building do not deviate to uncomfortable levels when the outdoor conditions are suitable. During summer months, the average outdoor temperatures are high therefore heat exchange between the indoor and the outdoor environment is limited. This allows the HVAC system to be turned off which causes the parasitic power consumers (such as fans) to contribute to load shedding. The reason that red line follows the green line very closely is that in the Level 3 case (depicted by the red line), only the HVAC system can contribute to DSR and if lighting is reduced, IEQ would fall below the allowed 99% mark. Hence in this simulation run, HVAC only and Level 3 only scenarios deliver very similar results. The blue line that depicts Level2+Level3 scenario manages a lower consumption because laptops do not cause a reduction in the IEQ levels.

5.8.2.2. Copenhagen 97.5% IEQ

When IEQ is reduced to 97.5%, two differences become apparent (Figure 55). First, the IEQ levels in the building for HVAC only scenario and Level 3 only scenario start to deliver different results especially during the summer months. Second, the difference between average power consumption of HVAC only scenario and others become significantly high as can be observed in the lower graph.

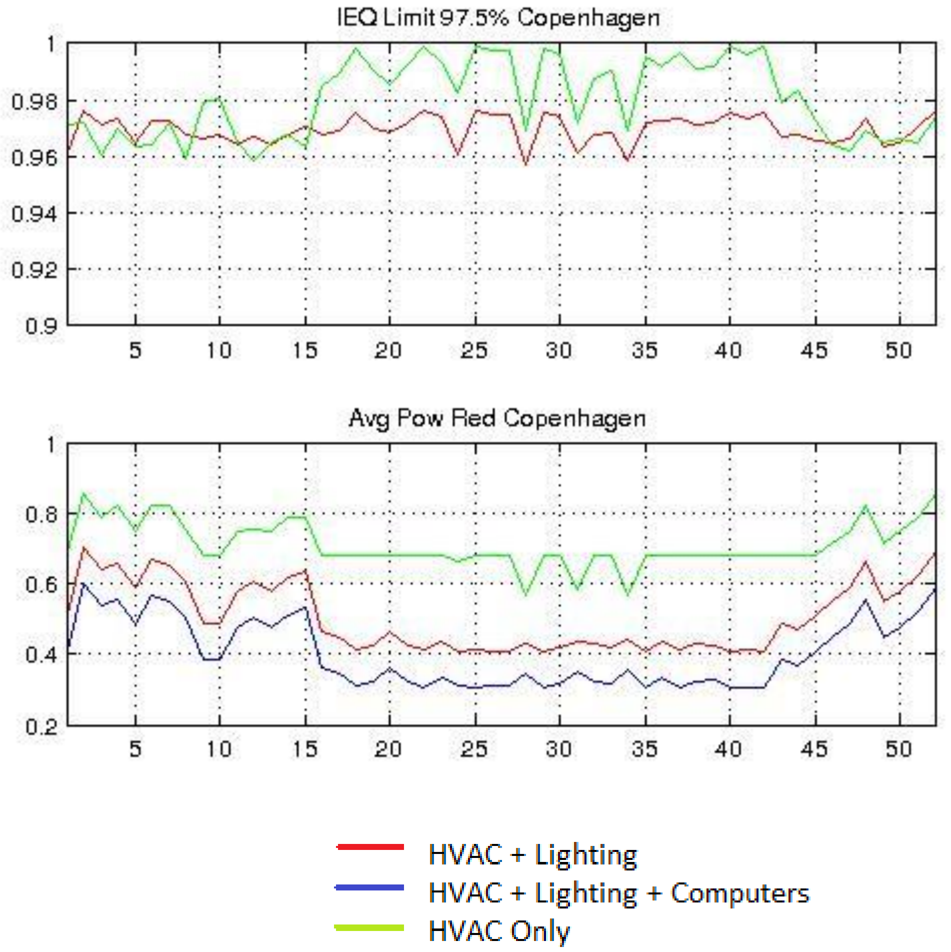


Figure 55:Copenhagen simulation result for 97.5% IEQ.

The reason that IEQ levels for the HVAC only scenario (green line) do not fall to the IEQ limit of 97.5 during summer months is that during these periods, the outdoor conditions are suitable for shutting down of the HVAC system. This does not cause much temperature change in the office. On the other hand, during the winter where outdoor temperatures are low, turning the HVAC system off causes the indoor temperatures to drop hence causing the IEQ levels fall to the IEQ limits. In contrast, the red line which depicts the Level 3 scenario follows the 97.5 band throughout the year. The reason for this is that during summer months, lighting levels help bring the IEQ down to the 97.5 rather than the HVAC system, contributing even more to the load shedding. In the power consumption graphs, two observations can be made. First, all of the scenarios contribute to DSR most during the summer months. The reason for this is that when outdoor temperatures are suitable, HVAC system can be turned off completely. The second observation is that, Level 3 only and Level2 + Level3 scenarios allow significantly lower consumptions throughout the year. This is a confirmation of the arguments presented in the previous chapter, that is, for the same productivity level, using both the lighting system and the HVAC system delivers better power reduction potential than using any of these parameters alone.

5.8.2.3. Copenhagen 95% IEQ

When IEQ levels are allowed to drop to 95%, the results are similar to the case of 97.5% (Figure 56). During the summer months, HVAC only scenario fails to drop the IEQ to the limits whereas Level 3 and Level2+Level3 scenario manages to drop to these levels to the IEQ limits of 95%.

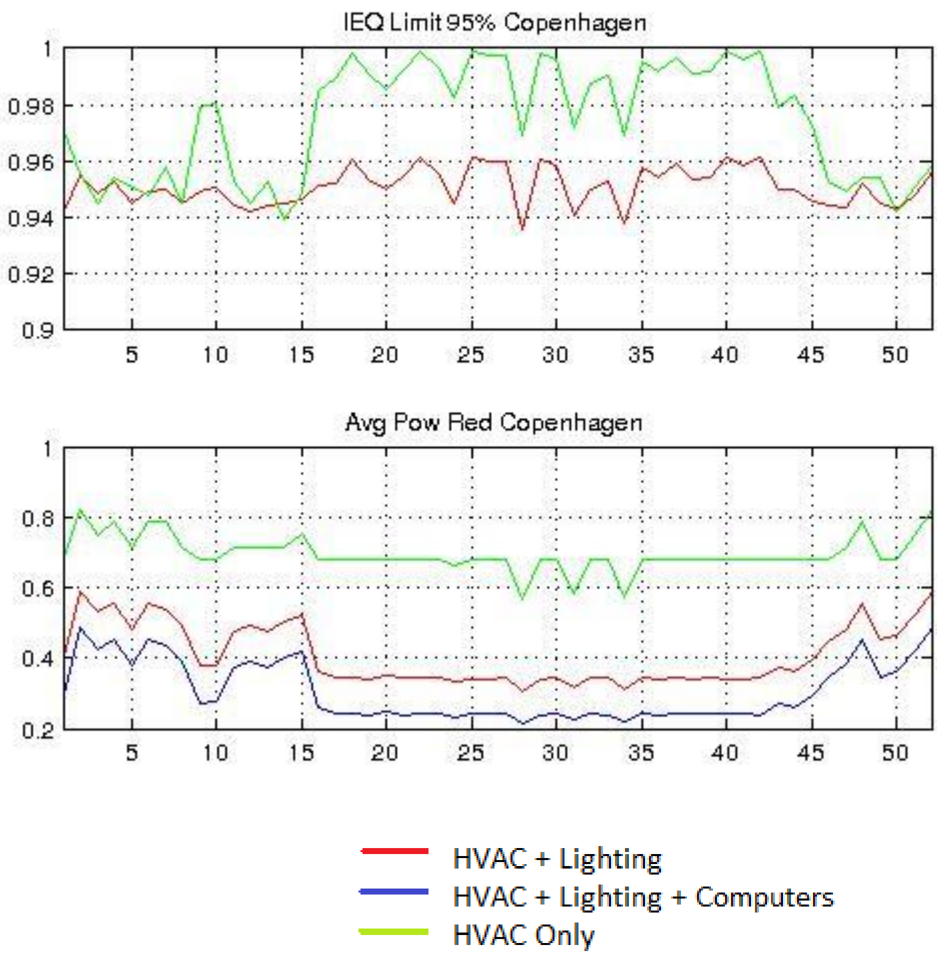


Figure 56: Copenhagen simulation result for 95% IEQ

The difference between power consumption levels are even greater compared to the 97.5% scenario. In this case, the power reduction potential during winter months only slightly improves. On the other hand, power reduction achieved in Level 2 and Level 2 + Level 3 scenarios are greater.

5.8.2.4. Summary of Results for Copenhagen

Table 14 summarizes the results found for Copenhagen.

Table 14: Summary of results for Copenhagen

IEQ Limit	95%		97.5%		100%	
	Average Power (%)	**Average IEQ (%)**	**Average Power (%)**	**Average IEQ (%)**	**Average Power (%)**	**Average IEQ (%)**
HVAC only	69	97.5	71	98.5	79.5	99.4
Level 1 Loads	40.6	95.1	50.3	97.2	77.6	99.3
Level 1 and Level 2 Loads	30.5	95.1	40.2	97.2	67.5	99.2

5.8.3. Simulation Run for Izmir

5.8.3.1. Izmir 99% IEQ

Similar to the Copenhagen case, when the simulation is run in Izmir for maximum IEQ there isn't a difference in average IEQ levels between the three levels of control (Figure 57). When it comes to average power consumption, Level 2 and HVAC only controls deliver nearly the same results. Average power reduction of Level2 + Level3 controls is lower than the other two because of their ineffectiveness on the IEQ levels.

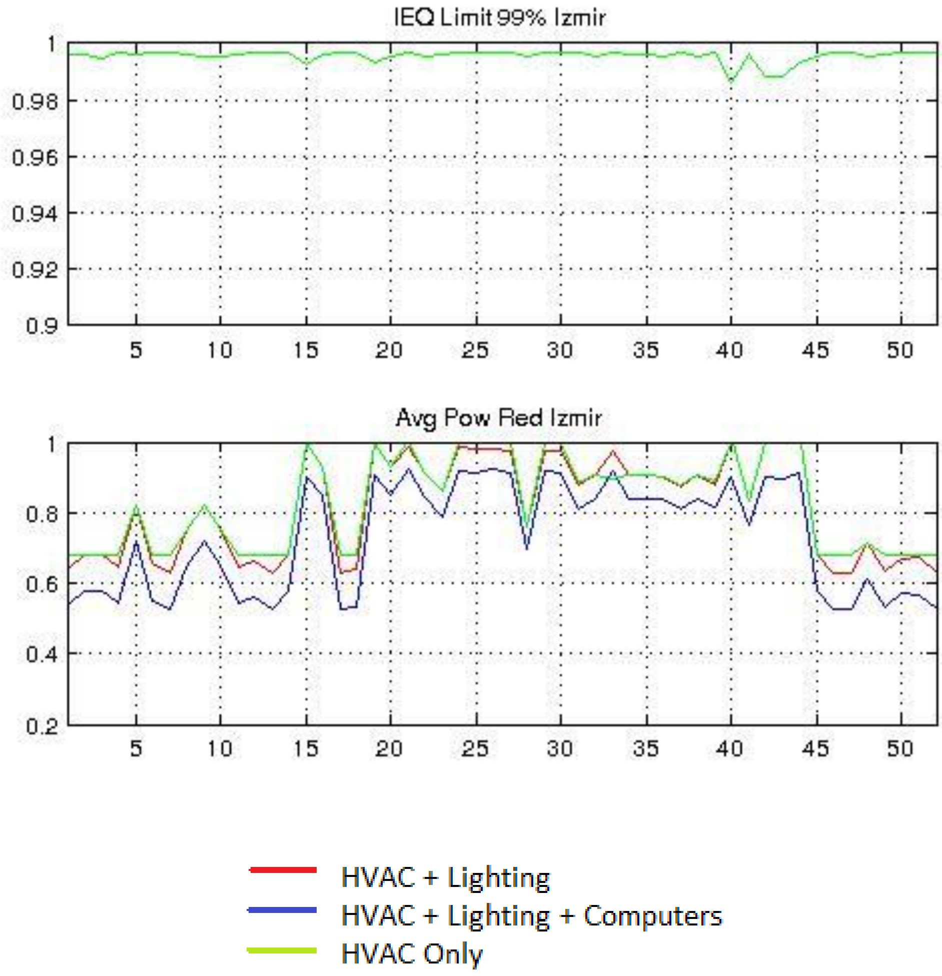


Figure 57: Izmir simulation result for 99% IEQ.

One of the noticeable differences between the Copenhagen case and Izmir case is that what happens in Copenhagen during summer happens in Izmir during the winter time. Average power consumption can be reduced without causing harm to the IEQ levels during the winter because outdoor weather conditions in Izmir are favourable at this time of the year.

5.8.3.2. 97.5% IEQ

If IEQ limit is set to 97.5%, HVAC only control cannot allow the IEQ to drop to this limit during winter time because of the favourable outdoor conditions (Figure 58). However during the hot weather in summer time, the absence of the HVAC system causes the temperatures to increase hence causing the IEQ to drop to the allowed limit.

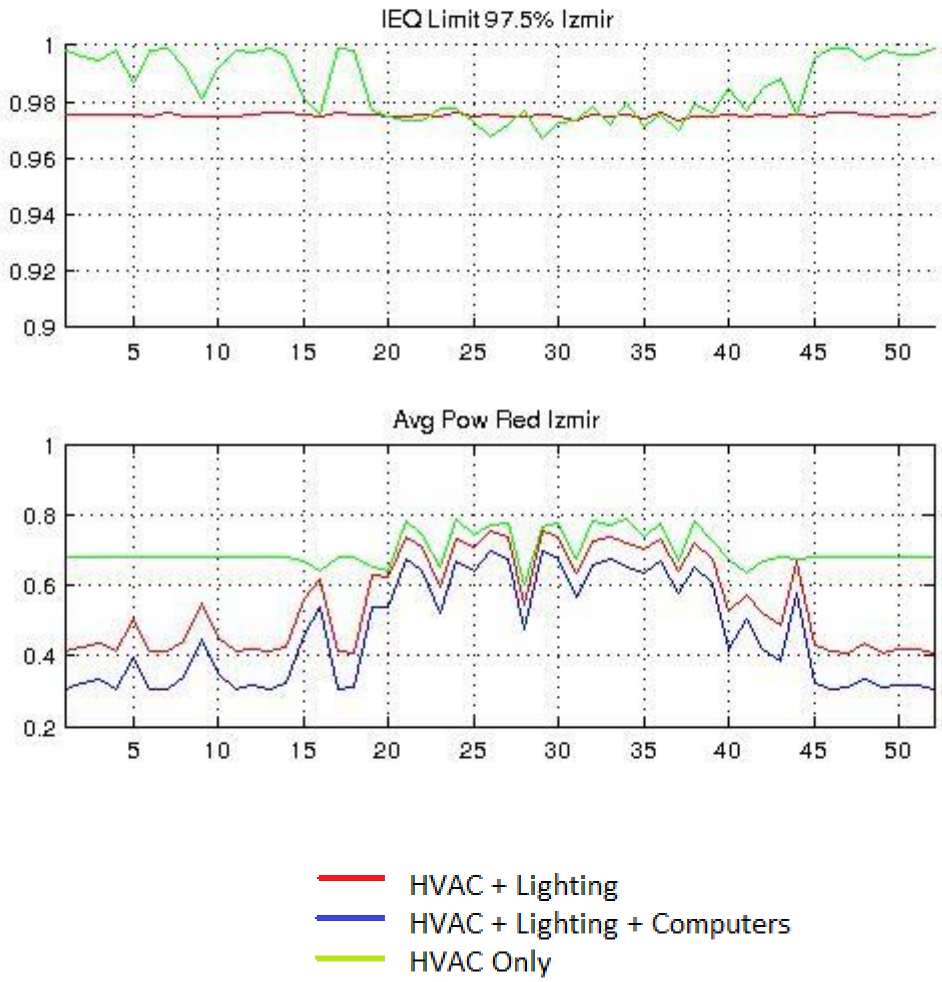


Figure 58: Izmir simulation result for 97.5% IEQ.

When it comes to the potential power reduction, HVAC only scenario fares worst compared to the other two. Especially in winter time, Level 2 + Level 3 and Level 3 control deliver significantly better results. During the summer, the difference between the three controls decrease to about 5% at worst.

The results delivered in this trial are caused by the same dynamics as in the Copenhagen case. During winter, the outdoor temperatures are favourable therefore absence of the air conditioning system does not cause much deviation in the indoor temperatures. For this reason, the allowed reduction of IEQ can be supplied by lighting which delivers significant reduction in power consumption. In summer time, the absence of air conditioning system causes the indoor temperatures to rise rapidly therefore the IEQ reaches its lower limit very quickly.

5.8.3.3. Izmir 95% IEQ

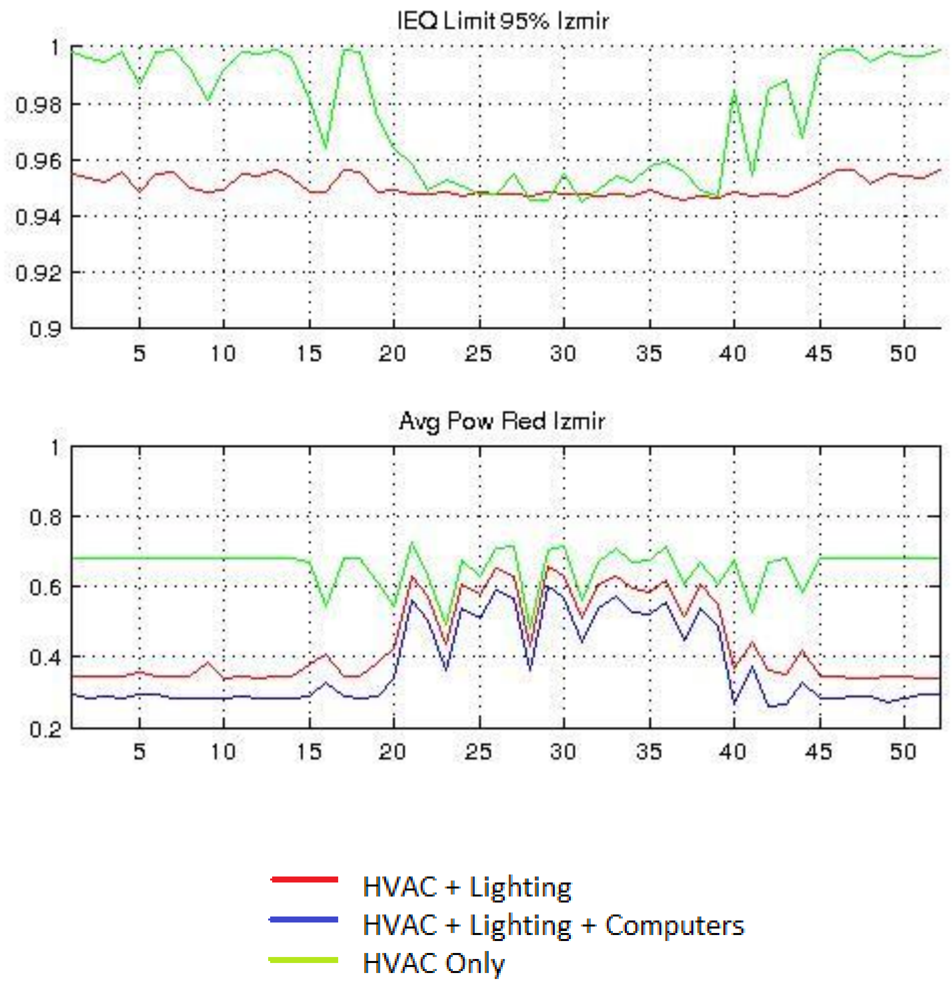


Figure 59: Izmir simulation result for 95% IEQ.

At 95% IEQ, the amount of load reduction between HVAC only and Level 2 scenarios increase even more during winter time (Figure 59). In summer, the difference among the three scenarios is similar though the overall achievable load reduction is better compared to the simulation run at 97.5% IEQ.

5.8.3.4. Summary of Results for Izmir

Table 15 summarizes the results found for Izmir.

Table 15: Summary of results for Izmir

IEQ Limit	95%		97.5%		99%	
	Average Power (%)	**Average IEQ (%)**	**Average Power (%)**	**Average IEQ (%)**	**Average Power (%)**	**Average IEQ (%)**
HVAC only	63.5	97.1	69.8	98.2	82.8	99.5
Level 1 Loads	45.9	95.6	55.3	97.5	81.6	99.5
Level 1 and Level 2 Loads	37.2	95.6	46.6	97.5	72.9	99.5

5.9. Discussion

Various outcomes are revealed from these simulation runs which are discussed in the following section.

5.9.1. Outdoor temperature vs. IEQ

Figure 60 shows outdoor temperature/average consumption pairs for the simulation run where IEQ is set as 95%. In order to span both the cold and hot climate, the results from Copenhagen and Izmir are combined. This graph shows that when the outdoor temperatures are around 15 degrees (plus or minus 5 degrees), average power consumption can be reduced to its lowest value (down to 25%). Also around these temperatures, the gap between HVAC only scenario (green) and the other two scenarios are maximum. This gap becomes smaller when the outdoor temperatures are above or below the 15 C mark. High temperatures yield better results for the HVAC only system where average consumption can be brought down to around 50%. Such an improvement is never achieved at low temperatures.

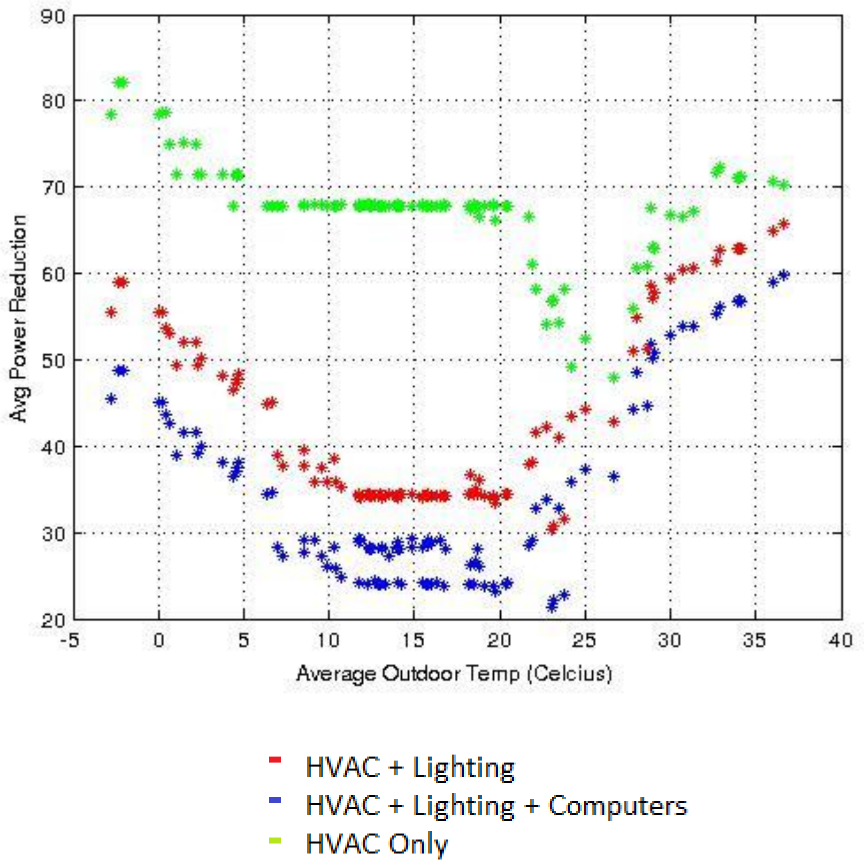


Figure 60: Average power reduction versus average outdoor temperatures for both simulation runs at 95% IEQ.

The main reason that the HVAC only scenario shows different behaviour for higher and lower temperatures is because of the compressor system. In a cold climate, the main heating element in the simulated building is a gas furnace which does not consume electrical energy. On the other hand, cooling in buildings can only be achieved with electrical energy because of the compressors. For this reason, the contribution of HVAC to DSR scenarios at warm climates is much higher than cold climates (if gas furnace is used for heating).

From control point of view, the outcome of this relationship shows that the average power reduction that can be achieved for a given IEQ limit is dependent on the external conditions and therefore variable. A fixed control set-point for achieving maximum IEQ/power reduction ratio does not exist. For this reason, an automatic DSR control system should be dynamic and be able to react to external conditions.

5.9.2. Three Levels of Control

HVAC system is the greatest energy consumer in buildings. For this reason, as revealed in the literature review, it is the main element that is thought of in load reduction strategies. However, as shown in the simulation runs, HVAC only scenario delivers the least reduction in all of the scenarios that have been tried for a given IEQ level. It can be argued that the IEQ equations that are used in this study might not be accurate. However, as the literature review has shown, humans can only be most productive between certain temperatures. This means that instead of pushing the limits with one environmental variable (being temperature in the HVAC case), using two environmental variables (in this case both temperature and lighting) is much more beneficial from load reduction point of view. This is also in line with common sense, on a hot summer day, instead of allowing the temperatures reach to 30° C, it is likely that workers will prefer 25C with less lighting on their desks. Hence using both lighting and HVAC, and carefully managing the balance between the two, is mandatory if productivity is to be kept maximum.

Inclusion of Level 2 loads (in this case laptops) deliver predictable results. Load reduction when laptops are included are always around 6-7% lower compared to Level 3 only scenario. This shows the importance of including battery operated devices into the DSR system in extreme outdoor temperatures. For example, in the worst case scenario in Izmir (when outdoor temperatures are highest), Level 3 control delivers 5% more load reduction compared to HVAC only control. Level2 + Level3 scenario at this instance increases the potential by another 5%. Therefore even though the contribution of battery operated devices in this modelled building is low, they can constitute a significant proportion of load reduction at most strained conditions.

5.9.3. Load Prioritisation

The results reveal that load prioritisation is likely to deliver pleasant work environments during a DSR period. Particularly in warm climates where air conditioning is used extensively, if Level 2 loads are prioritised, there will not be a reduction in IEQ levels if the requested reduction is below 5 to 7% (for the simulated building). Even if the requested load reduction is more than this, the resulting indoor environment will be better when compared to the scenarios where Level 2 loads are not utilised.

5.9.4. Assessment of the Assumptions

Various assumptions were made when the simulation environment for this study was set up. The possible outcomes of the simulation if these assumptions assessed in this section.

5.9.4.1. Effects of Ventilation System on IEQ

It was assumed that the affects of the HVAC system on the comfort of occupants would be limited to temperature and not fresh air because DSR periods are expected to be short time frames. If this assumption is invalid and the air freshness affects occupants' productivity during the DSR period, this would enhance the argument that using lighting and HVAC together is better than using HVAC alone. That is, HVAC only control would deliver worse load reduction potential compared to the load reduction potential of Level 3 control.

5.9.4.2. Determination of the IEQ Parameter

The previous chapter has shown that not much research has been carried out to determine the combined effects of both temperature and lighting on the productivity of occupants. Ncube's IEQ equation was selected as a productivity indicator hence it was implemented into the DSR control algorithm. Even if IEQ relationship found by Ncube is invalid, any other relationship would reveal that using both lighting and HVAC system is better than using any of these alone. This is because of the fact that both of these parameters allow certain flexibility and that when the limit is reached on one, using the other would allow further reduction in power consumption without affecting the indoor environment hence productivity.

5.9.4.3. Effects of Daylight on Lighting Levels

It was assumed that lighting in the simulated office environment would only come from artificial lighting and daylight would not be simulated. If day-lighting was simulated, Level3 load reduction strategy would have achieved less reduction. However, if it is assumed that modern buildings cannot be operated without artificial lighting, inclusion of lighting into DSR schemes will always deliver better results than using HVAC alone.

5.9.4.4. Usage of Electric Heating

In the Copenhagen case, it was assumed that gas heating is used. If electric heating was used, the difference between different levels of load reduction would be smaller. However as shown in the Izmir simulation, even though electricity is used as the main thermal element, combination of lighting and heating always delivers better results compared to using any of these parameters alone.

5.10. Conclusion

In this chapter, a DSR control algorithm is proposed. The simulation model that has been developed in the previous chapters has been used to show the effectiveness of this algorithm compared to common practices. The main outcome of the simulations described in this chapter is that if productivity is the main limitation in office buildings, then load reduction needs to be carefully managed to ensure that productivity is kept maximum. This means that loads need to be prioritised so that the most disruptive loads to productivity are shed last. Also, if lighting and HVAC system is to be used for load shedding, the amount of load reduction that needs to be carried out from each of these systems should be based on IEQ.

When IEQ is involved, the optimum solution for load reduction depends on the external environmental conditions. For warm climates where the HVAC system is more dominant, the contribution of the HVAC system is greater than the contribution of the lighting system. The opposite is true for more favourable outdoor conditions. This shows that the DSR control system needs to be dynamic therefore fixed distribution of load reduction is unlikely to deliver optimum results.

The description of an automatic DSR controller proposed in this chapter as well as the building that has been simulated was abstract therefore such a controller is far from being a real device. In the following chapter, the specifics of such a controller will be discussed. This will involve the technical challenges arising from the organisation of various loads in buildings and the limitations of state of the art communication technologies if an automatic DSR system is to be realised.

6. Controlling Lighting for DSR

6.1. Introduction

In the previous chapter, outline of a central DSR control system has been drawn. The simulation results have shown that in order to achieve highest productivity during a DSR period, both HVAC and lighting needs to be controlled simultaneously. It was assumed in the simulations that both lighting and HVAC consist of single controllable entities. In reality, it is known that these systems have different characteristics when it comes to control. Unlike HVAC, lighting is not considered as a central entity in an office environment. Offices are divided into lighting zones that are designed to be controlled locally and independently. The various tasks that are carried out by the users as well as their preferences of lighting are an obstacle that needs to be overcome to make productivity based DSR control a reality.

In this chapter, the problem of controlling lighting systems during DSR periods is tackled. The differences between the HVAC system and the lighting system are presented and a solution to allow simple distributed control of the lighting system is proposed.

6.2. The Difficulty of Controlling Lighting for DSR

Three categories of loads that could be utilised for DSR were investigated in the previous chapter. These were battery operated devices, HVAC system and lighting system. It had been found that to achieve significant load reduction, HVAC and lighting needs to be included in the load shedding process. For this reason, it is very likely that these loads (which have immediate effect on productivity) will need to be involved in every DSR scenario. However, controlling these loads for DSR purposes is not a trivial task. Because of their technical differences, they require different solutions to their control problems.

HVAC systems consist of central plants (such as a packaged air conditioner) and the auxiliary equipment (such as fans and pumps). Even though the individual components of these systems are physically distributed throughout the building, the thermodynamic requirements of the building and the operation of various components of HVAC systems such as the compressor or the heating element make it necessary that the control of the HVAC system is left to its specific HVAC controller. This means that in order to reduce energy consumption, global adjustments to the temperatures inside the building is the only feasible option. When it comes to adapting to DSR, the HVAC system has its own challenges such as predicting the outcome of a DSR command (discussed in previous chapter as open loop and closed loop control). However, control of the HVAC system for DSR is not as sophisticated as lighting because of its central nature.

Lighting systems have significant differences compared to HVAC that prevent them from being controlled as a central entity. Light fittings and their controllers are physically distributed in a building such that operation of lighting zones (or groups) might be completely independent from one another. Each of these groups might have different requirements for lighting hence might not be able to respond to global DSR commands as expected.

Another property which makes it more difficult to control lighting is the change in consumption during DSR periods. HVAC systems operate on fixed temperature set-points. The temperature in an air conditioning zone is unlikely to swing to its extremes just because of users. However, lighting requirements in a building change depending on various factors. For example, lighting might only be required in a corridor if someone is passing by. Lighting in a meeting room might not be allowed to contribute to DSR until the meeting is finished. Control of blinds by the users might complicate the conditions because of daylight coming in.

Change in lighting conditions that are caused by occupant behaviour is widely investigated by many researchers. In their study, Reinhart et al. [96] review the reasons (identified by other researchers) for intervention of lighting controls in office buildings by occupants. It can be understood from their research that even though the majority of change in lighting levels occur during the times when occupants enter or leave the office during shift hours, there are other times when lighting needs to be altered for efficiency, comfort or privacy.

Because of these reasons, energy consumption of lighting is more dynamic and prone to human intervention than the HVAC system. This dynamic nature of lighting presents a challenge if load reduction is to be carried out. Extra power that is required by an increase in consumption or excess power available from decrease in consumption needs to be handled by the DSR control system for optimum performance and productivity.

6.3. Lighting and Demand Response

The study of Rubinstein et al. [97] is one of the most comprehensive reviews on the involvement of lighting in DSR applications. In the beginning of their report they acknowledge that lighting is nearly as important as HVAC when it comes to shedding loads for DSR. They also identify that the popularity of controlling lighting for DSR is much lower compared to HVAC which is partly attributed to existing control infrastructure of buildings and also the fact that HVAC is more suitable to control centrally compared to lighting:

"Lighting in buildings should be considered as a potentially sheddable load during times of curtailment. HVAC and lighting system are two largest contributors to the commercial electrical peak. Many demand reduction programs focus on HVAC since HVAC systems are connected to energy management systems that are relatively easy to connect to a demand response communications infrastructure."

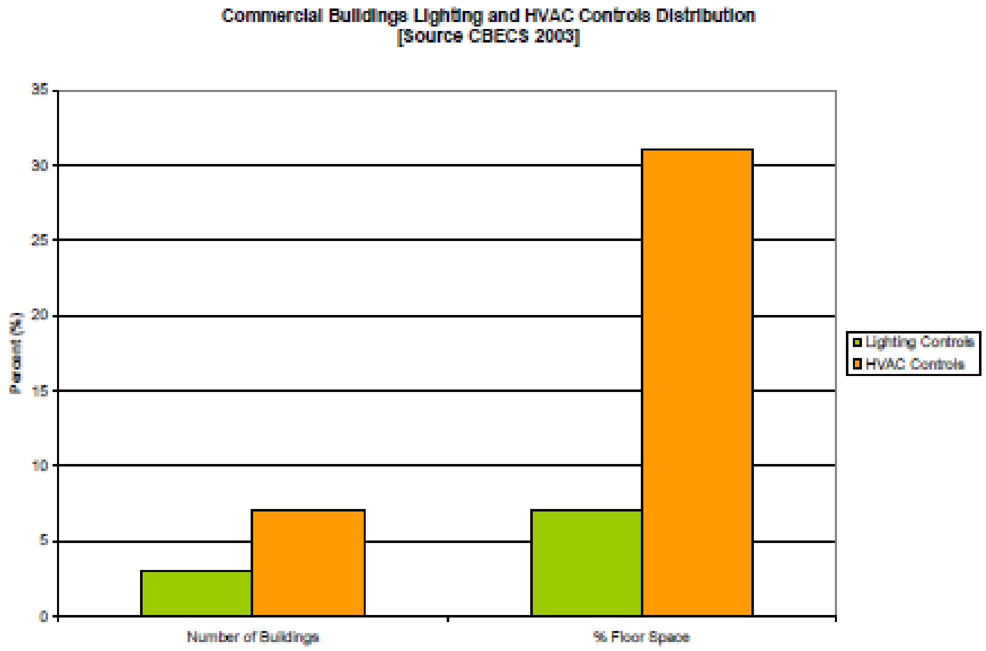


Figure 61: Commercial buildings lighting and HVAC controls distribution [97]

"Lighting controls is not common practice in the US. 3% of commercial buildings have lighting control making 7% of commercial floor space. By contrast, 7% of commercial buildings making up 31% of floor space have energy management and control systems.

(Figure 61)”

Another reason that they cite for the lack of popularity of lighting controls in DSR applications is the concerns on productivity:

“Lighting is usually associated with visual health and safety. Any change in lighting as the potential to directly affect the safety and well being of the occupants not to mention their productivity. Therefore, commercial building operators are apprehensive about using lighting for demand response. However, requirements for lighting depend on the task. Today's commercial buildings house many different tasks and technologies that enable the completion of these tasks. DR strategies for commercial buildings need to consider all the issues related to the tasks of the occupants and the function of the building. In addition to the function, DR lighting strategies are also limited by the lighting infrastructure in the buildings. Zone size, zone distribution and the balance of local and central controls directly affect the function and the cost of a lighting system and provide a frame for DR strategy development.”

Hence the document acknowledges that incorporating lighting into DSR schemes is more challenging than HVAC. In the following section, the problems related to various functions of lighting are expanded for further investigation.

6.4. Defining the Control Problem for Lighting

One of the major roles of a DSR controller during a DSR event would be to manage user intervention. In the case of lighting, if there is an increase in power consumption at a certain area, the lighting levels in other areas will need to be reduced. Conversely, if there is a decrease at a certain area, the lighting level in other areas will have to be increased to reduce the negative effects of DSR. Therefore the DSR controller needs to calculate the quantity of the increase or decrease that it needs to handle after a user intervention is carried out.

Once the quantity is determined, the task is to distribute the power to load controllers. This task is not trivial as well. User preferences might restrict the change in power consumption and it might not be possible to impose a new lighting level to all of the controllers. Therefore the DSR controller will need to pick the lighting zones that can comply with the new lighting level. Another aspect of power distribution is to ensure that the productivity in the environment is maximised. This means that, for example in the case where there is excess power available, it is delivered to the loads that are able to increase their productivity the most (or prioritised by the users).

6.4.1. Handling Human Intervention

If there is surplus power available because of user intervention to a lighting zone, it needs to be distributed to other zones to increase productivity. If more power is required because of a user intervention, it needs to be acquired from other controllers by reducing their consumption. Determining whether other lighting areas should increase or decrease is only part of the problem. The next decision that the DSR controller needs to make is to distribute the load to other controllers. This might not be a straightforward process because of the preferences that govern the amount of change in lighting zones.

6.4.2. Handling DSR Preferences

DSR causes the light levels to change. Office users might wish to restrict this change because of its negative effects. In his paper [98], Akashi reviews the work that has been carried out to determine the amount of acceptable change in lighting levels. He concludes that the amount of acceptable change depends on various factors such as advance information and the type of task being carried out. This and various other research in demand response in lighting shows that users might have varying preferences when it comes to controlling light levels for DSR.

To satisfy the preferences of the users, the following limitations can be set in the DSR system:

Extent of reduction: This parameter, which would determine the minimum lighting that is allowed in the office zone might depend on the usage of the lighting zone. For example, if the office zone is a reception area, minimum lighting that is allowed during a DSR event would probably be higher than other office areas.

Frequency of change: This parameter could be defined as the number of times an office zone is allowed to change its lighting level in a given time period. This requirement might arise from the necessity that frequent changes in lighting levels cause distraction and certain types of office zones might have limitations that restrict frequent changes in lighting conditions.

Duration of change: This could be the amount of time a zone is allowed to be in a DSR state. Similar to the requirements above, certain areas in the office might not be allowed to be lit below a given lux level for sustained periods of time.

Defining the exact parameters that would be required to control lighting in an office zone in the most convenient way is beyond the scope of this study. However, the few parameters mentioned above reveal another challenge that needs to be dealt by a central DSR controller. That is, when a lighting command is to be issued, the individual circumstances of the particular office zone needs to be taken into consideration.

A simple example in an environment where 1 Lux equals 1 Watts can be given as follows. If it's assumed that there are three office zones, Zone A, Zone B and Zone C that are controlled by the DSR controller and that the minimum lighting that is allowed for these is 400 lux, 350 lux and 200 lux respectively. If the DSR controller sets the global lux level to 400, all of the Zones would comply because it is above (or equal to) their minimum threshold value. If the DSR controller needs to set the lux level to 350, Zone A will not be able to comply and would only set itself to 400 lux. Even though the other controllers can reduce their lighting level to 350 lux, the overall power consumption (1100 Watts compared to 1050 calculated by the DSR controller) would exceed the limit that is initially set. For this reason, the DSR controller would need to distribute the available power to other zones as (1050-400)/2 = 325 Watts. However, this value would be below the limit of Zone B which is set as 350. Therefore, the DSR controller will need to set the lux level of Zone C as 1050-(400+350) = 300 lux. As a result, the distribution would be as follows: Zone A 400 lux, Zone B 350 lux and Zone C 300 Lux.

This example shows that zone preferences need to be taken into consideration when distributing DSR tasks. If these preferences are not taken into account, the resulting lighting conditions in the offices might cause increased inconvenience and reduced level of productivity.

6.4.3. Distributing for Maximum Productivity

Determining the quantity of increase or decrease depends on productivity as well. If there is no restriction caused by user preferences and all of the lighting zones are able to accept the amount of change, the DSR controller needs to distribute the power based on resulting total productivity. This can be shown with an example.

If it is supposed that a DSR controller needs to increase the average lux level from 350 lux to 375 lux and the initial state of the DSR controllers are the same as the result of the previous example (Zone A 400 Lux, Zone B 350 Lux and Zone C 300 Lux), then the increase in lux levels need to prioritise the zones that suffer the most from the DSR. In this case, Zone A will not be able to comply because its limit is 400 lux. Zone B and Zone C will need to share (1125-400)/2 = 363 lux. This means that both Zone B and Zone C will increase by a different amount (13 lux for Zone B and 63 lux for Zone C).

The fact that Zone C increases more than Zone B shows that relative increase during a DSR scenario is not possible. The amount of power that needs to be acquired or distributed should be based on the current conditions of the zones so that maximum productivity can be achieved.

6.5. Specification for DSR Lighting Control Algorithm

Based on the information above, in order to maintain the whole office environment at a given power level, the DSR controller that manages lighting should be able to achieve the following goals:

- Manage user interventions such that the power consumption is kept constant.
- When issuing commands for DSR, ensure that user preferences are taken into account.
- When issuing commands for DSR, ensure that the resulting office environment has maximum productivity that can be achieved with given amount of power.

The control system to achieve these objectives can be implemented in variety of ways but if it is to be modelled as a single entity, it will need to carry out the following routine to satisfy the requirements mentioned above (Figure 62):

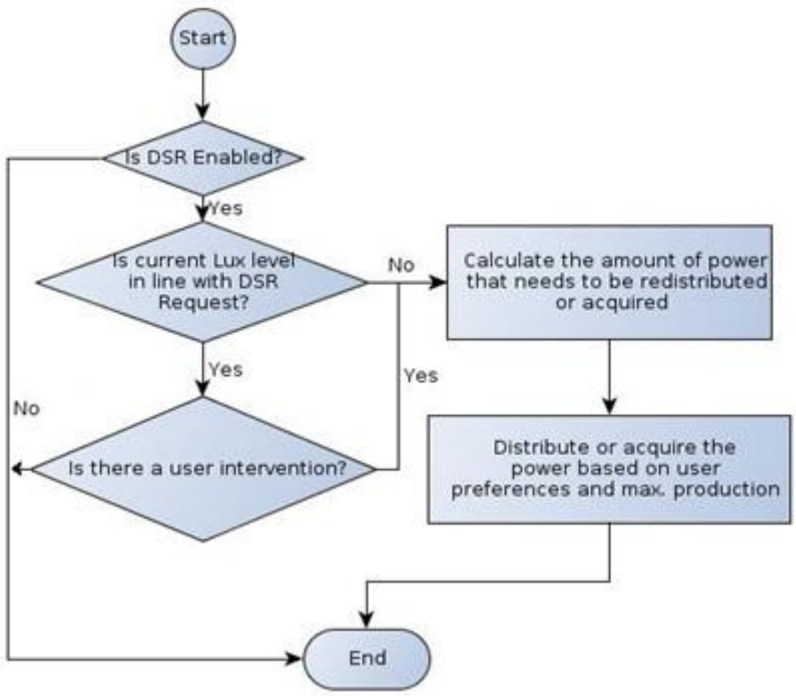


Figure 62: General control algorithm for lighting

The first task of the control system is to check if DSR is enabled. If it is enabled, it checks the amount of lux level and power consumption that is expected from the lighting system. It then checks if the lighting zones can comply to the specified lux level by taking individual circumstances of the zones into account. When DSR is enabled, another task of the DSR controller is to check if there is a user intervention in any of the lighting zones. If there is an intervention, the controller distributes the available power to ensure that the intervention is compensated. The loop continues until the DSR state finishes.

In the beginning of this chapter, it was highlighted that lighting controllers in offices are physically distributed therefore controlling these for DSR purposes is a challenge compared to other entities. The straight forward method in solving this problem is to implement a central controller. In this implementation, the DSR controller handles all the data and control commands. Any change in external lighting, user intervention and user preference is reported to the DSR controller. The controller has a complete picture of the lighting state of all of the office zones and can run the DSR routine within itself to micro manage the individual lighting controllers.

The properties of office environment show that the task of such a controller would be difficult. It would have to handle every user intervention by taking into account the existing state and user preferences of every office zone that is under its control. On the other hand, it might be possible to implement a distributed control system where lighting controllers communicate with one another to achieve the objectives of DSR without the requirement of a central lighting controller. Such a control system might be more suitable for an office environment where the numbers of zones are high and there is a greater chance of user intervention. This system can also offer greater reliability and would increase the chances of including lighting into DSR schemes.

6.6. Distributed Control and Multi Agent Systems

Distributed control is used in many areas where the physical distribution of various entities become a problem. The following literature review has been carried out to investigate the existing research in this field.

6.6.1. Introduction to Agent Systems

According to Michael Wooldridge [99], an agent is a computer system that is situated in some environment and that is capable of autonomous action in this environment in order to meet its delegated objectives. He defines autonomy as the ability and requirement to decide how to act in order to accomplish the goals. Wooldrige argues that every control system can be viewed as an agent. For example, a thermostat that is detecting room temperature and controlling a heater is an agent because it is embedded within the environment and is capable of manipulating the environment. Its actions will generally have an effect on the environment (by turning the heater on or off) but this manipulation is not guaranteed (e.g. if the window in the room is open, the temperature might not reach the desired level).

If approached from this perspective, control systems with numerous different control entities can be viewed as Multi Agent Systems or MAS. In MAS, more than one agent acts in an environment and their overall task is to solve problems that are designated by their designers. Mac Arthur et al. give a good introduction to MAS in their paper [100]. They indicate that even though MAS and other technologies like grid computing, web services and artificial intelligence might be used to harness distributed hardware and software resources to complete a specific task or objective, they differ in various aspects. Grid computing focuses on harnessing the computational power of hardware resources to solve complex problems. On the other hand, web services are designed to offer interoperability between software systems. Compared to Web Services, MAS support richer set of interactions (such as negotiation) that enable them to be used in wider range of applications. The main difference of MAS compared to the others though is highlighted as autonomy and social ability.

One of the areas that MAS is deemed suitable is power systems. According to MacArthur et al, the flexibility and extensibility of agent systems make them suitable to solve a number of problems in this field. For example, they can be used to model the dynamics of a power system by representing a real world situation of interacting power entities and provide ways to test various complex behaviours that might emerge. They can also be used in monitoring various sensors and interpreting data. Another use of MAS in power systems is distributed control which can include power system restoration, micro-grid control, control of electrical systems on ships etc.

6.6.2. Application of Agent Systems

Numerous publications are available in the field of power systems where researchers utilise MAS to solve problems. Lagorse et al's paper stands out from many of these because of its clear description of the problem and the simple yet intuitive solution that utilises MAS. In their paper [101], they present a bottom up approach to manage power in a hybrid power system. They first introduce the elements of the system which consist of PV panel, battery, super condensator, electricity grid and a DC bus. The system is set up to deliver DC power that is either generated locally or provided from the grid to an active load. The purpose of the system is to ensure that the load is supplied in the most cost effective way (ensuring that local generation facilities are utilised). The authors of the paper dismiss the idea of using a central controller because of its complexity and lack of flexibility. Instead, they propose an agent based approach where each entity that is critical to the system is represented as an agent in a communication environment.

In their implementation, they use a virtual token that can be kept by the agents such that whichever agent has the token is responsible of supplying the load with the necessary power. The token can be transferred from one agent to another by mutual agreement that is communicated through a communication network. If an agent has the token, other agents (except the grid agent) are allowed to request the token. The token is handed over to other agents only if the current state of the agent with the token makes it necessary. For example, if the battery cannot supply the load because of its charge status, it accepts to give the token to another agent. If an agent cannot find another agent that is willing to accept the token, it gives the token to the grid agent. The grid agent has a special status such that if it is given the token, it must accept it. When it does not have the token, it is not allowed to ask for it. It must also give the token to other agents if they ask for it.

By implementing a token system, it is ensured that only one source supplies the power to the load. By prioritising the agents other than the grid, it is ensured that available local generation facilities are utilised and no unnecessary power is requested from the grid. The system is flexible and expandable such that if a distributed generation system is added or removed, it can operate as normal and the control system can easily be modified.

In another paper, Jun et al present a multi agent solution to energy management in hybrid renewable energy generation system [102]. The system is proposed to solve optimisation problem of a power system that involves renewable power sources such as

PV and wind as well as storage facilities. The specific objectives are; optimal use of each component of the system, finding a way to compromise the system power performance and cost, reorganising the renewable sources in response to environmental changes. From this perspective, the objective of the system is similar to the one presented in Lagorse et al. However, their approach is different in the implementation such that the agents that are implemented communicate through an entity called a facilitator. A facilitator exists for each category of entity. PV systems report to PV facilitator, wind turbines report to wind facilitator etc. Agent communication is carried out among the facilitators. At any given time, a main facilitator is selected among the facilitators. The main facilitator is responsible of communicating with the facilitators and optimising the system. Once a decision is made, the information is conveyed to individual agents. The agents then report back whether the decisions are applicable. The process continues until a solution is found. The selection of main facilitator is determined by a token. If a facilitator holds the token, it acts as the main facilitator. Depending on the performance or weather conditions, the token is passed to other facilitators.

These examples show that even for similar applications, the implementation of MAS technology can differ significantly. Both Lagorse and Jun et al's problems involve utilising renewable power sources in a small power network. Also, they both implement MAS to tackle the issue of dealing with distributed entities that need to operate in harmony. However, their approach to the solution has significant differences. In Lagorse et al., there is no facilitator mechanism. Every entity in the system is represented in the agent environment. The agents only act on behalf of themselves and cannot issue commands to other agents. In Jun et al, there is an entity called the facilitator. The facilitator represents the agents that report to it. It might also act as a main facilitator.

When it is the main facilitator, it determines the operating set points of other facilitators. Hence it is possible to say that Jun et al have implemented a hierarchical agent system whereas Lagorse et al have implemented a completely distributed system.

6.6.3. Agent Systems in Building Management

In their paper, Mo et al. [103] present an agent based framework that can be used to resolve conflicts between occupants and building operators. Such conflicts occur because rules that are set by building operators for reducing costs cause uncomfortable environmental conditions in buildings. In those conditions, users intervene and override the central commands which cause increased energy consumption. The agent structures that they built operate as a central control system if there is no conflict involved. If there is a conflict, it is resolved by a negotiator agent who decides on a new set point by balancing the user request and cost saving principle. Mo et al.'s paper is one of the early papers in the field of resolving conflicts between users and automatic building management systems by utilising agent technology. They correctly identify the problems and propose agent technology as a viable tool to solve a difficult problem. However the fact that conflict resolving does not occur by negotiation between the agents but rather decided by a negotiator agent means that the agent architecture still relies on a central entity as well as basic set of rules that need to be defined by the building operator. Hence in their implementation, it would be difficult to argue that the benefits of using MAS overweight the benefits of using a central control system.

Another agent based building control system is presented by Davidsson et al. [104]. In their implementation, they adapt the MAS technology to save energy and increase worker satisfaction in an office building. The building zone that they use to test their ideas is equipped with sensors and actuators that communicate through a building automation system (LonWorks). In their experiments, they test to see if an enhanced interaction between agents that represent the workers and agents that represent the building controls could reduce overall energy consumption while maintaining the indoor environment in an acceptable condition. The results show that significant energy savings could be achieved while maintaining optimum comfort in the building. However, the advantages of using MAS as opposed to a classical control system are not justified in their study as well.

One of the papers that describe a control system that utilizes MAS to reduce consumption during an emergency event (e.g. disconnection from the grid) is [105]. In their paper, they propose to control temperature, lighting and air quality of a building by utilising agent technology and principles of fuzzy control. The agents in their paper are categorised into two; load agent and local agent. A central agent controller that determines the optimum operating conditions for these environmental parameters instructs local agent controllers. Local agent controllers then control specific load agents. During normal operation, the system maximises energy efficiency while maintaining user comfort. However, the system operates on emergency mode if it is supplied by a micro source controller. In this case, the loads are shed to ensure the flow of power and also to ensure that comfort is kept maximum. Wang et al.'s implementation captures the principles that are laid out in this research such that load reduction is carried out by taking occupant comfort into account. The operation of the building in an emergency event resembles the DSR scenario mentioned in the previous chapters. However, it is not made clear in their paper why the MAS technology is selected as the preferred method rather than selecting a central control system. No agent communication and no logic is defined for the agents that are expected to interact with each other.

One of the recent papers that is related to MAS in managing building energy consumption is authored by Wang et al [106]. In their paper, they present a multi agent based control system capable of resolving conflicts that might arise because of local energy efficiency policies. In their implementation, three types of agents exist; central agent, local agent and personal agent. Personal agents are agents that capture the preferences of building occupants. The information that personal agents collect throughout the day are passed on to local agents. Local agents are designed to control specific types of loads such as HVAC or lighting by assessing the feedback from the sensors in the building. A central controller interacts with the local agents to ensure that the overall control goals are achieved. When there are conflicts among other agents, the central agent or a local agent can act as a mediator to solve the conflicts. There are two case studies presented in the paper. The first case study demonstrates how a personal agent can collect specific information about users and be able to predict the comfort preferences of the users under certain environmental conditions. The information collected by the personal agents can be utilised by the local agents (e.g. HVAC agent for temperature) to achieve optimum energy consumption at any given time. In the second case study, a central agent interacts with the local power management agent which monitors the conditions of the utility grid. If there is a shortage of supply, the central agent communicates with the local agents so that the power consumption of the building is reduced while occupant comfort is kept at maximum.

Even though many of the concepts presented in Wang et al.'s paper are related to the work presented in this study, their reasons for adapting MAS in their implementation is not clear. There is information exchange among agents but the type of cooperation that is expected in a MAS system does not seem to exist. The question of; 'why is using MAS beneficial compared to known techniques of building management?' is left unanswered.

6.7. Defining an Agent System for DSR

An office building contains numerous sensors and actuators that operate based on certain rules. The actions of these systems are not deterministic; the building environment is not always expected to react in a predictable way. Moreover, users interact with the building management system to adjust the environmental parameters based on their preferences. From this perspective, an office building can be considered a multi agent environment.

6.7.1. Defining the Agents for DSR Control

In light of the literature review, how should the agents for DSR control be specified?

Firstly, the specification of the DSR controller defined in the previous chapter dictates that a central control entity that can carry out DSR calculations and issue operating set-points is necessary. Therefore a central control agent is fundamental to the operation of the overall system.

Next, the interaction between the central controller and the loads need to be managed. The central controller is only capable of determining the general control parameters for the building such as the temperature, lux level and the allowed power consumption. For this reason, there needs to be other agents that can translate this information to commands for the specific load types that are involved. An agent that can maintain the battery operated devices (provided that they have similar properties) is required. Another agent is required to operate the HVAC system based on the temperature and power consumption set-points. Finally, a lighting agent that can maintain the lighting system at given lux levels should be implemented. The agents that work as the translator are called 'System Agents' in this study.

Finally there are the physical loads or load controllers where power consumption occurs. Unlike the other agents described above, these might be physically distributed in the building. The number and type of actual loads might require various implementations for these agents. The proposed architecture is depicted in Figure 63.

It is hard to justify an agent implementation for the central DSR controller and system agents since these are an integral part of the system and are not expected to be physically distributed in the building. When it comes to individual loads and load controllers, it is argued in the beginning of this chapter that the lighting system consumes significant power, is physically distributed and is more prone to user intervention compared to other loads and that a lighting system agent cannot cope with the dynamic lighting environment in an office building. Hence, a novel agent implementation would be most beneficial to lighting system in an office building than any other type of load.

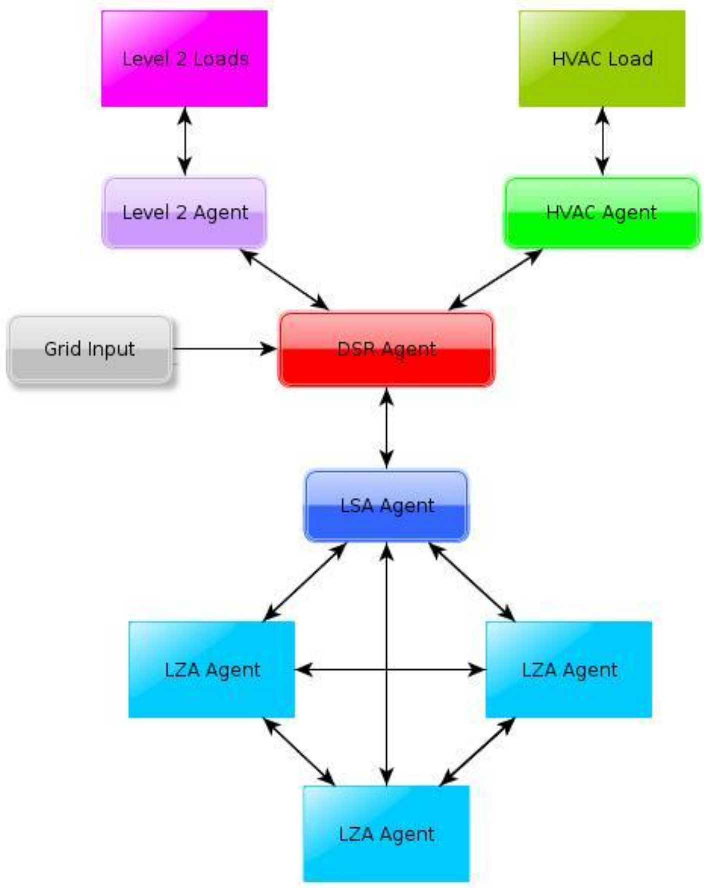


Figure 63: General Agent Communication Structure for DSR in Office Buildings

6.7.2. List of Equipment that is Expected to Operate in the Building

For any implementation of load control to be realistic, the office building needs to incorporate certain electronic equipment. In this section, this essential equipment is listed.

- **Central DSR Controller**

Central DSR controller is the electronic device that determines the benchmarks for best temperature and lux level point. It is capable of calculating the energy consumption of the building for the given productivity level. It is possibly a central computer system that interacts with the open ADR system. Central DSR controller is not a device that directly issues commands to the individual load controllers but broadcasts target temperature and lighting levels.

- **Light Sensor**

Light sensors are devices that measure the amount of light in a given office zone. These can be incorporated inside the lighting zone controllers or can be remotely positioned to have better measurements of the zones.

- **Lighting Zone Controller**

These control the amount of light in a given office zone. They gather information from the light sensor and instruct light fittings to reduce and increase the amount of artificial light to maintain the indoor lighting in a static lux level.

- **Temperature Sensor**

Temperature sensors are devices that measure the temperature in a given office zone.

- **Global Temperature Controller**

These collect temperature information from the office zones and instruct the HVAC system to change the temperature of the office environment globally.

In the next section, the definition, communication and implementation of an agent system intended for enabling DSR in lighting systems is described.

6.7.3. Specification of the Lighting Zone Agents

Each lighting zone in a building is considered to be an agent in this study. The zones are represented by their lighting zone controllers therefore the agent language and protocols are expected to be carried out by the zone controllers. The zone agents are only active during the DSR period therefore DSR specific communication or negotiation does not occur in non-DSR conditions.

6.7.3.1. Goals of the Agents

During the DSR period, the agents have two goals to achieve, primary and secondary:

- Primary goal: Adjust lighting based on user demands and preferences.
- Secondary goal: Ensure that DSR requirements are met.

The primary goal is simple to follow because it is assumed that users demand various lighting conditions in order to increase their productivity. Therefore if a user demand cannot be met, the productivity of the zone is assumed to be worse than that can be achieved by the DSR system.

The secondary goal is more difficult to follow. The DSR requirements of the building depend on power consumption. Power is a resource that needs to be shared by each lighting zone. Therefore the agents need to communicate and cooperate to achieve their secondary goal. For example, during a DSR period, if there is a user intervention in a lighting zone such as increase in light levels, the lighting agent will need to increase the lighting to meet its primary goal. However, because energy consumption will increase, the agent will not be able to meet its secondary goal. In order to do so, it will need other agents to cooperate and lower their consumption provided that the primary goals of those agents are met. If a lighting agent receives a request from another agent to lower consumption, as long as its primary goal is met, it needs to cooperate otherwise it will not be able to achieve the secondary goal. For this reason, the purpose of agent communication is to meet the secondary objectives of the agents.

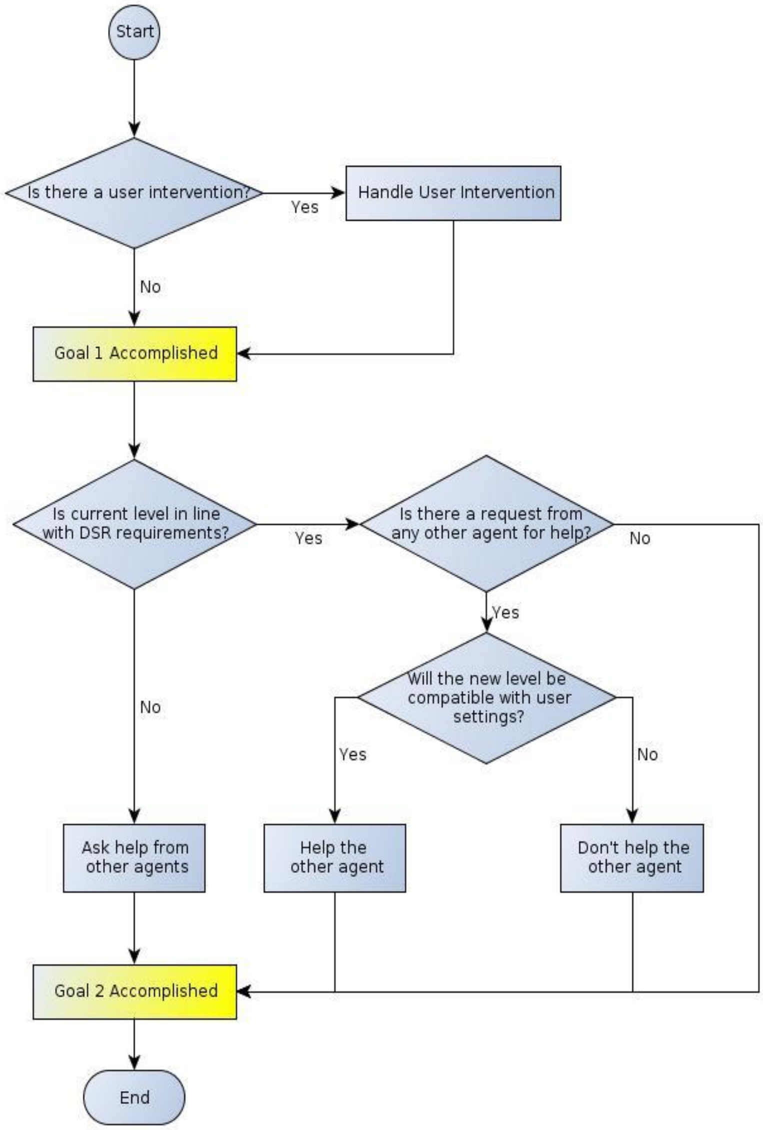


Figure 64: LZA goal achievement algorithm.

As shown in Figure 64, the specific conditions for the primary and the secondary goals of the agents are as follows:

6.7.3.2. Achieving the Primary Goal

Primary goal of the agent will be satisfied if there is a user intervention and if the agent adjusts the lighting level according to the demand from the user.

Another condition of the primary goal is to ensure that the lighting level that is automatically set by the controller for DSR reasons complies with the initial settings that might be put to restrict the DSR.

6.7.3.3. Achieving the Secondary Goal

If the primary goal is achieved, the agent will check if the secondary goal is met. Meeting the secondary goal will depend on several conditions.

Condition 1: If the controller is not assisting other agents on their secondary goal, the agents own secondary goal will be considered accomplished if it can reduce its consumption to the levels set by the lighting system agent.

Condition 2: If the controller is not assisting other agents on their secondary goal but needs to change its consumption because of a user intervention (as part of the primary goal), the controller needs to ask for assistance from other agents. The secondary goal will be considered as accomplished after it asks for assistance.

Condition 3: If the controller receives a request to assist other agents, to achieve its secondary goal, it needs to do so provided that its own primary goal is still achievable.

6.7.3.4. Goals of the System

The purpose of having a MAS is to ensure that the individual goals of the agents lead to the achievement of the overall goal of the system:

System Goal: Ensure that DSR requirements are met such that when a Central DSR agent defines a power consumption limit and an average lux level, these are satisfied even though the users in the building might have conflicting demands.

In order to meet the system goal, the agents should satisfy their secondary goals in a specific way that ensures maximum productivity. This means that:

- Only the required amount of power should be reduced
- Zones that have less impact on their occupants' productivity should be prioritised over others.
- Only the zones that can comply with the load reduction demand should be asked to reduce their consumption.

Similar problems have existed in other areas such as resource sharing in computers. One of the solutions that has become popular and has been implemented in other fields is the contract net protocol.

6.8. Contract net Protocol

In their paper, Smith [107] describes the contract net protocol that specifies problem solving, communication and control for nodes in a distributed problem solver. They describe distributed problem solving as "cooperative solution of problems by a decentralized and loosely coupled collection of knowledge sources (KS's) located in a number of distinct processor nodes". The KS's cooperate because no one of them has sufficient information to solve the entire problem. Mutual sharing of information is necessary to allow the group of KS's to produce an answer. The system is decentralized because both control and data are physically distributed. It is also loosely coupled because KS's spend most of their time in computation rather than communication.

The author defines connection problem as; “nodes with tasks can find the most appropriate idle nodes to execute those tasks”. Connection problem has two aspects; resource allocation and focus. Effective resource allocation is achieved by balancing the computational load among the nodes. Focus is achieved by effective selection of tasks for allocation to nodes and by effective selection of KS's for execution of tasks. Nodes with tasks and resources engage each other in discussions that resemble contract negotiation to solve the connection problem.

The negotiation process that is used to solve the connection problem has four important components:

- It is a local process that does not involve centralised control.
- There is a two way exchange of information.
- Each party to the negotiation evaluates the information from its own perspective.
- Final agreement is achieved by mutual selection.

The collection of nodes is referred to as a contract net and the execution of a task is dealt with as a contract between two nodes. Each node in the contract net takes on one of two roles; manager or contractor. Manager is responsible for monitoring the execution of a task and processing the results of its execution. Contractor is responsible for the actual execution of the task. The role of manager or contractor is not designated a priori, it changes dynamically depending on the circumstances of the network.

A contract is established by a process of local mutual selection based on two way transfer of information. Available contractors evaluate task announcements made by several managers and submit bids on those which they are suited. The managers evaluate the bids and award the contracts to the nodes they determine to be most appropriate. In this way, control is distributed because processing and communication are not focused at particular nodes but rather every node is capable of accepting and assigning tasks.

The basic messages that are explained in the paper can be summarised as follows:

Task announcements: A manager node advertises the existence of a task to other nodes. A task announcement message contains various information about the task such as eligibility specification, task description, bid specification and expiration time.

Task announcement processing: Upon reception of a task announcement, the node checks if the task that is under consideration is suitable for itself. This is done by checking the eligibility, expiration and description fields. If a task is achievable by the node, it is put in a ranking list until a final decision is made in the bidding process.

Bidding: The nodes submit their bids to the most attractive tasks by making a task specific decision on whether to submit a bid or wait for further task announcements. The bids consist of the capabilities of the node that are relevant to the announced task.

Bid Processing: Contracts are queued locally by the manager that generated them until they can be awarded. When a bid is received, the manager ranks the bid relative to others under consideration. If any of the bids are determined to be satisfactory, the contract is awarded to the associated bidder. If not, the manager waits for further bids. Successful bidders are informed that they are contractors by an announced award message.

Contract Processing: Once a contract is awarded to a node, information is exchanged between the node and the manager on the state of the task. A final report is issued by the node after the completion of the task.

The issues that might arise because of simultaneous awarding of contracts or refusal of bidding are discussed in the paper. The authors propose various solutions to these problems.

6.9. Contract Net for DSR - CNDSR

Many similarities exist between the system that is described in Smith's paper and the DSR system that is proposed in this study. Firstly, the definition of a distributed system (being decentralised and loosely coupled) is what exists in a lighting environment of a building. The zones operate independently from one another though communication exists between them to allow simple control tasks. Secondly, cooperation and communication is necessary among Lighting Zone Agents to solve the DSR problem. Thirdly, the connection problem that is described is similar to power distribution in the lighting case such that the power needs to go to the lighting zones that have the greatest affect on productivity.

Starting from this similarity, a negotiation process to achieve effective power distribution between the LZA's can be specified. The negotiation process would have the same components (decentralised, two way exchange of information, decision on own perspective, mutual selection). Similarly, the LZA's can act as both managers and contractors depending on the circumstances. The specifics of such a system, which is called contract net for DSR (CNDSR) is explained in the following section:

6.9.1. The Basis for Negotiation

The basis for negotiation is determined by the DSR controller. The DSR controller has a prediction on how much power will be consumed for a given lux level. It calculates the optimum power consumption and productivity level as described in the previous chapter. Based on this prediction, the DSR controller specifies a lux level that needs to be maintained by the lighting system. The DSR controller is not aware of user interventions or the specific requirements of the lighting zones. Once a lux level is issued, all of the zones that are able to switch to the new level are expected to do so by changing their consumption.

If there are LZA's that can not comply to the new lighting conditions (as explained in the examples at the beginning of this chapter) they become managers and ask for assistance from other agents by broadcasting the amount of power that they require to meet their goals. All of the LZA's are expected to receive these messages and decide on whether to assist the managers or not. If their circumstances allow, they submit their bids which consist of the amount of power that they can contribute. Along with their bids, they also specify the amount of productivity loss that they will suffer as a result of the load reduction.

Once the bids are received by the managers, the winners are determined. The main criteria is to make sure that bids that have the least productivity loss or most productivity gain are prioritised among the others. If the total number of bids reach the amount of power that is required, the contracts are granted to the corresponding bidders. Upon reception of the grants, the LZA's change their consumption.

From DSR controller point of view the building still consumes certain amount of power for certain amount of lux level. In reality, lighting zones that are intervened by the users consume different amount of power than other zones. The balance is achieved by shifting power from zones that are more flexible to reduce their consumption further to the zones where intervention occurs.

6.9.2. Definition of Manager and Contractor

In the CNDSR case, if there is an LZA that cannot meet its secondary goal because of Condition 2, it will need the assistance of other agents. In this case, it becomes the manager. If an LZA receives assistance request and falls into Condition 3, it becomes a contractor. Just like the CNET, the state of being a contractor or manager is not defined in advance. Circumstances such as user intervention might cause agents to become a manager hence other agents to be potential contractors.

6.9.3. Negotiation Process

6.9.3.1. Task Announcement

The announcement of tasks only happens during the DSR period. Two conditions cause task announcement to take place:

- Upon reception of a new lighting set point from the DSR controller, the LZA's that can not comply to the new lighting level.
- After a user intervention to the lighting zone, if the new lighting in the zone is different than that set by the DSR control agent.

6.9.3.2. Task Announcement Processing

Upon receiving a task announcement, the LZA's determine if they are suitable to change their consumption by the amount requested by the manager. This means that after changing the consumption, the new conditions should still allow the LZA to achieve its goals. If so, they bid for the task.

6.9.3.3. Bidding

The bidding message involves four components, the manager address, the bid id, the amount of power that can be reduced or increased and the amount of productivity loss or gain that will be incurred after the change.

Because of the complicated relationship between productivity and power consumption, a single bid would prohibit the selection of multiple LZA's to contribute to power reduction. For this reason, the LZA's submit multiple bids in power steps that are predetermined. This feature will be explained in more detail in the following sections.

6.9.3.4. Bid Processing

The manager LZA's collect the bids that are addressed to them. They then sort the bids based on their productivity loss or gain. Once sorted, the managers start awarding contracts from their list until the sum that has been awarded is equal to the sum of the contract.

6.9.3.5. Contract Processing

Once a task is granted, contractor LZA's change their power consumption. No more message exchange occurs between the contractor and manager LZA's after this.

6.9.3.6. Structure of the Bids

The bids are central to the success of the control process therefore they will be explained in more detail in this section.

When an LZA decides that it can change its consumption, it will need to inform the quantity that it can offer together with its effect on productivity to occupants in its own zone. The bid structure consist of the following fields:

Bid Number: A random bid id to identify the bid

Bid Amount: The amount of power that the LZA is willing to contribute

Productivity affect: The amount of change in productivity (positive or negative) if the bidding LZA is granted the bid. The effect on productivity can be defined as the product of IEQ change and the number of occupants residing in the lighting zone. The specifics of this parameter is not important since it is assumed that the agents in the building will have a common productivity parameter of some form.

One feature of the bid structure that is different compared to the CNET example is that for large sums of power request, the contractor LZA's need to bid in small chunks that is predetermined (either in the auction process or set as a priori). The reason for this can be explained in the following example:

If it is supposed that there are 5 LZA's (A,B,C,D and E) in a building who are initially operating at 600 Watts (where 1 lux equals to 1 watts of power for all LZA's). During a DSR event, the DSR controller asks the LZA's to reduce their consumption to 400 Watts. Because of its restriction, LZA-A cannot reduce its consumption therefore it needs to keep itself at 600 Watts. For this reason, it acts as a manager and requests other LZA's to reduce their consumption further to compensate its consumption. The state of other LZA's are more flexible. They can all reduce their consumption to 400 Watts but except LZA-E which can reduce its consumption further to 200 Watts, none of them can go any further because of their configuration. In this case, LZA-E which can reduce its consumption further to 200 Watts bids for 200 Watts together with its loss of productivity (calculated as the IEQ level at 20 Celsius for the relevant lux level and multiplied by 1000 for ease of comparison). Because no other LZA bids for the contract, LZA-A grants the contract to LZA-E. An optimum solution is found. Table 16 summarises this operation.

Table 16: Only one agent bidding

LZA	**Type**	**Min Pow**	**Initial**	**Request**	**Bid**	**Final**	**Prod Loss**	**Total Loss**
A	Manager	600	600	200		600		25
B	Contractor	400	400		0	400		
C	Contractor	400	400		0	400		
D	Contractor	400	400		0	400		
E	Contractor	200	400		200	200	25	

The result in the above example would not be optimum if all of the LZA's could reduce their consumption to 200 Watts. In this case, because every bid would be equal to that of LZA-E's bid, LZA-A would still need to pick only one contractor for its purpose (Table 17). Hence the amount of productivity loss would be equal. However this productivity loss is not the minimum that can be achieved. If all of the LZA's bid for 50 Watts rather than 200 Watts, and if LZA-A accepts the bids of all of the LZA's to sum 200 Watts, the total productivity loss would be less than the first condition where one LZA reducing to 200 Watts. Table 18 summarises this condition.

Table 17: All of the agents bidding in large chunks

LZA	**Type**	**Min Pow**	**Initial**	**Request**	**Bid**	**Final**	**Prod Loss**	**Total Loss**
A	Manager	600	600	200		600		25
B	Contractor	200	400		200	400		
C	Contractor	200	400		200	400		
D	Contractor	200	400		200	400		
E	Contractor	200	400		200	200	25	

Table 18: All of the agents bidding in small chunks

LZA	**Type**	**Min Pow**	**Initial**	**Request**	**Bid**	**Final**	**Prod Loss**	**Total Loss**
A	Manager	600	600	200		600		16
B	Contractor	200	400		50	350	4	
C	Contractor	200	400		50	350	4	
D	Contractor	200	400		50	350	4	
E	Contractor	200	400		50	350	4	

The reason that this happens is because of non-linear relationship between productivity and lux level. As lux level is reduced, the loss of productivity increases more rapidly. For this reason, a homogeneous reduction of lux level in a wider office area is more preferable than a steep reduction in one particular area. This also makes sense in a real world situation. A slight reduction in lighting level might not be noticed by the occupants but a steep reduction in one office zone might cause a significant discomfort in that area.

In this case, because contractors are unaware of others' bids and the number of contractors, they cannot determine the optimum number of bids that are to be submitted. For this reason, a predetermined bid step is required so that the potential contractors can bid in incremental steps. This would enable the manager LZA to compare and pick the optimum combination of contractor LZA's so that maximum productivity is achieved for minimum disruption.

6.9.3.7. Bidding Process

In this section, bidding process is explained with an example. The process starts with an agent (acting as a Manager) announcing an auction for the amount of power that it requires to meet its user demand. Figure 65 shows the manager agent broadcasting a requirement of 300 Watts where the bidding step is fixed at 100 Watts.

When other agents receive this information, depending on their circumstances, they start to submit their bids. In this example, Agent 1 is capable of fulfilling the 300 Watts that is asked. Therefore beginning from 100 Watts, it starts submitting its bid. For each increment, it calculates the productivity loss that it will suffer. As the amount of power reduction increases, the amount of productivity loss increases as well therefore while 100 Watts correspond to 1 productivity loss, 300 Watts corresponds to 3.6 productivity loss. Other agents bid for the auction as well. Because Agent 2 is already consuming less than Agent 1, it only can bid for 200 Watts. Agent 3 is consuming less than both Agent 1 and Agent 2 therefore it only bids for 100 Watts.

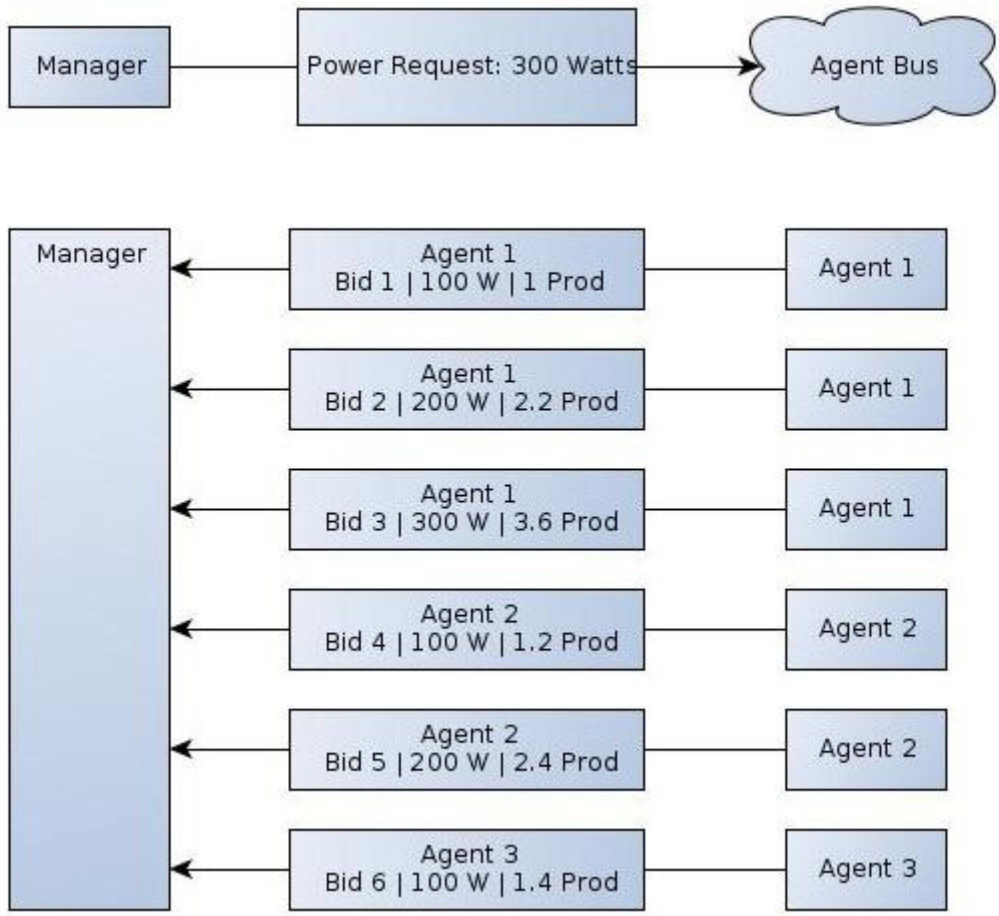


Figure 65: Auction initiation and bidding process

Figure 66 shows the process inside the manager agent. The manager now has a collection of bids and it has to decide on how to grant the contracts. It starts with the unit step of 100 Watts and checks which agent offers the least productivity loss for this reduction.

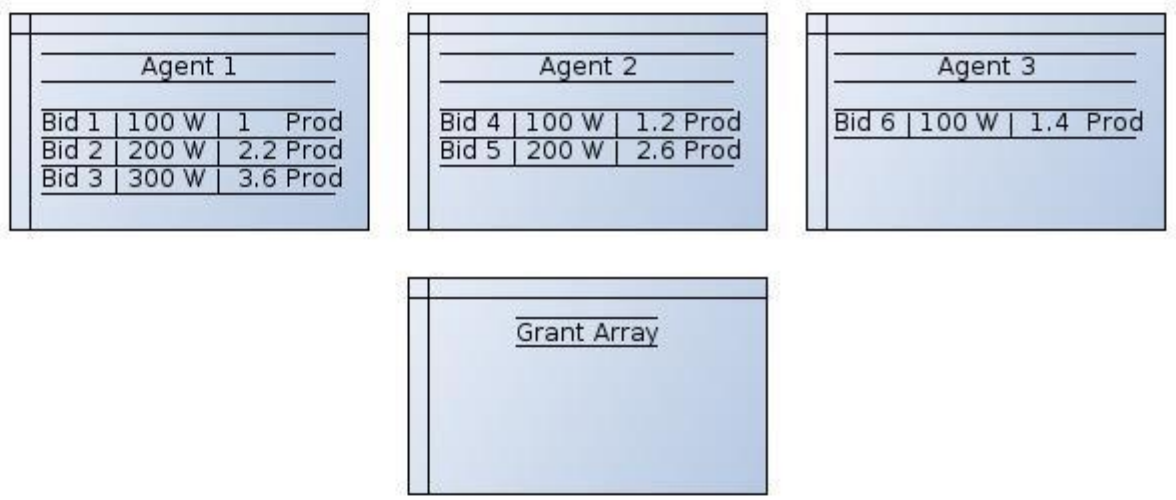


Figure 66: First step of the bid selection process

Figure 67 shows the result of the selection process. When all the bids corresponding to 100 Watts are compared, Agent 1's bid is the best bid because it offers the least productivity loss. This bid is added into an array called 'Grant Array'. After this, the bid value of Agent 1 is subtracted from rest of the bids of this agent so that in the next step, other bids can still be compared.

Figure 67: Second step of the bid selection process

Figure 68 shows the result of the following step. This time, both Agent 1 and Agent 2 offers the same power consumption for the same productivity loss.

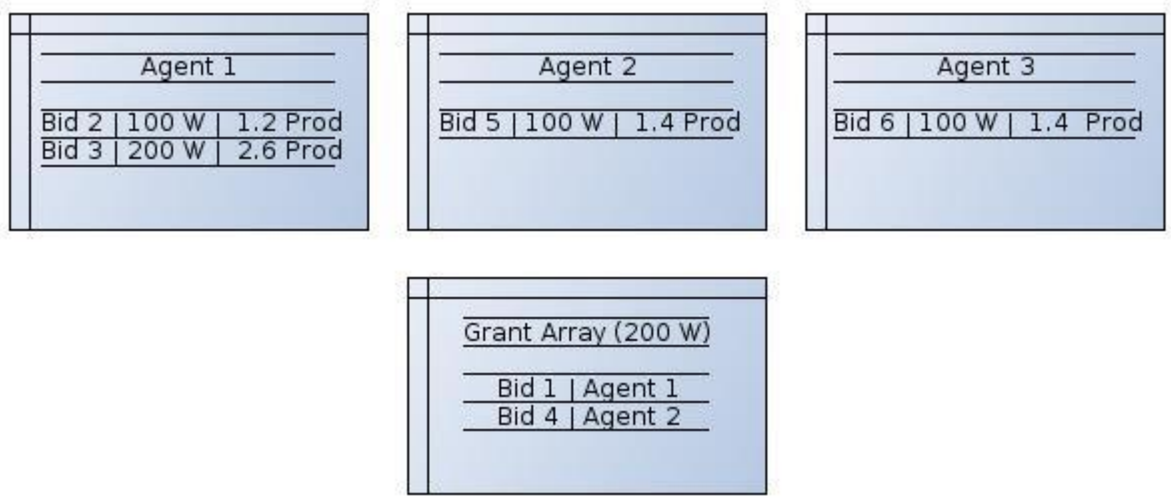


Figure 68: Third step of the bid selection process

In this case, the manager randomly selects Agent 2's bid and adds this to the Grant Array. Like in the previous step, Agent 2's bid is subtracted from its subsequent bid for comparison in the next stage.

Figure 69 shows the final selection. This time, Agent 1's bid is more favourable than

Agent 2's bid therefore its second bid is selected. When this bid is added to the grant array, the previous bid of Agent 1 is replaced by its higher bid.

Figure 69: Final step of the bid selection process

Once the manager agent reaches its objective, it announces the winning bids to the bus. Agents that win the contracts reduce their consumption to compensate the manager agent's increase (Figure 70).

In this example, Agent 3 does not win a contract for its bid because it's bid causes a higher productivity loss compared to other agents' bids. In a real world scenario, this behaviour would be in line with expectations. If a lighting zone is already operating below a given set-point, it should have less priority compared to other zones that are consuming more.

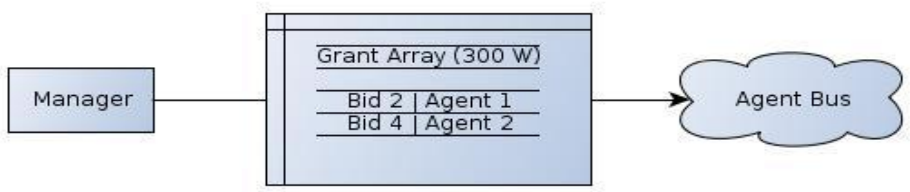


Figure 70: Manager announcing the bids.

6.10. Simulation and Experiments

In this section, the simulations that have been carried out to assess the feasibility of using CNDSR are explained. The simulation environment and the elements that are implemented in it are described first followed by the definitions of the experiments and the results.

6.10.1. Simulation Environment

MATLAB has been used as the programming environment for defining and simulating the interaction between the agents. The main objective of the simulations has been:

- To define the principal algorithms that are expected to operate in LZA's.
- To assess whether or not CNDSR is capable of meeting the requirements of an office environment.
- To determine the requirements of the communication layer that CNDSR would operate.

The methodology for simulation has been simple; software objects that represent LZA's are created and their interaction in a 'market' are simulated by looping until every interaction is handled for a given simulation step.

Agent code that is constructed for this is explained in the next section.

6.10.2. Components of the system

6.10.2.1. LZA Object and Its Attributes

The center of the simulation is the LZA object. The object has four main components; the attributes, contractor algorithms, manager algorithms and simulation specific code.

LZA has the following attributes:

Current Lux Level: The lux level that is maintained by the LZA.

Expected Average Temperature: The expected temperature that will apply to the lighting zone during the DSR period. This is announced by the DSR controller to all LZA's so that they can submit accurate bids.

Minimum Lux Level Assigned by the User: The minimum lux level that the LZA is allowed to fall in order to satisfy its secondary goal. Under any circumstance, the LZA is not allowed to fall below this value.

Maximum Lux Level Assigned by the User: The maximum lux level that the LZA is allowed to ascend in order to satisfy its secondary goal. Under any circumstance, the LZA is not allowed to go above this value.

Bidding Step Size: The minimum step (power) that the LZA is to bid.

User Intervention Flag: This is to indicate that a user intervention has been carried out. It prohibits the LZA to engage in bidding communication since the user has a specific lux level that is set.

6.10.2.2. LSA Object

The LSA is the agent that determines the average lux level that needs to be consumed by all of the LZA's. It sets the average lux level that is allowed (per person or per floor area). It acts transparently in the simulator. If the agents fail to meet a specific lighting demand because of user intervention, the LSA (depending on the requirement) removes or adds extra power. This extra power is sourced from other elements such as HVAC.

6.10.3. Bidding Agent Algorithm

When there is a request from any other agent, it is generated as a form of auction. This consists of the amount of power that is either requested or offered by the agent. When an LZA receives such a request, it is processed in its bid processing algorithms.

The bid processing algorithm is implemented as follows (Figure 71):

- Determine the bid limit: The bid limit corresponds to the power equivalent of the minimum or maximum lux level that is defined in the agent attributes. However if the power that is offered or requested in the auction does not cause the LZA to go beyond these limits, then the bid limit is defined as the lux level equivalent of existing power consumption plus (or minus) the amount of power that is offered (or requested).
- Determine current productivity: This is done by calculating IEQ from projected temperature and existing lux level.
- Starting from existing power level until the bid limit is reached, do the following: Increase (or decrease) the power consumption by step size and calculate the corresponding change in productivity. Record the results into the bid array. Assign a

random bid id to the bid.

- Once the bid limit is reached, submit the bid.

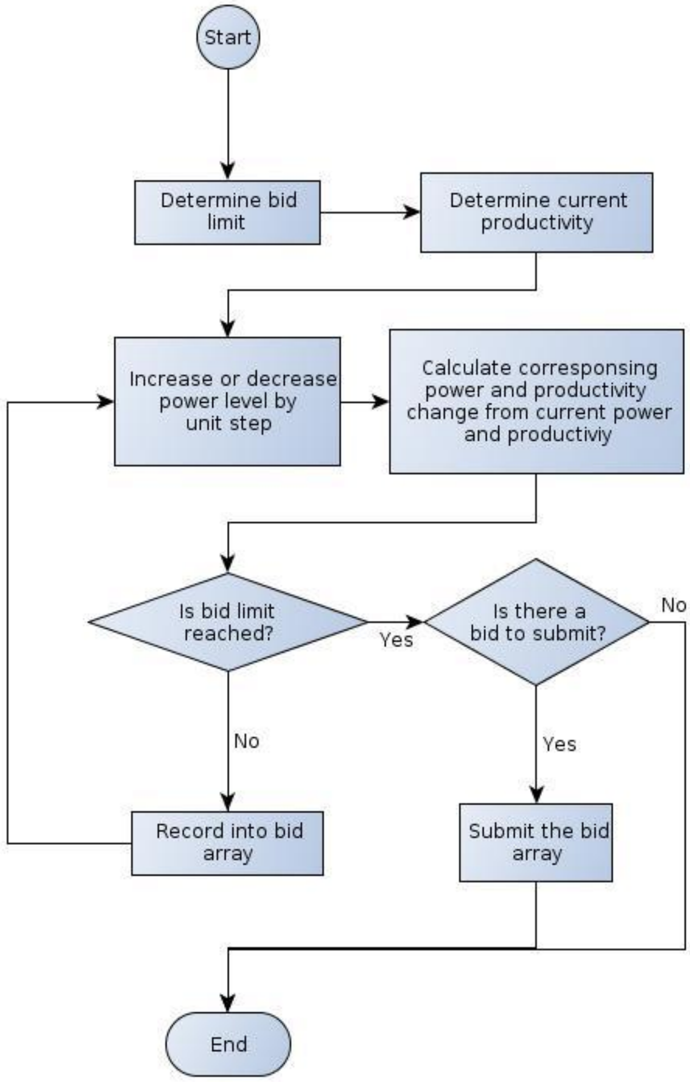


Figure 71: Bid Processing Algorithm

In the simulation, the submitted bids are collected by the simulation engine into an array. Once all the bids are collected, these are passed to the managing LZA to be processed.

6.10.4. Managing Agent Algorithms

6.10.4.1. Submit Auction

If an agent receives a user intervention that causes it to change its consumption, it submits an auction to other agents. The auction consists of the manager ID and the amount of power that is requested or that is available to other agents.

6.10.4.2. Grant Contract Algorithm

When all the agents have submitted their bids, they are processed in order to grant contracts to winning LZA's (Figure 72).

- The first process that is carried out by the manager LZA is to arrange the bids so that every bidding agent's bids are grouped.
- Once the bids are grouped, the manager checks if there is sufficient amount of bid to cover the auction. This is done by adding the maximum bids of each bidding LZA. If the sum cannot cover the auction, then the maximum bid that is submitted by every agent is granted straight away and the missing or surplus power is dealt by the LSA.
- If the sum of the maximum bids that are offered by the bidders is above the auction limit, the manager LZA starts a loop to determine the winning bids depending on whether it is granting or asking power:
- If the LZA has surplus power, it grants the bids to the LZA's that offer the greatest productivity increase.
- If the LZA is in need of power, it grants the bids to the LZA's that offer the least productivity decrease.
- In this context, the bid that is most advantageous is called the most *favourable bid*.

- The loop starts by comparing the productivity changes of the first set of bids which constitute a unit step change. The most favourable bid is selected based on the criteria above.
- Once a bid is found to be most favourable, the amount of power and productivity change caused by the bid is subtracted from the subsequent bids of the bidder. This ensures that in the next step, the subsequent bids of the same LZA can still be compared with the bids of other LZA's.
- The bid is recorded in a 'Grant Array'.
- When the loop starts again, the state of the bids is similar. If another agent is granted a bid, it is added to the Grant Array. If the same LZA that won a previous bid wins again, its bid is added to the its previous winning bid.
- The loop continues until the target auction is reached.
- At the end of the auction, the Grant Array is published.

In the simulation, the grant array is used by the simulation engine to distribute the new lux levels to winning bidders.

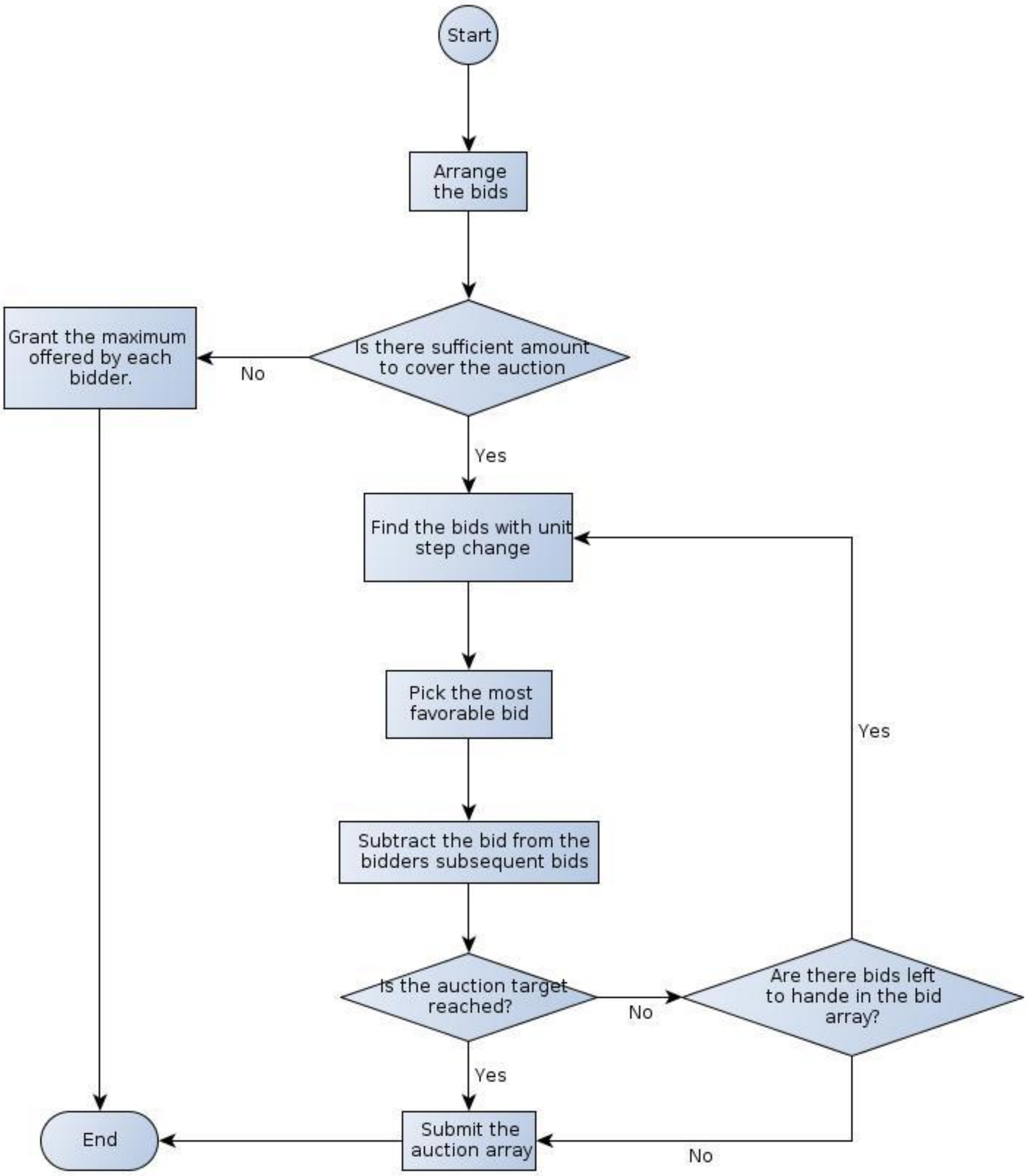


Figure 72: Grant Contract Algorithm

6.10.5. Simulator Specific Functions

The simulator functions consist of three main parts; agent initialisation, main loop and result presentation (Figure 73).

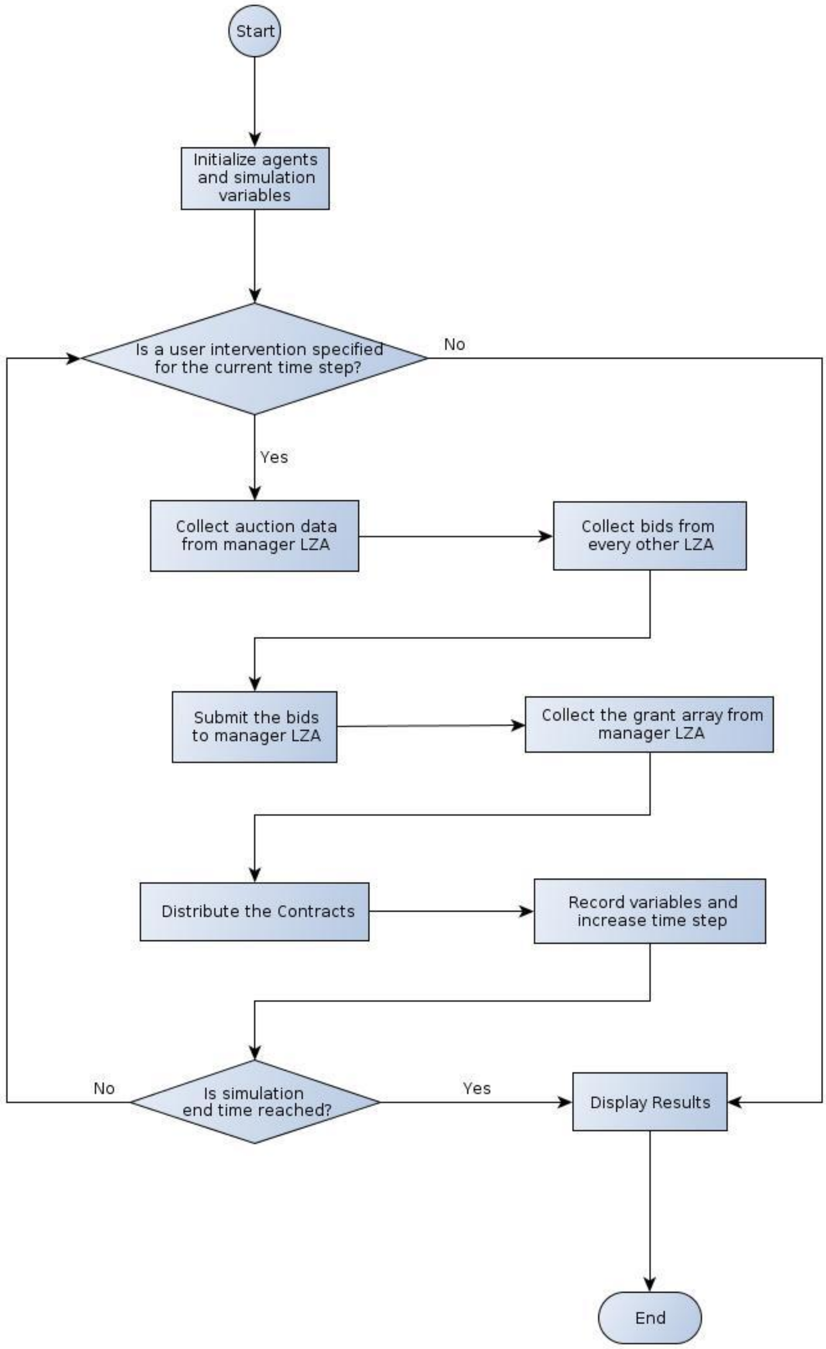


Figure 73: Simulation Algorithm

6.10.5.1. Initialisation

- Simulation parameters and agents are initialised in the beginning of a simulation run.
- The user sets the following parameters that are used in the initialisation:

Simulation End Time: This defines the number of cycles the simulation is to run. .

User Intervention: This parameter defines the interventions that are introduced into the system during a simulation run. The parameter consists of an array that defines the time of the event, the id of the agent and the magnitude of the intervention that is desired.

Substandard Agents: Certain agents in the system can be set to have different parameters as opposed to default ones. These are stored in the Substandard Agents array. The array consists of the agent and the parameters that are different (for example Minimum Lux Level).

- When the simulator starts, it generates the agents. It then changes the parameters of the substandard agents using the Substandard Agent Array.
- Once the initialisation is complete, the main loop starts.

6.10.5.2. Main Loop

The main loop runs until the simulation time reaches the simulation end time. At the start of each loop, the simulator checks if there is a user intervention in the User Intervention array. If there is an intervention, it carries out the auction and bidding algorithms.

Specifically, at each time step, the simulator carries out the following tasks:

- Check if the user intervention array specifies an intervention for that time period.
- If there is a user intervention event, trigger the event by changing the parameters of the

LZA that is intervened. In this case, the intervened agent becomes the manager agent and submits the auction information.

- For every agent, submit the auction information and collect the bids.
- Once the bids are collected, submit the bid array to the manager agent for bid processing.
- Collect the Grant Array from the manager agent.
- Submit the new power levels to winning agents.
- At the end of the loop, record the Lux level for post-simulation analysis.

6.10.5.3. Result Presentation

The power level of every agent for each time step is recorded. Also, the average power level that is assigned by the LSA is also recorded to compare the actual power levels of the agents with the average power that is expected by the LSA.

6.11. Experiments with CNDSR

Various simulation runs have been carried out to test the effectiveness of the algorithms. Certain level of abstraction was necessary to simplify the implementation of the algorithms and make it easier to understand the results. These are as follows:

Power and Lux Level: The relationship between the Lux level and power is assumed to be identical. That is, to generate 1 Lux of light on desk level, the light fittings are assumed to consume 1 Watts of power. Also, this relationship is assumed to be linear.

Office Zones and People Working in the Zones: All of the zones are assumed to be identical, with equal number of people and equipment in them.

External Lighting: No external lighting is assumed to exist in the system, all of the changes are caused by users.

Operation of the LSA: The ideal operation of the LSA should be such that when the lighting system can not comply with the average lux levels, it should convey the information to the DSR agent which would change the temperature set-points to compensate the difference from the HVAC system. This would change the temperature of the environment and the productivity calculations of the agents. Because the simulation of the DSR agent is not carried out, the LSA is assumed to keep the temperature set-points constant.

6.11.1. Design of the Experiments

The purpose of the experiments is to determine if the algorithms would be useful in a real world situation. Intervention and prohibitive user preferences are difficult challenges in achieving DSR therefore the experiments are focused on these. User intervention is simulated as users reacting to the DSR conditions and changing the Lux levels of the office zones which are governed by the LZA's. Prohibitive user preferences are simulated as agents not having default DSR values such as minimum or maximum levels that are common to other agents.

When it comes to selecting the number of office zones to simulate, the focus has been on a number that simulate the most challenging environment from DSR point of view. Surely if the number of zones are large, user intervention on a few office zones might go unnoticed. For this reason, the simulations have been carried out on small number of agents.

Because the simulations focus on the effectiveness of the algorithms, communication specific problems are not included. For example, simultaneous user interventions are not simulated since the issues arising from these would be part of an implementation problem. Similarly, the exact communication methods are not specified, the message exchanges among the agents are presented in an abstract way.

Initially, an ideal scenario is presented where all of the agents can reduce their consumption without any difficulty. Then, a positive intervention (increase in consumption) is tested where an agent cannot reduce its consumption because of a user intervention. Afterwards, the same intervention is simulated again but this time with an agent not being able to contribute to the request of the intervened agent due to its configuration. The following scenario is to test if negative intervention delivers the expected results as a positive intervention.

The resulting average power level that is expected by the LSA and the real average power levels are compared to verify if the individual objectives of the agents can lead to the overall objective of the system to be achieved.

6.11.2. No Intervention Case where all of the Agents Comply to DSR

Simulation time	: 15
Number of Agents	: 4
Power Level During DSR	: 300 Watts

Intervention : None

Agents with different settings : None

When the LSA announces a drop in power levels and if there is no intervention throughout the DSR period, all of the LZA's comply to the demand of the LSA. Figure 74 shows the status of the agents throughout the simulation period. At time step 2, the LSA announces a new power Level for the agents which require them to drop to 300 Watts. In this case, all of the agents comply (upper graph) and the resulting average power level of all the agents is 300 Watts (lower graph).

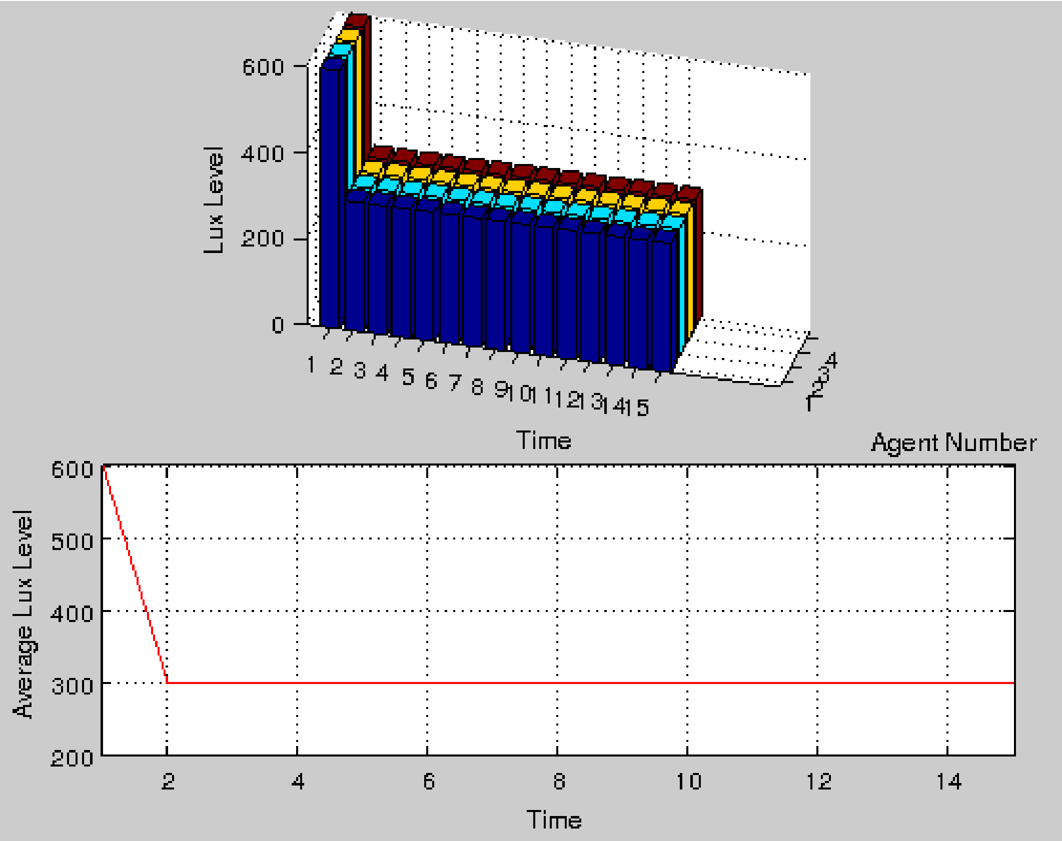


Figure 74:No Intervention Case where all of the Agents Comply to DSR

6.11.3. Positive User Intervention

Simulation time	: 15
Number of Agents	: 4
Power Level During DSR	: 300 Watts
Intervention	: Agent 4 +300 Watts at time 2
Agents with different settings	: None

When the LSA announces a drop in power levels and if there is an intervention on one of the agents, other agents reduce their consumption further to accommodate the intervention. The result of this experiment is shown in Figure 75. On the upper graph, it can be observed that agent 4 cannot stay at 300 Watts because of a user intervention in time step 2. When this happens, the auction process starts and as a result, other agents are contracted to reduce their consumption further. The agents reduce their consumption by equal amount because this is the only way to minimise the overall productivity loss caused by the intervention. Hence their consumption is reduced to 200 Watts and the average power level (power consumption) stays at the equivalent of 300 Watts per agent. The lower graph shows the average power level of agents (blue) compared to the power level required by the LSA (red). In time step 2, the average power Level is higher than 300 Watts because agent 4 is intervened. This changes in the following time step where other agents reduce their consumption to compensate the intervention.

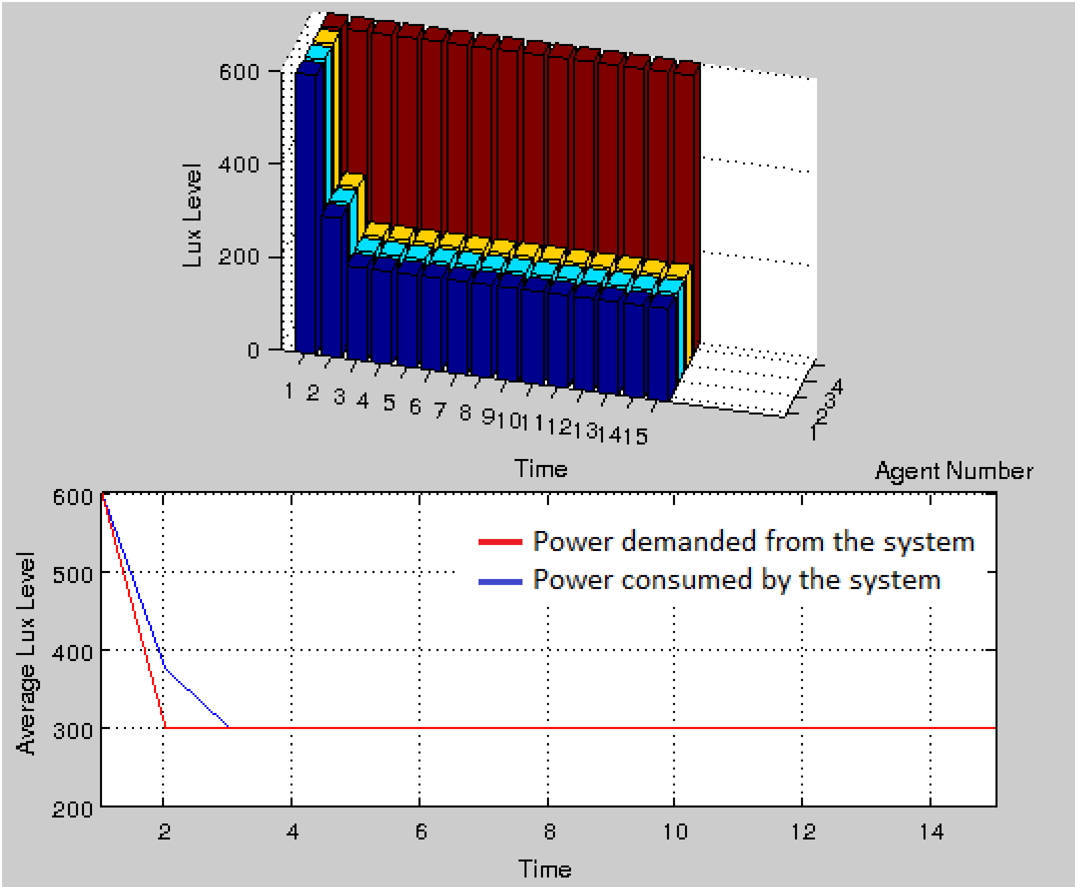


Figure 75: Positive User Intervention

6.11.4. Positive User Intervention with Limited Agent

Simulation time	: 15
Number of Agents	: 4
Power Level During DSR	: 300 Watts
Intervention	: Agent 4 +300 Watts at time 2
Agents with different settings	: Agent 3 has minimum power Level of 300

Watts.

When the experiment in the previous example is repeated with an agent that has non-default settings, the results turn out to be different. In the experiment, the minimum power Level of Agent 3 has been set as 300 Watts. When the simulation is run, this agent does not bid to the auction of Agent 4 because it is already operating at its minimum allowed power level. Hence even though the other agents reduce their power levels to their minimum of 200 Watts, Agent 3 stays at its existing level. This causes the intervened agent to recover only 200 Watts of its 300 Watts increase. The missing 100 Watts is supplied from the LSA. The LSA in this case is assumed to find the missing 100 Watts from other sources (HVAC) and the average power Level in the market increases to 300 Watts + 100Watts/4 = 325 Watts. This can be observed in the lower graph of Figure 76. The red line which represents the allowed power level for all the agents is increased after step 2 when the intervened agent cannot find the extra 100 Watts.

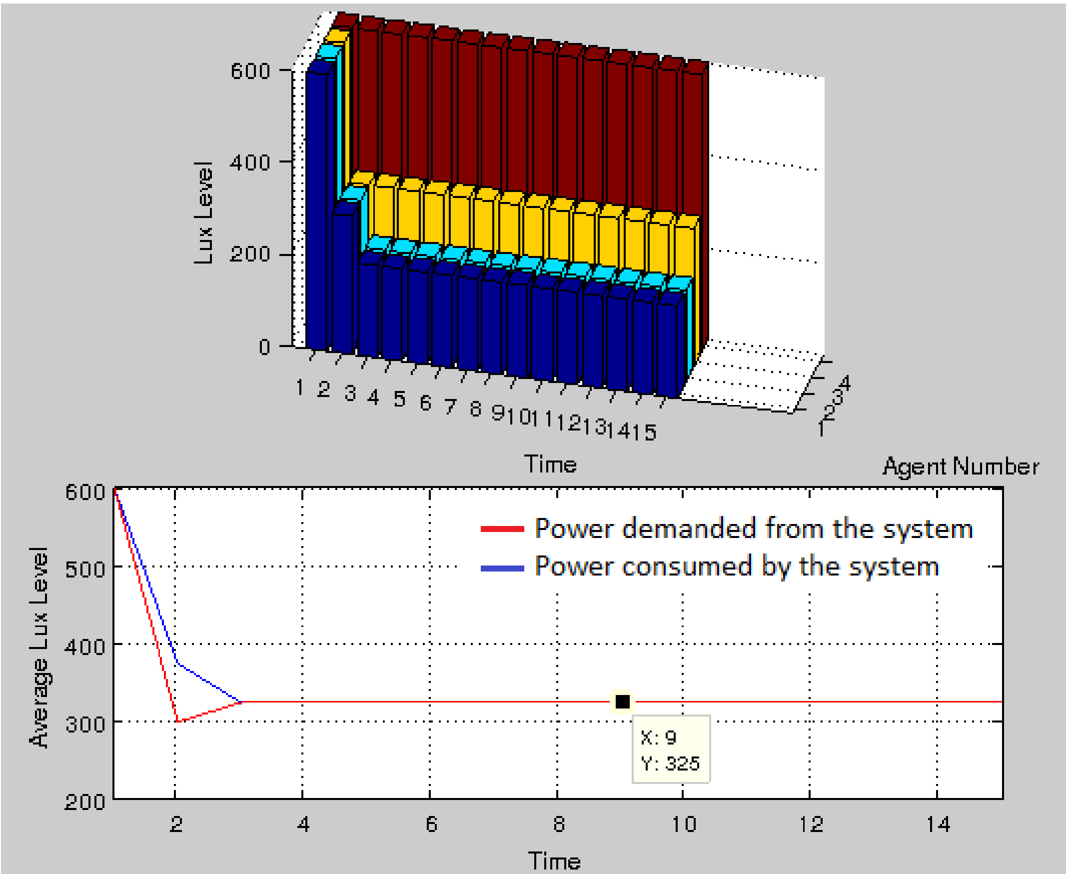


Figure 76: Positive User Intervention with Limited Agent

6.11.5. Positive and Negative User Intervention with Limited Agent

Simulation time	: 15
Number of Agents	: 4
Power Level During DSR	: 300 Watts
Intervention	: Agent 4 +300 Watts at time 2
	Agent 4 -300 Watts at time 5
Agents with different settings	: Agent 3 has minimum power Level of 300 Watts.

Following the previous example, if another intervention causes Agent 4 to drop to 300 Watts, the results are as shown in Figure 77. Agent 4 is reducing consumption at time step 5 therefore it has extra power (300 Watts) that it needs to auction to other agents. However, because the LSA had previously provided the extra 100 Watts that is needed in the intervention, Agent 4 can only auction for 200 Watts. The extra 100 Watts that is returned to LSA causes the DSR market to return back to 300 Watts per agent. Hence Agent 4 auctions the 200 Watts to other agents. In this auction, all of the agents including Agent 3 bid for the extra power. The winning bidders are selected as Agents 1 and 2 and they share the 200 Watts equally among each other. The reason that Agent 3 cannot get any of the available extra power is because its productivity increase is lower compared to other agents. Agents 1 and 2 are operating at a lower power level therefore their increase in productivity is higher compared to Agent 3. Hence they are prioritised over Agent 3 and win the extra power.

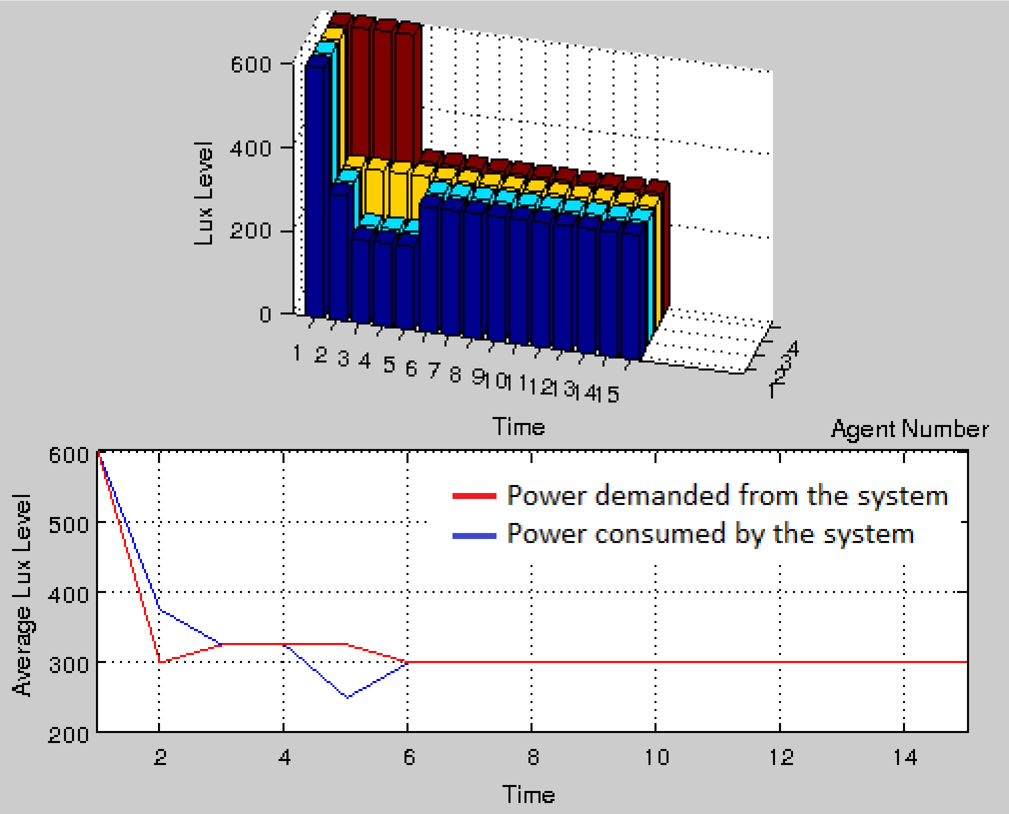


Figure 77: Positive and Negative Intervention with Limited Agent

6.11.6. Negative User Intervention

Simulation time	: 15
Number of Agents	: 4
Power Level During DSR	: 300 Watts
Intervention	: Agent 4 +300 Watts at time 2
	Agent 4 -300 Watts at time 5
	Agent 1 -200 Watts at time 7
	Agent 1 +200 Watts at time 9
Agents with different settings	: Agent 3 has minimum power Level of 300

Watts.

Following the previous experiment, Agent 1 is intervened to drop its power level to 100 Watts at time step 7 and return back to 300 Watts at time step 9 (shown in Figure 78). When it drops its power Level to 100 Watts, it auctions the 200 Watts that is now extra. The auction results in other agents receiving equal share of the extra power. When Agent 1 returns back to 300 Watts, it again carries out an auction to demand 200 Watts from other agents. The auction results in agents donating equal amount of power to Agent 1. All of the agents complete the simulation with equal power Levels.

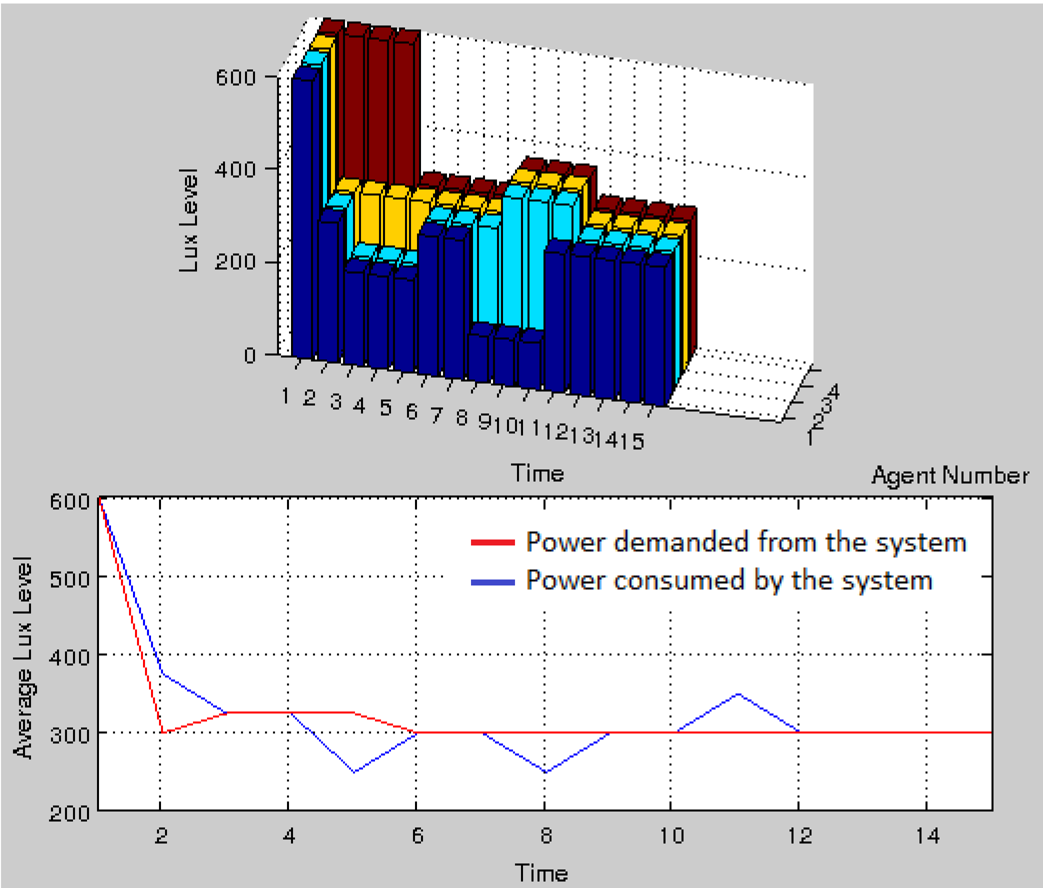


Figure 78: Negative User Intervention

6.12. Assessment of the Results

6.12.1. Expected Behaviour

If there had been no user intervention, the operation of the system would have been straight forward as shown in the first simulation. Thus, the main contribution of the CNDSR algorithm is to allow user intervention to be managed locally between the agents rather than involving a central controller. When it comes to intervention, if there is a change in consumption on one of the office zones, it is expected that all of the other office zones (as long as their configurations permit) to contribute equally to cover the change. If there is abundant power available, the zones that have been in the most dire state are expected to be prioritised over the others.

From this perspective, the results of the simulations show that the algorithms are successful. In the second simulation, it can be seen that if there is a zone which cannot change its consumption (because of its configuration), it does not bid for the auction. The remaining zones that bid are given equal shares of the burden. Moreover, in the following example, even though all of the agents bid for the extra power that is available, only Agents 1 and 2 are awarded. The productivity increase of Agent 3 did not justify its demand for power. However because Agent 3's configuration does not prohibit it from increasing its consumption, in the following example where Agent 1 is intervened causing it to demand less power, the additional power that is available is distributed equally to every agent (including Agent 3).

6.12.2. Assessment of the Assumptions

Power and Lux Level: If power to Lux level relationship was not constant, the bid structure of the agents would not change; they would still submit the amount of productivity change for given amount of power reduction. The system would automatically pick agents that consume more power for a given amount of productivity therefore agents that consume more would be asked to reduce more.

Office Zones and People Working In them: If office zones had different number of people working in them, provided that the LZA's are aware of this, the zones that have more people would suffer less reduction during a DSR. This is because their change of productivity for given amount of power would be higher than the others.

External Lighting: User interventions in the simulations did not consider external lighting. However external lighting and user intervention would result in the same reaction from the agents. Absence of external lighting would result in lux level in an environment to drop which would require the agent to ask for power from other agents. Similarly, if daylight became suddenly available, the agents would auction the extra power to other agents.

6.13. Advantages and Drawbacks of CNDSR

It is shown in the experiments that CNDSR algorithms can achieve the task of a central controller. However, because of its distributed nature, it has some considerable benefits compared to a system where DSR is managed centrally.

The first advantage is dealing with intervention. In the case of a central controller, every user intervention needs to be dealt by a central controller which might not be able to handle all the requests in a timely manner. A hierarchical solution might help solve the problem but this would increase the complexity of the overall system. In CNDSR, every LZA is capable of controlling other LZA's during a user intervention which allows the distribution of the DSR tasks to individual controllers.

The second advantage is in handling preferences. In the case of a central controller, user preferences need to be conveyed to the central controller before a DSR command is issued. These preferences might not be standardised which would make the task of implementing a central controller very difficult if it is to store and process this information. If the central controller operates on a query basis where it queries agents whether they can achieve a certain task or not rather than issuing direct commands, then every intervention would cause the central controller to query every LZA at its disposal to find the best candidates for the task. If the number of agents and the number of interventions are considered, this implementation might not be practical in large buildings.

Another advantage of CNDSR is the flexibility in implementation. The philosophy of CNDSR allows it to be implemented into existing buildings because other agents such as the DSR and HVAC are not fundamental in its operation. If a building does not have the means to control HVAC system or a fixed operating set-point for the HVAC system is the only available option, the lighting system would still deliver optimum results for productivity provided that an LSA like entity can inform the agents on the amount of Lux level that is allowed in the office.

On the other hand, CNDSR that is proposed in this system is based on productivity. This parameter is vital in the success of this distributed control system. The implementation and adjustment of such a parameter into a real office building might not be easy.

Also, the agent implementation puts considerable amount of strain on the underlying communication infrastructure. It is not clear whether existing communication infrastructure can handle the message traffic during a DSR event. This issue will be tackled in the following chapter.

6.14. Integration of Other Loads

Even though the scope of this chapter was limited to lighting, other types of loads can be integrated into CNDSR provided that the productivity aspects of these loads can be presented. In this section, the integration of individual zone temperature controllers and office equipment into a DSR system will be discussed.

6.14.1. HVAC and CNDSR

As explained in the beginning of this chapter, HVAC systems operate on a central basis. For this reason, it might be difficult for a room temperature controller to participate in CNDSR discussions. However, if it is assumed that energy consumption characteristics of HVAC zones are known, these can actively participate in CNDSR discussions.

If it is assumed that an office floor consists of independent zones that have both zone lighting controllers and temperature controllers, then each controller would act as an agent representing its own source of power consumption. However, because productivity is influenced by temperature and lighting, then the zone controller pairs of lighting and temperature need to coordinate their actions in order to avoid unproductive indoor environments. The main reason for this is that temperatures in offices tend to increase or decrease gradually whereas lighting can be changed instantly. A lighting zone controller calculates the productivity of an office zone **assuming** that the office zone will be at a certain temperature during which the lighting zone controller participates in the auction. This assumption is likely to be based on sensors providing temperature data of the relevant zone. However, during a transition period where temperatures are expected to ramp up from one point to another, the current state of temperature from the sensors might not reflect the long term condition of the office zone.

If it is assumed that 400 Lux at 22.5 Celsius is equal to same productivity as 600 Lux at 24.5 Celsius and that the productivity at these states is assumed to be 98% of the optimum conditions, the following table provides an insight in what happens when both temperature controller and lighting controller bid for CNDSR. At time T1, both the lighting zone controller and temperature zone controller receive a request for an auction. The temperature controller calculates the amount of productivity loss based on 600 Lux light level which is the current state. It bids for the auction calculating that it can achieve 98% productivity at 600 Lux and 24.5 Celsius. On the other hand, the lighting controller calculates that the productivity of the office will be 98% if it reduces lighting level to 400 Lux because the temperature is 22.5 Celsius. Both of them bid for the auction. The managing agent which does not know the internal conditions of the zones and decides purely on the amount of productivity loss and power gain accepts bids from both of these agents. However, the lux level drops to 400 Lux immediately and temperature increases to 24.5 Celsius gradually resulting in productivity level at T5 to be 95% which was not anticipated by both of the agents and which is clearly not optimum.

Table 19: Example of both Lighting and Temperature Controller Bidding the Same Auction

	T1	**T2**	**T3**	**T4**	**T5**
Lighting	600	400	400	400	400
Temperature	22.5	23	23.5	24	24.5
Productivity	1	0.98	0.97	0.96	0.95

In order to overcome this issue, both the lighting and temperature agent need to coordinate their actions. Two simple rules can be implemented to achieve this coordination:

1. For the same auction, only one entity will bid assuming the other will stay the same.
2. If one of the entities is not willing to bid, it should provide the other with an indication of the state of the room that is related to its control.

Simple control sequence that depicts how this can be achieved in a building is shown in Figures 79 to 81.

In Figure 79, the both temperature control agents and lighting controller agents receive the auction announcements.

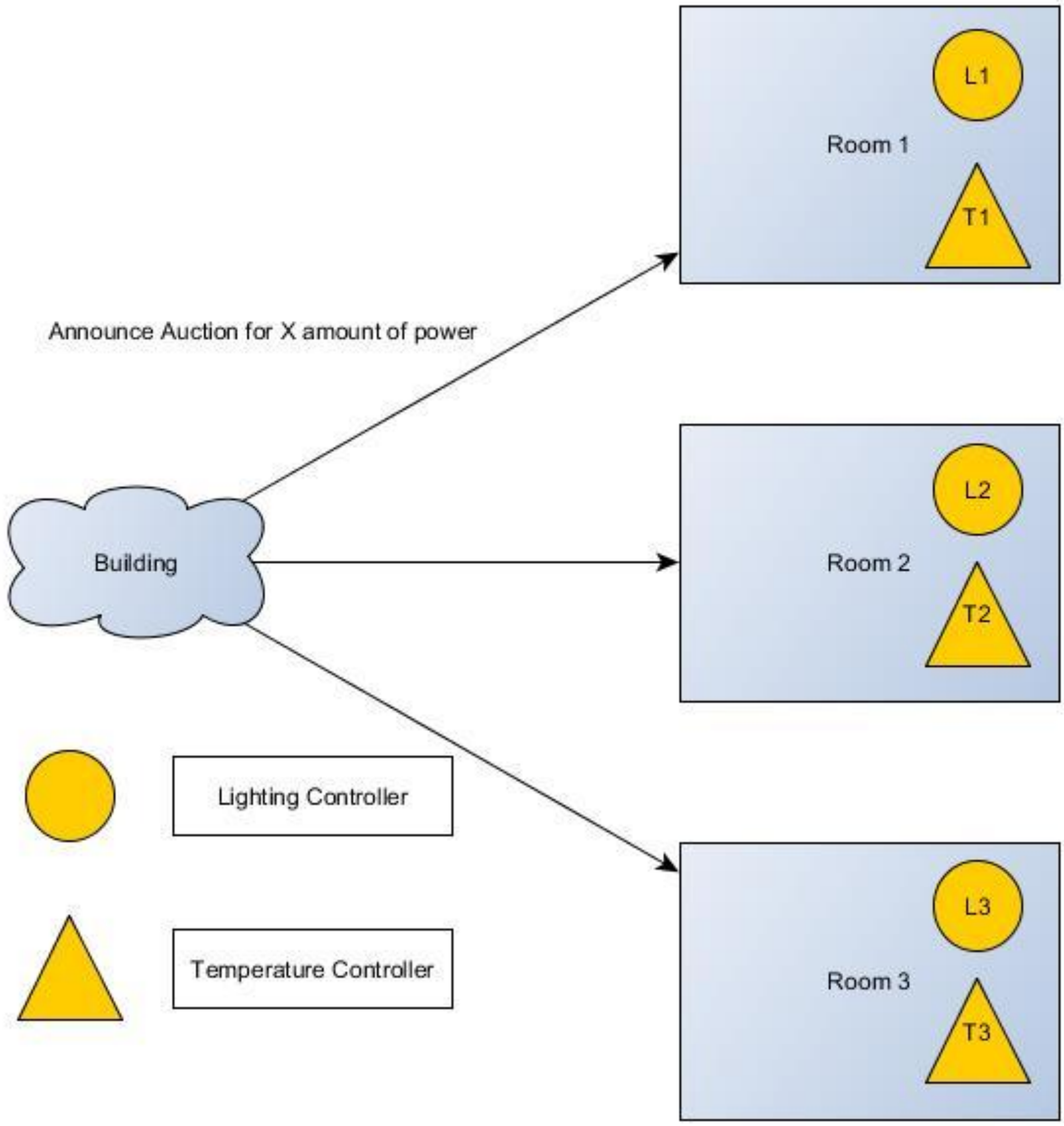


Figure 79 Announcement of Auction to Room Controllers

Figure 80 depicts the discussions of the temperature and lighting controller within the same room. Lighting control agent announces its intention to bid for this auction to the temperature controller. The announcement includes the amount of power that will be reduced. The temperature controller which has no intention to bid for the auction responds by telling the lighting control agent that it will not bid. It also informs the temperature that is expected in the room. In this case, the lighting control agent adjusts its bid based on this temperature and announces its bid to the auctioneer. As a result, only lighting is reduced in the office zone.

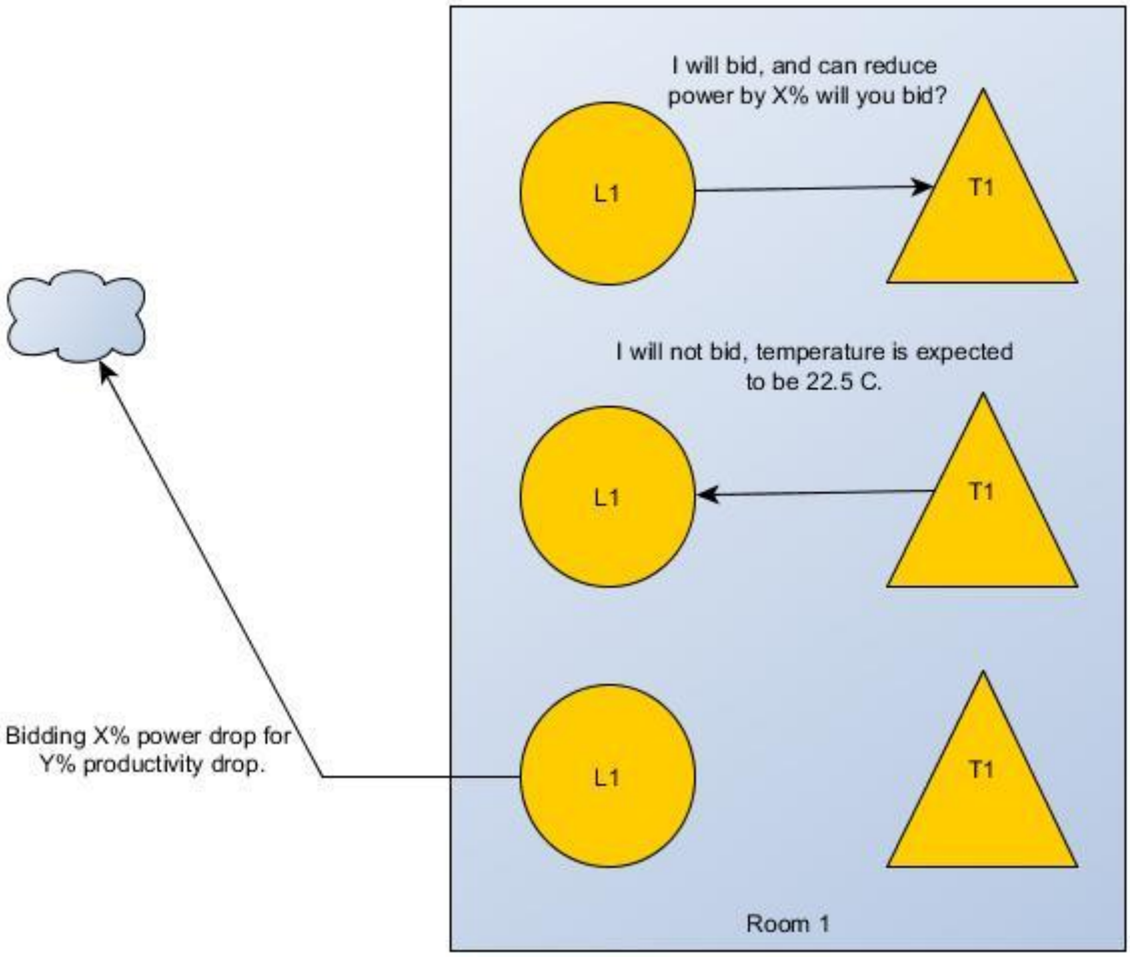


Figure 80: Only Lighting Control Agent Bids

In Figure 81, the Temperature control agent responds to the lighting control agent that it wishes to bid for this auction as well. It announces that it has a better power reduction promise. In this case, the Lighting control agent accepts that the bid of the Temperature controller is better and informs that it should bid. The temperature controller agents then bids for the auction. As a result, only temperature is reduced.

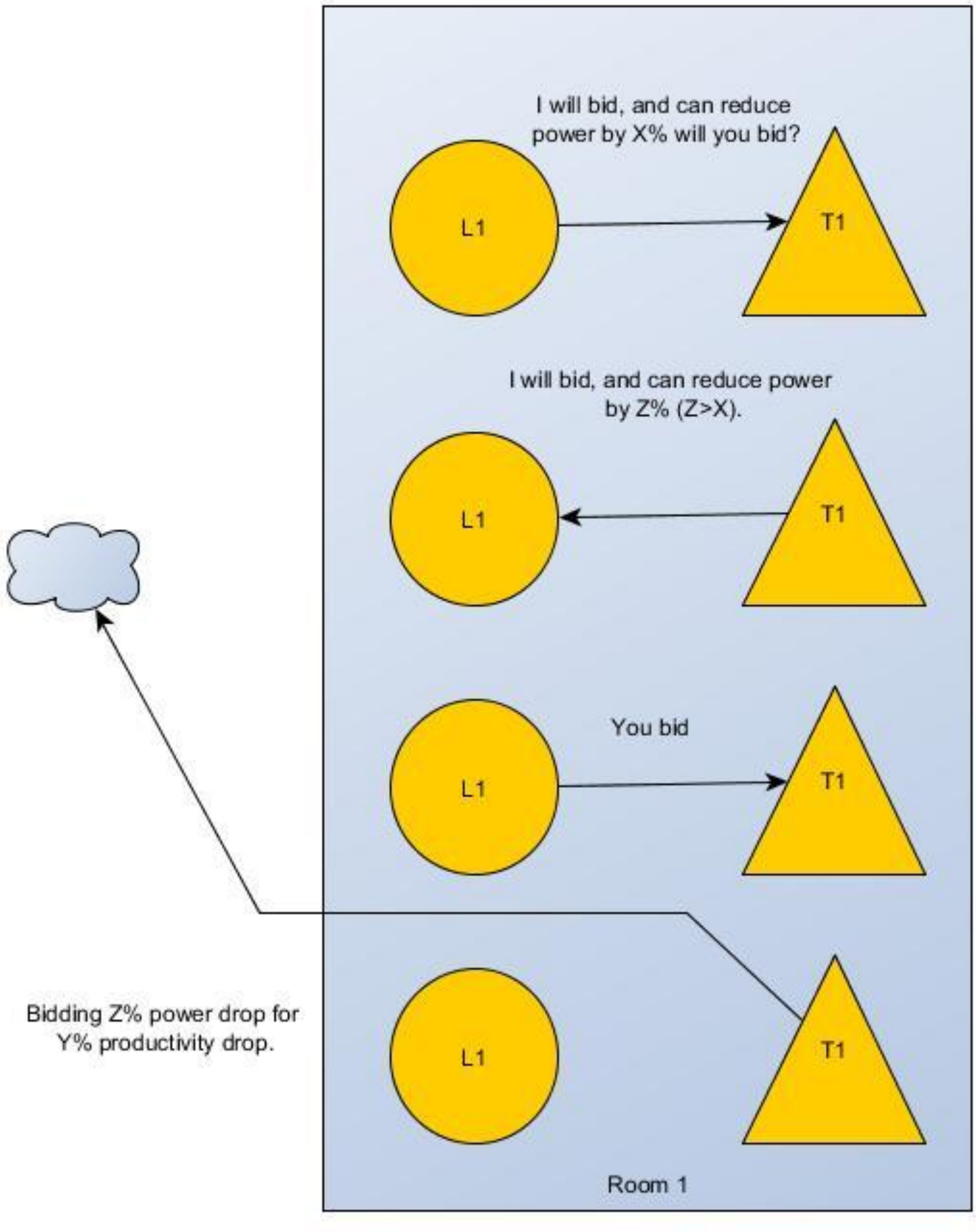


Figure 81: Only Temperature Controller Bids

In these examples, for the sake of simplicity, either temperature or lighting is allowed to be reduced. If more complex discussions between the local temperature controller and lighting controller can be carried out, then both can contribute to power reduction by sharing the task among themselves.

6.14.2. Office Equipment and CNDSR

The prospect of implementing office equipment into CNDSR discussions is easier provided that productivity aspects of these on the occupants can be quantified. For example, an LCD monitor might reduce its brightness or a photocopier might work at slower speeds during the DSR period. In all of these cases, the power consumption versus productivity loss needs to be quantified precisely so that the resulting condition in the office is accurate.

6.15. Conclusion

Lighting system has been identified to be the most difficult element to control in an office building during a DSR scenario because of its distributed nature, susceptibility to intervention and varying degree of configuration. For this reason, implementing a central control system to control lighting is likely to be impractical. On the other hand, similar problems are solved in other fields with the help of distributed programming and multi agent systems. Literature review has shown that these methods are successfully applied in various fields which include power systems and building management.

Contract Net has been identified as a viable method to solve the DSR control problem. CNDSR which is an adaptation of CNET to DSR is proposed to achieve DSR without involving a central command system. In CNDSR lighting zones are represented as agents with goals. User interventions are handled by auction and bidding process that allows power consumption to be kept at designated levels while maximising productivity and maintaining the lighting zones in comfortable conditions.

A simulation environment in MATLAB has been developed to test the ideas. Various user intervention and zone configuration scenarios are tested. The results of the simulations have shown that CNDSR can provide the same functionality as a central control system while offering many other advantages such as flexibility and improved reliability. In the following chapter, the suitability of underlying communication infrastructure to support CNDSR will be investigated.

7. Integrating Multi Agent DSR Control to Building Automation Systems

7.1. Introduction

In this chapter, the problem of implementing an agent based control using a building automation protocol is tackled. The agent based control in this case is the CNDSR protocol and the bus communication standards are standards that are utilised for building automation. Initially, literature review is carried out to determine how other researchers approached the problem of implementing agent communications on fieldbus networks. Then, these methodologies are combined with building specific data to determine if building automation networks are capable of handling multi agent communications like CNDSR.

7.2. Literature Review

The key element in multi agent systems is communication. When it comes to building automation and control, communication standards that are prevalent in this area have evolved significantly over the years to meet the demands of building automation systems. Kastner et al summarise the key differences between standards that are developed for process control (factory automation) and building automation [69]. They identify that building automation can be regarded as a special case of process automation. However, they outline some major differences which reveal that BAS's have not evolved to handle high data traffic. Since multi agent systems rely on extensive communication, application of MAS in automation networks has been a problem which was investigated by other researchers. In the following section, the literature review concerning this problem is presented.

7.2.1. Reviewing Communication Cost of Multi Agent Systems

In his PhD thesis, Palensky [108] discusses the role of agents in Field Area Networks (FAN’s). He lists some of the issues in implementing agent architecture to FAN enabled embedded systems as:

- Memory and resource constraints of micro devices (e.g. microcontrollers).
- Bandwidth of the communication network that link these agents.

Because of these limitations, he argues that FAN enabled real time control systems can only accommodate simple agent implementations as opposed to complex ones such as BDI based agent algorithms. Even though his thesis is closely related to building automation systems, no further evaluation is made regarding the problems associated with agent communication in Field Area Networks.

Unfortunately, it is not possible to find many research papers that are focused on agent implementation in FAN's. Part of the reason for this is the diversity of the two disciplines and the expertise required to operate a FAN based system. To overcome the latter difficulty, some researchers have developed agent platforms focused on real time systems in order to investigate agent communication algorithms. SIMBA is one of these, as explained in [109]. It is meant to operate on a Linux RT operating system and communicate using Foundation for Intelligent Physical Agents (FIPA) Agent Communication Language (ACL). The authors give building automation as an example though they have not made it clear how the underlying communication infrastructure would be implemented. As demonstrated in their paper, because communication in FAN is expected to be slow, predicting the performance of agent control algorithms using agent development platforms is difficult. For this reason, although such platforms are useful in developing theory, they will likely fall short of predicting real time performance of agent based control schemes.

Another obstacle in assessing FAN's performance is defining the exact ACL. Researchers usually choose standard ACL's when implementing their agent communications to their platforms. ACL's defined by FIPA for CNET is particularly popular. This approach of using a standard ACL to assess the communication infrastructure might not deliver accurate results as explained in Theiss et al's paper [110].

Theiss et al argue that most agent work that is available in the literature is focused on management layer and more attention should be focused on the application. They also argue that overall performance of a MAS greatly relies on how more complex interactions between agents are realized. They give an example of directory facilitator service defined under FIPA ACL. This service might not be necessary in a FAN based ACL because agents can send broadcast commands rather than enquiring to the directory facilitator (DF). Also, multicast messaging can be used to submit and receive bids rather than peer to peer communication. They then implement the solution on a network simulator that models full duplex Ethernet with various assumptions for transport delay, frame size and message payload. The results show that broadcast messaging is more efficient compared to peer to peer communication when it comes to utilising the communication bus.

7.2.2. Discussion of the Literature Review

Based on the ideas of these papers, several conclusions can be drawn about MAS in FAN's:

- Agent platforms are useful in developing algorithms for management layer. When it comes to developing such platforms for real time systems, the underlying communication infrastructure has a lot of influence on system timing hence without a strong network simulation component, it is unlikely that such platforms will deliver useful results.

- ACL's defined in standards might not be suitable for testing the performance of a communication network for several reasons. First, they might not be realistic because of the extra and unnecessary overhead that they impose. For example, a directory facilitator is defined in FIPA. However, as Theiss argues, such a facilitator might be unnecessary in a bus system where every agent can be discovered with a broadcast command. Second, the structure of the underlying communication system might have an influence on how the ACL is implemented. This might cause deviation from the standard ACL making it irrelevant.

Hence, an assessment of BAS can only be carried out with a realistic implementation of the underlying protocol. The rest of this chapter will be dedicated to this task.

7.3. Measuring the Capacity of Building Automation Systems to Carry Out Agent Communications

As mentioned in Chapter 2, three of the BA standards that are popular throughout the world are BACNet, LON and KNX. Among these KNX has a slow (9600 bps) bit rate on its popular twisted pair physical layer therefore it provides a good benchmark for testing MAS communication. This slow speed is likely to have adverse effects such as bus load and delays when agent tasks are to be carried out. In this section, parameters that are used to measure bus load are determined.

7.3.1. Bus Load in KNX Standard

Like every standard, KNX prohibits any device on its network from creating excessive bus load. In this standard [72] bus load is defined as "... the ratio of the time the bus is occupied by a signal transmitted by a single or several bus participants divided by the measured time." It is a percentage value:

Busload [%] = 100 * Sum(Bus Occupancy Time of a Character i)/measuredTime

Busload is an important parameter in a CSMA based communication system like KNX. It affects both the reception and response of the nodes. When it comes to reception, excessive bus load might overwhelm the nodes causing them to miss frames that might be addressed to them. It also influences the time it takes the node to deliver its message to the bus. Modern embedded systems are designed to operate at high frequencies therefore reception should not be a major concern for them. However, transmission is medium dependent and therefore is independent of the speed of the hardware that is sending the message. In a BAS, excessive delay might cause various problems as discussed by Theiss et al. [110]. For example, if a read request is received by a node, it might have to respond within a given time frame for its result to be valid.

For these reasons, KNX Defines 3 busload categories. These are high, medium and low busload.

High Busload (>75%): The devices are expected to receive and handle all the information. For answering, the device is expected to answer to at least one frame that is addressed to itself but is allowed to drop subsequent frames with a read request and send BUSY response.

Medium Busload (5 to 75%): Almost every device is expected to send in a medium busload condition. Some exception is given to devices that might have limited hardware preventing them to carry out certain operations such as writing to EEPROM.

Low Busload (<5%): Devices need to be able to send and respond without any issues under this busload.

Based on this information from KNX, it is possible to argue that:

- If there is excessive busload, it might take very long for the particular node to transmit its message.
- If a read request is made, the nodes that receive the request might not be able to respond.

This is in line with Kastner et al.'s arguments about the capacity of BAS's. As they have explained in their paper, BA systems are not expected to handle excessive amount of information because of the nature of equipment in buildings. On the other hand, if agent communication is implemented, the amount of communication might increase significantly.

In order to estimate the additional bus load that would occur in a MAS communication, a network model can be used. In the next section, a network model that is developed by other researchers is used to calculate the additional bus load on a KNX network if an agent communication is implemented.

7.3.2. Network Model to Determine the Additional Bus Load on a BA System

To calculate the additional bus load that would incur on KNX, the communicating elements of the bus need to be modelled. This was done by other researchers who used different bus protocols to assess their performance. For example, in his paper, Plönings et al. [111] present a generic traffic model which can be used for such a purpose. They first present a basic device model and then define various events that generate network load. These events are categorised based on their nature such as stochastic, deterministic, or time triggered. They develop various models that predict the probabilities of these events in a building environment. Finally they use their model to find the utilisation of a common bus that is based on LonWorks. The resulting utilisation is found to be around 2% though they note that further assessment is required for a better estimate.

Even though their approach in modelling targets a much comprehensive simulation purpose (such as weather or stochastic events), it gives valuable insight in how agent communication in a FAN can be evaluated before it is implemented.

The model that they use to determine network load is based on a simple node representation as shown in Figure 82. In this representation, a device consists of inputs where it receives telegrams, outputs where it sends telegrams and gain where it processes the telegrams. The most critical section in this device model is the gain where the number of telegrams might be multiplied by a factor before they are transmitted to the output.

A simple example can be used to explain the operation of a node acting as a lighting actuator that controls two lamps in a network. In this case, the actuator receives switch command from its input, instructs two lamps to switch on and reports the status of the two lamps from its outputs. Hence, the actuator has a gain of two because for every switching instruction, it generates two other telegrams.

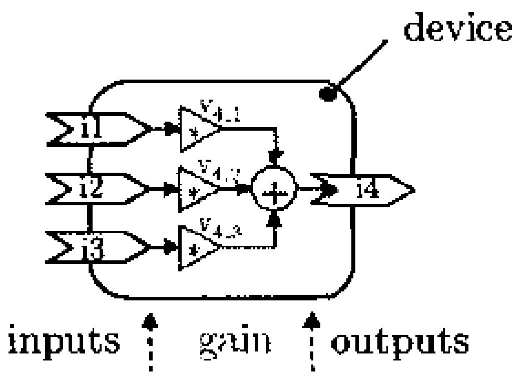


Figure 82: Node Representation of Plönnigs et al. [111]

7.3.3. Network Analysis of a Basic CNDSR Algorithm

Network analysis of a KNX bus that utilises CNDSR can be done as explained in Theiss et al’s paper. In this case, modelling the behaviour of a manager agent would be sufficient to calculate the additional load that will occur on the system since there would only be one active auction at any given instance.

Three stages that will lead to bus load on BAS can be defined for CNDSR. These stages, which are depicted in Figure 83 are as follows:

Stage 1: Auction Announcement

After a user intervenes to a lighting zone and changes the light level to a value that is different than is set by the central DSR controller the zone controller broadcasts the auction to other zone controllers.

Stage 2: Bid Collection

When a zone controller receives an auction announcement, it first determines whether it will be able to bid or not. If it decides to bid, the number of bids will depend on the amount of contribution that this zone controller will make. The number of messages generated on a network will be the sum of bids that each bidding zone controller makes after receiving an auction.

Stage 3: Winner Announcement

Once the manager receive the bids, it decides on the winning bids and announces the results. The number of results depend on the number of different contributors.

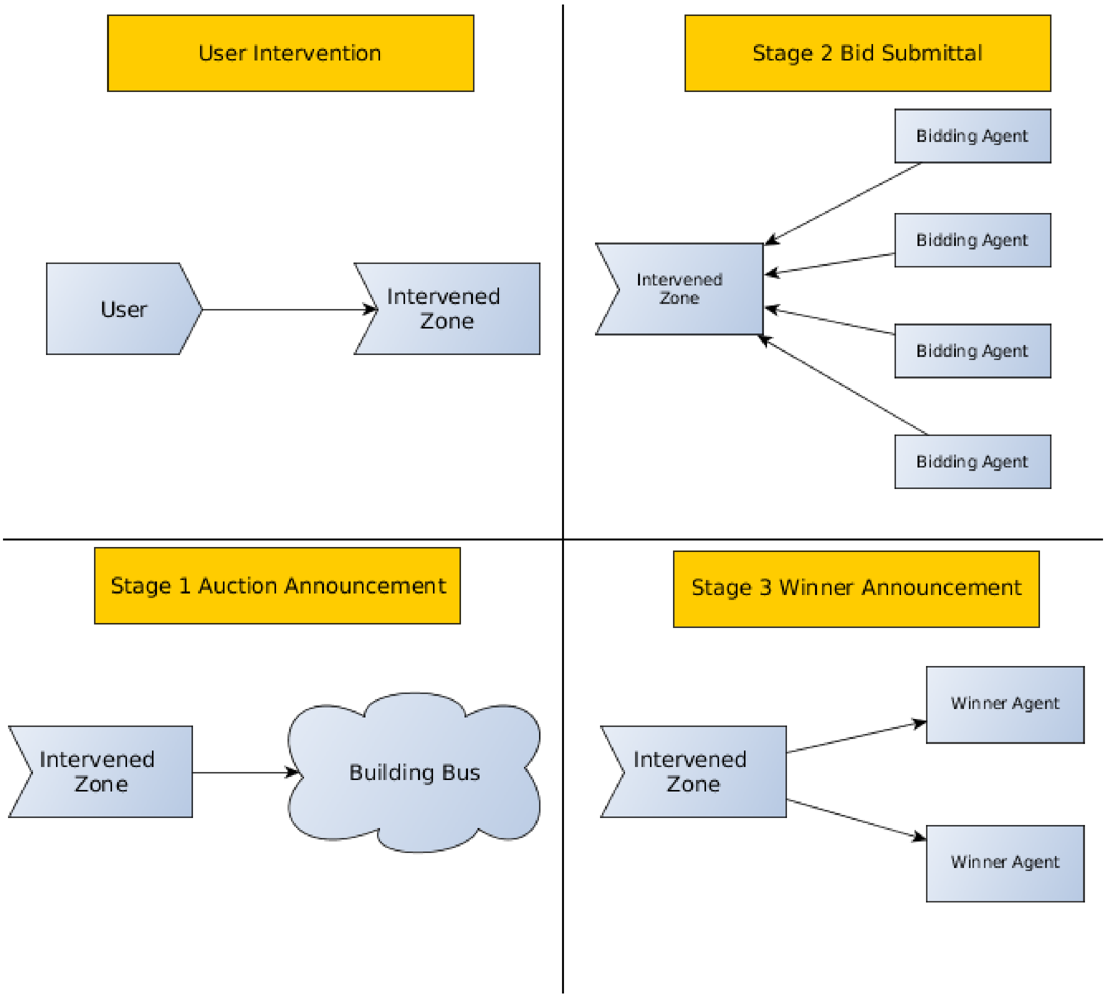


Figure 83: Communication Stages in CNDSR

In this case, every user intervention results in a number of message exchanges among different nodes which can be formulated as follows:

NM T= NM1 + NM2 + NM3 where

NMT: Total number of messages for each intervention

NM1 - NM3: Number of messages generated in stages 1, 2 and 3.

For Stage 1, the number of messages that are generated is equal to the number of user interventions carried out at that instance.

For Stage 2, the number of messages depends on two factors, the number of zones that are bidding and the size of messages of each bidding frame.

For Stage 3, the number of messages depends on the size of the request, the resolution of bids and the variety of bidders that are awarded a contract.

It can easily be estimated that the majority of the communication overhead will occur on Stage 2 of the model. This is because all of the agents that receive an auction message will want to submit their bids. In this case, a key variable that will determine the success of the communication is the number of agents that are expected to communicate on the market. This variable depends on the actual application of the protocol which can only be determined with real data.

7.4. Data to Estimate the number of Agents in a CNDSR Application

In a lighting control application which utilises CNDSR, agents will be in the form of lighting zone controllers. Zone control, arrangement of switch groups and the usage of a lighting zone might depend on the architecture of a building. In order to have fair estimate of this information, lighting zone control information of office buildings with various floor areas is collected from a company that provides lighting control devices and commissioning services in the UK. The information is based on building floor drawings and based on these drawings, valuable information such as the number of light fittings, number of lighting zones, floor area usage (toilets, office, stairs etc.) has been extracted.

7.4.1. Data Extraction Methodology

Figure 84 shows a portion of an office building drawing that details the lighting infrastructure. The legend (Figure 85) provides details of the equipment that is depicted in the drawing. Each LCM (Lighting Control Module) is a KNX bus node that receives commands from a PD (presence detector) which is also a bus enabled node. The PD in this case is a zone controller that instructs the LCM to switch on or off the light fittings that are attached to it. Hence the number of PD's (and other similar sensors) indicates the number of lighting zones in an office building. The light fittings are indicated as A for standard luminaries, AE for luminaires with self contained emergency ballasts and B's for down-lighters. The wattage information is provided as well which allows the estimation of how much power is consumed by a specific zone.

For open plan offices, it can be observed that the control zones are homogeneously distributed throughout the building. Certain areas such as toilets, rooms or canteens might have different light configurations. The specific usage information in some buildings are available such as the one shown in Figure 85. It can easily be observed that there is a wide canteen area with kitchen and spaces to relax. This information might be valuable in determining the number of zones that can be used to shed during a DSR event.

7.4.2. Summary of Data That Has Been Processed

The plans of 24 buildings have been acquired. All of the buildings are intended for office use. Most of these buildings were newly built at the time of their commissioning.

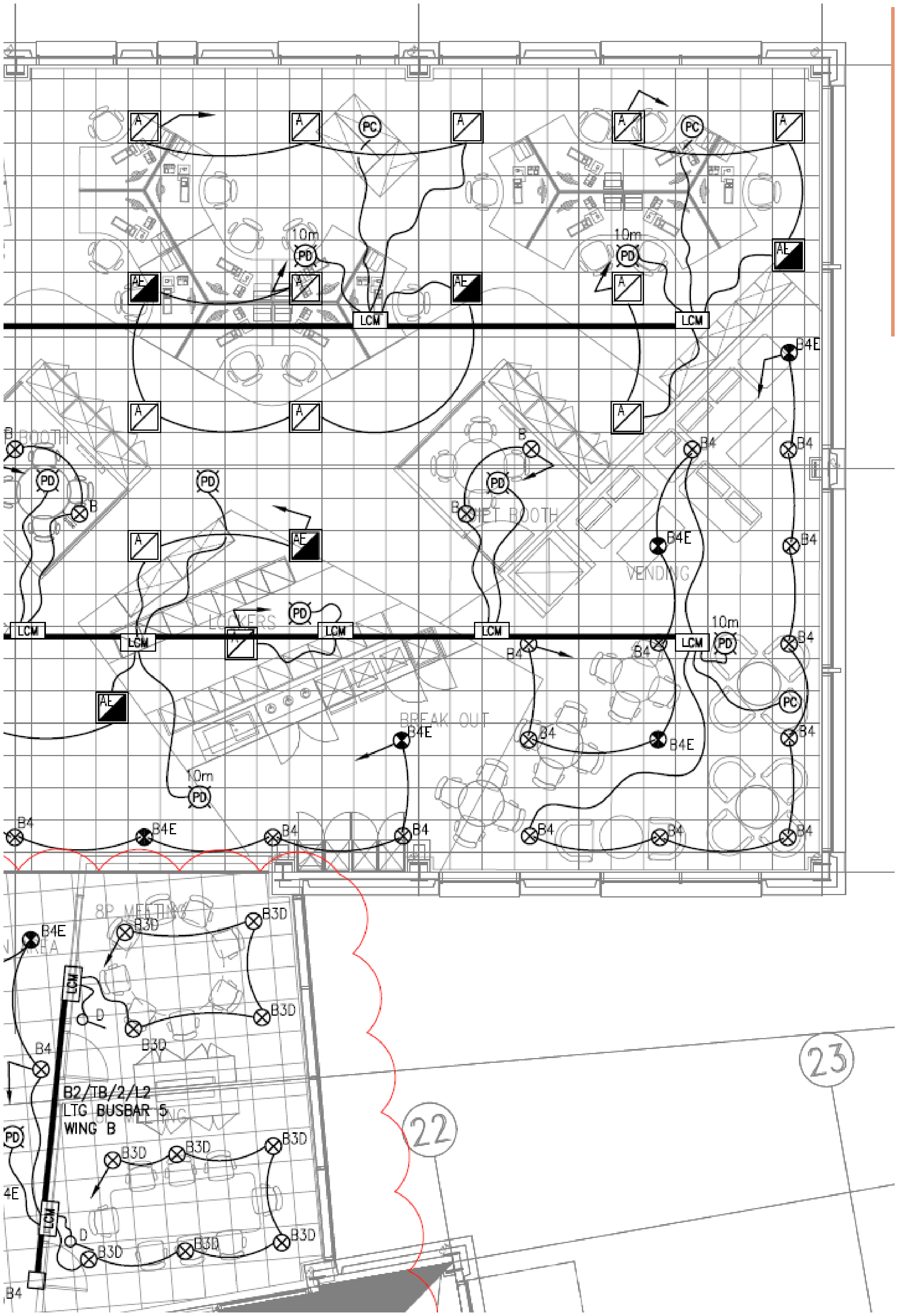


Figure 84: A portion of a building drawing that details an open plan office, canteen area, light fittings and nodes.

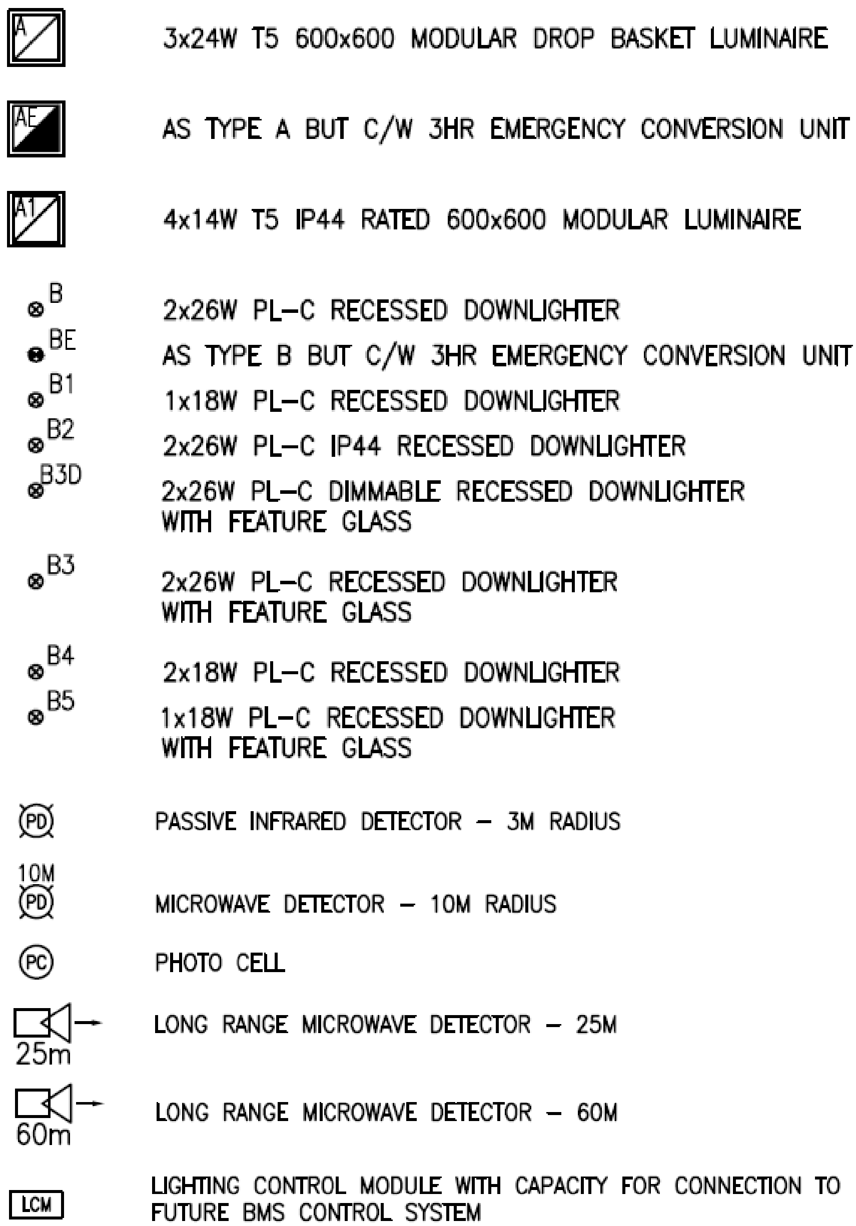


Figure 85: Legend of the drawing shown in previous Figure

Table 20 shows summary of the data that has been extracted from the drawings. For confidentiality, the name and location of the buildings are not disclosed. Figure 86 shows floor area of the buildings. Average floor area is 4760 square meters.

Table 20: Summary of the data that has been collected

Sample No	Type	Floor Size (m^2)	Number of Floors	Number of Zones Per floor	Number of LCM's Per floor	Total Number Of Fittings
1	Office	11340	1	422	234	1404
2	Office	6300	1	190	175	717.5
3	Research Office	1500	6	50	25	1500
4	Office	1300	10	44	30	2200
5	Office	1600	2	40	40	480
6	Office	450	1	17	17	102
7	Office	1740	5	60	65	1620
8	Council Office	3000	5	90	50	2250
9	Office	1200	2	40	36	432
10	Office	850	2	25	25	300
11	Police HQ	1200	2	40	50	500
12	Office	2200	2	100	60	800
13	Office	650	1	22	21	88
14	Office	1500	1	70	40	280
15	Office	700	14	20	15	1822.5
16	Council Office	1200	7	38	24	1512
17	Office	1200	2	31	31	372
18	Office	1375	2	33	33	330
19	Office	1000	2	18	16	252
20	Office	800	2	16	20	320
21	Design Office	1200	2	43	40	720
22	Office	500	4	16	16	336
23	Office	600	4	15	15	360
24	Health Office	2000	1	90	64	450

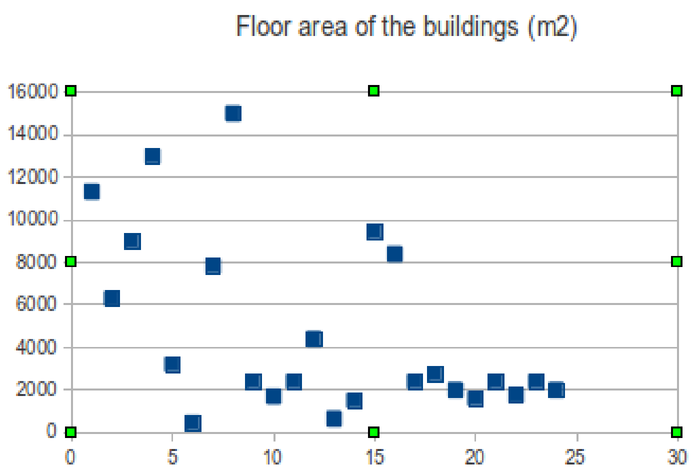


Figure 86: Floor area of the sample office buildings.

7.4.3. Floor area per zone

When the number of zones in each office drawing is counted and divided by the floor area of the building, average floor area per lighting zone can be determined. Most buildings had similar number of zones per floor area though some buildings had larger floor areas. Average floor area per zone is 32 m^2's. Figure 87 shows average floor area lighting zones in each building.

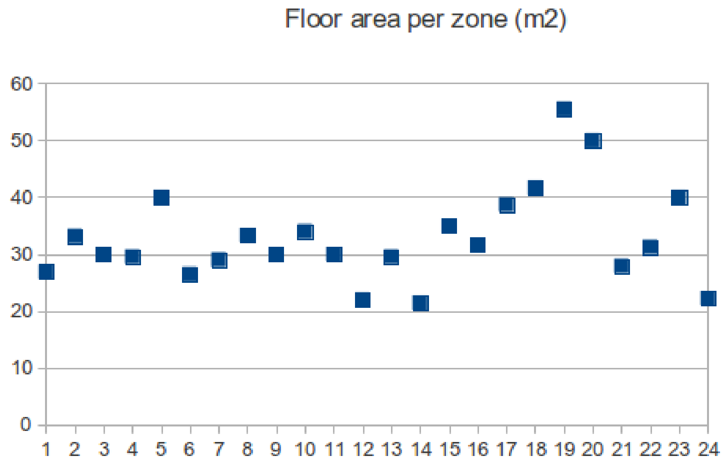


Figure 87: Floor area that is controlled by a zone controller.

7.4.4. Number of light fittings and power per zone

Average light fitting is calculated to consume 67.5 Watts of power. When this is combined with the average number of light fittings per zone, the amount of power that is under control of the zone controllers can be determined (Figure 88). Average power consumption of each zone is found to be 375 Watt's. It can be observed that certain buildings consumed more power per zone. This might be caused by the fact that such buildings are designed to be illuminated more than average because of their intended purpose. For example, Sample 21 is the head quarters of a yacht design and building company.

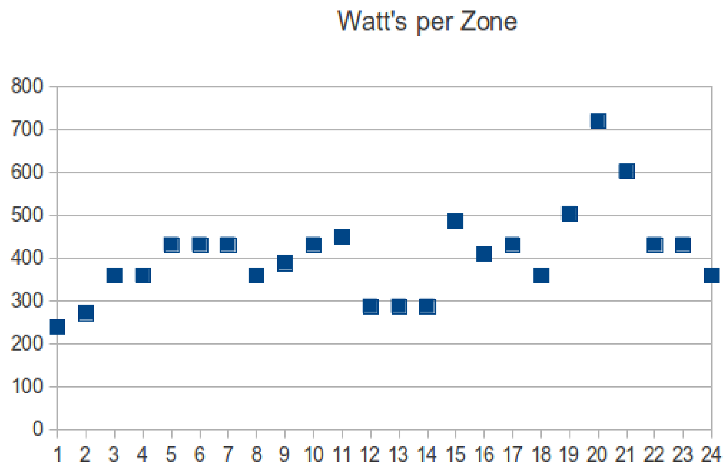


Figure 88: Lighting power controlled by each zone controller

7.5. Evaluation of KNX Bus that utilises CNDSR

The data collected in the previous section allows a realistic assessment of a building automation system to be made. In this section, this data is going to be used to evaluate KNX standard's ability to carry out agent communication using CNDSR protocol. Initially a simple frame that is defined by the KNX standard is used to determine the time it will take for it to be transmitted in the KNX bus. Then, the number of messages is going to be determined by calculating NM1, NM2 and NM3.

7.5.1. Estimating the Number of Messages on a KNX Bus

In KNX, Character Classes are defined for bytes in a frame that have significant importance with regards to the physical transmission of the frame. To calculate the amount of time required on the KNX bus to transmit a frame, the time it takes to transmit the character's needs to be identified. A simple frame would have three character classes: Start of Frame Character, Inner Character (Payload) and ACK Character. Each of these Characters (or Char's) require different bus times to progress through the channel. These are as follows:

Start of Low Priority Frame Char: 64 Bit Times

Inner Frame Char: 13 Bit Times

ACK_Char: 26 Bit Times

Where 1 Bit Time equals to 1/9600 seconds on twisted pair.

The reason that bit times are different for various Char's is that physical layer requires the bus to be free for certain amount of time before a bit is transmitted. In the simple frame case, the bus is expected to be idle for around 60 bit times before its transmission starts. Afterwards, 26 bit times is required for the ACK Char to arrive to indicate a successful transmission.

Based on the example above, for a simple switching telegram of 8 Bytes, the total time is 64+8x13+26 = 191 bit times (Around 20.21 ms).

Because there is enough information on the number of zones that are expected to bid to an auction, the capability of the bus to handle CNDSR can be calculated. If the number of bit times for each stage is defined as NS where NS being equal to the sum of total bit times for each of the three stages mentioned in Section 7.3.3, then it can be said that:

NS = NS1 + NS2 + NS3

(22)

In this case, the total number of bit times need to be calculated for each stage of the auction process. This can be formulated as follows:

NS1 = NA1xFS1

NS2 = NA2xPB2xFS2

NS3 = NA3xFS3

(23)

Where

NS1 – NS3	: Bit time it will take to complete stages 1 to 3
NA1	: Number of interventions for stage 1
FS1	: Frame Size for the auction announcement frame
NA2	: Number of agents on the bus
PB2	: Probability of an agent willing to bid to an auction
FS2	: Frame size of the message that carries the bid
NA3	: Number of messages sent at stage 3 to announce winners
FS3	: Size of frames that announce winning bids

Determining NS1

Number of Interventions on Stage 1 (NA1): This is equal to the number of times a user intervenes at a given interval of time. This value is assumed to be equal to 1 because the purpose of this example is to determine the number of messages during a single auction process.

Frame Size for the auction announcement frame (FS1): The auctioneer requires the following bytes in order to announce the auction:

6 Bytes for KNX Headers (Address, destination etc).

1 Byte: Auction ID

1 Byte: Required amount of power

Total Frame Size (Including headers): 8 Bytes

Determining NS2

Number of Agents on the Bus (NA2): In CNDSR case, the number of agents is equal to the number of lighting control zones in the building. The size of the office building that was modelled in Chapter 3 was 5000 m^2. The data presented on Section 7.4 showed that on average, 32 m^2 per zone is expected per lighting controller. Therefore for this building, the number of zones will be 5000m^2/32(m^2/zone) = 151 Zones.

Probability of an Agent Bidding to an Auction (PB2): This parameter depends on how the zones are set up. At the start of a DSR period, all of the lighting zones would be able to contribute to DSR. In this case, the probability of an agent bidding to an auction is expected to be close to 1. However, if there are lighting zones that are constrained (prevented from contributing to DSR), this probability will be smaller. For a worst case scenario where all of the agents on the bus are expected to bid, PB2 can be considered as 1.

Frame size of the message that carries the bid (FS2): In order to respond to an auction, the bidders need to disclose the amount of power contribution versus the amount of productivity loss in their zones. Based on the collected data, each zone was expected to consume 375 Watts on average at 600 lux. If these zones are allowed to drop to 250 lux, the amount of power reduction is expected to be (350/600)x375 = 220 Watts. As discussed in Section 6.9.3.6, the bids will be submitted for a unit power level. If 20 Watts is selected as the unit power level, there will be 11 Power – Productivity pairs. Each pair is expected to have a random bid id (at least 2 bytes). In this case, the bidders that are consuming the most power will require the following bytes to respond to an auction that requires maximum power reduction:

6 Bytes for KNX Headers (Address, destination etc)

11 times the following

2 Bytes: Bid ID

1 Byte: Power Reduction

1 Byte: Productivity Loss

Total Frame Size (Including Headers): 50 Bytes

Determining NS3

Number of message sent at stage 3 to announce winners(NA3): For every auction, there will be a single message to announce the winners therefore this value is 1.

Frame size of the message that announces the auction (FS3): The auctioneer requires the following bytes in order to announce the auction:

6 Bytes for KNX Headers (Address, destination etc)Number of frames sent at stage 3 to announce winners

11 times the following frame

1 Bytes: Bid ID that won the contract.

Total Frame Size (Including headers): 17

7.5.2. Estimating the Time It Will Take the KNX Bus to Deliver the Messages

The following formula can be used to determine how long it will take for a frame to progress through the channel:

T = (FT + FS x BT)/BR

(24)

Time (T): This is the amount of time it will take the frame to progress through the channel in seconds.

Fixed Time (FT): This is the amount of bit time the bus needs to be free before a frame is sent. It consists of the fixed start of frame char and ACK char.

Frame Size (FS): This is the frame size of the message in octets. In the case above, it was 50 bytes for the auction frame.

Unit Byte Time (BT): A frame consists of octets which might have various start and stop bits. Therefore unit byte time represents the number of bit times a unit byte will consume. This is 13 bit times for a standard byte.

Baud Rate (BR): This is the number of bits the communication channel is able to carry in one seconds.

When all of these values are added, NS can be found as:

NS1 = 64 + 26 + (13x8) = 191 Bit Times

NS2 = (64 + 26 + (13x50)) x 150 = 111000 Bit Times

NS3 = 64 + 26 + (13x17) = 311 Bit Times

NS = 111502 Bit Times

The amount of time it will take the bus to handle these messages is: 111502x(1/9600) = 11.6 seconds

7.5.3. Discussion

For a simple agent communication algorithm that is implemented on KNX, 11.6 seconds is a very long time. This long time frame will have two significant effects: Firstly, the ability of the system to respond to any user intervention that triggers agent communication will take very long time to be completed. Secondly, because the bus will be very busy with DSR messages such that other essential bus traffic will be impeded for a long time.

It should not be forgotten that this example is based on a worst case scenario for the building that is modelled. Several factors might reduce the amount of agent communication. For example, not every node is expected to bid in the auction because of its limitations. Also, it is assumed that the auction is for highest power reduction (which is 220 Watts). In most cases, there will be a request for lower power reduction and this would translate into bids that require smaller frames.

If the number of bidders is expected to be half of the total, and the amount of auction is halved as well, the result for NS2 would be:

NS2 = (64 + 26 + (13x25) x 75 = 415 x 75 = 31125 bit times which is 3.24 seconds.

Hence even an optimistic scenario shows that when there is a user intervention which triggers agent communication, the bus will be flooded with messages for a significant amount of time.

Based on these calculations, this simple agent based communication cannot be carried out on a bus system like KNX unless a solution that can prevent excessive bus load is presented. This will be discussed in the following section.

7.6. Solution to the Problem

The exercise carried out in Section 7.5.2 shows that the majority of agent communication occurs on stage 2 where bids are collected. The communication overhead caused by both NS1 and NS3 combined is 424 bit times which is only 53 milliseconds. Hence a clever solution is required to address the problems caused by bid collection on Stage 2.

The problem of bid collection taking too long can be separated into two main components:

- The first component is excessive busload caused by simultaneous bids. This would cause the bus to be flooded with messages hence communication that is critical to building controls might be prevented from being transmitted at a reasonable time.

- The second component is reducing Auction Completion Time (ACT). This would prevent the DSR actions from being completed in reasonable amount of time

In this section, these two components will be addressed separately for a complete solution to the problem.

7.6.1. Preventing Excessive Bus Load

Preventing excessive bus load by managing it can only be achieved by allowing the potential bidders to bid in a controlled way. This can be done by querying and collecting the bids individually from the bidders. Extra time can be allowed between the queries to reduce bus load. One possible method of achieving this is to have the manager agent querying the bidding agents individually (one by one). This way, the manager agent can manage the amount of messages on the bus by managing the timing of its queries. This solution would fix the first problem. However because of the extra allowed time to free the bus, the amount of time it would take to collect the bids would increase exacerbating the second problem (auctions taking too long to complete during a DSR event). Therefore another solution is required. This solution can be found by investigating the properties of CNDSR protocol.

In CNDSR, there will only be small number of winners compared to the number of bidders. This means that most of the bids will be discarded by the auctioneer. If the bidders can be prevented from submitting these bids, the amount of message traffic will decrease. This can be done in a multicast messaging system because the bidders will be able to assess whether their bids can win over the others. In this case, the amount of traffic will depend on the probability of each bidder having a bid better than the bids previously submitted.

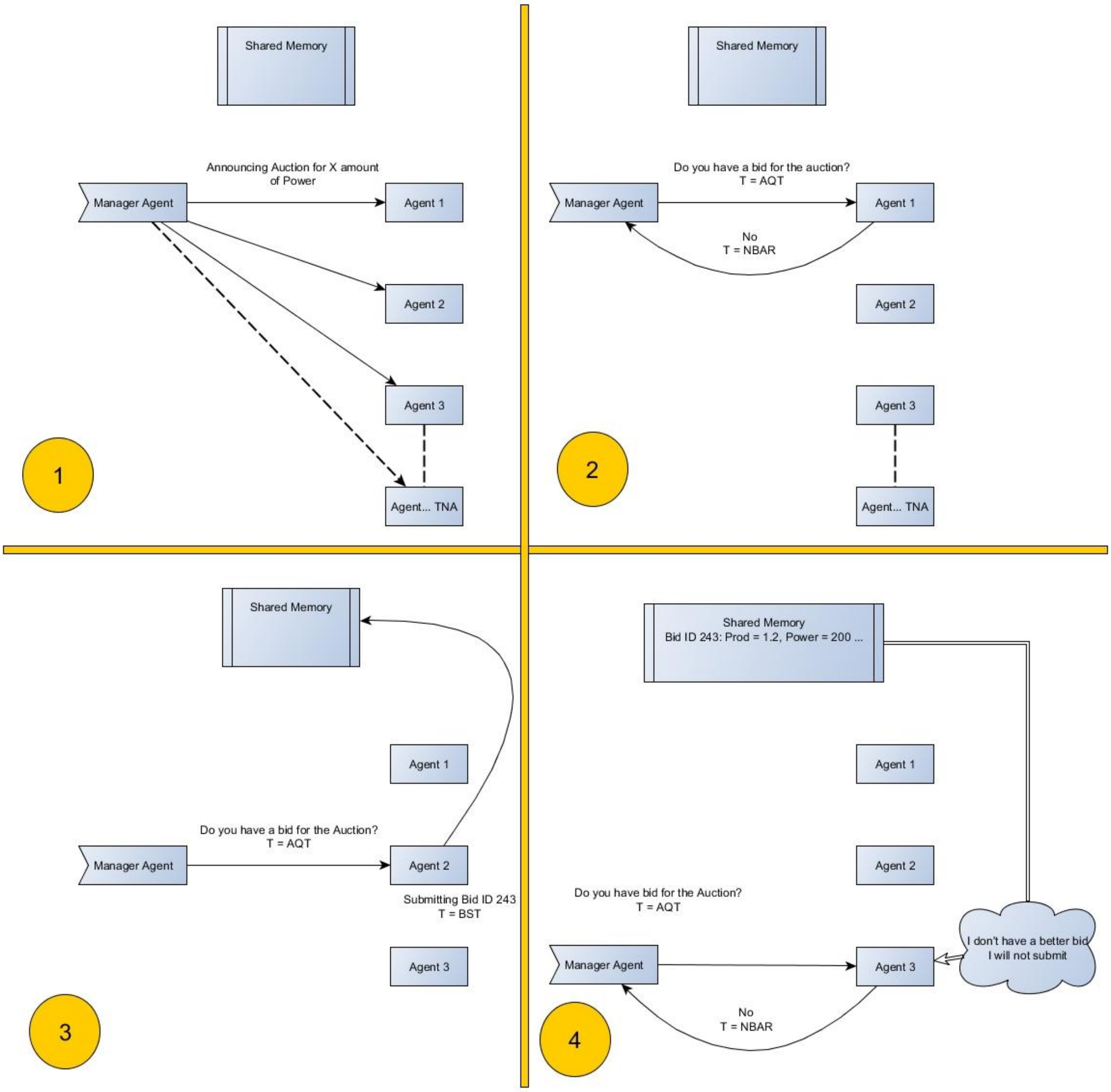


Figure 89: Token based Auction mechanism - Agents check shared memory before submitting bids

Simplified version of the bidding process in Token based Auction is depicted in Figure 89. In this figure, the shared memory area is capable of storing only one bid whereas in a realistic application, this will be capable of holding several bids. The operation of the algorithm depicted in the figure is as follows:

- Manager agent announces an auction to all of the agents. It then starts querying the agents one by one and asks if they want to bid.
- If the queried agent is able to bid it checks the existing bids which are stored in the buffer.
- If there aren't any bids, the agent places its bid.
- If the buffer is not full, the agent compares its bid with the others'. If it has a better bid, it writes its bid on top of the auction buffer and shifts other bids.
- If there are bids but no empty slots and the agent has a better bid, it removes the worst bid from the buffer and inserts its bid.
- If there are bids but no empty slots and the agent does not have a better bid, the agent passes the token to the next agent. In the case of Figure 89, Agent 3 in Step 4 does not bid because the existing bid stored in the shared memory is better than its own bid.

The time it would take to complete the auction can then be calculated as follows:

$$EB = PB \times (TNA)$$

(25)

Where,

EB : Expected Number of Bidders

PB : Probability of an agent having a better bid

TNA : Total Number of Agents

EB defines the expected number of agents bidding when queried by the auctioneer. This number is used to calculate the amount of time it will take the auction to be completed.

If the following variables are bid submit time and agent query time,

BST = (FT + AFS x BT) x EB

NBAR = (FT + RFS x BT) x (TNA – EB)

AQT = (FT + QFS x BT) x TNA

(26)

Where,

BST : Bid Submit Bit Time

NBAR : Non Bidding Agent Reply Bit Time

AQT : Agent Query Bit Time

AFS : Auction Buffer Frame Size

QFS : Query Frame Size

RFS : Reply Frame Size

To find the real time in seconds, we add the time and divide by Baud Rate.

ACT = [(BST + NBAR + AQT] x (1/BR) x BL

(27)

Where,

ACT : Auction Completion Time

BL : Bus Load Adjustment Factor

This equation shows that if the auctioneer queries every agent for their bids, there will be three operations that consume time:

- The time consumed by the query frame (AQT). This is sent to all agents.
- The amount of time it will take for the bidders that have a bid to submit (BST). In this case, EB is multiplied with the amount of time a bidding frame will be submitted.
- The amount of time it will take for non bidding agents to reply to the auctioneer (NBAR). This is equal to total number of agents minus total number of bidders.

The sum of these three parts is valid for 100% bus load. Hence if bus load is to be reduced, the auctioneer needs to put a delay between subsequent queries to allow other (non-Agent) traffic to progress through the bus. In this case, the total amount of time for the bidding process to be completed will be BL times longer.

The auction method explained above satisfies the first problem because the amount of traffic on the bus can be managed by the manager agent. If sufficient time is allowed between the queries (using the BL variable), bus load which is caused by bidding agents will decrease. This will allow other more essential traffic to progress in the communication channel.

7.6.2. Reducing Auction Completion Time

The speed of a fieldbus is a determining factor in the completion time of an auction. As discussed in the previous section, in order to find the best agents for load reduction, the auctioneer needs to query every node on the bus. In this case, the limitations of the physical layer cannot be avoided. The time it takes for the smallest packet to travel to each node on a bus that is operating at 9600 baud rate and that has 150 nodes is around 3 seconds. After adding the methods discussed in the previous section this time will be even higher.

Auction completion time becomes a greater problem if agents need to start an auction simultaneously. In a building where there are 150 zones, 15 zones calling out an auction would need significant amount of time (in the order of 10's of seconds) to complete their auctions. In a one off case, this time frame might be acceptable. However, load prioritisation described in the previous chapters means that the central controller might need to change lighting set points rapidly in order to mitigate the effects of consumption change caused by other loads. In this case, the quicker the LZA's can complete their auctions, the faster the DSR controller can change the setpoints making it a more efficient system. Two methods that can reduce the completion time of an auction is proposed in this section. These are the token and auction buffer.

7.6.2.1. Token for Bid Synchronisation

In the case of the auctioneer querying the agents, agents need to respond regardless of whether they are willing to bid or not. If they can bid, they write their bids to the shared variable. If they cannot, they inform the auctioneer that they have no bid to submit.

The response time of an agent that is not willing to bid increases the auction time considerably because the fixed time cost of submitting a frame is high in CSMA networks. This response can be avoided if the query mechanism is handled by the agents themselves rather than the auctioneer. In this case, once an auction starts, a token would be passed from one agent to the other. The agent that has the token would either bid (if it has a valid bid) or pass the token to the next agent. This approach would reduce the number of responses caused by responding back to the auctioneer. Hence the total time it would take to complete an auction would reduce to:

ACT = [(BST + AQT] x (1/BR) x (BL)

(28)

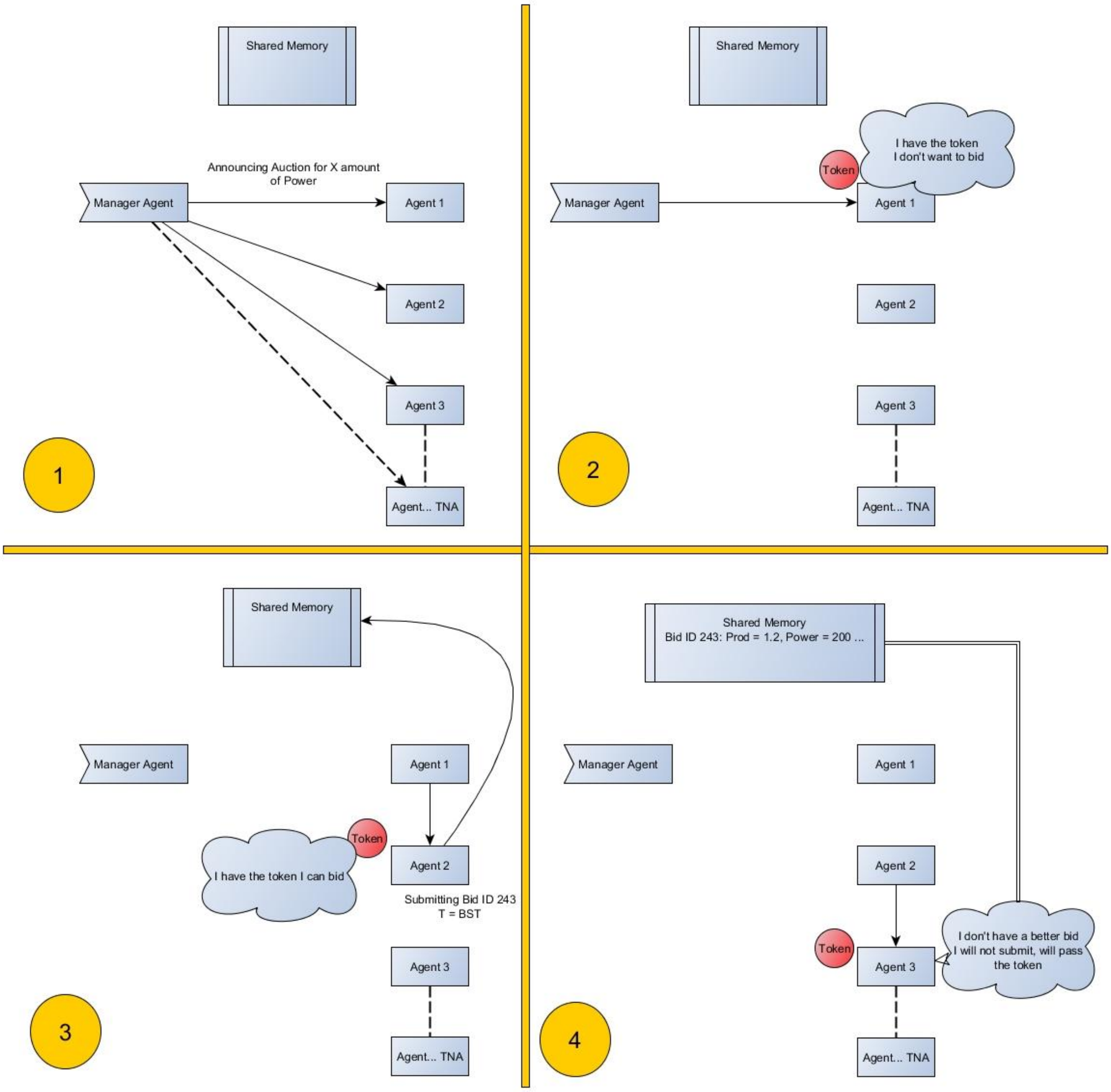


Figure 90: Token based auction

This is because as shown in *Figure 90*, the manager agent does not query potential bidders. Instead, the agent pass on a virtual entity called 'Token' to organise their bid submitting times. Because the response time caused by non bidding agents is eliminated, this algorithm works more efficiently compared to SA. This can also be understood in equation 28. As can be noticed, the NBAR component is removed from the equation. Because NBAR is equal to AQT minus BST and BST is expected to be small, removal of NBAR reduces ACT considerably.

7.6.2.2. Adding an Auction Buffer

The token mechanism reduces the time it takes to complete an auction though it would still take longer than 3 seconds on a 9600 baud rate bus. Another innovation is required to reduce it further.

If agents can submit their bids before an auction starts, the auction would be completed instantly. This can be achieved by agents bidding continuously to a virtual auction that is called for a large power reduction request. In this case, the agents' bids will already exist in the auction buffer and when a real auctioneer calls for power reduction, the agents whose bids sum up to the value that is auctioned would reduce their consumptions.

Another advantage of having a virtual auction is, if the power that is called in the virtual auction is large, there will be enough bids to carry out another auction right after the first one is completed. For example if the virtual auction is for 1000 watts and a real auction has called for 500 Watts of power, there will be bids to cover another auction worth 500 Watts. In this case, as the buffer size increases, the chances of carrying out simultaneous auctions increases as well.

This proposed algorithm which is called VTA (Virtual Token based Auction) algorithm is explained in more detail in Figure 91:

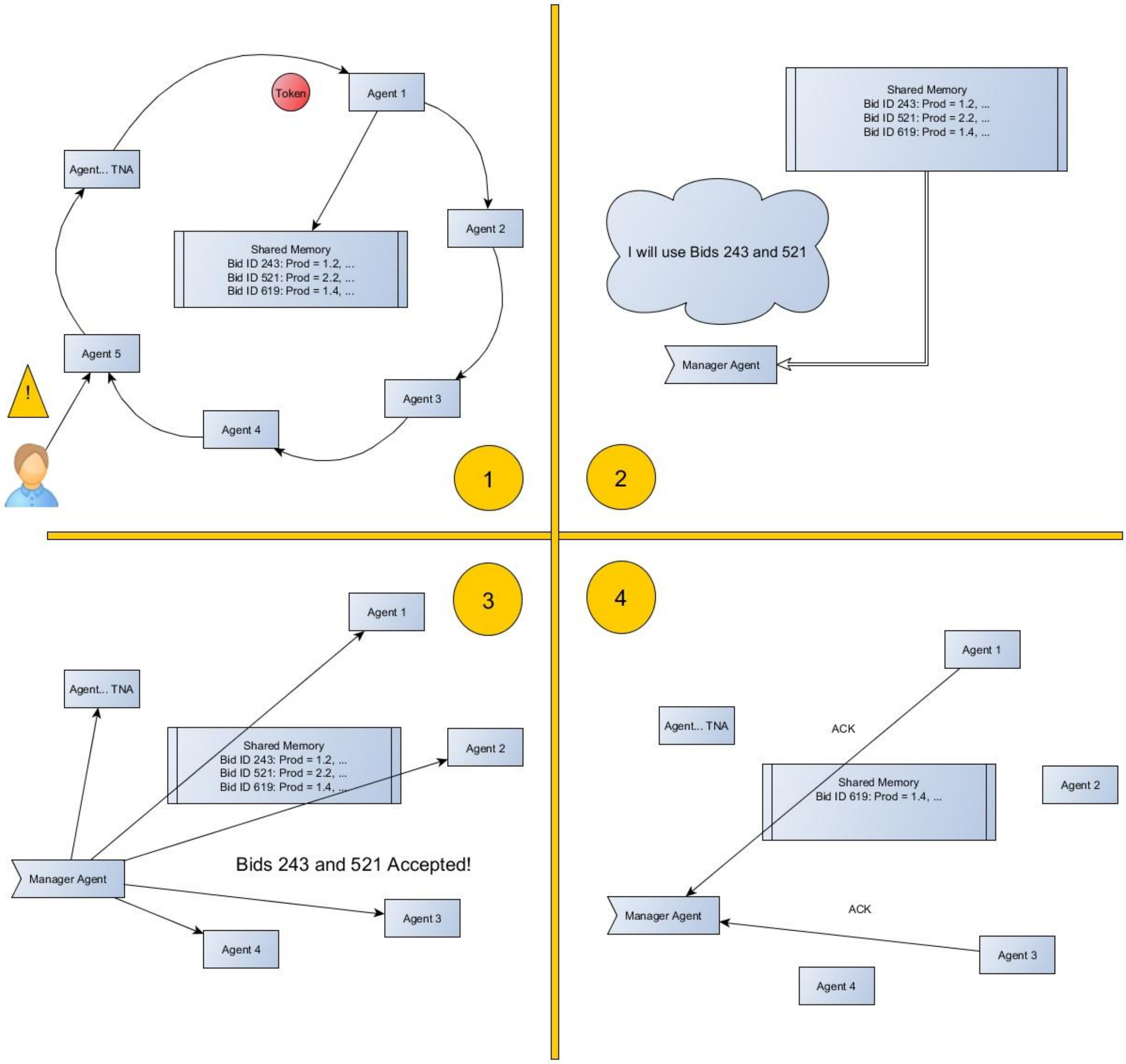


Figure 91: Operation of the VTA Algorithm

- A virtual token operates continuously on the bus. The purpose of its existence is to manage the bidding process and avoid bid rush. When there isn't an auction, the token is passed from one agent to the next.
- When an agent has the token, it has the chance to bid to a virtual auction.
- The virtual auction is for an arbitrary amount of power that is large.

- Once an agent has the token, it is allowed to bid for the auction. The agent can only bid if its bid is better than the existing bids on the virtual auction.
- After the bidding process, the agent passes the token to the following agent.
- When a user intervention occurs, the agent which controls the area becomes the manager agent. It checks the existing bids on the memory and then announces the winning bids to other agents. In this case, the virtual token stops circulating.
- The agents whose names are on the virtual auction buffer send a confirmation to the auctioneer and shed their loads.
- The auctioneer agent deletes their bids from the virtual auction buffer. The virtual token starts circulating again.

7.6.3. Specific Requirements of Virtual Token Based Auction

Compared to an individual auctioneer calling for an auction, VTA has some specific requirements that needs to be fulfilled.

Virtual Auction Type**:** In CNDSR, agents can both offer or request power through auctions. The virtual auction should cover both auction types. Therefore, two types of buffer is required, one for positive power, the other for negative power.

Bid Frame: If an individual agent is calling for an auction, the size of the data point is not required to be too large because the amount of power required by one LZA would be limited. On the other hand, if multiple auctions are to be covered, the size of the buffer needs to be substantially large. For example, the following bytes were fundamental in defining a bid for unit step of power:

2 Bytes : Bid ID

1 Byte : Productivity cost

1 Byte : Required power

If the amount of power is set as 200 Watts and the unit bid is 25 Watts, there will need to be 8 bid slots making the total size of the datapoint 4 x 8 = 32 Bytes. However in the virtual auction, the size of the auction needs to be large to cover large auctions. If 1000 Watts is to be covered, the size of the buffer needs to increase 5 fold to 160 Bytes.

7.6.4. Analysis of Virtual Token Based Auction

When VTA is employed, expected number of bidders (EB) increases because now, the buffer needs to be filled as well. Average number of bidders depend on how much the buffer is worth and on average how much each agent will be able to bid (Expected Bid Size):

NBC = BW/EBS

(29)

Where,

NBC : Number of Bids Collected

EBS : Expected Bid Size (Watts)

BW : Buffer Worth (Watts)

Expected number of bidders will be equal to the sum of agents bidding for the empty buffer (NBC) and probability of other agents bidding for the buffer that is already full

(TNA-NBC).

$$EB = PB \times (TNA - NBC) + NBC$$

(30)

Where,

EB : Expected Number of Bids

TNA : Total Number of Agents

PB : Probability of Bidding to a Full Buffer

In the case of the token algorithm, an agent either bids to the auction or passes the token to the following agent. In this case, the time that is consumed consists of the sum of bids for the agents that are bidding and the token passes (which indicate agents that are not bidding):

$$BST = (FT + AFS \times BT) \times EB$$

$$TCT = (FT + TFS \times BT) \times (TNA - EB)$$

(31)

Where,

BST : Bid Submit Bit Time

TCT : Token Circulation Bit Time

AFS : Auction Buffer Frame Size

TFS : Token Frame Size

Hence ACT is equal to:

ACT = BST + TCT

(32)

In this case, ACT is equal to the time it takes a token to circulate all of the agents. When the token finishes its circuit, there will be a number of bids in the buffer. This number indicates the number of auctions that can be carried out in unit time. Therefore total auction time is equal to auction completion time divided by the expected number of auctions covered:

NAC = BW/EAS

UAC =ACT/NAC

(33)

Where,

NAC : Number of Auctions Covered

EAS : Expected Auction Size

UAC : Unit Auction Time

This equation shows that in a VTA Scheme, when the token completes its circuit, the buffer will be full of bids which are worth X Watts of power. This allows NAC number of auctions to be carried out instantly. The size of NAC depends on how large the buffer is and how large the expected auction is to become. Hence, the time required for a single auction to be completed (UAC) is found by dividing ACT with NAC.

7.7. CNDSR Using Bus Communications: Comprehensive Assessment

In the preceding sections, not only the problems associated with running agent communication on a building automation system are highlighted but also solutions to these problems are proposed. However, the effectiveness of these solutions can only be revealed with a sensitivity analysis.

A simple example is the number of agents that are expected to communicate on the bus. It is assumed that this number is expected to be 150 on an average sized building. However, what happens if the number of zones is higher than this average? Also, if another bus communication standard is utilised such as LON, can the problems be eliminated because it has a faster baud rate?

Not only fundamental variables like the speed of the communication network or the number of agents communicating on the bus but also other variables that depend on the implementation of the agent communication language might determine the success of the protocols. How will the size of the auction buffer mentioned in Section 7.6.2.2 affect the performance of agent communications?

For these reasons, sensitivity analysis that can reveal if CNDSR protocol can be used under a building automation protocol is carried out in this section.

7.7.1. Defining the Variables

Two sets of variables can be defined for sensitivity analysis: Variables that depend on the communication standard and variables that depend on the application.

Communication standards define various layers that influence ACT. Physical layer and data link layers define the baud rate which is the most important element. However, other layers such as network layer or transport layer define the sizes of the frames which also influence ACT.

Application is influenced by many factors such as user preferences (agent constraints), the size of the building, size of the zones, step size for the bids have an effect on the number of messages on the bus.

7.7.1.1. Variables that Depend on the Automation Standard

- Variables that Depend on the Physical Layer are:

BR: Baud Rate

FT: Fixed time

- Variables that Depend on Other OSI Layers are:

Frame overhead (adds to the payload)

BT: Unit byte time

In order to investigate the performance of the algorithms; twisted pair layers of the two known standards, KNX and Lonworks have been selected. The variables that are related to these standards are listed in Table 21.

Table 21: Frame sizes for TP for KNX and Lonworks

	KNX Twisted Pair	**LonWorks Twisted Pair**
Baud Rate (bps)	9600	78125
Fixed Time (bit time)	64: Start of Frame 26: ACK Frame 90: Total	23.5: Preamble 50: Idle Time Note: ACK is not mandatory in Lonworks 73.5: Total
Frame Overhead (bytes)	1: Header 1: Network 2: Source Address 2: Destination Address 6 : Total	1: Header 3: Address 1: Domain 2: Network 2: CRCs 9: Total
Unit Byte Time (bit time)	2: Idle 1: Start 8: Data 1: Parity 1: Stop 13: Total	8: Total (Data)

7.7.1.2. Variables that Depend on the Application

Variables that are related to the application are not fixed. For this reason, instead of assessing fixed values, possible ranges that might be used for sensitivity analysis are defined in Table 22.

Table 22: Variables selected for the application examples

Variable	Minimum	Expected	Maximum
Total Number of Agents (TNA)	30	150	1000
Expected Auction Size (EAS)		100 Watts	
Expected Bid Size (EBS)		100 Watts	
Unit bid Step Size (UBS)	20 Watts	25 Watts	50 Watts
Buffer Worth (BW)	500 Watts	1000 Watts	3000 Watts
Probability of Agent Bidding to an Auction (PB)	0.05	0.1	1
Auction Unit Buffer Frame Size For 1 Bid (AFS)	3 Bytes (10 Bit Bid Id, 7 Bit Power Reduction, 7 Bit Productivity Cost)	4 Bytes (2 Bid Id, 1 Power Reduction, 1 Productivity Cost)	
Query Frame Size (QFS)		2 Bytes	
Reply Frame Size (RFS)		2 Bytes	
Bus Load Adjustment Factor (BL)	0.25	0.5	0.75

Total number of agents depends on number of zones in the building which increases with the size of the building. This is expected to be around 150 in a typical office building. For small buildings, 30 Zones and for large buildings 1000 zones is selected.

Estimated auctions size is the size of average auction expected from the agents. This depends on the average amount of power that is controlled by the agents. Office building data showed that on average, agents controlled 375 Watts of power. If expected amount of reduction is around 100 watts, then agents that can not comply with this amount will auction for 100 Watts so this is selected as the expected value.

Estimated bid size is the amount of power each agent is expected to bid during an auction. This is the amount of power an agent is allowed to curtail therefore the expected value for this is the same as EAS.

Unit bid size depends on the minimum amount of power an agent can curtail. This can be increased up to the size of the auction size. If the value is too small, the number of bids for an average auction will increase significantly making it longer for an auction to be completed. However if the value is large, then the number of agents responding to an auction will decrease causing greater productivity cost. For this reason, 25 Watts is selected for this value with a range changing from 20 to 50 Watts.

Buffer Worth is the amount of power the buffer is expected to hold under the VTA scheme. If this value is high, more auctions can be completed in unit time. The upper boundary of the buffer is limited by two factors. First, the larger the buffer, the longer it will take the agents to submit their bids since they will be able to bid freely to the empty buffer. The expected value is selected as 10 times the expected auction size which allows 10 auctions to be covered once the buffer is full.

Probability of Bidding is a variable that is put in to have a plausible prediction of the traffic that would occur on the network. It is very hard to predict this because the probability of agents having a better bid than others depends on the application. However this value is expected to be low because an agent is not allowed to bid if there is already a bid that is equal to or better than its own bid therefore even under conditions where all of the agents are in a similar state, most of the bidding will be avoided. Based on these assumptions, 10% is selected the probability of bidding. The value might change from 1% (only one agent out of 100 has a better bid than what is on the auction buffer) to 100% (every agent has a bid better than the others).

Unit auction frame size is the number of bits a unit bid is expected to hold. As discussed earlier in the chapter, a unit bid consists of a bid id, power reduction size and productivity cost. Bid id needs to be random therefore 2 Bytes is selected to reduce the chance of bids having the same bid ID. The following two bytes would be the amount of power (up to 250 Watts) and productivity cost making the total 4 bytes. If a compact representation can be achieved, 3 Bytes can be used to represent all this information therefore this value is selected as the minimum.

Query frame size and reply frame sizes are selected as 2 byte frames since these need to submit very small information.

Bus load coefficient defines the amount of time the agents will hold the tokens before passing them on. This enables the bus to be free hence allowing other traffic on the bus to flow. The longer agents keep hold of the token, the longer it will take the auctions to be completed. The quicker they release the token, the higher the bus load will be. This value is changed 25% to 75% with 50% being the expected value.

7.7.2. Analysis Method

Two algorithms are tested, the simple Simple Auction (SA) algorithm explained in Section 7.3.3 and the VTA algorithm explained in Section 7.6.2.2. The variables that are of interest are; the amount of time it will take an auction to be completed and the number of auctions that can be completed in unit time. For SA algorithm, the two are equal. However for VTA, auction buffer allows multiple auctions to be held hence once the virtual auction is completed (or the token circulated).

The two communication standards deliver different results because of their various properties therefore both of these algorithms are tested under these two standards.

When it comes to sensitivity analysis, variables under the 'Expected' column in Table 22 were held constant and ACT are checked for; TNA, UBS, BW PB, AFS and BL.

7.7.3. Total Number of Agents

Figure 92 shows total amount of time for an auction to be completed for both algorithms and both standards. Figure 93 shows unit auction completion time.

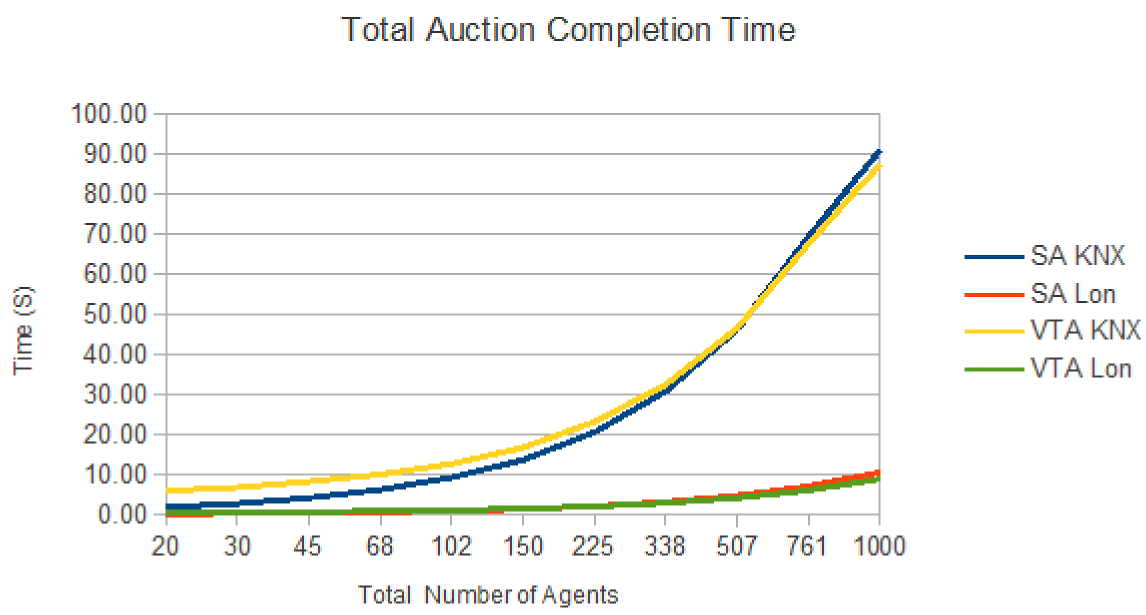


Figure 92: Total auction completion time for both algorithms

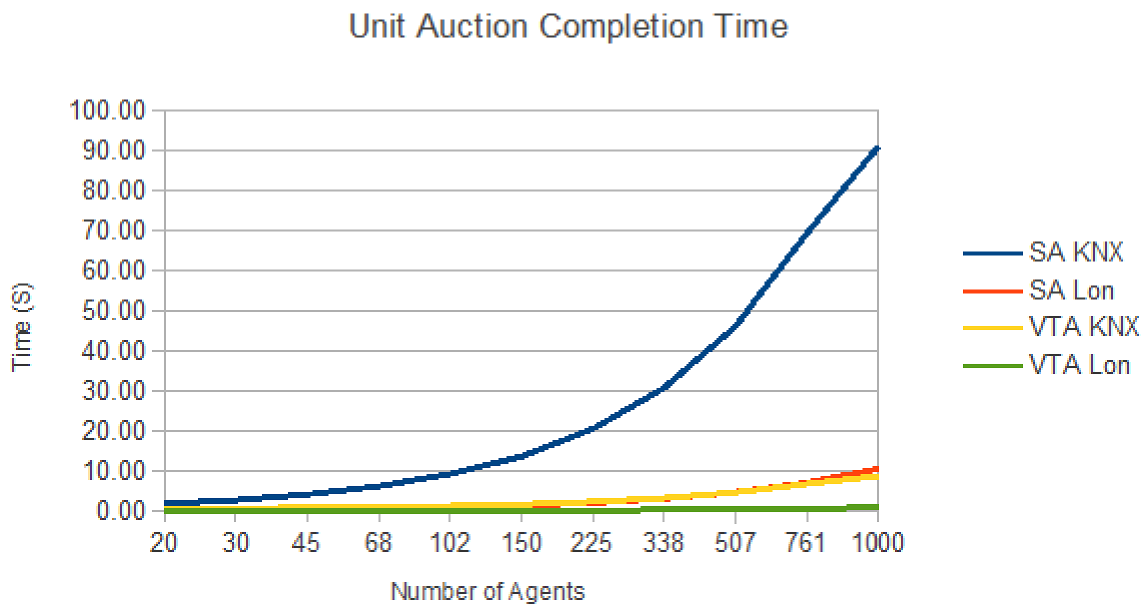


Figure 93: Unit auction completion time for both algorithms

Table 23 shows the values for comparison.

Table 23: Results for Total Time and Unit Auction Time

	Total Time to Complete Auction (s)		**Unit Auction Completion Time (s)**	
TNA	**SA KNX**	**SA Lon**	**VTA KNX**	**VTA Lon**
20	1.82	0.18	0.59	0.05
30	2.73	0.27	0.68	0.05
45	4.15	0.41	0.82	0.07
68	6.22	0.62	1.00	0.08
102	9.27	0.92	1.27	0.11
150	13.67	1.38	1.68	0.14
225	20.55	2.08	2.32	0.20
338	30.82	3.13	3.25	0.29
507	46.23	4.69	4.66	0.41
761	69.34	7.03	6.76	0.61
1000	91.13	10.55	8.75	0.89

From the table, several conclusions can be drawn:

- When it comes to completing auctions in unit time, VTA algorithm proves to be much superior compared to SA algorithm. For KNX, this might be a game changer because for 150 agents, 10 seconds for an individual auction can be considered too long whereas 1.7 seconds might make it feasible to apply CNDSR.

- The speed of LonWorks TP is very useful in decreasing the overall time to complete an auction, it is almost 10 times faster regardless of the number of agents on the bus.

- Because LonWorks TP is already fast, SA algorithm might be preferred for applications where there are less than 150 zones since it is much simpler than VTA algorithm.

7.7.4. Unit Bid Size

Table 24 shows auction completion times for 150 agents when the unit bid size is 20 Watts, 25 Watts and 50 Watts. As the unit bid size increases, the number of traffic on the bus decreases which allows quicker auction completion.

Table 24: Auction Completion Time for 150 Agents for different Bid Sizes

Unit Auction Completion Time (seconds)				
Unit Bid Size (Watts)	**SA KNX**	**SA Lonworks**	**VTA KNX**	**VTA Lon**
20	14.08	1.41	1.95	0.16
25	13.67	1.38	1.68	0.14
50	12.86	1.32	1.13	0.10

7.7.5. Buffer Size

When there is a buffer, the number of auctions that can be carried in unit time increases. However, increasing the buffer to hold too many bids has its negative effects. Firstly, the time it takes to fill the buffer increases because the frame size of the buffer becomes bigger. Secondly, as the buffer starts circulating, the empty slots are easily filled. This increases the number of agents bidding to the virtual auction. Table 25 shows unit auction completion times for 150 agents and for different buffer sizes.

Table 25: Unit auction completion times for different buffer sizes

Unit Auction Completion Time (seconds)				
Buffer Size (Watts)	**SA KNX**	**SA Lonworks**	**VTA KNX**	**VTA Lon**
500	13.67	1.38	2.06	0.19
1000	13.67	1.38	1.68	0.14
1500	13.67	1.38	1.69	0.14
2000	13.67	1.38	1.81	0.15
3000	13.67	1.38	2.14	0.17

The condition above is depicted for transition period between the buffer being empty and all the agents bidding. However, once the system reaches steady state, the number of bidders will decrease since it will be harder for the agents to find an empty slot. Therefore more realistic simulation is required to assess the effect of the buffer in the long run.

7.7.6. Probability of Bidding

When the probability of bidding increases, more agents try to write to the buffer increasing bus traffic. However, because agents are not allowed to bid if the existing bids are better than theirs, the chances of agents bidding will decrease as the token is circulated. Table 26 shows the time it takes to complete an auction for different probabilities. As the probability of agents bidding increases, the amount of traffic increases significantly.

Table 26: Auction completion time for different bidding probabilities

Unit Auction Completion Time (seconds)				
Probability of Bidding	**SA KNX**	**SA Lonworks**	**VTA KNX**	**VTA Lon**
0.05	12.95	1.33	1.38	0.12
0.1	13.67	1.38	1.68	0.14
0.25	16.04	1.56	2.66	0.22
0.5	19.84	1.86	4.24	0.34
1	27.56	2.46	7.45	0.59

7.7.7. Unit Auction Frame Size

If unit auction frame size can be made more compact, the amount of time it will take to complete an auction decreases. Table 27 compares completion times for two frame sizes; 3 Bytes and 4 Bytes.

Table 27: Auction completion times for two frame sizes

Unit Auction Completion Time (seconds)				
Unit Auction Frame Size	**SA KNX**	**SA Lonworks**	**VTA KNX**	**VTA Lon**
3 Bytes	13.26	1.35	1.41	0.12
4 Bytes	13.67	1.38	1.68	0.14

7.7.8. Bus Load Coefficient

Bus load coefficient allows bidding process to spread over time to avoid congestion. In a sophisticated implementation, this coefficient can be managed dynamically either by a central monitoring agent or the bidding agents themselves. This might increase efficiency and allow auctions to be completed in shorter time frames at times when other bus traffic is low. Table 28 shows auction completion times for different BL coefficients.

Table 28: Unit auction completion times for different BL coefficients

Unit Auction Completion Time (seconds)				
BL Coefficient	**SA KNX**	**SA Lonworks**	**VTA KNX**	**VTA Lon**
0.25	27.34	2.76	3.35	0.29
0.5	13.67	1.38	1.68	0.14
0.75	9.11	0.92	1.12	0.10
1	6.83	0.69	0.84	0.07

7.8. Experimental Assessment

Two problems were identified with a straightforward implementation of auction mechanism; sudden rush of bids causing excessive bus load and auction process taking too long to complete. In order to observe this phenomenon, an experimental set-up was prepared using KNX nodes. The set-up consisted of 6 KNX nodes that can be programmed and a computer with bus monitoring equipment as shown in Figure 94.

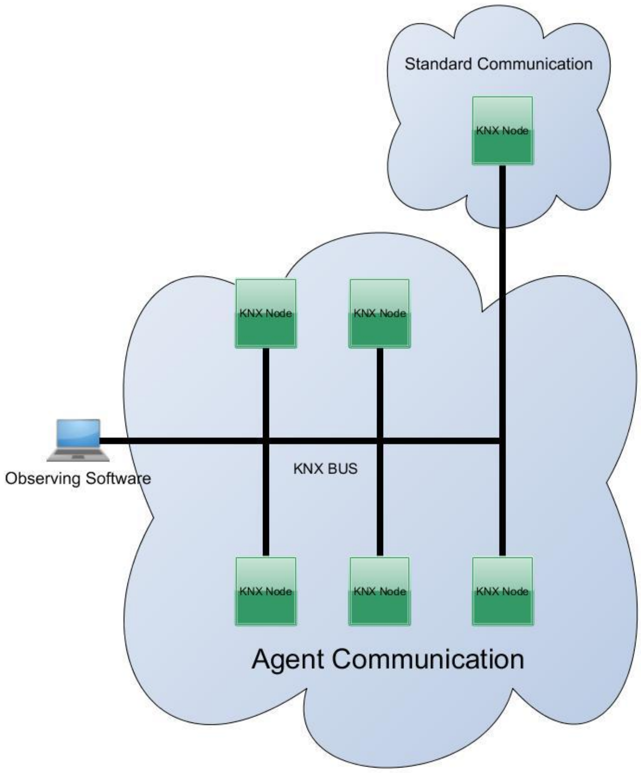


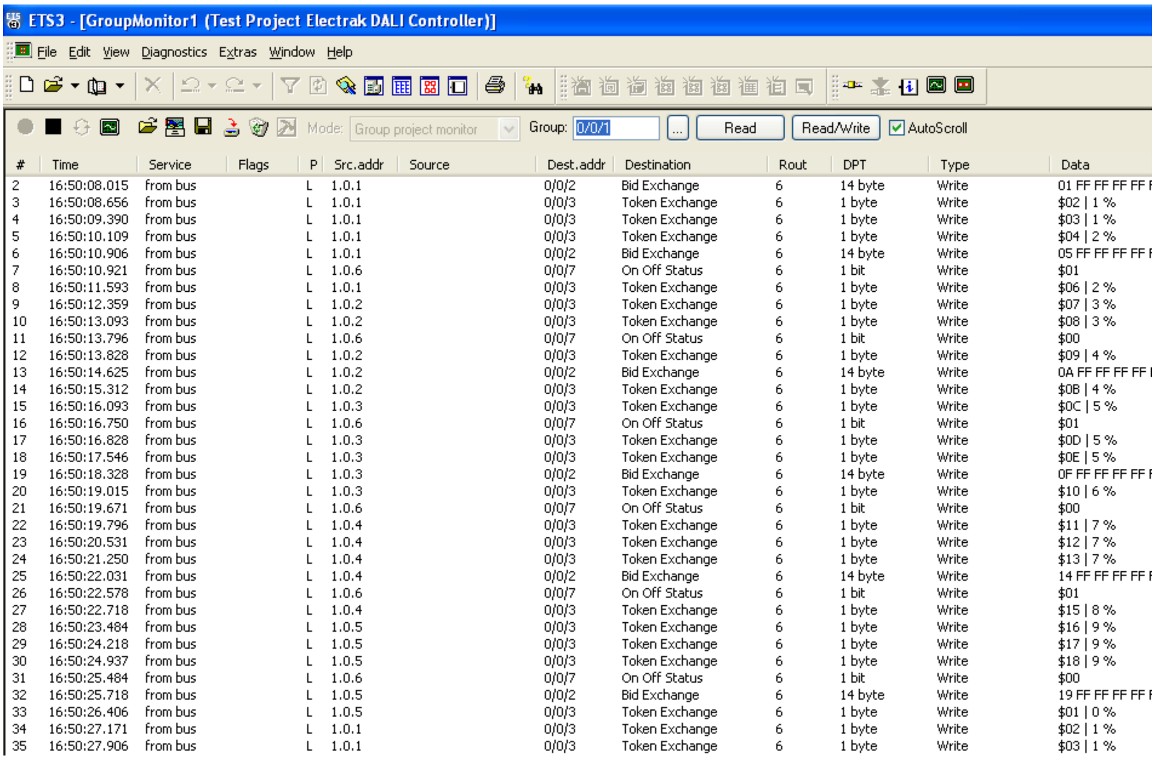
Figure 94: Schematic of the experimental setup.

The firmware on the nodes was modified to carry out experimental tasks. The monitoring software on the PC was programmed to trigger auctions and record reactions of the nodes particularly the time it took the nodes to respond to commands during heavy bus load.

Each node is a KNX certified lighting controller that is powered by an STR7 microcontroller operating at 16 MHz. The nodes are able to connect to KNX bus through a standard KNX TP-UART interface operating at 9600 bps.

The source code for the firmware of the nodes was available for modifications. This allowed implementation of basic CNDSR functions to test the implications of agent communication on the KNX bus.

KNX provides various tools to monitor traffic on the bus. The standard tool that is used is called ETS (Engineering Tool Software). ETS allows various data points to be linked to each other which can be used to create agent communication links. These data points can then be used to send commands to the nodes on the bus. The bus monitor application of ETS allows the reaction of the nodes to be recorded as well as in Figure 95. The logs provide valuable information like which commands were sent by which node and the exact timing that the messages were observed on the bus.



#	Time	Service	Flags	P	Src.addr	Source	Dest.addr	Destination	Rout	DPT	Type	Data
2	16:50:08.015	from bus		L	1.0.1		0/0/2	Bid Exchange	6	14 byte	Write	01 FF FF FF FF F
3	16:50:08.656	from bus		L	1.0.1		0/0/3	Token Exchange	6	1 byte	Write	$02 | 1 %
4	16:50:09.390	from bus		L	1.0.1		0/0/3	Token Exchange	6	1 byte	Write	$03 | 1 %
5	16:50:10.109	from bus		L	1.0.1		0/0/3	Token Exchange	6	1 byte	Write	$04 | 2 %
6	16:50:10.906	from bus		L	1.0.1		0/0/2	Bid Exchange	6	14 byte	Write	05 FF FF FF FF F
7	16:50:10.921	from bus		L	1.0.6		0/0/7	On Off Status	6	1 bit	Write	$01
8	16:50:11.593	from bus		L	1.0.1		0/0/3	Token Exchange	6	1 byte	Write	$06 | 2 %
9	16:50:12.359	from bus		L	1.0.2		0/0/3	Token Exchange	6	1 byte	Write	$07 | 3 %
10	16:50:13.093	from bus		L	1.0.2		0/0/3	Token Exchange	6	1 byte	Write	$08 | 3 %
11	16:50:13.796	from bus		L	1.0.6		0/0/7	On Off Status	6	1 bit	Write	$00
12	16:50:13.828	from bus		L	1.0.2		0/0/3	Token Exchange	6	1 byte	Write	$09 | 4 %
13	16:50:14.625	from bus		L	1.0.2		0/0/2	Bid Exchange	6	14 byte	Write	0A FF FF FF FF I
14	16:50:15.312	from bus		L	1.0.2		0/0/3	Token Exchange	6	1 byte	Write	$0B | 4 %
15	16:50:16.093	from bus		L	1.0.3		0/0/3	Token Exchange	6	1 byte	Write	$0C | 5 %
16	16:50:16.750	from bus		L	1.0.6		0/0/7	On Off Status	6	1 bit	Write	$01
17	16:50:16.828	from bus		L	1.0.3		0/0/3	Token Exchange	6	1 byte	Write	$0D | 5 %
18	16:50:17.546	from bus		L	1.0.3		0/0/3	Token Exchange	6	1 byte	Write	$0E | 5 %
19	16:50:18.328	from bus		L	1.0.3		0/0/2	Bid Exchange	6	14 byte	Write	0F FF FF FF FF F
20	16:50:19.015	from bus		L	1.0.3		0/0/3	Token Exchange	6	1 byte	Write	$10 | 6 %
21	16:50:19.671	from bus		L	1.0.6		0/0/7	On Off Status	6	1 bit	Write	$00
22	16:50:19.796	from bus		L	1.0.4		0/0/3	Token Exchange	6	1 byte	Write	$11 | 7 %
23	16:50:20.531	from bus		L	1.0.4		0/0/3	Token Exchange	6	1 byte	Write	$12 | 7 %
24	16:50:21.250	from bus		L	1.0.4		0/0/3	Token Exchange	6	1 byte	Write	$13 | 7 %
25	16:50:22.031	from bus		L	1.0.4		0/0/2	Bid Exchange	6	14 byte	Write	14 FF FF FF FF F
26	16:50:22.578	from bus		L	1.0.6		0/0/7	On Off Status	6	1 bit	Write	$01
27	16:50:22.718	from bus		L	1.0.4		0/0/3	Token Exchange	6	1 byte	Write	$15 | 8 %
28	16:50:23.484	from bus		L	1.0.5		0/0/3	Token Exchange	6	1 byte	Write	$16 | 9 %
29	16:50:24.218	from bus		L	1.0.5		0/0/3	Token Exchange	6	1 byte	Write	$17 | 9 %
30	16:50:24.937	from bus		L	1.0.5		0/0/3	Token Exchange	6	1 byte	Write	$18 | 9 %
31	16:50:25.484	from bus		L	1.0.6		0/0/7	On Off Status	6	1 bit	Write	$00
32	16:50:25.718	from bus		L	1.0.5		0/0/2	Bid Exchange	6	14 byte	Write	19 FF FF FF FF F
33	16:50:26.406	from bus		L	1.0.5		0/0/3	Token Exchange	6	1 byte	Write	$01 | 0 %
34	16:50:27.171	from bus		L	1.0.1		0/0/3	Token Exchange	6	1 byte	Write	$02 | 1 %
35	16:50:27.906	from bus		L	1.0.1		0/0/3	Token Exchange	6	1 byte	Write	$03 | 1 %

Figure 95: ETS Bus monitoring program of KNX Standard

The log on this bus monitor shows how the exchange is carried out among the agents. The time column is the stamp of the time the message appears on the bus. Source column shows the node address that the message originates. Destination address (Dest.Addr) column shows the multicast address of the message. Destination column shows the name of the multicast address. In this case, three type of destination address is apparent. Bid exchange is the address where agents submit their bids. Token exchange is the address to pass the token that allows agents to bid. On Off Status is the dummy frame that simulates typical non-DSR bus traffic on the bus. DPT column shows the size of the data pointer that is used. For bid exchange, large data pointer is used (14 Bytes). For token exchange, only 1 Byte is used since the token is just a variable that keeps the address of the agent. For On/Off status, 1 bit object is used. The Type column shows the type of frame that is sent, which is in this case Write command because all of the agents are writing to the common memory. Finally, the Data column shows the actual payload of the message. For bid frames, this is just a dummy frame consisting of 0xFF values. For token frame, the data contains the address of the agent. On/Off status commands only indicate zero or one.

7.8.1. Timing Experiment

The first experiment was carried out to observe if the amount of time calculated for completion of auctions are in line with reality. In this experiment, virtual agents were created on the nodes and these agents were then initiated to start submitting bids on the bus. The bus monitoring equipment was used to observe the amount of time it took for all of the agents to complete sending their bids.

The payload of the bid frames that agents sent were limited to 14 Bytes because of the restrictions of the devices that are used to carry out the simulations. Table 29 shows comparison of the calculated time versus the observed time for auctions to be completed when all of the agents are asked to submit bids.

Table 29: Calculated time versus observed times for auctions under KNX

Number of Agents	**Calculated Time (s)**	**Observed Time (s)**
5	0.22	0.25
10	0.43	0.46
15	0.65	0.68
30	1.30	1.30
50	2.16	2.13
75	3.24	3.24
150	6.48	6.72
300	12.97	13.36
500	21.61	22.65
1000	43.23	44.21

The table shows that predicted completion times are in line with what would be observed in a real world situation. For example, for 150 agents, it takes up to 6.5 seconds for an auction to be completed.

7.8.2. Experiments Related to Bid Rush

The purpose of the bid rush experiment was to observe the negative effects of excessive bus load caused by agent communication. To achieve this, one of the nodes was programmed to carry out standard communication where the other five were programmed to carry out agent communication and generate excessive bus load.

The nodes were programmed to contain up to 1000 agents in total in order to ensure that agent communication lasted long enough (around 45 seconds). The test was initiated with a start command from the commissioning tool. Upon reception of the start command, all of the agent nodes were programmed to start submitting their bids. Similarly, upon reception of the start command, one of the nodes that were not programmed for agent communication was instructed to start submitting a dummy control frame (on/off) to the bus every three seconds. Because all of the nodes received the start frame at the same time, the dummy frame would appear on the bus in three second intervals. The expectation in this case was, when the bus is busy, the node sending out the dummy frame will not be able to put this into the bus because of excessive bus load. Hence, the late arrival of the dummy frame would be observed on the log.

Before starting the experiment, the node submitting the dummy frame is tested to ensure that its frames appear on the bus at three second intervals when there is no bus load. Then the experiment was conducted.

Table 30 shows a sample from one of the simulation runs which started at 13 seconds. The first row shows the expected time of the dummy frame and the second row shows the time it actually appeared on the bus.

Table 30: Expected time vs observed time for a dummy frame sent on a busy bus

	Dummy 1	**Dummy 2**	**Dummy 3**	**Dummy 4**	**Dummy 5**	**Dummy 6**
Expected Time (s)	15.968	18.968	21.968	24.968	27.968	30.968
Observed Time (s)	16.093	24.125	24.187	25.296	28.14	31.171
Difference (s)	0.125	5.157	2.219	0.328	0.172	0.203

The experiment shows the difficulty of the non bidding node in injecting a standard command to the bus. The frames Dummy 2 and Dummy 3 are more than five and two seconds late compared to their intended times. In a real world application, the late arrival of an on/off message for this long would most likely be unacceptable.

7.8.3. Experiments with Token Ring

Using the same setup to test the bid rush algorithm, an experiment to observe the effectiveness of VTA in mitigating excessive bus load is carried out. In this case, agents were programmed to wait for a token to submit their bids. The passing of the token was achieved by programming a datapoint which would be updated by each node. To simulate 10% bid submit rate, each node was programmed to submit a bid once for every ten token passing. The nodes were also programmed to keep the token for a fixed time in order to reduce bus load by 50%.

Table 31 shows the repetition of the experiment explained in 7.8.2. In this experiment, no delays were observed from the node that tried to communicate in the bus when the agents were busy submitting their bids. The times that the dummy frame was observed matched the times that they were expected on the bus.

Table 31: Expected time vs observed time for a dummy frame sen on a busy bus with VTA algorithm

	Dummy 1	**Dummy 2**	**Dummy 3**	**Dummy 4**	**Dummy 5**	**Dummy 6**
Expectec Time (s)	42.81	45.81	48.81	51.81	54.81	57.81
Observed Time (s)	42.875	45.843	48.843	51.859	54.859	57.859
Difference (s)	0.065	0.033	0.033	0.049	0.049	0.049

7.9. Conclusion

In this chapter, an assessment was made on whether or not existing building automation standards are capable of handling basic agent communication. It is found that these standards are developed to handle event based communication that is not expected to occur frequently. The simple agent based algorithm that was presented in the previous chapter was combined with the data that is collected from existing lighting control arrangements in office buildings allowed a realistic assessment to be made. As a result of this assessment, two drawbacks of existing building automation standards became apparent; 1) In CSMA based data link layers that are slow, excessive communication causes the bus to be flooded for long periods of time which prevents other (building control specific) communication from being conducted. 2) If an auction is to be carried out, the slow speed of the bus prevents the auctions from being completed in reasonable amount of time.

A solution to tackle both of these issues is proposed. If a token is used to manage bid submit times, the amount of bus load can be reduced. Also, VTA can be used to collect the bids from the agents before an auction starts hence allowing auctions to be completed instantly. Successive auctions can be carried out provided that the buffer is large enough.

An experimental setup was prepared to observe the negative effects of agent communication. This experiment showed that excessive communication does deteriorate the performance of the bus and prevent other traffic from being passed on to the bus. When VTA based solution was simulated, it was observed that the negative effects diminished and building control specific messages could easily progress through the bus.

8. Conclusion and Future Work

The purpose of this study has been to propose a valid automatic control method for DSR in office buildings and assess the capability of existing building automation systems in achieving this control method. As a result of this research, it can be concluded that a valid automatic control method for DSR in office buildings can only be achieved by including productivity as a parameter for the control system. When productivity is included, two requirements become apparent to maximise productivity:

- Both Lighting and HVAC system need to be controlled simultaneously.
- Loads need to be prioritised.

As observed in the proposed control algorithms based on productivity, involvement of the lighting system brings agent based control as a valid option for the lighting system. Prioritisation of the loads as well as possible intervention to lighting system during a DSR period means that this agent based control needs to operate quickly. Hence, the slow speed of building automation standards become a bottleneck if a productivity based control method is implemented.

To test the feasibility of existing building automation standards, an agent based DSR control system called CNDSR is developed. Theoretical and experimental data shows that implementing this control system directly using existing fieldbus communications might cause two major problems. First, the bus might become inoperable during agent communication because of the excessive number of message exchanges among the agents. Second, the slow speed of the bus prevents quick operation that is required by a DSR system. For this reason, the agent communication needs to be modified to take the circumstances of the physical layer of the bus into account. In this study, virtual token based auction mechanism is proposed as a valid solution to this problem. This solution utilises the idle time of the bus when no user intervention is carried out and no auction is present. However, other solutions to overcome these problems can be developed by researchers interested in this area.

Apart from the major conclusions, several other conclusions can be drawn from this research regarding the subjects covered in the individual chapters. These are as follows:

8.1. Building energy consumption modelling

In Chapter 3, the simple tool that is developed to investigate power reduction strategies has provided valuable results in devising a load control strategy for DSR. The tool which was developed in Matlab provided yearly power consumption results similar to a much powerful simulation program called Energyplus. However because it was custom built to run in small steps, it allowed observation of indoor temperatures during a DSR event.

Even though the tool was valuable for the specific requirements of this research, it highlighted the requirement of more sophisticated Demand Response tools which are not readily available for the research community.

8.2. IEQ as a Productivity Indicator

In Chapter 4, it has been shown that productivity aspects of environmental variables is not well understood when more than one variable is sub-optimum inside a building. In spite of this, IEQ can be proposed as a valid measure of productivity since it is supported by some experimental data. However, more research is required to investigate the combined effects of lighting and temperature on the performance of human beings carrying out office tasks.

8.3. Using IEQ to Control Loads in Office Buildings

Even with limited information on IEQ and a simple tool to simulate the environmental conditions in an office building, it has been found that combining both lighting and heating to control the loads in an office building produces better results. In this case, if IEQ is used, better environmental conditions can be created for the same amount of power reduction or more power reduction can be achieved for similar environmental conditions.

The findings explained on Chapter 5 show that buildings should not have fixed control schemes for DSR. This is because buildings have different energy requirements throughout the year and the proportion of power that is curtailed from lighting or HVAC changes with outside temperatures. For this reason, an automatic control system needs to be smart enough to adjust the mixture of contribution from these two categories of loads.

Another finding of Chapter 5 is that load prioritisation is necessary if productivity of the environment is to be kept maximum. In this case, contribution of battery operated devices such as portable computers is valuable because they can be curtailed without having a negative effect on the environment.

8.4. Control Strategy for DSR

OpenADR protocol shows that there needs to be a central controller in the building that would decide how much load to shed by monitoring the existing power consumption and translating the ADR signals. When this is combined with IEQ based control strategy, this controller needs to decide the temperature and average lighting inside the building. Moreover, the controller needs to prioritise loads that have little or no immediate effect on the productivity of the occupants. These decisions which need to be carried out rapidly throughout the DSR period requires a fast responding control system.

Appendix A

2. Sizing Calculations for the Heating and Cooling Elements of the HVAC System

$$SupplyAirTemp = \frac{351 \times Q \times tR + 273 \times SH}{351 - SH}$$

Where,

SH: Heat input through windows and walls (kW)

Q: Air flow rate (m^3/seconds)

tR: Room Temperature (Celsius)

Office Window Size: 2 x 3m x 2m = $12m^2$

Office Wall Area: $35.75m^2$ - $12m^2$ = $23.75m^2$

Internal Load: Lighting + Equipment

: (11 W/m^2 + $11W/m^2$) x $160m^2$ = 3.5kW

Building UA: 3304 W/K = 137.6 W/K (per office)

Izmir Summer

Maximum Outdoor Temp: 41^o C

SH = Internal Gain + External Gain

3.5kW + ((41-23) x 137.6) = 6 kW

From the formula above, supply temperature:

tS = 13.69^o C @ 1.214 kg/m^3

Enthalpy of Supply Air: 35.31 kJ/kg

Mixture air temperature: 0.143 x (41 – 23) + 23 = 25.57^o C

Outside Moisture: 41^o C @ 30% = 14.738 gr

Moisture of the Mixed Air: 14.738 x 0.143 + (1-0.143) x 8.78 = 9.63 gr/kg

Mixture Enthalpy: 9.63 gr @25.57 = 50.25 kJ/kg

Total Power Required:

$(0.59m^3/s) \times (50.25 – 35.31)kJ/kg \times 1.214\ kg/m^3 = 10.7\ kW/office$

= 257 kW Total

Izmir Winter

Minimum Outdoor Temp: -9^o C

SH = Internal Gain + External Gain

3.5kW + ((22+9) x 137.6) = 1.18 kW

From the formula above, supply temperature:

tS = 23.67^o C @ 1.173 kg/m^3

Enthalpy of Supply Air: 35.31 kJ/kg

Mixture air temperature: -0.143 x (22 + 12) + 22 = 17.13^o C

Outside Moisture: -9^o C @ 80% = 1 gr

Moisture of the Mixed Air: 1 x 0.143 + (1-0.143) x 8.78 = 7.66 gr

Mixture Enthalpy: 7.66 gr @ 17.13 = 36.63 kJ/kg

Total Power Required:

$(0.59m^3/s) \times (45.5 – 36.63)kJ/kg \times 1.158\ kg/m^3 = 6.08\ kW/office$

= 145 kW Total

Copenhagen Winter

Minimum Outdoor Temp: -21^o C

SH = Internal Gain + External Gain

3.5kW + ((22+21) x 137.6) = -5.89 kW

From the formula above, supply temperature:

tS = 25.53^o C @ 8.53 kg/m^3

Enthalpy of Supply Air: 47.4 kJ/kg

Mixture air temperature: 0.143 x (21 + 22) + 23 = 15.8^o C

Outside Moisture: -20^o C @ 80% = 0.5 gr/kg

Moisture of the Mixed Air: 0.5 x 0.143 + (1-0.143) x 8.78 = 7.6 gr/kg

Mixture Enthalpy: 7.6 gr @15.8 = 35.12 kJ/kg

Total Power Required:

(0.59m^3/s) x (47.4 – 35.12)kJ/kg x 1.214 kg/m^3 = 8.42 kW/office

= 202 kW Total

Copenhagen Summer

Maximum Outdoor Temp: 32^o C

SH = Internal Gain + External Gain

3.5kW + ((32-23) x 137.6) = 4.74 kW

From the formula above, supply temperature:

tS = 15.41^o C

Enthalpy of Supply Air: 36.65 kJ/kg

Mixture air temperature: 0.143 x (32 – 23) + 23 = 24.28^o C

Outside Moisture: 32^o C @ 38% = 11.345 gr

Moisture of the Mixed Air: 11.345 x 0.143 + (1-0.143) x 8.78 = 9.14 gr/kg

Mixture Enthalpy: 9.14 gr @24.28 = 47.71 kJ/kg

Total Power Required:

(0.59m^3/s) x (47.71 – 36.65)kJ/kg x 1.208 kg/m^3 = 7.88 kW/office

= 190 kW Total

3. Sizing Calculations for the Supply and Return Fans

Total duct length: 78m x 2 x 3 + 9 = 477m

Total Number of supply grilles: 24

Design air flow: 13.2m^3/s

Avg Filter Pressure Drop: 0.5 x (50 +175) = 112.5 pa

Straight Duct Pressure Drop: 1 pa/m

Supply grille pressure drop: 5pa @ 2m/s

Total Pressure Drop: 477 + 240 + 125 = 717 pa

Fan Velocity Pressure: 72.6 pa

Motor Efficiency 80%

Impeller Efficiency: 90%

Power Factor: 0.9

Motor Input Power = Q x FTP/(Imp x Motor x PF) = 22.67kW

Bibliography

[1] A. J, “Demand Side Activities for Electric Load Reduction,” Lund University, Sweden, 2007.

[2] G. Strbac, “Demand Side Management: Benefits and Challenges,” *Energy Policy,* vol. 28, no. 2, pp. 4419 - 4426, 2008.

[3] L. Freris and D. Infield, Renewable Generation in Power Systems, Wiley, 2007.

[4] W. Sweet, “Get Rich Quick Scheme,” *IEEE Spectrum,* no. 65, pp. 28 - 32, 2006.

[5] C. Goldman, M. Reid, R. Levy and A. Silverstein, “National Action Plan for Energy Efficiency,” Lawrence Berkeley National Laboratory, California, 2010.

[6] “Benefits of Demand Response,” U.S. Department of Energy, Washington, 2006.

[7] J. Page, S. Kiliccote, J. H. Piette, A. K. Chiu, B. Kellow, E. Koch and P. Lipkin, “Automated Demand Response Technology Demonstration for Small and Medium Commercial Buildings,” Lawrence Berkeley National Laboratory, California, 2011.

[8] “Demand Side Management in the Non-Domestic Sector,” Elementery Energy, London, 2012.

[9] M. Wilks, “Assessment of DSR Price Signals,” PÖYRY Management Consulting Ltd., London, 2011.

[10] D. A. McIntyre, Indoor Climate, Applied Science Publishers, 1980.

[11] “Best Practice Programme Guide: Energy Use in Offices,” UK. Government Dept. of Energy, London, 2003.

[12] D. Westphalen and K. Scott, Energy Consumption Characteristics of Commercial Building HVAC Systems, Arthur D. Little Inc, 1999.

[13] C. Willis, Form Follows Science: Skyscrapers and Skylines of New York and Chicago, Princeton Architectural Press, 1995.

[14] G. H. Douglas, Skyscrapers: A Social History of the Very Tall Building in America, McFarland & Co Inc, 2004.

[15] M. Reichler, “Modeling of Rooftop Packaged Air Conditioning Equipment,” University of Wisconsin Madison, 1999.

[16] “Control of Ventilation and Air Conditioning Plants,” Siemens Building Technologies Division, 2008.

[17] W. Wang, S. Katipamula, Y. Huang and M. Brambley, “Energy Savings and Economics of

Advanced Control Strategies for Packaged Air-Conditioning Units with Gas Heat," Pacific Northwest National Laboratory, 2011.

[18] D. Westphalen and K. Scott, Energy Consumption Characteristics of Commercial Building HVAC Systems, Arthur D. Little Inc, 1999.

[19] "Lighting in buildings : environmental aspects," Department of the Environment, UK, London, 1993.

[20] P. V. Tichelen, B. Jansen, T. Greerken, V. Bosch and V. Vanhoof, "Preparatory Studies for Eco-design Requirements of EuPs Final Report," Study for the European Commission, Brussels, 2007.

[21] "Energy Design Brief: Lighting Controls, How to get the Right Amount of Light Where it is Needed When its Needed," [Online]. Available: http://energydesignresources.com/media/1765/EDR_DesignBriefs_lightingcontrols.pdf?tracked=true. [Accessed December 2013].

[22] "An Introduction to DALI," [Online]. Available: http://www.lighting.philips.com/main/subsites/dynalite/library_support/technical_support/useful_information/dali_introduction.wpd. [Accessed December 2013].

[23] "Lighting: Five Steps to Savings," [Online]. Available: http://www.facilitiesnet.com/lighting/article/Occupancy-Sensors-Eliminate-Energy-Waste--9607?source=part. [Accessed December 2013].

[24] "History of IBM," [Online]. Available: http://www-03.ibm.com/ibm/history/history/history_intro.html. [Accessed March 2010].

[25] K. Kawamoto, J. G. Koomey, B. Nordman, R. E. Brown and M. A. Piette, "Electricity used by office equipment and network equipment in the US," Lawrence Berkeley National Laboratory, California, 2000.

[26] K. W. Roth, F. Goldstein and J. Kleinman, "Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings," National Technical Information Service, Springfield, 2002.

[27] "Global notebook shipments finally overtake desktops," [Online]. Available: http://arstechnica.com/uncategorized/2008/12/global-notebook-shipments-finally-overtake-desktops. [Accessed April 2012].

[28] G. Dunn and I. Knight, "Small power equipment loads in UK office environments," *Energy and Buildings,* vol. 37, no. 1, pp. 87 - 91, 2005.

[29] M. Bray, “Review of Computer Energy Consumption and Potential Savings,” [Online]. Available: dssw.co.uk/research/computer_energy_consumption.pdf.

[30] J. Koomey, “Estimating total power consumption by servers in the U.S. And the World,” Lawrence Berkeley National Laboratory, California, 2008.

[31] J. A. Roberson, C. A. Webber, M. C. McWhinney, R. E. Brown and M. J. Pinckard, “After hours Power Status of Office Equipment and Energy Use of Miscellaneous Plug-Load Equipment,” Lawrence Berkeley National Laboratory, California, 2004.

[32] GreenComputing, “U.K. Office Workers 'Addicted' to Paper,” [Online]. Available: http://www.greenbiz.com/news/2010/08/23/uk-office-workers-addicted-paper. [Accessed April 2012].

[33] “Moderate thermal environments—determination of the PMV and PPD indices and specification of the conditions for thermal comfort,” International Standards Organisation, 1994.

[34] R. T. Wilkinson, “Psychological and physiological responses to raised body temperature,” *Applied Physiology,* vol. 19, pp. 287 - 291, 1964.

[35] I. D. Griffiths, “Performance and thermal comfort,” *Ergonomics,* vol. 14, pp. 457 - 468, 1971.

[36] G. D. Mayo, “Effect of temperature on technical training,” *Applied Physiology,* vol. 39, pp. 244 - 246, 1955.

[37] D. P. Wyon, “The effects of moderate heat stress on typewriting performance,” *Ergonomics,* vol. 27, pp. 499 - 509, 1973.

[38] G. Langkilde, “The influence of the thermal environment on office work,” in *WHO Conference,* Copenhagen, 1978.

[39] O. Seppanen, W. Fisk and Q. H. Lei, “Room Temperature and Productivity in Office Work,” Lawrence Berkeley National Laboratory, California, 2006.

[40] R. Niemelä, J. Railio, M. Hannula, S. Rautio and M. Reijula, “Assessing the effect of indoor environment on productivity,” in *Clima 2000,* Napoli, 2001.

[41] L. Lan, P. Wargocki and Z. Lian, “Quantitative measurement of productivity loss due to thermal discomfort,” *Energy and Buildings,* vol. 43, no. 5, pp. 1057 - 1062, 2011.

[42] R. Kosonen, “Assessment of productivity loss in air-conditioned buildings using PMV index,” *Energy and Buildings,* vol. 36, no. 10, pp. 987 - 993, 2004.

[43] W. P. Jones, Air Conditioning Engineering, Routledge 5'th Edition, 2000.

[44] C. P. Yaglou, E. C. Riley and D. Coggins, “Ventilation Requirements,” *ASHVE Transactions,*

vol. 42, pp. 133 - 143, 1936.

[45] B. Berg-Munch, B. Clausen and P. Fanger., “Ventilation requirements for the control of body odor in space occupied by women,” *Environment International,* vol. 12, pp. 195 - 199, 1986.

[46] P. Wargocki, “Improving Indoor Air Quality Improves the Performance of Office Work and School Work,” Energy Systems Laboratory Texas A&M Univresity, Austin, 2008.

[47] R. a. F. T. Kosonen, “The effect of perceived indoor air quality on productivity loss,” *Energy and Buildings,* vol. 36, pp. 981 - 986, 2004.

[48] M. S. Rea, “Toward a Model for Visual Performance,” *Journal of the Illuminating Engineering Society,* no. Summer, pp. 41 - 73, 1986.

[49] P. R. Boyce, “Illuminance Selection Based on Visual Performance—and other Fairy Stories,” *Journal of the Illuminating Engineering Society,* vol. 25, no. 2, pp. 41 - 49, 1996.

[50] P. R. Boyce, “Lighitng and Human Performance and Overview,” [Online]. Available: http://resource.npl.co.uk/optical_radiation/ormclub/member/content/dec06/boyce.pdf. [Accessed April 2012].

[51] W. J. M. Bommel and G. Beld, “Lighting for work: a review of visual and biological effects,” *Lighting Research and Technology,* vol. 36, pp. 255 - 266, 2004.

[52] W. W. R. Küller, “Melatonin, cortisol, EEG, ECG and subjective comfort in healthyhumans: impact of two fluorescent lamp types at two light intensities,” *Lighting Research and Technology,* vol. 25, no. 2, pp. 71 - 80, 1993.

[53] P. Boyce, J. Beckstead, N. Eklund, R. W. Strobel and M. Rea, “Lighting the graveyard-shift: the influence of a daylight-simulating skylight on the task performance and mood of night shift workers,” *Lighting Research and Technology,* vol. 29, no. 3, pp. 105 -134, 1997.

[54] “Lighting and Safety at Work,” H & S Executive UK, 1997.

[55] “Code for Lighting,” CIBSE, 2002.

[56] H. Juslen and A. D. Tenner, “Mechanisms involved in enhancing human performance by changing the lighting in the industrial workplace,” *International Journal of Industrial Ergonomics,* no. 35, pp. 843 - 855, 2005.

[57] H. T. Juslen, M. Wouters and A. D. Tenner, “The influence of controllable task-lighting on productivity: a field study in a factory,” *Applied Ergonomics,* vol. 38, no. 1, pp. 39 - 44, 2007.

[58] H. Hempala and J. Eklund, “A visual ergonomics intervention in mail sorting facilities: effects on eyes, muscles and productivity,” *Applied Ergonomics,* vol. 43, no. 1, pp. 217 - 229, 2012.

[59] J. E. Sounders, “The role of the level and diversity of horizontal illumination in an appraisal of a simple office task,” *Lighting Research and Technology,* vol. 1, no. 1, pp. 28 - 36, 1969.

[60] T. M. Chung and J. Burnett, “Lighting Quality Surveys in Office Buildings,” *Indoor Built Environment,* vol. 9, pp. 335 - 341, 2000.

[61] K. W. Mui and L. T. Wong, “Acceptable illumination levels for office occupants,” *Architectural Science Review, University of Sydney,* vol. 49, no. 2, pp. 116 - 119, 2005.

[62] B. R., M. R. and D. S., “Effects of indoor lighting (illuminance and spectral distribution) on the performance of cognitive tasks and interpersonal behaviors: The potential mediating role of positive affect,” *Motivation and Positive Effect,* vol. 16, no. 1, pp. 1 -33, 1992.

[63] W. J. Fisk, “Health and productivity gains from better indoor environments and their relationship with building energy efficiency,” *Annual Review of Energy and the Environment,* vol. 25, pp. 537 - 556, 2000.

[64] Q. Jin, M. Overend and P. Thompson, “Towards productivity indicators for performance-based façade design in commercial buildings,” *Building and Environment,* vol. 57, pp. 271 - 281, 2012.

[65] A. Kawamura, S. Tanabe, N. Nishihara, M. Haneda and M. Ueki, “Evaluation methods for effects of improvement of indoor environmental quality on productivitiy,” in *Clima,* Helsinki, 2007.

[66] L. Wong, K. Mui and P. Hui, “A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices,” *Building Environment,* vol. 48, pp. 1 - 6, 2008.

[67] M. Ncube and S. Riffat, “Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK – A preliminary study, Building and Environment,” *Building and Environment,* vol. 53, pp. 26 - 33, 2012.

[68] L. Huang, Y. Zhu, Q. Ouyang and B. Cao, “A Study on the Effects of Thermal, Luminous and Acoustic Environments on Indoor Environmental Comfort in Offices,” *Building and Environment,* vol. 49, pp. 304 - 309, 2012.

[69] W. Kastner, G. Neugschwandtner, S. Soucek and H. M. Newmann, “Communication Systems for Building Automation and Control,” *Proceedings of the IEEE,* vol. 93, no. 6, pp. 1178 - 1203, 2005.

[70] “BACnet Website,” [Online]. Available: www.bacnet.org. [Accessed December 2013].

[71] “LonWorks Web Site,” [Online]. Available: http://www.echelon.com/technology/lonworks/. [Accessed December 2013].

[72] "KNX Standard," [Online]. Available: www.knx.org. [Accessed September 2012].

[73] R. Yin, S. Kiliccote, M.A.Piette and K.Parrish, "Scenario Analysis of Peak Demand Savings for Commercial Buildings with Thermal Mass in California," in *ACEE Summer Study on Energy Efficiency in Buildings*, California, 2010.

[74] P. Xu and R. Yin, "Demand Shifting with Thermal Mass in Large Commercial Buildings in a California Hot Climate Zone," Lawrence Berkeley National Laboratory, California, 2009.

[75] J. B. Braun, K. W. Montgomery and N. Chatuvedi, "Evaluationg the Performance of Building Thermal Mass Control Strategies," *HVAC & R Research*, vol. 7, no. 4, pp. 58 - 68, 2001.

[76] K. Lee and J. E. Braun, "Model Based Demand Limiting Control of Building Thermal Mass," *Building and Environment*, vol. 43, no. 10, pp. 1633 - 1646, 2008.

[77] P. Xu, P. Haves, M. A. Piette and J. E. Braun, "Peak Demand Reduction from Pre-Coolinlg with Zone Temperature Reset in an Office Building," in *ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, 2004.

[78] B. C.A., "The role of thermal mass on the cooling load of buildings. An overview of computational methods," *Energy and Buildings*, vol. 24, no. 1, pp. 1 - 10, 1996.

[79] I. Richardson, M. Thomson, D. Infield and A. Delahunty, "Domestic Lighting; A High Resolution Energy Demand Model," *Energy and Buildings*, vol. 41, pp. 781 - 789, 2009.

[80] I. Richardson, M. Thomson, D. Infield and C. Clifford, "Domestic Electricity Use: A High Resolution Energy Demand Model," *Energy and Buildings*, vol. 42, pp. 1878 - 1887, 2010.

[81] J. Paatero and P. Lund, "A model for generating household electricity load profiles," *International Journal of Energy Research*, vol. 30, pp. 273 - 290, 2006.

[82] A. Capasso, W. Grattieri, R. Lamedica and A. Prudenzi, "A Bottom-up Approach to Residential Load Modelling," *IEEE Transactions on Power Systems*, vol. 9, pp. 957 - 964, 1994.

[83] R. Yao and K. Steemers, "A Method of Formulating Energy Load Profile for Domestic Buildings in the UK," *Energy and Buildings*, vol. 37, pp. 663 - 671, 2005.

[84] M. Stokes, "PhD Thesis: Removing Barrirers to Embedded Generation: A Fine Grained Load Model to Support Low Voltage Network Performance Analysis," De Montfort University, Leicester, 2005.

[85] D. B. Crawley, J. W. Hand, M. Kummert and B. T. Griffith, "Contrasting the Capabilities of Building Energy Performance Simulation Programs," Lawrence Berkeley National Laboratory, California, 2005.

[86] T. R. Nielsen, “Simple Tool to Evaluate Energy Demand and Indoor Environment in the Early Stages of Building Design,” *Solar Energy,* vol. 78, pp. 73 - 83, 2003.

[87] J. M. Schults and S. Svendsen, “A Simple Simulation Program for Evaluating the Influence of Windows on Heating Demand and Risk of Overheating,” *Solar Energy,* vol. 63, pp. 251 - 258, 1998.

[88] M. Deru, K. Field, D. Studer, B. Liu, M. Halverson, D. Winiarski, M. Yazdanian, J. Huang and D. Crawley, “U.S. Department of Energy Commercial Referance Building Models of the National Building Stock,” U.S. National Renewable Energy Laboratory, Golden Colorado, 2011.

[89] “Energy Plus Weather Data,” [Online]. Available: http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm. [Accessed July 2012].

[90] D. V. Chadderton, Air Conditioning: A Practical Introduction, London: Routledge, 1998.

[91] “Software, Energy Plus Simulation,” [Online]. Available: http://apps1.eere.energy.gov/buildings/energyplus/utm_source=EnergyPlus&utm_medium=redirect&- utm_campaign=EnergyPlus%2Bredirect%2B1.

[92] I. Korolija, V. Hanby, Y. Zhang and L. Marjanovic, “HVAC Systems Energy Demand vs Building Energy Demand,” in *IESD PhD Conference* , Manchester, 2010.

[93] “Lighting Control Technologies and Strategies to Cut Energy Consumption,” CIBSE, [Online]. Available: http://www.cibsejournal.com/cpd/2010-11/. [Accessed December 2011].

[94] G. Ghatikar, J. Mathieu and M. Piette, “Open Automatic Demand Response: Dynamic Pricing Technologies and Demonstration,” in *Akuacom,* Los Angeles, 2013.

[95] N. Motegi, M. Piette, D. Watson, S. Kiliccote and P. Xu, “Introduction to Commercial Building Control Strategies and Techniques for Demand Reponse,” Lawrence Berkeley National Laboratory, California, 2007.

[96] D. Bourgeois, I. MacDonald and C. F. Reinhart, “Adding advanced behavioral models in whole building energy simulation: a study on the total energy impact of manual and automated lighting control,” *Energy and Buildings,* vol. 38, no. 7, pp. 814 - 823, 2006.

[97] F. Rubinstein and S. Kiliccote, “Demand Responsive Lighting: A scoping study,” Lawrence Berkeley National Laboratory, California, 2007.

[98] Y. Akashi, “Is It Okay to Dim Your Lights for Load Shedding,” *Lighting Design and Applictation,* vol. 34, pp. 12 - 14, 2004.

[99] M. Woolridge, An Introduction to Multiagent Systems, John Wiley & Sons, 2009.

[100] S. D. J. McArthur, E. M. Davidson, V. M. Catterson, V. M. Dimeas, N. D. Hatziargyriou, F. Ponci and T. Funabashi, "Multi-Agent Systems for Power Engineering Applications—Part I: Concepts, Approaches, and Technical Challenges," *IEEE Transactions on Power Systems,* vol. 22, no. 4, pp. 1743 - 1752, 2007.

[101] J. Lagorse, D. Paire and A. Miraoui, "A multi-agent system for energy management of distributed power sources," *Renewable Energy,* vol. 35, no. 1, pp. 174 - 182, 2010.

[102] Z. Jun, L. Junfeng, W. Jie and H. W. Ngan, "A multi-agent solution to energy management in hybrid renewable energy generation system," *Renewable Energy,* vol. 36, no. 5, pp. 1352 - 1363, 2011.

[103] M. Z. Chun and M. Ardeshir, "An agent based simulation assisted approach to bilateral building systems control," in *Eight International IBPSA Conference,* Eindhoven, 2003.

[104] P. Davidsson and M. Boman, "Distributed monitoring and control of office buildings by embedded agents," *Information Sciences,* vol. 171, no. 4, pp. 293 - 307, 2005.

[105] Z. Whang, R. Yang and L. Wang, "Multi-agent intelligent controller design for smart and sustainable buildings," in *4'th Annual IEEE Systems Conference*, San Diego, 277 - 282.

[106] R. Yang and L. Wang, "Development of multi-agent system for building energy and comfort management based on occupant behaviours," *Energy and Buildings,* vol. 56, pp. 1 - 7, 2013.

[107] R. G. Smith, "The Contract Net Protocol: High-Level Communication and Control in a Distributed Problem Solver," *IEEE Transactions on Computers,* vol. 29, no. 12, pp. 1104 - 1113, 1980.

[108] P. Palensky, "PhD Thesis: Reactive Communication of Agent Networks," Technical University of Vienna, Vienna, 1999.

[109] V. Julian, C. Carrascosa, M. Rebollo, J. Soler and V. Botti, "SIMBA: An Approach for Real Time Multi Agent Systems," *Lecture Notes in Computer Science,* pp. 282 - 293, 2002.

[110] S. Theiss and K. Kabitzch, "Efficient Agent Interaction in Automatic Networks: A Simulation Study," in *Emerging Technologies and Factory Automation*, Toulouse, 2011.

[111] J. Ploennigs, M. Neugebauer and K. Kabitzsch, "A Traffic Model for Networked Devices in the Building Automation," in *IEEE International Workshop on Factory Communication Systems,* 2004.

[112] Energy Standards for Buildings Except Low-Rise Residential Buildings 90.1 - 2004, ASHRAE.

[113] J. Karlsson and A. Roos, "Modelling the Angular Behaviour of the Total Solar Energy Transmittance of Windows," *Solar Energy,* vol. 69, pp. 321 - 329, 2000.

[114] H. Awbi, Ventilation of Buildings, London: Spon Press, 2003.

[115] T. Sterling, "Productivity metrics and models for high performance computing," *International Journal of High Performance Computing Applications,* vol. 18, no. 4, pp. 433 - 440, 2004.

[116] "KNX Web Site," [Online]. Available: www.KNX.org. [Accessed December 2013].

[117] S. L. K.C.Lee, "Performance Evaluation of Switched Ethernet for Networked Control Systems," in *IEEE 28'th Annual Conference of the Industrial Electronics Society,* 2002.