A study of current and possible future Industrial Engineering methodologies used to increase energy efficiency

by
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Abstract

Energy-related costs are increasing steadily. This is especially true in South Africa where we have been dealing with an energy crisis during the past couple of years. The increase in energy-related costs puts energy dependent industries under financial pressure. It is therefore imperative to find ways to improve the efficiency with which energy is being consumed in order to decrease the amount of money that has to be allocated to energy costs.

The efficient consumption of energy at a facility is crucial and to increase that efficiency, Energy Management Programs (EMPs) should be implemented. An important component of EMPs is ascertaining the current energy consumption of a facility in order to identify areas where possible improvements can be made. This is done by completing an energy audit at the facility. After the energy audit has been completed and Energy Conservation Methods (ECMs) have been identified, the implementation of these methods should commence.

The aim of this study is to determine how Industrial Engineering (IE) methods can play a more integral role in making South Africa more energy efficient. As part of this study, research was done to identify current EMCs being implemented in different areas and for different equipment in facilities. This information was compared to IE methods to identify the possible relationship between the ECMs and IE methods.

Content analyses were completed on both IE and energy efficiency corpora using the Content Analysis Toolkit (CAT) program. These analyses identified important topics in these corpora and correlations between these topics in order to show correlations between the IE and energy efficiency fields. The most significant correlations identified, were between statistical methods and various energy efficiency topics.

A case study was completed at a company in the Western Cape that manufactures electronic and integrated circuit products to implement the relevant ECMs. As part of the case study, an energy audit was completed at the facility. The implementation of a number of the ECMs has shown reductions in the daily kilowatt hours (kWh) consumptions. These reductions were obtained through the implementation of a Shut Down Management program, which highlights the importance of management in an energy conservation project.

The application of optimisation algorithms for energy efficient design was examined through the optimisation of lighting design, using a Genetic Algorithm. It was found that a Genetic Algorithm is applicable to lighting design but requires further refinement in order to generate the most optimal design solutions.

Opsomming

Kostes verbonde aan energieverbruik is voortdurend besig om toe te neem.Dit is veral relevant in Suid-Afrika waar ons tans ’n energiekrisis beleef. Hierdie toename in energieverwante kostes plaas energie-afhanklike industrieë onder groot finansiële druk. Dit is daarom belangrik om maniere te vind om energieverbruik meer effektief te maak sodat die bedrag geld wat aan energieverwante kostes toegestaan word, verminder kan word.

Effektiewe energieverbruik by ’n fasiliteit is kritiek en om hierdie effektiwiteit te verbeter behoort ’n energiebestuursprogram by die fasiliteit geïmplimenteer te word. ’n Belangrike komponent van energiebestuursprogramme is die bepaling van die huidige energieverbruik en dit word gebruik om die areas te identifiseer waar moontlike verbeteringe aangebring kan word. Die energieverbruik word bepaal deur ’n energie-oudit. Nadat die energie-oudit voltooi en die energiebesparingsmetodes bepaal is, moet hierdie metodes by die fasiliteit geïmplementeer word.

Hierdie studie probeer vasstel hoe bedryfsingenieurswesemetodes ‘n groter rol kan speel in die proses om Suid-Afrika meer energie-effektief te maak. Navorsing is gedoen oor energiebesparingsmetodes wat in verskillende areas en vir verskillende toerusting in fasiliteite geïmplementeer word. Hierdie inligting is daarna vergelyk met bedryfsingenieurswesemetodes om juis die moontlike verhouding tussen hierdie twee tipe metodes te identifiseer.

Analises was gedoen in bedryfsingenieurswese en energie-effektiwiteitskorpusse met die gebruik van die ‘Content Analysis Toolkit’ program. Belangrike onderwerpe en verwantskappe tussen hierdie onderwerpe in die korpusse is identifiseer om sodoende korrelasies tussen die bedryfsingenieurswese- en energie-effektiwiteitsveld uit te lig. Die mees betekenisvolle korrelasies was tussen statistiese metodes en verskeie energie-effektiwiteitsonderwerpe identifiseer.

’n Gevallestudie is by ’n maatskappy in die Wes-Kaap wat geïntegreerde elektroniese stroombane vervaardig gedoen, om die relevante energiebesparingsmetodes te implementeer. ’n Energie-oudit is as deel van die gevallestudie by die fasiliteit gedoen. Die aantal energiebesparingsmetodes wat wel geïmplementeer is, het ’n verlaging in die kilowatt-ure (kWh) teweeggebring. Hierdie verlagings is verkry deur die implementering van ’n afskakelingsbestuursprogram wat die belangrikheid van bestuur in ’n energiebesparingsprogram uitlig.

Die toepaslikheid van optimiseringsalgoritmes vir energie-effektiewe ontwerp is getoets deur die optimisering van ’n liguitlegontwerp met behulp van ’n genetiese algoritme. Daar is gevind dat ’n genetiese algoritme wel toegepas kan word, maar dat dit verbeteringe benodig.

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Glossary

CDF - Cumulative Distribution Functions

CRI - Colour Rendering Index

CUSUM - Cumulative Sum Deviation Method

DDC - Direct Digital Control

ECMs- Energy Conservation Measures

EMPs- Energy Management Programs

Energy Accounting - Determining the energy content of a product

EUI - Energy Usage Index

F-PS - Fitness-proportionate selection

GA - Genetic Algorithm

HVAC -Heating, Ventilation and Air Conditioning

IE - Industrial Engineering

KVA - Kilo Volt Ampere

kWh - Kilowatt hours

LED - Light Emitting Diodes

LPW - Lumens Per Watt

NPI - Normalized performance indicators

O&Ms - Operation and Maintenance Procedures

SANS - South African National Standards

SPE - Standard Performance Equation

SUS - Stochastic Universal Sampling

TOU - Time of Use

VAV - Variable-Air-Volume

VBA - Visual Basic for Applications

1. Introduction

1.1 Background

Faced with a global and national energy emergency, it is imperative that energy is used as efficiently as possible. Energy efficiency is seen as one of the best methods for sustainable development (Sebitosi, 2008).

In South Africa, an electricity shortage has forced individuals and groups to start using energy more efficiently. The South African Department of Minerals and Energy (DME) published their Energy Efficiency Strategy in 2005, where certain targets related to energy efficiency were established (Sebitosi, 2008).

During 2008, South Africa found itself in the midst of an electricity crisis. A lack of electricity generating capacity forced Eskom to implement a load shedding plan, which impacted negatively on the South African economy. According to Eskom, it needs to build new power plants in order to eliminate the shortage of capacity (Inglesi, 2010).

A steady rise in electricity tariffs was implemented by Eskom in order to help gather capital for building these new power plants (Unknown, 2009). The increase in costs related to electricity is putting a strain on energy dependent industries. To minimise the impact that increasing electricity tariffs and the threat of electricity shortages have on these industries, it is imperative for companies to increase their energy efficiency.

In Figure 1 it is clearly shown that the industry sector accounts for the highest percentage of energy usage in South Africa (Department of Minerals and Energy, 2008). The focus of this study will be on the industry sector since it accounts for the largest percentage of electricity consumption.

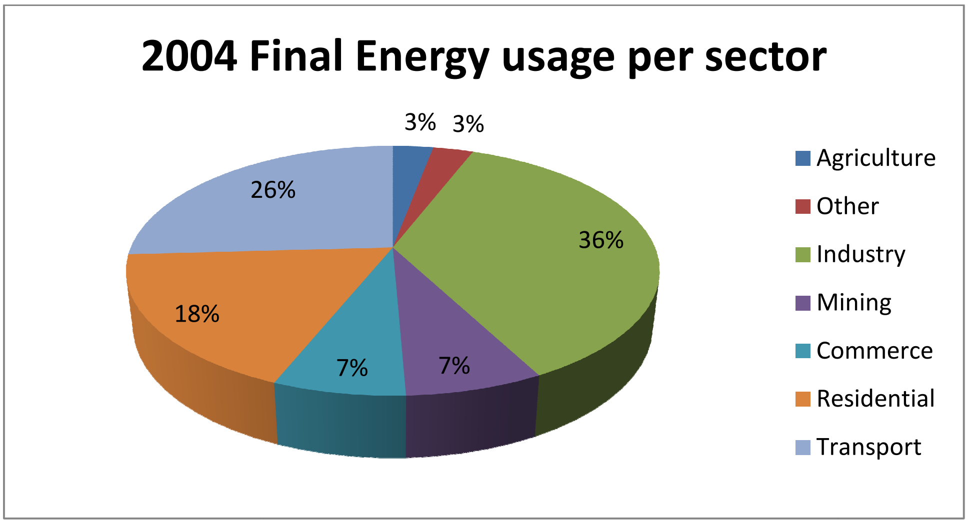


Figure 1 - 2004 South African energy usage per sector

Energy Efficiency is described by the International Energy Agency as the ratio between energy input and output (International Energy Agency, 2004). Therefore, the improvement of energy efficiency would be to get more output from the same energy input or to get the same output from reduced energy input (Audit Scotland, 2008).

In order to achieve a sustainable improvement in energy efficiency, companies should implement Energy Management Programs (EMPs) at their manufacturing plants. The aim of EMPs is to identify power saving opportunities and implement improvements options for these opportunities. To identify power saving opportunities, a detailed study must be completed on the current energy usage.

Ascertain the level of energy efficiency of a company's manufacturing plant requires an energy audit to be completed. Auditing the energy usage of the plant will provide a general overview as well as an in depth analysis of the energy usage. During the analysis (Thumann & Younger, 2008), possible improvement areas are identified which form the foundation for energy management (Thumann, Younger 2008).

Industrial Engineers (IEs) work in many different fields, including different parts of the industry sector. Their main focus is improving the efficiency of systems in general. Energy management and using energy efficiently should form part of this main focus. IE methods may be applicable to EMPs and energy efficiency improvement.

During the execution of energy audits and the application of energy management strategies, many Industrial Engineering methods could be applied. Some of these methods may include scheduling, process optimisation (Kreith & Goswami, 2007), facility design (Harvey 2009) and information systems (Caudana, Conti, Helcke, & Pagani, 1995).

This study will try to identify IE methods that are applicable in the energy management and energy efficiency fields and prove the correlation between the IE and energy efficiency fields.

1.2 Problem Statement

As a result of the current national and international energy crisis, energy must be used as efficiently as possible. Industrial engineers play a cardinal role in the management of facilities and production. They can thus influence the efficiency with which energy is used. An evaluation should be done to ascertain what contribution Industrial Engineers can make to improve the efficient use of energy in facilities.

1.3 Project Goals

The goals set for this project are as follow:

- Gain knowledge of Energy Management Programs and more specifically focussing on energy auditing with the goal to identify Energy Conservation Measures
- Identify ECMs specific to high energy usage areas in production facilities
- Identify general Industrial Engineering methods that form the core of Industrial Engineering
- Identify areas in energy management and ECMs where IE methods can possibly be applied
- Identify correlations between the IE and energy efficiency fields and possible applications for IE methods for improving energy efficiency by means of an literature analysis
- Evaluate the applicability of the IE methods by applying them to a production facility as part of a case study, with special focus on lighting, the design of a lighting system and how it can be optimised

1.4 Research Methodology

The following steps are included in the research methodology for this project:

- Literature review:
  This study will start with a literature review of energy usage analysis and management. Focus will be placed on Energy Management Programs and energy audits. Research will also be done on fundamental Industrial Engineering methods. This research will form the foundation for the comparison of the Energy Conservation Measures with the IE methods as well as the practical application of the ECMs in a case study.

- Industrial Engineering methods in Energy Management:
  The IE methods that were identified will be compared with the ECMs to find possible applications. The applications of the IE methods will be categorised according to main focal areas for the improvement of energy efficiency.

- Literature analysis:
  A literature analysis, using a content analysis tool, will be done on an IE corpus and an energy efficiency corpus to identify the most significant topics for these two fields. A further analysis of these topics will be done to identify correlations between these topics and therefore correlations between the IE and energy efficiency fields.

- Case study:
  A case study will be conducted at a production facility to implement the applicable ECMs and IE methods in order to evaluate the improvement made through the implementation. The case study will consist of an energy audit that is completed at the facility and the suggestion and implementation of applicable ECMs.

- Lighting design algorithm:
  Research will be done on methods for optimising lighting design. A method will be selected and applied to lighting design and the applicability of the selected method will be evaluated.

The relationships and information flow between the different research methodology steps were illustrated in a diagram. Figure 2 shows a visual representation of the proposed research methodology:

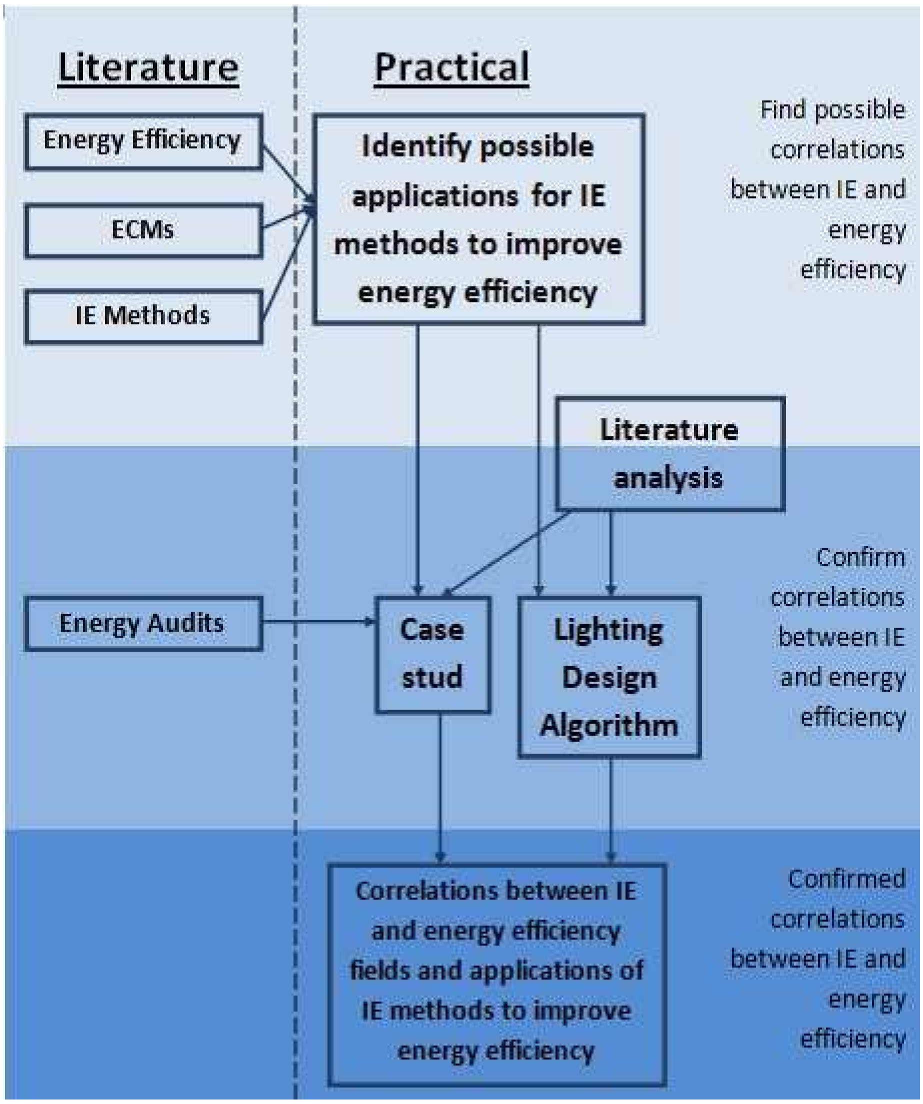


Figure 2 - Research Methodology Diagram

1.5 Research Scope

This study will focus on the improvement of energy usage in a production facility in South Africa. This is due to the nature of the case study. The case study was conducted at a South African production company. As part of the case study, at the request of the company, research was done on lighting and the design of a lighting system for a specific area. This research leads to the evaluation of optimisation of lighting design.

IE is an extensive field of study and therefore the focus was placed on identifying major IE methods, rather than trying to identify all possible IE methods. One key aspect of IE is optimisation and this particular method was applied specifically to lighting design due to the focus placed on lighting by the company involved with the case study.

2. Literature Review

2.1 National and International Energy Efficiency:

Several national and international organisations and programs exist to promote the efficient use of energy and the development of renewable energy sources. Some international organisations include the International Institute for Energy Conservation, the International Partnership for Energy Efficiency Cooperation and the International Energy Agency. On a national level, Eskom has launched several programs to assist with the reduction of energy consumption. Other organisations promoting energy efficiency in southern Africa include the Southern Africa Association for Energy Efficiency as well as the Department of Minerals and Energy.

The International Institute for Energy Conservation (IIEC) develops partnerships between key policy makers and the industry to assist with the design of policies and the implementation of energy conservation programs. This international institute focuses on developing and industrialising countries. Projects have been launched in countries such as Chile, Thailand, Poland, Hungary and the Philippines. The IIEC provides the following specific services (*IIEC homepage*):

- End-Use Energy Efficiency
- DSM Planning and Evaluation
- Energy Efficiency Standards and Labelling
- Renewable Energy
- Energy Efficiency Finance Design
- Environmental Management
- Water Resource Management
- Climate Change and Energy Policy
- Transport Planning

The International Partnership for Energy Efficiency Cooperation (IPEEC) provides leadership on energy efficiency. IPEEC collaborates with developed as well as emerging countries to assist governments with the implementation of policies and programs. Task groups, consisting of several countries, work together to implement the IPEEC work programme. Current initiatives include (*IPEEC - international partnership for energy efficiency cooperation*):

- Assessment of Energy Efficiency Financing Mechanism (AEEFM)
- Energy Management Action Network for Industrial Efficiency (EMAK)
- Policies for Energy Provider Delivery of Energy Efficiency (PEPDEE)

- ❖ Global Superior Energy Performance Partnership (GSEP)
- ❖ Improving Policies through Energy Efficiency Indicators (IPEEI)
- ❖ Super-efficient Equipment and Appliance Deployment Initiative (SEAD)
- ❖ Sustainable Buildings Network (SBN)
- ❖ Worldwide Energy Efficiency Action through Capacity Building and Training (WEACT)

The International Energy Agency (IEA) addresses global energy security, environmental protection and economical growth issues. The agency promotes worldwide collaboration on these issues (*International energy agency (IEA)*). The IEA consists of three man directorate:

- ❖ Energy Markets and Security (EMS): This directorate analyses the energy market and energy security policies. It also Initiates and monitors key policy issues raised (*IEA about - directorate of energy markets and security (EMS)*).
- ❖ Global Energy Dialogue (GED): This directorate advances the cooperation between member and non-member countries. Better cooperation between IEA and major energy consumers, producers and transport countries is crucial to the success of energy policies and conservation programs. Energy policies of member countries are peer reviewed by this directorate of the IEA (*IEA about - directorate of global energy dialogue*).
- ❖ Sustainable Energy Policy and Technology (SPT): This directorate is responsible for Sustainable Energy Policy and the Energy Technology policy. This directorate consists of several divisions and units. The Energy Efficiency and Environmental Division (EED) assess and designs policies regarding energy-related CO2 emissions. This division comprises of the Climate Change Unit (CCU) and the Energy Efficiency Unit (EEU). The Energy Technology Policy Division (ETP) assesses technologies in order to hasten the market penetration of these technologies. The Carbon Capture and Storage Technology Unit (CCS) analyses the capture, transport and storage technologies for carbon (*IEA about - directorate of sustainable energy policy and technology*).

In South Africa, the Department of Minerals and Energy has developed an Energy Efficiency Strategy. This strategy's goals are social, environmental and economic sustainability. Programmes were created for five different sectors, namely the industrial sector, power generation sector, commercial and public buildings sector, residential and transport sector. As part of these programmes, energy management programs and energy audits are encouraged (Department of Minerals and Energy, 2008).

Eskom has launched the Integrated Demand Management program to improve energy efficiency. This program has been applied worldwide and has been implemented in South Africa in collaboration with the Department of Minerals and Energy and the National

Electricity Regulator. IDM was implemented in four sectors: residential, commercial, agricultural and industrial (*Industrial « eskom IDM*). Elements included in IDM are(*IDM*):

- Power and energy purchase agreements
- Fuel switching and energy optimisation
- Energy management systems
- Walk through audits
- Investment grade audits
- Remote monitoring

Eskom also developed an Energy Service Company (ESCo) model that establishes partnerships between Eskom, the ESCo and the customer. This model enables customers to receive funding from Eskom to evaluate and improve their energy efficiency (*Esco model « eskom IDM*).

Another key role player in the improvement of energy efficiency in South Africa is the Southern Africa Association for Energy Efficiency (SAEE). The SAEE offers vital information regarding ongoing initiatives and focuses on reaching out to energy users, suppliers, service providers, researchers and developers in energy efficiency and energy training providers. Although the SAEE does not offer training in energy efficiency, it organises training sessions as well as public events to raise awareness and reward excellent energy efficiency practice (*The southern african association for energy efficiency (SAEE)*).

2.2 Energy Management Program

Energy Management Programs (EMPs) are management programs that are implemented at a facility to manage the energy consumption of the facility. The need to manage energy is important and will stay relevant due to the following reasons (Doty & Turner, 2009):

- Energy management yields direct economic returns
- Energy management can provide a competitive edge to a company by improving the energy efficiency of products and therefore making the products more marketable
- Energy management requires the constant evaluation of rapidly changing energy technologies
- Energy management incorporates energy security
- Energy management will reduce the impact of inevitable future energy price increases.

A typical process for launching EMPs consists of five main steps (Kreith & Goswami, 2007):

1. Review historical energy usage:
    a. Evaluate annual variations and trends
    b. Review past trends
    c. Compare future electricity usage with goals
2. Complete energy audit – to find high energy usage areas:
    a. Compare audit results with historical energy usage records
    b. Audits show detailed breakdown
    c. Audits allow for identification of key energy-consuming areas
3. Identify management opportunities for the high usage areas:
    a. Make overall estimate of how effectively energy is used by facility
    b. Examine key energy-consuming areas:
        i. Is the truly necessary?
        ii. How can this equipment be used more effectively?
        iii. How can less energy be used to accomplish the same goal?
        iv. Can the equipment be modified to increase energy efficiency?
        v. Would it be cost-effective to install new more efficient equipment?
4. Implement changes:
    a. Complete an economic analysis on the ECMs
    b. Implement ECMs that satisfy the economic criteria
5. Monitor improvements:
    a. Set goals to provide targets to gauge performance by

EMPs consists of three main phases. Firstly, the commitment of management for EMPs is secured. The second phase consists of an energy audit and the analysis of the results to identify power management opportunities. The last phase is the implementation phase, where improvements for the power management opportunities are put into action (Kreith & Goswami, 2007).

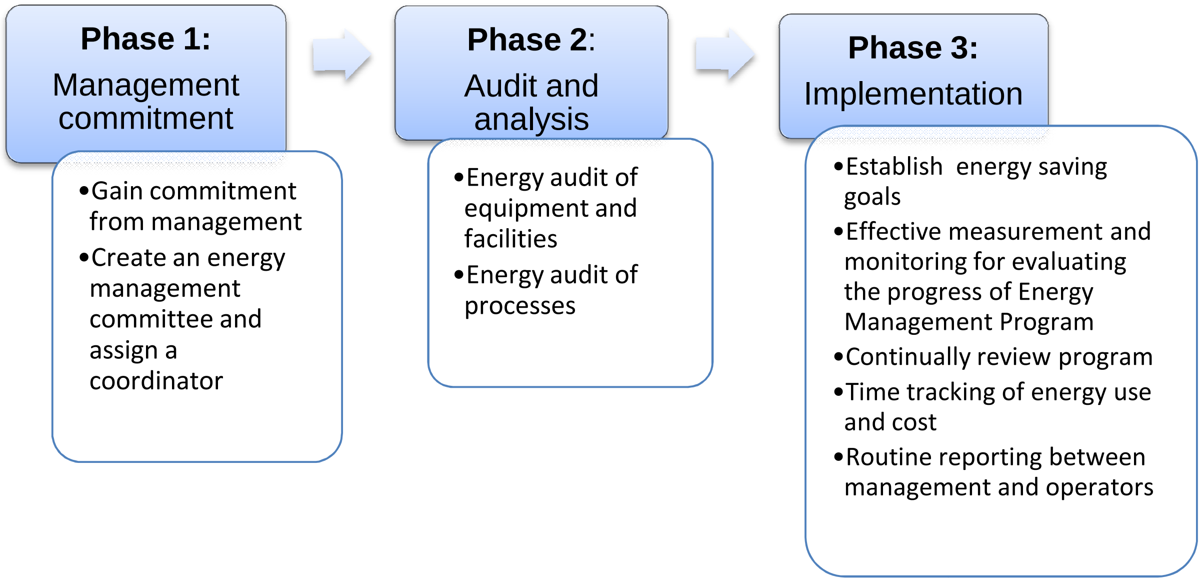


Figure 3 - Phases of Energy Management Program

Phase 2 and 3 of EMPs incorporates the 5 steps listed above for launching EMPs. A considerable part of both the steps and those two phases consist of energy auditing. In the next section the focus will be on energy auditing and the ECMs that can be identified through the completion of an energy audit.

2.3 Energy Auditing

"Energy auditing is the first phase in improving the energy efficiency of a facility",(Hoshide, 1995). An energy audit is usually performed as part of the construction of an energy management strategy in order to determine current energy usage in facilities and to identify possible measures for improving energy usage (Beggs, 2002; Kreith & West, 1997).

One of the uses of energy audits, is informing management as well as engineering and other plant staff of the current energy consumption in the plant. This information can then be utilised by management during decisions that need to be made with regards to the energy conservation. Energy audits also uncover poor housekeeping practices in the plant, which in turn forms the baseline for a plan of action that can be followed to improve the energy consumption of the plant (Kreith & West, 1997).

Anenergy audit should identify issues that require immediate attention along with issues that require further investigation and it should raise awareness on energy conservation in general throughout the facility (Beggs, 2002). These issues can, however, not be identified if the correct data on the current energy consumption is not gathered first.

2.3.1 Levels of Energy Auditing

There are three levels to energy auditing, namely The Preliminary Audit, The Standard Audit and the Comprehensive Audit as seen in Figure 4. As an energy audit progresses through the levels, the detail of the audits increases and therefore the effort required increases with each level (Beggs, 2002; Thumann & Younger, 2008).

2.3.1.1 Preliminary Energy Audit

A Preliminary energy audit is the most basic audit. It has a wide field of focus, usually the whole facility, but it does not go into a lot of detail. This type of audit consists of two main components. Firstly, the walk-through of the facility (Kreith & Goswami, 2007; Thumann & Younger, 2008), where the quantity and cost of each form of energy used is estimated (Beggs, 2002) and straightforward energy conservation measures are identified (Kreith & Goswami, 2007). The second component of a Preliminary energy audit is the analysis of the utility costs. The data gathered from utility suppliers over a number of years is evaluated to identify patterns in the usage. These patterns can assist to develop Energy Conservation Measures (ECMs) to reduce the energy consumption at high consumption areas (Kreith & Goswami, 2007).

2.3.1.2 Standard Energy Audit

The Standard energy audit starts with a more detailed review and analysis of the equipment, systems and operational characteristics (Thumann & Younger, 2008) in order to develop a baseline for the energy usage in the facility (Kreith & Goswami, 2007). After the baseline is developed, the energy efficiency of specific systems is measured and tested (Thumann & Younger, 2008) in order to identify ECMs for these systems. The objective is to recommend ECMs that should be implemented (Beggs, 2002). In order to find the best ECM, a targeted analysis of the identified measures must be completed (Beggs, 2002) where cost-effectiveness and related energy costs are examined (Kreith & Goswami, 2007).

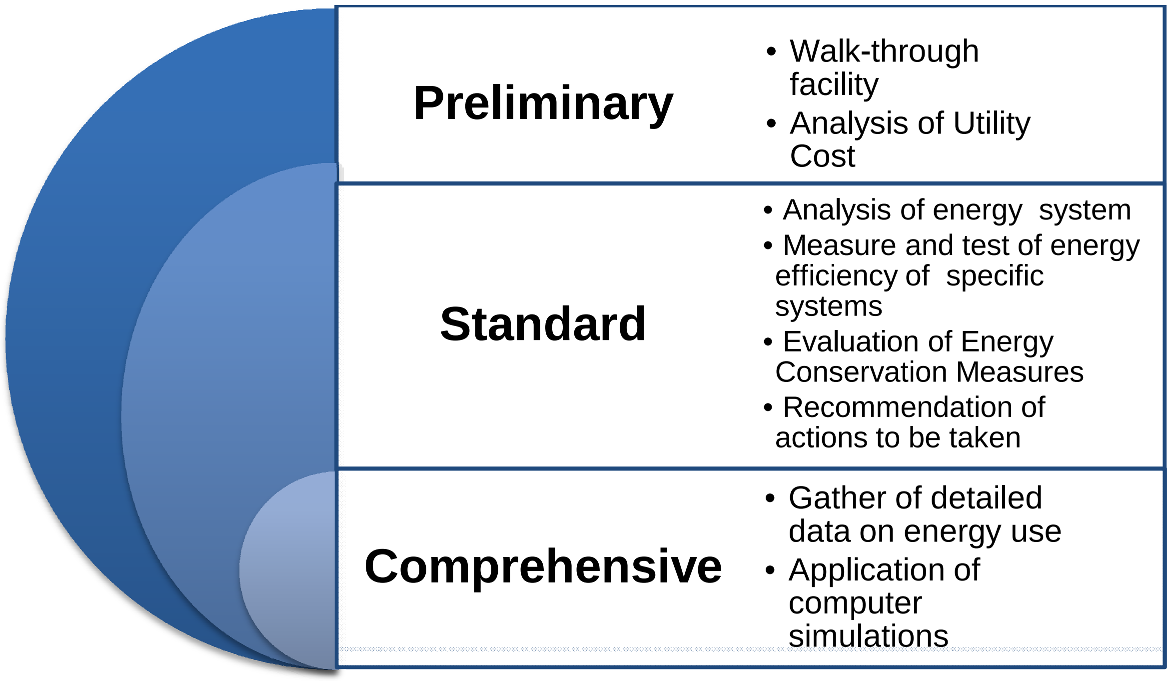


Figure 4 - Three Levels of energy auditing

2.3.1.3 Comprehensive Energy Audit

The Comprehensive energy audit is the most in depth level of energy auditing. The basis of this level of energy auditing is the detailed data that is gathered on the energy inputs and flows in the facility (Beggs, 2002). The energy inputs and flows are measured for the whole facility as well as for individual systems, such as lighting, office equipment and HVAC systems (Kreith & Goswami, 2007). Once the necessary data has been gathered, it is used to develop a computer simulation (Beggs, 2002; Thumann & Younger, 2008) which is then used to evaluate the energy usage patterns of the facility systematically (Thumann & Younger, 2008) and to evaluate ECMs (Kreith & Goswami, 2007).

It is important to select the appropriate energy audit type. In many situations it is possible to identify ECMs by merely doing a Preliminary energy audit and applying some simple analytical techniques. A Comprehensive energy audit should be avoided, as it is costly and takes up a lot of time and effort. (Beggs, 2002)

2.3.2 Components of an Energy Audit

Each energy audit consists of four main components. These components are the Pre-site work, On-site work, Post-site work and writing of the energy audit report (Hoshide, 1995; Thumann & Younger, 2008). Figure 5 shows the four components of energy audits and the tasks that make up these components.

2.3.2.1 Pre-site Component

Before the energy auditor visits the site that is being audited, vital Pre-site tasks should first be completed. Part of the Pre-site tasks is ensuring the support of the company's management, which is crucial to the success of an energy audit since the Auditor needs to gather large amounts of data on energy usage and production that will most likely be obtained from management (Kreith & West, 1997). The support of management is also crucial in the correct implementation and sustainability of energy conservation and energy management measures.

A minimum of two year's utility data should be reviewed in order to recognize usage patterns corresponding to seasons, to discover unusual spikes in usage and to verify the accuracy of the billings (Thumann & Younger, 2008). A thorough evaluation of utility data can also reveal potential ECMs through the further evaluation of the patterns identified (Kreith & Goswami, 2007). Data on the geography surrounding the facility and the weather patterns over the same period as the utility data evaluation must be collected to enable the assessment of the seasonal patterns in energy usage (Beggs, 2002).

It is important that energy auditors familiarise themselves with the facility that they are auditing. Mechanical, architectural and electrical drawings and specifications are good representations of the facility and can then be used by the energy auditor to draw up a basic floor plan, to calculate the gross square footage and to identify and document important buildings and equipment (Thumann & Younger, 2008). A building profile should also be constructed consisting of the buildings' occupancy patterns and equipment usage patterns (Hoshide, 1995). Any plans for future building or retrofitting should also be studied by the energy auditor, since certain changes will impact on the energy usage and on the efficiency and the ability to implement potential ECMs.

The Energy Usage Index (EUI) of the facility being audited must be calculated by converting the energy usage of all fuel types into Btu/year and then dividing that value by the floor area of the facility (Thumann & Younger, 2008). The EUI is indicative of a relative potential for energy savings, where a higher EUI value indicates a greater potential for energy savings. Information should also be gathered on the energy usage and EUI of similar facilities to enable a comparison between the facility that is being audited and similar facilities (Beggs, 2002).

Production data should also be gathered to allow the comparison between the energy usage of a facility and the production levels (Beggs, 2002). Since the function of the facility is to produce products, it is crucial that the relationship between the production and the energy usage is understood by the energy auditor to allow conversant development of ECMs.

The final part of the Pre-site energy audit component is the development of ECMs and Operation and Maintenance Procedures (O&Ms) based on the data gathered during this component (Thumann & Younger, 2008). These measures and procedures are only preliminary since the facility has not been visited and they have not been properly evaluated for feasibility and cost-effectiveness.

2.3.2.2 On-site Component

Once the tasks that form part of the Pre-site energy audit component have been completed, the next step is to visit the facility that is being audited. This component is known as the On-site energy auditing component. The On-site component consists of several tasks that have to be completed during the visit to the facility in order to gather necessary data for the energy audit.

While at the facility, the energy auditor has the opportunity to review the energy consumption profile (Thumann & Younger, 2008) constructed with the information gathered during the Pre-site energy audit component with the facility manager (Beggs, 2002). The floor plan and occupancy patterns that were drawn up must also be confirmed while at the facility. It is very important that the energy auditors check the collected information to ensure that their observations are accurate.

A helpful tool for energy auditors is an audit data sheet. It helps to organise the facility visit and acts as a reminder of missing data from pre-site documentation (Thumann & Younger, 2008). Audit data sheets contain essential information on all energy consuming equipment as well as the buildings. The energy consuming equipment usually included on these data sheets are lighting equipment, HVAC systems, service water heating, machines and equipment and electric motors. For each of these types of equipment, certain information should be collected, as listed below (Hoshide, 1995):

- Lighting equipment information:
    - Number of lights
    - Lighting levels
    - Hours of usage
    - Controls
- HVAC systems information:
    - Air Conditioning
    - Heating systems
    - Heat pumps
    - Set points
    - Controls
- Service water heating information:
    - Insulation
    - Water temperatures
    - Shower heads

  - Toilets
  - Faucets
- ❖ Machines and equipment information:
  - Office equipment
  - Refrigerators and freezers
  - Cooking equipment such as stoves and microwave ovens
  - Washing and drying machines
  - Heat reclamation equipment
  - Industrial and shop equipment
  - Air compressors
- ❖ Electric motors:
  - Nameplate data
  - Operating speed
  - Operating hours

Information collected of the buildings will include information of the walls, the roof, the floors, the windows, the doors, infiltration, insulation and shading. A collective name for all these elements is the building envelope (Hoshide, 1995; Kreith & Goswami, 2007).

Measurements should be taken of the energy consumption of the different energy consuming equipment. This is done by the energy auditor using a hand-held meter to measure the electricity input into equipment. These measurements can then be summed to obtain more specific energy consumption data than the utility invoice.

Taking photographs at the facility is a good way of documenting the current state of the equipment and the building. Photographs assist when discussing issues with colleagues and also during the introduction and explanation of ECMs and O&Ms to building occupants and administrators (Thumann & Younger, 2008). It is important to keep a log of the photographs taken and to arrange and name them properly to eliminate the chance of errors (Hoshide, 1995).

It is important that the energy auditor keep the ECMs and O&Ms in mind while moving through the facility in order to assess their applicability and to identify any restrictions at the facility that might hinder the implementation of the ECMs and O&Ms (Hoshide, 1995).

2.3.2.3 Post-site Component

The third component to an energy audit is the Post-site component. During this part of the energy audit, the information and data gathered during the first two components are reviewed and clarified. Charts, graphs, the building descriptions, audit data sheets, notes and photographs are organised and documented to facilitate the analysis of the data (Thumann & Younger, 2008).

The next task to be completed during the Post-site work is the analysis of the data gathered in order to identify patterns and areas where energy consumption can be improved. There are various techniques existing that can be utilised to do the analysis. A more detailed discussion of these techniques will be done in section 2.3.3.

During the analysis of the data, it is helpful to construct process flow charts that show the energy consumptions of the processes running at the facility (Kreith & West, 1997). It is important to keep comprehensive documentation of the data as well as the analysis process, since energy audits can be ongoing processes and thorough documentation assists in the final reporting on the energy audit (Hoshide, 1995).

After all the necessary Pre- and On-site data has been gathered, this data must be utilised to determine the energy content of the products being manufactured at the facility. This process is known as Energy Accounting. Energy Accounting breaks the energy content of a product down into three main elements, namely the energy content of the raw materials, the energy required to convert the raw material into the product and the energy required to treat, re-use or sell waste or by-products (Kreith & West, 1997).The Energy Accounting process will be described in section 2.3.5

The most important part of the Post-site energy auditing component is the final evaluation of the ECMs and O&Ms. The significance of this evaluation lies in the fact that it enables the energy auditor to identify the best ECMs and O&Ms to implement at the facility. The techniques available to do the evaluation will be discussed in section 2.3.5.

The final component of an energy audit is writing the report to present to management on the current energy consumption and on possible ECMs and O&Ms to improve the current energy consumption (Thumann & Younger, 2008).

The correct structure for the report is essential, since the report is the main form of communication the energy auditor has available to convey their findings. The report should include all the necessary technical data but be constructed in such a way as to communicate effectively with management. Therefore, an executive summary is vital in the report. The executive summary should include a brief overview of the current energy consumption of the facility and a list of the proposed ECMs and O&Ms and highlight the advantages of implementing them (Beggs, 2002; Thumann & Younger, 2008).

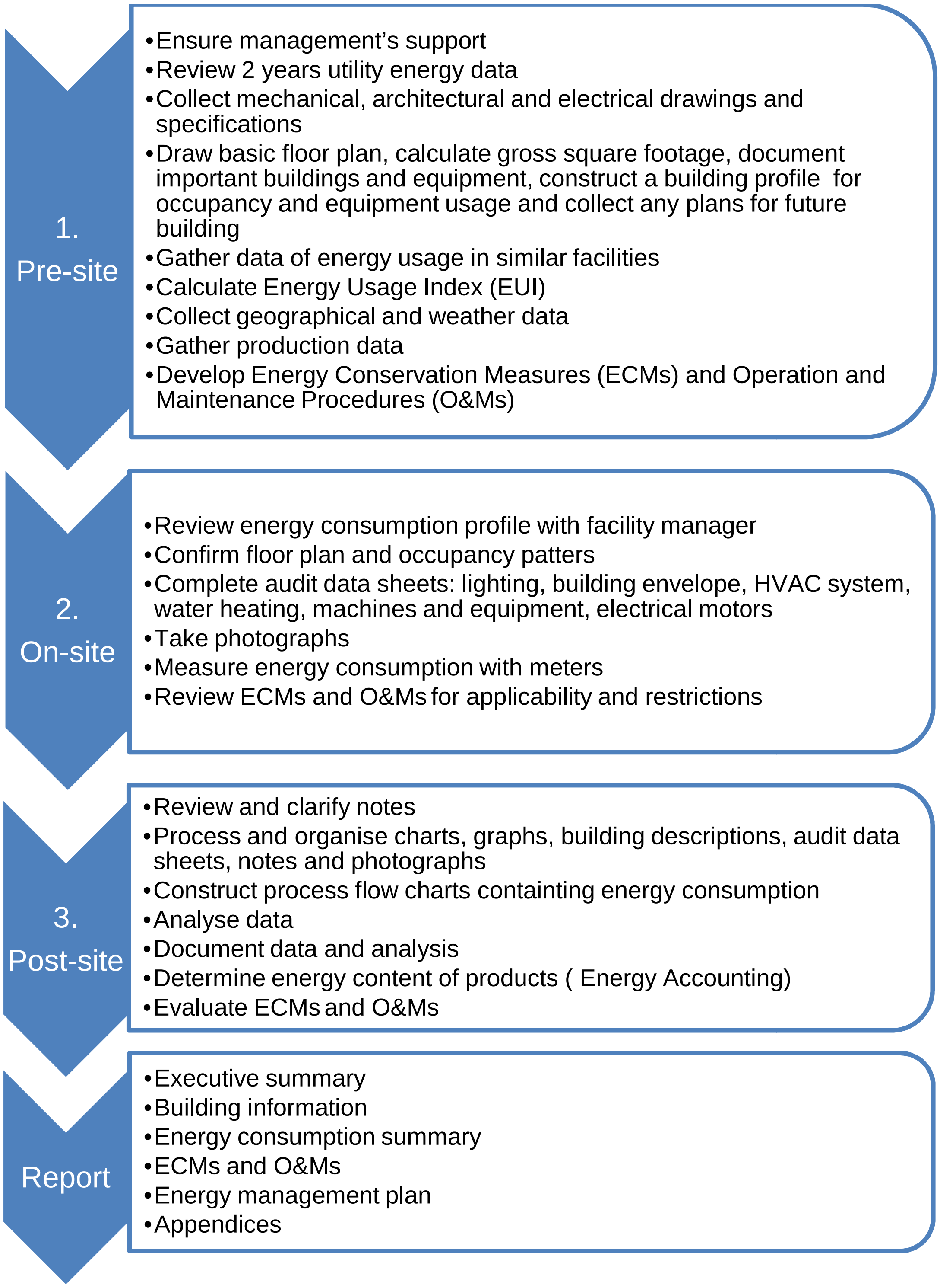


Figure 5 - Energy audit components

An overview of the facility should be incorporated in the report. This section provides information about the buildings in the facility and includes layout drawings, information about the building envelope, construction details, operating schedules, occupancy patterns, equipment lists and relevant material, and product flows (Beggs, 2002; Thumann & Younger, 2008).

After the facility overview, a summary of the energy consumption must be included in the report. This summary comprises of a utility summary of the last couple of years accompanied by a description of the utility contracts and tariffs, the energy consumption data gathered during the initial energy audit components and the analysis of this data. In this section of the report it is advised to make use of graphs to convey the data in order to make it easier for management to evaluate the data (Beggs, 2002; Thumann & Younger, 2008).

Once the current states of the facility and the energy consumption have been discussed thoroughly, the next part of the report must include the ECMs and O&Ms that were identified during the analysis of the data. The analysis of the ECMs and O&Ms are also included in this section in order to show the process of identifying the ECMs and O&Ms that comply with the conditions set by management. Emphasis should be placed on the economic analysis and the potential energy savings of the ECMs and O&Ms. It is good practice to include any assumptions that were made during the analysis and calculations (Beggs, 2002; Thumann & Younger, 2008).

The final section in the report is the Energy Management Action plan which consists of a implementation schedule for the ECMs and O&Ms identified in the previous section of the report and a plan for continuous monitoring of energy consumption in the facility. Any additional supporting information and most of the detailed data gathered during the energy audit should be included in the appendices (Beggs, 2002; Thumann & Younger, 2008).

2.3.3 Analysis of Audit data

The analysis of the data gathered can be done using one or more from a variety of techniques. These techniques are listed below (Beggs, 2002; Kreith & Goswami, 2007; Thumann & Younger, 2008):

- Percentage breakdown of annual energy consumption
- Normalised Performance Indicators (NPI)
- Time Dependent Analysis
- Linear Regression:
  - Single independent variable
  - Correlation coefficients
  - Multi-variable
- Cumulative Sum Deviation Method (CUSUM)
- Evaluation of characteristics of energy systems and energy consumption patterns:
  - Building/ Facility characteristics

   - Energy consumption patterns
- Energy Usage index (EUI)
- Electrical load analysis
   - Base loads
   - Seasonal loads
   - Consumption trends

Each analysis technique will be described in the following paragraphs in order to explain their significance and the procedures that are entailed during each analysis.

The percentage breakdown of annual energy consumption is a straightforward technique to compare the consumption of different fuel types and when this comparison is backed up by historical data, it highlights differences in consumptions over a period of time. The most important part of the breakdown is to convert all the fuel consumptions into the same standard units. Kilowatt hour (kWh) is usually used as the standard unit. When the units have been converted, the total energy consumption and cost are broken down into the different fuel types. The numbers can then be tabulated or graphed to ease the comparison between the fuel types and the comparison to historical data (Beggs, 2002). It is important to take the start-up and shut down losses into account when analysing the energy consumption (Kreith & Goswami, 2007).

Normalised performance indicators (NPI^s) make it possible to compare a facility to buildings similar in type and function. This is done by comparing Yardsticks. A Yardstick is measured as kWh per m^2 of floor area or as kWh per m^3 of building volume, which is determined through the statistical analysis of measured energy consumption survey results. Yardsticks are not absolute values, but should rather be used as guidelines when comparing facilities to establish energy conservation priorities (Beggs, 2002).

Time dependent energy analysis is the basic graphing of energy consumption against time. In order to plot a useful graph enough data (energy consumption at specific times) must be gathered. However, this is a simple method for identifying exceptions from the normal energy consumption pattern. This technique is only comparative and cannot be used as an absolute measurement (Beggs, 2002).

The linear regression technique is used to identify and quantify the relationships between variables of energy consumptions. There are several variable comparisons that are commonly made:

- Gas consumption versus the number of heating days experienced
- Gas consumption versus the number of units produced
- Electricity consumption versus the number of units produced

- Electricity consumed by lighting versus the hours of occupancy
- Water consumption versus the number of units produced

The regression technique is heavily dependent on the quantity and quality of the data used. Even if no relationship is shown by the analysis, there might still be a relationship between those two variables. Table 1 shows a list of variables that can influence energy consuming activities:

Table 1 - Variables influencing energy consumption

Energy consuming activity	Influencing variable
Outside security lighting	Hours of darkness
Space heating	Heating degree days
Air conditioning	Cooling degree days
Steam-raising in a boiler	Amount of steam generated
Air compressing	Air volume delivered
Vehicles	Tonne-miles (Tonne-kilometres) hauled
Production process	Production volume

There are three types of linear regression analysis techniques, each addressing different variable conditions. The first technique addresses a single independent variable with a linear relationship. In this case, the equation for the best fit straight-line is found through the plotted points. This can be done by summing the squares of the distances from the straight line to the various plotted points. The equation can then be used for future energy consumption predictions (Beggs, 2002).

The second technique is used when the sample data points are scattered and an equation cannot be derived. It is crucial to determine how well the best-fit line correlates to the sample data. This is done by calculating the Pearson Correlation Coefficient. The Pearson Correlation Coefficient gives an indication of the reliability of the line drawn. The value of the Pearson Correlation Coefficient ranges between 0 and 1, where a value of 1 represents a 100% correlation (Beggs, 2002).

The final regression technique is used for multi-variable analyses. This technique is used where energy consumption is influenced by several different factors. Multi-variable analyses require specialised software to calculate the statistical relationship between the variables (Beggs, 2002).

Another data analysis method is the Cumulative Sum Deviation Method (CUSUM), which is used to measure the progressive deviation from standard energy consumption patterns. This is done by calculating the cumulative summation of the difference between the actual and the target energy consumption. The target energy consumption is also known as the Base Line energy consumption and is calculated from the Standard Performance Equation (SPE).

A CUSUM analysis can be done by completing the following five steps:

- Plot a scatter graph of the two variables under consideration for the Base Line period and derive the SPE. Using to the single independent variable regression technique
- Predict Energy consumption for each month, using the SPE
- Calculate the deviation at each data point by subtracting the predicted energy consumption from the actual energy consumption
- Calculate the cumulative total deviation (CUSUM value)
- Plot the CUSUM values against time

Characteristics of the building can be accumulated from architectural, mechanical and electrical drawings, as well as from the building manager (Kreith & Goswami, 2007). These characteristics are useful when conducting the EUI analysis of the energy consumption in the facility.

It is vital to understand the energy consumption in the facility and to identify which factors influence consumption the most. The energy consumption can be understood by identifying the energy systems in the facility and analysing their usage patterns. Annual energy consumption should be broken down into two types of loads, i.e. the base and the seasonal loads (Kreith & Goswami, 2007).

The base loads of a facility are the energy systems that consume continuous amounts of energy throughout the year. These loads typically include lighting, office equipment, appliances and ventilation. A simple technique is used to determine the base loads: a graph is drawn up of either the energy consumption or cost against time and then a horizontal line is drawn at the average point of the lowest consumption. When the base loads are high, it indicates that energy can be conserved at these areas (Thumann & Younger, 2008).

Seasonal loads are energy consumption that fluctuates due to changing circumstances. These circumstances include weather changes during the seasons as well as operational changes due to influencing factors, such as school seasons. Heating and air conditioning are typical seasonal loads. The seasonal loads are identified as the energy consumption curve above the horizontal line drawn on the energy consumption or cost graph. High seasonal loads signify energy conservation opportunities such as improvements to the heating and air conditioning equipment, the temperature controls and the building envelope (Thumann & Younger, 2008).

Identifying energy consumption trends is a very basic technique. It entails merely graphing a number of years' worth of monthly energy consumption data and then observing any upward or downward trends in the energy consumption (Thumann & Younger, 2008).

2.3.4 Energy Accounting

Energy accounting is the method used to calculate the energy content of a product. This entails summing the energy content or usage for three components of the production process. Firstly, the energy content of the raw material is determined. This includes the energy used to extract and refine the material and the inherent heating value before the material has been processed (Kreith & West, 1997).

Secondly, the amount of energy required to convert the raw material into the product should be determined. This comprises of all the utilities and fuels that enter the facility for the conversion (or production) process. Lastly, the energy consumption of the waste streams and by-products are determined. The energy consumption in the waste stream is the energy used to treat and dispose of the waste. This includes the energy consumed during the transportation of the waste (Kreith & West, 1997).

Two procedures can be followed with the by-products, i.e. the by-products are either re-used in the process or sold. If the by-products are recycled for re-use, the energy consumption is calculated by subtracting the energy used during recycling from the energy content of the raw material. If the by-products are to be sold, the energy content is determined by using the relative value ratio of the by-product to the primary product (Kreith & West, 1997).

The net energy content per product can be calculated once the energy contents and consumptions for the above mentioned components of the production process are known. This is done by totalling all the energy contents and consumptions and dividing that total by the number of products produced (Kreith & West, 1997).

2.3.5 Evaluation of ECMs and O&Ms

Two main evaluation phases exist when analysing ECMs and O&Ms. Firstly, the ECM or O&M should be analysed and evaluated for its applicability in the facility. Restrictions to the implementation of the ECM or O&M should be identified. A decision should then be made if the restriction can be minimised and/or eliminated or if the restriction renders the ECM or O&M inoperative (Kreith & Goswami, 2007).

Once the plausible ECMs and O&Ms have been established, the second evaluation phase, an economic evaluation, is performed. Several economic evaluation methods exist:

- Payback period
- Net savings / Net benefit

- Life Cycle Cost (LCC)
- Internal Rate of Return (IRR)
- Savings-to-Investment Ratio (SIR)
- Overall Rate of Return (ORR)
- Discounted payback (DPB)
- Levelised cost of energy (LCOE)
- Net present value

The first and least complicated economic evaluation method is calculating the payback period. The payback period is the time it takes for the savings made by the ECM or O&M to offset the initial capital investment. The shorter the payback period, the better the investment in the ECM or O&M. There are two ways of calculating the payback period. The least complicated is calculating the simple payback period where the current fuel prices are used to calculate the energy savings (Thumann & Younger, 2008).When the time value of money is taken into account, it is known as the Discounted Payback method.

The net benefits method (also known as the net savings method or net present value method) is used to calculate the present value of the surplus of benefits, from an ECM or O&M, over the costs involved with the implementation. The benefits are the energy cost savings incurred by the ECM or O&M. If the costs exceed the benefits, the net losses are calculated. This method is especially suited for long-term profitability, but it is not useful for comparing investments that provide different services (Kreith & Goswami, 2007).

A life cycle cost (LCC) analysis compares ECM and O&M alternatives on the basis ofthe total costs incurred during their life cycles while subtracting any income amounts. These costs include: acquisition costs, inflation, maintenance costs, repair costs, replacement costs, energy costs, fuel escalation costs and any other costs incurred. Income amounts refer to the salvage values associated with that specific ECM or O&M. The LCC calculation takes the discount rate of money into account. Therefore, the calculations are done with the present values. It is thus important to document the timeline of the costs incurred during the life cycle of the ECM or O&M. This method can, however, not be used to compare ECMs or O&Ms that provide different services (Kreith & Goswami, 2007; Thumann & Younger, 2008).

The Saving-to-Investment Ratio (SIR) illustrates the ratio between the benefits (by savings) and the investment costs. This method is also based on discounted cash flows, which takes into account the time value of money.

The values included in the numerator and the denominator of the ratio depends on the objectives. In some cases only the initial investment cost is included in the denominator and the other costs are subtracted from the energy cost savings. The formulation of the ratio impacts on the outcome of the ratio. It is thus important to formulate the ratio to fit with the decision maker's objectives. The benefit of calculating a ratio is the elimination of dimensions. This simplifies the interpretation of this analysis: the higher the ratio, the higher the savings that will be realized with the implementation of the ECM or O&M (Kreith & Goswami, 2007).

When an investor has a minimum rate of return for the ECM or O&M to repay the initial investment cost, the Internal Rate of Return (IRR) is calculated and compared to the investor's minimum rate of return. This method is similar to calculating the Net Present Value (NPV) of a cash amount, but it does not use the discount rate. Instead, it is solved to get the discount rate. If the IRR is more than the investor's minimum rate of return, it is desirable to implement the ECM or O&M (Kreith & Goswami, 2007). To calculate the IRR, a method of trial and error is usually employed. These iterations are often done by computer algorithms and graphical techniques to ease the calculation (Kreith & Goswami, 2007; Thumann & Younger, 2008).

IRR is a popular analytical method, but it is important to execute it correctly. There are some shortcomings to this method that might hinder the success of the analysis. When the sum of the non-discounted returns during the period are less than the initial investment cost, no solution will be found. Multiple solutions can be found due to some costs occurring later than some of the returns. The method can also fail to give an overall rate of return because of the assumption that returns which occur during the analysis are reinvested at the IRR, which may not always be possible (Kreith & Goswami, 2007).

The Overall Rate-of-Return (ORR) method improves on the IRR method by incorporating an explicit reinvestment rate (eliminating the assumption that reinvestment is done at the IRR) that makes it possible to use the future values of the cash flows..

During both phases of evaluation, simulations can be run based on the facility and the effect the ECM or O&M will have on the facility, production and the economic impacts (Thumann & Younger, 2008). It is also crucial to account for interaction between different ECMs and O&Ms during the analysis, since the total energy savings cannot simply consist of the summation of all the ECM and O&M energy savings. A sequence that should be followed to account for interaction during the analysis is as follows (Hoshide, 1995):

- System loads, including lighting, water heating, internal equipment, heating etc.
- Distribution loads, including air handler, pumping etc.
- Generation loads, including boilers, chillers, cooling towers, etc.

An ultimate analysis method that can be applied is to simulate the alternative ECMs or O&Ms. By using simulations, the overall effect of the ECMs or O&Ms can be analysed. Simulations are complex analysis methods and if applied, they must be done accurately to ensure that the correct outcomes are obtained. The economical analysis methods discussed in the previous paragraphs can also be done using simulations, which make simulations a very versatile analysis technique (Thumann & Younger, 2008).

Through the in-depth examination of energy audits and the different components and steps it comprises of, a better understanding of this crucial process is gained. The energy audit is an invaluable tool for any company endeavouring to improve their energy efficiency.

2.4 Energy Conservation Measures and Operational and Maintenance Procedures

Several energy consuming systems and equipment have been identified through energy audits to be more likely targets for ECMs and O&Ms. In the following sections these systems and equipment will be discussed alongside possible ECMs and O&Ms that can be implemented to reduce their energy consumption. The identified systems and equipment are listed below.

- ❖ Lighting
- ❖ HVAC:
    - Heating
    - Regulates Ventilation
    - Air Conditioning
- ❖ Building envelope
- ❖ Electric drives
    - Electric motors
    - Machining operations
    - Compressors
    - Fans
    - Pumps
    - Blowers
- ❖ Electrolytic Operations
    - Welding
- ❖ Office Equipment

According to R. Stephen (2009) the three areas of industrial technology that requires specific attention when managing energy and improving energy efficiency is the HVAS system, lighting and motor systems (Stephen, 2009). Eskom's Integrated Demand Management also places focus on these three areas (*Industrial « eskom IDM*). In the following section the systems and equipment identified above will be discussed with regards to possible improvements that can be made to energy consumption. Lighting will be discussed separately, since the company that partook in the case study requested special attention to be given to lighting.

2.4.1 HVAC Systems

The HVAC systems contribute largely to the energy consumption of a facility. An HVAC system includes the heating, ventilating and air conditioning systems of a facility. The HVAC system consists of the individual space conditioning systems and a distribution system that connects the different areas in the facility with the central space conditioning systems. ECMs and O&Ms can be implemented for the HVAC system as a whole as well as separately for the different components of a HVAC system. General and specific ECMs and O&Ms will be discussed in the subsequent paragraphs.

A number of ECMs and O&Ms are identified for the complete HVAC system. Three approaches can be taken to reduce the energy consumption of the HVAC system. The foremost approach is to evaluate all the spaces to ensure that it is not unnecessarily conditioned. This also relates to the capacity of the HVAC system. Excessive capacity must be avoided in order to keep the energy consumption as low as possible (Kreith & Goswami, 2007).

The second approach focuses on improving the performance of the space conditioning equipment (Thumann & Younger, 2008). This is done primarily by making use of a suitable maintenance program. Other actions that can also be taken into account include the recirculation of conditioned air, either hot or cold, where feasible, and making use of Variable-Air-Volume (VAV) rather than constant air flow (Kreith & Goswami, 2007).

The third approach is to review the controls of the HVAC system (Kreith & Goswami, 2007). Several initiatives can be taken to improve the controls. Auto-timers can be installed to switch the entire HVAC system off at specific times, for example, at the end of the day or shift (Kreith & Goswami, 2007). Programs can be developed for different operating modes depending on the season, the time of day, occupancy patterns as well as the different areas in the facility (Institute of Electric and Electronic Engineers, 1996). The controls should be equipped with feedback loops to enable automatic monitoring of the system and to give feedback on the status of the system to the personnel (Institute of Electric and Electronic Engineers, 1996).

Manual and automatic controls can also be installed. As part of manual controlling, the operators can be equipped with remote controllers. This will enable them to switch fans on and off as needed. A setback with manual controls is the lack of consistency which makes overall control of the system difficult. Automatic controlling, on the other hand, is done by a computer which is linked into a closed-loop feedback system. This is known as Direct Digital Control (DDC)(Institute of Electric and Electronic Engineers, 1996).

The HVAC distribution system can also be targeted for energy conservation. This distribution system is responsible for transporting the heating and cooling liquids from the central plant to the different conditioned spaces. The main approach to energy conservation for the distribution system is the reduction of energy losses. This is accomplished by maintaining the insulation and repairing any leaks in the system (Thumann & Younger, 2008). The distribution system, can also be controlled by implementing a DDC (Institute of Electric and Electronic Engineers, 1996).

Generating heat is an energy intensive process. As a result, heating is one of the focal points for energy conservation. In a facility, heat is required to perform two main tasks. The first task is to heat the working areas and the second task is heating for processes, either as part of the production process or in the form of steam (Hoshide, 1995; Kreith & Goswami, 2007; Thumann & Younger, 2008).

At some geographical positions and in certain industries it is necessary to heat the working environments in order to keep employees comfortable. This requires a facility-wide heating system that regulates the indoor temperature of the facility. Five major problems are encountered with the heating of areas.

Firstly, the heating systems may not be designed properly (Beggs, 2002). The correct heating system needs to be installed for the facility's specific heating requirements. A holistic view must be taken when designing the heating system (Kreith & Goswami, 2007). The whole facility must be analysed as well as the building envelope and other heating or cooling systems in the facility. Only areas that require heating should be heated and therefore any unnecessary systems that usually impact the whole facility, and unnecessary breakdowns must be avoided (Beggs, 2002).

The third problem encountered when heating working areas, is poorly designed and insulated building envelopes, as it leads to high heat losses. Therefore, it is important to assess the building fabrics and the mechanical heating systems to identify areas where the insulation must be improved. Poor control of the heating system is the fourth problem. Proper control systems need to be set in place to control the heating system as energy efficiently as possible (Beggs, 2002).

The final problem found with heating systems to heat working areas, is poor operating practices. These heating systems are intricate and the operators should be trained in the proper usage of the system. The effective training of the operators will minimise heat loss, energy consumption and damage to the system (Beggs, 2002).

The second heating task that required heat to perform, is water and steam heating. In general this form of heating consumes less energy than the heating of work areas (Thumann & Younger, 2008). There are several energy conservation methods that can be implemented to reduce the energy consumption of these types of heating systems. Some of the energy conservation methods correspond to those of the work area heating systems.

The insulation of the system is crucial in order to eliminate heat losses. Proper operation and maintenance are also imperative. As part of the maintenance process, the system must regularly be checked for leaks or faulty valves. Operation schedules must be constructed to be as close to continuous schedules as possible, to minimise the start-up time (Kreith & Goswami, 2007; Thumann & Younger, 2008).

The production of steam can also be utilised to generate electrical energy, and vice versa. This process is known as cogeneration and is only feasible in medium to large industrial plants. The capital expenditure required to implement cogeneration is too high to make implementation in small plants feasible. Three forms of cogeneration are possible. For the first form, steam is produced at a higher pressure than is required for processes and it is then expanded through a back-pressure turbine to generate electrical energy. The exhaust steam from the back-pressure turbine is then used for the processes. The second cogeneration form uses the exhaust gasses from the diesel engine that drives the electricity generator to generate steam for processes. As a third form of cogeneration, the hot exhaust gasses of a gas-turbine can be used to generate steam (Kreith & Goswami, 2007).

An integrated approach to reducing energy consumption due to heating, is heat recovery. Heat recovery is the process of collecting waste heat from processes in the facility and transferring the heat for other heating purposes such as working area or water heating (Kreith & Goswami, 2007). Heat recovery reduces the energy consumption as well as the power demand by reducing the amount of heating that needs to be done in order to satisfy the heating requirements of the facility (Thumann & Younger, 2008). Waste heat is the energy that is rejected from processes, operations and equipment, for example, electric motors, crushing operations, grinding operations, compressors, etc. into the air or into water. Waste heat is transferred by radiation, conduction or convection, depending on the matter through which the heat is transferred (Kreith & Goswami, 2007).

It is important, when designing a heating system, that a holistic view is taken when identifying heat recovery opportunities (Beggs, 2002). The interaction between heating and cooling components is vital. The waste heat that is to be recovered should be matched to a possible heat requirement in the facility to ensure that heat is not recovered unnecessarily. Recovered heat can be used to pre-heat the air for combustion processes. This improves the combustion conditions, whichin turn improves the efficiency of the loads.

Heat recovery equipment is needed to recover heat in a facility. Heat recovering equipment is categorised into four groups, namely heat exchangers, heat-storage systems, combination heat storage-heat exchange systems and heat pumps (Kreith & Goswami, 2007).

Heat exchangers transfer heat from one medium to another by the use of an exchange medium. Heat-storage systems store excess heat until it is needed for another purpose. A combination of a heat storage-heat exchange system, also known as heat wheels, exchange heat by means of rotary cylinder with pores and ducts for heat transfer. This eliminates the exchange mediums required by normal heat exchangers and thus improves the efficiency with which heat is transferred. The heat pump is used in refrigeration cycles to transfer energy from a low temperature source to a high temperature load (Kreith & Goswami, 2007).

The second space conditioning system is the ventilation system. Ventilation is the control of the air flow in the facility. The basic approach to reduce the energy consumption of the ventilation system is to reduce the air flow. By eliminating the excess flow of air, the energy consumption is reduced (Kreith & Goswami, 2007; Thumann & Younger, 2008).

The final space conditioning system is the air conditioning system. The ECMs and O&Ms for air conditioning have two key goals: to reduce the time the air conditioning system is running and to reduce the amount of heating and cooling that the systems need to do. The air conditioning system should only be running when it is necessary. Timers can be installed to switch the air conditioners off at the end of the day or sensors can be installed to detect when the last occupant has left the space and the air conditioners should be switched off. To reduce the amount of heating and cooling that need to be done, the thermostats of the air conditioners can be set higher for cooling and lower for heating when the space is not occupied (Kreith & Goswami, 2007).

2.4.2 Building Envelope

Building envelope, as described in section 2.3, is the collective name given to the different building blocks of the facility, namely the walls, roof, floor, windows and the doors (Hoshide, 1995; Kreith & Goswami, 2007). ECMs and O&Ms targeting building envelopes have two objectives:

- ❖ Reduce the heat exchanged between the building and the outside environment.
- ❖ Control the solar and internal heat gains.

To reduce the amount of heat exchange through the building envelope, specifically through the roof or ceiling and the floor, insulation should be added. This approach is very effective in facilities without any insulation, but in insulated facilities the current insulation can be re-examined to ensure that the best possible insulation is installed for that facility (Beggs, 2002; Kreith & Goswami, 2007; Thumann & Younger, 2008).

Controlling the heat gains is focussed on the windows where the solar heat gain occurs. Two methods exist for controlling the heat gains (Kreith & Goswami, 2007; Thumann & Younger, 2008). Windows can be covered with reflective film to reflect solar heat away from the building. Interior and exterior shading can be installed at the windows to reduce the amount of sunlight to reach the windows directly. Furthermore, the windows should be checked to ensure that they are air tight (Kreith & Goswami, 2007). In general, the air leakage through the building envelope should be eliminated or kept to a minimum by employing weather stripping techniques (Kreith & Goswami, 2007).

New technologies have been developed to assist with ECMs and O&Ms. These technologies include spectrally selective glass, chromogenic glazing and building integrated photovoltaic panels. Spectrally selective glass is designed to optimise solar gains and shading. Chromogenic glazing is able to change automatically to adjust to temperatures and light levels. Building integrated photovoltaic panels create electricity while absorbing the solar radiation and heat gain that would otherwise be absorbed by the building (Kreith & Goswami, 2007).

2.4.3 Electric Drives

Electric drives refer to operations and equipment in an industrial facility that consumes electricity. Different ECMs and O&Ms applicable to the different operations and equipment will be discussed in this section. These operations include:

- electric motors
- machining operations
- compressors
- fans
- pumps
- blowers

To improve the efficiency of electric motors, two main approaches can be followed. The first approach is to retrofit the existing motor. Retrofitting consists of modifying the mechanics of the motor, changing or increasing the lubrication, improving the cooling of the motor and recovering heat from the motor where possible. The second approach is to replace the existing motor with a more energy efficient motor (Kreith & Goswami, 2007).

When installing a motor, ensure that the motor is the correct size for the load. The motor must run as close as possible to its full load ratings. Furthermore, some energy savings can be obtained by paring cogged or synchronous belts with the motor. These belts transmit more of the power from the motor to the load (Kreith & Goswami, 2007).

Several ECMs and O&Ms have been identified for machining operations. Unnecessary operations must be eliminated and the scrap produced during the operations must be reduced. Stretch forming can also be implemented before machining operations to reduce the energy consumed while forming (Kreith & Goswami, 2007). If the machining of a product includes heat treatment, it is worthwhile to utilize less energy intensive heating treatments. These treatments include (Kreith & Goswami, 2007):

- Induction heating
- Plating
- Metalizing
- Flame spraying
- Cladding

To reduce the energy consumption of painting operations, the drying temperature of the paint should be taken into account. For instance, powder coating dries at a lower temperature than solvents, and thus consuming less energy (Kreith & Goswami, 2007).

Energy intensive processes such as hot forging should be substituted with less energy intensive processes just like cold forging or squeeze forging. These alternatives require lower preheat-temperatures and thus use less energy (Kreith & Goswami, 2007).

The transportation of materials in the facility can also become energy intensive if materials have to be moved around the facility unnecessarily. To avoid unnecessary transportation of materials, combine processes or relocate machinery closer to one another. All transportation equipment should be switched off when not needed and gravity feeds should be employed whenever possible (Kreith & Goswami, 2007).

Another big consumer of energy is a compressor. It is therefore crucial to install the appropriate type and size compressor, depending on the flow rates and pressure demands of the system. Whenever it is possible, reciprocal compressors should be installed in the place of rotary compressors and electric motors rather than pneumatic motors. The air intake of the compressor should be at the lowest possible temperature and if possible heat should be recovered from the compressor for use in other areas of the facility. Compressors should be operated and maintained properly; air leaks in the lines should be eliminated and the pressure in the system should be kept as low as possible. (Kreith & Goswami, 2007)

Finally, there are some measures that can be taken to reduce the energy consumption of fans, blowers and pumps. Switches and timers can ensure that this equipment does not run unless it is required by the process. The requirements should be checked to ensure that there is no excess capacity that is being wasted. Variable speed drives should be installed which will allow the variation of speed according to the requirements of the process (Kreith & Goswami, 2007).

The power factor of a facility also plays an important role in the energy consumptions and cost. Power factor is the mathematical ratio of Active power compared to Apparent power.

$$Power\ factor = \frac{Active\ power}{Apparent\ power} \tag{1}$$

Active power, also referred to as "real power", is the power supplied power system to turn a motor. Apparent power is the absolute value of complex power, which is measured in volt-ampere. The power factor of a facility can be improved by the installation of capacitors. The benefits associated with the improvement of the power factor are (Doty & Turner, 2009):

- Increased plant capacity
- Reduced power factor penalty charges from utility
- Improvement of voltage supply
- Decreased power losses

2.4.4 Electrolytic Operations

One of the electrolytic operations encountered in industrial facilities is welding. To minimise the energy consumption of the welding operation, the correct type of welder should be installed. An automatic alternating current welder is the most energy efficient. It has better power factors, better demand characteristics, and more economical operations, and since it is automatic it requires up to 50% less energy than a manual welder (Kreith & Goswami, 2007).

2.4.5 Office Equipment

Office equipment is also becoming a focal point for ECMs and O&Ms. Office equipment includes computers, fax machines, printers and copiers (Hoshide, 1995). The operating time of any office equipment should be kept as low as possible. A simple method for minimising the operating time is to check that the equipment is switched off when the office is not occupied. Alternatively, or in conjunction with minimising operating time, energy efficient office equipment should be installed (Kreith & Goswami, 2007).

2.5 Lighting

Lighting is one of the main areas of energy consumption in facilities. The amount of energy consumed by the lighting system of facilities varies depending on the building types. Some of the factors influencing the energy consumed by lighting are the lighting levels, the usage patterns and the design of the lighting system.

Through the use of more efficient lighting technologies, advanced lighting design practices and control strategies, immense potential exists for saving electricity, reducing the emission of greenhouse gasses associated with electricity production, and reducing consumer energy costs (Kreith & Goswami, 2007).

This chapter will give an overview of lighting in a facility. Important lighting terminologies will be defined, the process of conducting a lighting audit will be described, lighting energy management programs are discussed and the lighting design process is described.

2.5.1 Lighting Audits

Before any improvements can be made to a lighting system, a thorough understanding of the current lighting system is required. A lighting audit, similar to an energy audit, is a study of the current lighting system (Hordeski, 2003; Hoshide, 1995). Lighting audits gather the required information that allows for an analysis of the current lighting system in order to identify possible improvements to the system.

A lighting audit consists of three main steps:

- ❖ Gather data on current lighting system:
  - Measure current lighting intensity and wattage
  - Gather information on current lighting system
  - Measure daylight impacts on facility
- ❖ Compare current lighting intensity with required lighting intensity
- ❖ Identify possible improvements to lighting system:
  - Identify measures to get current lighting intensity at the required level
  - Identify measures to reduce the energy consumption of the lighting system

The first step of a lighting audit is to gather data on the current lighting system. The data that is collected should include measurements of the lighting intensity measured with a lux light meter in all areas of the facility. Along with that measurement, the wattage of the luminaires should be documented as well (Hordeski, 2003; Hoshide, 1995).

All possible information should be gathered about the current lighting system. This information is crucial for the identification and evaluation of possible improvements to the current system. Types of information that should be gathered include:

- Number of luminaires (lamps and ballasts)
- Lamp types:
    - Wattage
    - Lifetime
- Ballast types
    - Wattage
    - Lifetime
- Ceiling height
- Lighting controls
- Maintenance plan

It is important to note the amount of daylight that is available at a facility, since daylight can greatly influence lighting in a facility (Du Toit, 2010; Hordeski, 2003; Hoshide, 1995; Thumann & Younger, 2008). The influence of daylight is dependent on it being permitted to shine into the facility through windows and doors as well as on any obstructions that could block it out. Once information regarding daylight is gathered, it can be used to evaluate the possibility of incorporating daylight into the lighting system.

The second step of a lighting audit is to compare the current data with the specified lighting that is required. The required lighting is dependent on the use of an area. Lighting requirement specifications that provide very detailed task-specific lighting requirements are available. The lighting intensity of the current system must be compared with these lighting specifications to ensure that health and safety requirements are met and that lighting is correct for the tasks that must be completed in an area (Hordeski, 2003; Hoshide, 1995).

The final step in a lighting audit is to identify possible improvements to the current lighting system. These improvements can be to either increase or decrease the lighting intensity as required or improvements which can be made to reduce the energy consumption of the lighting system.

2.5.2 Lighting Energy Management

Energy efficient lighting systems strive to optimising lighting quality, maximise energy savings, meet ergonomic needs and contribute to the aesthetics of a facility and to comply to the consumer's preferences (Hordeski, 2003; Kreith & Goswami, 2007). An energy efficient lighting system can be implemented at a facility by employing a lighting energy management program.

The goal of a lighting energy management program is to provide the required lighting intensity in a facility in the most energy efficient way possible. Several energy saving opportunities exist for lighting systems:

- Replace existing lights with more efficient lighting (Hordeski, 2003; Institute of Electric and Electronic Engineers, 1996; Kreith & Goswami, 2007)
- Reduce wattage of lights (Hordeski, 2003; Kreith & Goswami, 2007)
- Improve lighting controls (Hordeski, 2003; Kreith & Goswami, 2007)
- Change fixtures (Hordeski, 2003; Institute of Electric and Electronic Engineers, 1996)
- Reposition lights (Hordeski, 2003)
- Maintenance programs (Beggs, 2002; Institute of Electric and Electronic Engineers, 1996; Kreith & Goswami, 2007)
- Utilising daylight (Beggs, 2002; Du Toit, 2010; Hoshide, 1995; Kreith & Goswami, 2007).

In this section, the three main tasks of lighting energy management will be discussed. These tasks are to identify light quantity and quality required to perform visual tasks, to increase light source efficiency and to optimise lighting controls (Hordeski, 2003). The process of identifying the required quantity and quality of lights is known as lighting design. Lighting design concepts and methods will be discussed in section 6.2.2.

The second lighting energy management task is to increase the light source efficiency. Light source efficiency is calculated by dividing the amount of light emitted by the power consumed by the luminaire to produce the light to give an efficiency rating (Institute of Electric and Electronic Engineers, 1996; Kreith & Goswami, 2007).

Different factors influence the efficiency of a luminaire. Some of these factors include:

- The cost of the luminaire
- The size of luminaire
- The lifetime of the luminaire
- Optical controllability
- Dimmability
- Lumen maintenance
- Reliability
- Simplicity
- Convenience

Optical controllability is the extent to which a user is able to direct the light of the luminaire to an area.This controllability depends on the fixture and the size of the light omitting area. Lumen maintenance refers to the sustainability of the lumens emitted by the luminaire (Kreith & Goswami, 2007).

Different lamps possess different colour properties. Colour properties consist of two measurements, namely the colour temperature of a lamp and the colour rendering index of a lamp. The colour temperature of a lamp is the measure of the colour appearance of the light emitted by the lamp. The unit used for colour temperature is degrees Kelvin (°K). A low colour temperature is below 300K and is known as a warm white light. A high colour temperature is higher than 3500K and is known as a cool white light (Institute of Electric and Electronic Engineers, 1996; Kreith & Goswami, 2007).

The Colour Rendering Index (CRI) measures the surface colours when the surface is illuminated by the lamp. The index works on a scale with a maximum of 100. If a lamp has a CRI equal to 100, no difference can be perceived between the object illuminated by the lamp and the reference source. A CRI between 70-100 is categorised as good and a CRI below 20 is categorised as poor (Institute of Electric and Electronic Engineers, 1996; Kreith & Goswami, 2007).

The quality of lighting not only depends on the lighting source, but also on the furniture positions and the orientation of the worker. To minimise this dependence, task lighting must be implemented. Furniture- or ceiling-integrated task lighting can be implemented (Hoshide, 1995; Kreith & Goswami, 2007; Siminovitch, Navvab, Kowalewski, & Jones, 1991). Predefined interior layout or task station lighting can also be implemented, to which task lights can be added as needed (Kreith & Goswami, 2007; Siminovitch et al., 1991).

The efficient operation of lighting also contributes to increasing the efficiency of the light sources. Efficient lighting controls consist of a combination of the following two components:

- Efficient lighting technologies
- Commissioning and maintenance of lighting systems

The efficiency of the light source can also be increased by replacing existing lamps with lower wattage, but equal brightness (Hordeski, 2003; Kreith & Goswami, 2007). The type of ballast also influences the energy efficiency of the luminaire, and thus the most energy efficient ballast for a specific type of lamp should be installed. Recommendations for lamp and ballast replacement can be to:

- Replace incandescent lamps with fluorescent or compact fluorescent lamps (Hordeski, 2003; Hoshide, 1995)

- Replace fluorescent lamps with energy efficient fluorescent lamps (Hordeski, 2003)
- Replace Mercury Vapour or high wattage incandescent lamps with metal halide or high or low pressure sodium lamps (Hordeski, 2003; Hoshide, 1995)
- Replace magnetic ballasts with electronic ballasts (Du Toit, 2010)
- Replace T-12 lamps and energy efficient magnetic ballast withT-8 triphosphor lamps and electric ballasts (Du Toit, 2010; Hordeski, 2003; Hoshide, 1995).

Commissioning of the lighting system refers to the task of ensuring that the lighting systems perform correctly according to its design (Kreith & Goswami, 2007). Maintenance for the lighting system consists of replacing and cleaning lamps and ballasts. The cleaning and relamping should be scheduled in such a way to keep the disruption of normal work to a minimum. One way to minimise the disruption is to implement group relamping, where lamps are only replaced once a certain number have failed (Beggs, 2002; Kreith & Goswami, 2007).

The final lighting energy management task is the optimisation of the lighting controls. The aim for controlling the lighting in a facility is to reduce the usage hours in order to reduce the energy consumption and cost incurred by the lighting system. The most basic approach to lighting control is by making employees aware of the importance of switching off unnecessary lights (Du Toit, 2010). This approach is cost effective and can be combined with other lighting controls to maximise the benefits.

Lighting control approaches can be categorised into six categories. These categories are listed below and will be discussed in the following paragraphs:

- Time-based controls
- Daylight-linked controls
- Occupancy-linked controls
- Localised switching
- Integrated workstation sensors
- Building management systems

Time-based lighting controls are constructed of timers being set to switch the light on and off at pre-set times. These timers should be programmable to enable the times to vary depending on working shifts and seasons. Different shift times can be programmed into the timers and then activated depending on the shifts on a specific day. It is also crucial to make provision for the seasonal change in daylight times. A further feature that should be incorporated into the timers is an override function to allow an employee to override the pre-set timer if necessary (Beggs, 2002; Kreith & Goswami, 2007).

The second type of lighting control is based on taking daylight into account. Lighting is adapted depending on the amount of available daylight. In order to adjust the lighting, the amount of daylight should first be measured using a sensor. A program can determine whether any additional lighting is required or the amount of lighting that is required to provide the necessary lighting, once the amount of available daylight has been measured. With this control technique it is important to incorporate a time delay. This delay will prevent unnecessary switching or dimming of the lights due to a passing cloud or other obstruction reducing the daylight (Beggs, 2002; Du Toit, 2010; Hoshide, 1995; Kreith & Goswami, 2007).

Occupancy-linked lighting controls adjust the lighting depending on the occupancy of the facility. Movement or noise sensors are installed to detect the presence of an employee which will trigger the lights to switch on and when the sensors do not detect an occupant in the space the lights are switched off automatically. As with daylight controlling, it is important to incorporate some time delay in the system to avoid lights switching off while an employee is still occupying a space (Beggs, 2002; du Toit, 2010; Hordeski, 2003; Hoshide, 1995; Kreith & Goswami, 2007; Thumann & Younger, 2008).

It can be beneficial to install localised switching in a facility. This will give employees control over the lighting in their working area. Localised switching should be combined with an employee awareness campaign to make employees responsible for switching lights on and off at the beginning and end of the day (Beggs, 2002; Du Toit, 2010; Hordeski, 2003).

Integrated workstation sensors do only not focus on lighting. They integrate the control of lighting, heating, cooling, etc. with the use of sensors. These sensors detect occupancy and daylight at a specific workstation and are linked to dimmers and switches to adjust the lighting, heating, cooling, etc. at that workstation (Kreith & Goswami, 2007).

The last lighting control approach is the implementation of a building energy management system. This system will not only focus on lighting, but also on the HVAC system and the security and safety systems. This system is programmable to adjust HVAC in order to keep the employees comfortable, but also keeping the energy consumption of the facility to a minimum (Kreith & Goswami, 2007).

3. Industrial Engineering Methods in Energy Management

With a strong focus on management, Industrial Engineering (IE) can be applicable in an extensive array of fields. These fields include energy management. Industrial Engineering methods may be applicable to energy management and the efficient use of energy in facilities. This chapter will try to identify IE methods that can be applied to energy management and used to increase energy efficiency.

A list of the foremost IE methods is given in section 3.1. This is followed (section 3.2) by a summary of possible energy management and energy efficiency fields where some of these IE methods may be applicable. Short discussions of the major IE methods are provided. Section 3.3 contains an analysis of the possible correlations between publications in the IE and energy efficiency fields by means of a content analysis tool.

3.1 Fundamental IE methods

Different methods, tools and procedures form part of the fundamental IE toolkit. They encompass diverse fields of study and applications, i.e. operations, maintenance as well as financial management. A summary of these methods, tools and procedures are listed below (Du Preez, Essman, Louw, Schutte, & Marais, 2009; Uys, Schutte, & Van Zyl, ; Zandin, 2001):

- ❖ Operations analysis and design:
    - Methods Engineering:
        - Bottom-up micro perspective
        - Charting
        - Product design
        - Standard operating Procedures
    - Work Measurement:
        - Labour reporting
        - Time studies
    - Ergonomics:
        - Work environment design
    - Facilities planning and design:
        - Location of facility
        - Component layout at facility
        - Space groupings of components
        - Equipment selection and arrangement
        - Building envelope
    - Simulation:

        - Simulation of complex processes
    - Material handling:
        - Reduce the amount of material handling
        - Compare inter-operational material handling with intra-operational material handling
    - Computer integrated manufacturing
        - Computer Aided Design (CAD)
        - Computer Aided Process Planning (CAPP)
        - Computer Aided Quality Assurance (CAQ)
        - Computer Aided Manufacturing (CAM)
        - Automatic data collection
- ❖ Operations Control:
    - Supply chain management
    - Production planning and scheduling:
        - Scheduling of orders to production floor
        - Controlling orders to production floor
        - Line balancing
    - Just-in-Time:
        - Reduce work-in-progress
    - Inventory control:
        - Point-of-use storage at machine or process
        - Continuous supply from local supplier
        - Match supply and demand to reduce inventory
    - Quality control:
        - Quality Function Deployment to understand cause of faults
        - Reporting of causes and use of Pareto Analysis to identify most important causes
        - Design product to reduce causes of faults
    - Intelligent systems and methods
- ❖ Operations Management:
    - Planning and control
    - Team based:
        - Self-directed groups of employees
        - Better motivation
    - Continuous improvement:
        - Total quality management
- ❖ Maintenance:

  - For building envelope
  - For equipment
- Information systems
- Optimisation:
  - Operational research
  - Linear and Non-linear optimisation
  - Dynamic and Heuristic programming
- Statistical Analysis
- Project management
- Financial management

3.2 Possible applications of IE Methods in Energy Management

A matrix was constructed to compare the applicable IE methods and the areas or equipment where energy can be conserved. This matrix is shown in Figure 6. It gives a more general idea of areas where IE methods may be applicable.

A summary of the typical ECMs and O&Ms discussed in sections 2.4 and 2.5 was made and assembled into Table 2. The ECMs and O&Ms are listed alongside IE methods that might be applicable to each specific ECM or O&M. The IE methods were gathered from section 3.1 and compared with the ECMs and O&Ms to identify possible logical areas of application.

The format of Table 2 lists the area or equipment in the facility first, followed by typical ECMs and O&Ms implemented for each specific area or equipment. The last column lists the IE methods that might be applicable to the different ECMs and O&Ms. This format places the focus on the ECMs and O&Ms rather than the IE methods. In the discussion of Table 2, the focus will be on the IE methods and the areas or equipment where the implementation of these methods may help to reduce energy consumption.

3.2.1 Operations Analysis and Design

Operations analysis and design consists of seven categories, namely methods engineering, work measurement, ergonomics, facility planning and design, simulation, material handling and computer integrated manufacturing.

3.2.1.1 Methods Engineering

Methods engineering is the process of evaluating and improving the production system in order to make it as efficient as possible. This process makes use of different methods, as listed in section 3.1. Part of this efficiency can also be the energy efficiency of the production system. The charting system used in the facility can be adjusted to include measurements of the energy consumption to assist with the monitoring of the facility's energy consumption.

Products can be designed according to the most energy efficient production operations to eliminate unnecessary energy intensive production operations (Kreith & Goswami, 2007).

Standard operating procedures can also help to reduce energy consumption. These standard operating procedures can be designed to take into account the most energy efficient operating procedure for a specific system or piece of equipment. Operating the system and equipment according to the standard operating procedures will result in energy savings. Standard operating procedures can be applied to the HVAC system, lighting system, electric drives as well as office equipment.

3.2.1.2 Work Measurement

Work measurement is concerned with the measurement and reporting of data regarding the work being done at a facility. This includes labour reporting used in conjunction with time studies to report on the standard times for operations and the achievements of employees compared to the standard times. These studies assist with improving the efficiency with which employees work.

The other aspect of work measurement is standard operating procedures which links directly to the standard operating procedures discussed in section 3.2.1.1. As mentioned before, standard operating procedure might have the potential to impact on energy efficiency if properly incorporated.

3.2.1.3 Ergonomics

Ergonomics is the study and design of work areas. This includes the actual work areas as well as the conditioning of the space. The space conditioning aspect of ergonomics can potentially help to reduce the energy consumption of the facility, since it is concerned with the HVAC system of the facility. The HVAC system’s energy consumption can be reduced by setting the thermostat slightly higher for the cooling action and slightly lower for the heating action. This reduces the amount of energy required to reach the thermostat settings.

Specific lighting can be installed at work areas where intricate visual tasks have to be performed. This eliminates the need to install high intensity lighting throughout the facility. By reducing the intensity level of the lighting, the energy consumption is also reduced.

		Lighting	HVAC	Building Envelope	Electric drives	Electric motors	Machining operations	Transportation of materials	Compressors	Fans, pumps, blowers	Electrolytic operations	Office equipment	Energy Management	Analysis of data and ECMs	Energy Efficient Production
Operations Analysis and Design	Methods Engineering												X		X
	Work Measurement												X		X
	Ergonomics	X	X												
	Facility Planning and Design	X	X	X	X	X		X	X	X	X	X			
	Simulation	X	X	X	X	X	X	X	X	X	X	X	X		
	Material Handling							X							
	Computer Integrated Manufacturing												X		X
Operations Control	Production Planning and Scheduling						X						X		X
	Just-in-Time						X								X
	Inventory Control												X		
	Quality Control						X						X	X	X
	Intelligent Systems and Methods						X								
Operations Management	Planning and Control						X						X		X
	Team-based Operations Management						X	X					X		X
	Continuous Improvement												X		X
	Maintenance	X	X	X	X	X			X	X	X	X			
	Information Systems												X	X	X
	Optimisation	X	X	X	X	X	X	X	X	X	X	X			X
	Statistical Analysis												X	X	
	Project Management												X		X
	Financial Management												X	X	

Figure 6 - Matrix comparing IE methods and energy conservation areas and equipment

Table 2 - Applicable Industrial Engineering methods for ECMs and O&Ms

Energy conservation areas/equipment	Typical ECMs and O&Ms	Applicable IE methods	General Applicability	Applicability to masters project
Lighting	Increase light source efficiency:			
	Efficient lighting technologies	Operations analysis and design: Facility planning and design: Equipment	H	M
	Commissioning and maintenance of lighting systems	Maintenance	H	M
	Optimise lighting controls:			
	Employee awareness	Operational management: Team Management	H	H
	Task lighting	Operations analysis and design: Ergonomics	M	H
	Timers	Operations control: Production: Control	M	H
	Sensors	Operations control: Production: Control	M	M
	Centralised switches	Operations analysis and design: Facility planning and design: Layout	L	M
General HVAC system	Avoid unnecessary space conditioning	Operations analysis and design: Facility planning and design: Layout	H	L
	Improve performance of equipment:			
	Correct maintenance	Maintenance	H	H
	Recirculation of conditioned air			
	Review Controls:			
	Auto-timers	Operations control: Production: Control	H	M
	Programs	Operations control: Production: Control	H	M
	Automatic monitoring and feedback	Information systems	H	M
HVAC distribution system Heating	Maintenance	Maintenance	M	M
	Correct heating system	Operations analysis and design: Facility planning and design: Equipment	L	L
	Correct insulation of system			
	Correct insulation of building envelope	Operations analysis and design: Facility planning and design: Building envelope	H	L
	Control of heating system	Operations control	L	L
	Proper operating practices	Operations analysis and design: Methods Engineering: Standard Operating Procedures	M	L
Water and steam heating	Insulation	Operations analysis and design: Facility planning and design: Building envelope	H	L
	Maintenance	Maintenance	H	L
	Operating schedules	Operations control: Scheduling	L	L
	Cogeneration		H	L
	Heat recovery	Operations analysis and design: Facility planning and design: Equipment	M	L
Ventilation system	Reduce air flow	Operations analysis and design: Facility planning and design: Layout	L	L
Air conditioning	Eliminate unnecessary operation:			
	Timers	Operations control: Production: Control	H	M
	Sensors	Operations control: Production: Control	H	L
	Reduce amount of heating or cooling:			
	Higher reference temperature for cooling	Operations analysis and design: Ergonomics	M	H
	Lower reference temperature for heating	Operations analysis and design: Ergonomics	M	H
Building Envelope	Reduce heat exchange through building envelope:			
	Insulation	Operations analysis and design: Facility planning and design: Building envelope	H	H
	Control heat gains:			
	Glaze windows	Operations analysis and design: Facility planning and design: Building envelope	H	L
	Air tight windows and doors	Operations analysis and design: Facility planning and design: Building envelope	M	M
Electric motors	Retrofit existing motor	Operations analysis and design: Facility planning and design: Equipment	H	L
	Replace with more energy efficient motor	Operations analysis and design: Facility planning and design: Equipment	H	L
Machining operations	Eliminate unnecessary operation	Operations analysis and design: Methods Engineering: Standard Operating Procedures	H	M
	Reduce scrap produced	Quality Control: Quality Control	H	L
	Utilise less energy intensive heating treatments	Operations analysis and design: Facility planning and design: Equipment	M	L

Energy conservation areas/equipment	Typical ECMs and O&Ms	Applicable IE methods	General Applicability	Applicability to masters project
Transportation of materials	Avoid unnecessary transportation:			
	Combine processes	Operations analysis and design: Material Handling	M	L
	Switch off when not in use	Operations management	H	L
Compressors	Appropriate compressor	Operations analysis and design: Facility planning and design: Equipment	M	M
	Lowest possible air intake temperature	Operations control: Production: Control	L	L
	Maintenance	Maintenance	M	H
Fans, pumps, blowers	Eliminate unnecessary operation:			
	Timers	Operations control: Production: Control	M	L
	Sensors	Operations control: Production: Control	M	L
Welding	Correct type of welder	Operations analysis and design: Facility planning and design: Equipment	M	L
Office equipment	Eliminate unnecessary operation	Operations analysis and design: Methods Engineering: Standard Operating Procedures	H	H
	Replace with more energy efficient equipment	Operations analysis and design: Facility planning and design: Equipment	H	L
General	Raise awareness of EMP	Information systems	H	M
	Shut Down Management program	Operational management	H	H
Analysis of data and ECMs	Energy auditing and management	Statistical analysis	H	H

Two columns were added to Table 2. The first column gives an indication of the general applicability and impact of the identified IE method. The second column gives an indication of the applicability and impact of the IE method with regards to this project. It is difficult to quantify the applicability of the methods. Therefore, a scaling system is used to indicate the applicability. H refers to a high applicability and a large impact that can be made through the implementation of the method. M refers to a medium applicability and impact. L refers to low applicability and a small impact made by implementing the method.

3.2.1.4 Facility Planning and Design

Facility planning and design plays a major role in increasing the efficiency with which energy is used in a facility (Harvey, 2009). The role of facility planning and design can be divided into the acquirement and arrangement of the appropriate equipment, the layout of the facility, and aspects of the building envelope. The applicability of these components for use to reduce energy consumption will be discussed separately in the following paragraphs.

The main objective for the acquisition and arrangement of the equipment in the facility is to ensure that the correct equipment is installed for that specific facility. This relates to the lighting system, the HVAC system, electric drives and office equipment. The systems that are installed should not have unnecessary capacity. One of the considerations during this part of facility planning is the energy efficiency of the equipment (Bruening, 1996). Whenever possible, the most energy efficient equipment should be installed. For some of the heating equipment and electric motors, the option of heat recovery should also be investigated. It is also imperative that the acquired equipment be installed correctly. The correct insulation should be installed at the HVAC and the HVAC distribution system to minimise heat losses and gains.

While planning a facility, the layout of the facility is also designed. During this process, some factors can be taken into account which can help to reduce the energy consumption and assist with EMPs. Where lighting is concerned, the switches should be localised to one location for a big area. This will assist with the management of the start-up and shut down of the lights. With regard to the ventilation, the facility layout design can take the air flow into account. The more natural air flow that can be utilised, the less ventilation has to be installed at the facility. Similarly, the layout of the facility can also influence the amount of space heating that is required. The layout of equipment in the facility is also important for the correct work flow. Better work flow leads to reduced material handling during manufacturing which could reduce the energy required to handle materials.

The building envelope also influences the energy consumption of a facility. Heat is gained and lost through the building envelope, which influences the HVAC system's operation. The more heat that is gained and lost through the building envelope, the more energy is consumed to keep the spaces in the facility properly conditioned. Therefore, it is important to ensure that the building envelope is properly insulated and that windows and doors are air tight (Kreith & Goswami, 2007). Another measure that can be taken to reduce heat gain and loss, is the glazing of windows (Kreith & Goswami, 2007; Thumann & Younger, 2008).

3.2.1.5 Simulation

Simulations are used when complex processes need to be analysed. They can be used when analysing the possible effectiveness of ECMs and O&Ms in a complex system in the facility. By simulating processes, multiple variables can be taken into account and manipulated to find the optimal operating settings for processes. Once the optimal operating settings are known, ECMs and O&Ms can be applied to reach these optimal settings.

3.2.1.6 Material Handling

Reducing the amount of material handling in a facility will reduce the energy consumed by the material handling system and thus also reduce the energy consumption of the facility. By combining processes that are in sequence in the production line, the distance that the material needs to travel is reduced, and in some cases even eliminated. This reduces the material handling and therefore also the energy consumption. Installing more energy efficient material handling equipment is another way of reducing the energy consumed by material handling.

3.2.1.7 Computer Integrated Manufacturing

Computer integrated manufacturing incorporates different applications of computers in the design and manufacturing process. Some of these applications include: Computer Aided Design (CAD), Computer Aided Process Planning (CAPP), Computer Aided Quality Assurance (CAQ), Computer Aided Manufacturing (CAM) and automatic data collection.

CAD can be applied to designing products that are more energy efficient to produce. This could impact on the types of equipment required to manufacture the product. More energy efficient equipment could be implemented in order to reduce energy consumption. Energy efficiency could be incorporated in process planning and be monitored as part of the quality assurance of the manufacturing process.

3.2.2 Operations Control

Operations control consists of supply chain management, production planning and scheduling, Just-in-Time discipline, inventory control, quality control and intelligent systems and methods.

3.2.2.1 Production Planning, Scheduling and Control

In general, scheduling can be applied to the reduction of energy costs by reducing the Kilo Volt Ampere (KVA) peaks reached at the facility. This is done by scheduling energy intensive equipment or processes sequentially to avoid a spike in the KVA load. More specific to production, scheduling can eliminate unnecessary operations and thus reduce unnecessary energy consumption.

Control is crucial in a facility. It can also be applied to reduce energy consumption. Timers and sensors can be installed as part of the lighting system to switch lights off when an area is not occupied (Beggs, 2002). This reduces the operation times of the lights, which reduces energy consumption and lengthens the lifespan of the lights. Timers and operation computer programs can be used as part of the HVAC system to eliminate unnecessary usage in order to produce the same benefits as with the lighting system (Kreith & Goswami, 2007). Similarly, timers and sensors can be implemented for fans, pumps and blowers (Kreith & Goswami, 2007). For compressors, the temperature of the air intake should be controlled to remain as low as possible.

3.2.2.2 Just-in-Time Principle

The aim of the Just-in-Time principle is to reduce the work in progress in the facility. This also contributes to energy savings by eliminating unnecessary production and material handling.

3.2.2.3 Inventory Control

Inventory control is put into practice to reduce the inventory. This can be done by implementing point-of-use storage, continuous supply from a local supplier or by matching the supply and the demand of the facility and the customers. The elimination of inventory reduces the amount of energy required to store inventory.

3.2.2.4 Quality Control

Quality Function Deployment is a technique or tool employed to translate customer demands into quality specifications. In order to understand the causes of faults in products, methods such as process diagrams, fish bones or root cause methods can be constructed. The causes are then reported and a Pareto analysis is done to determine which causes are the most important and should be targeted. Once these causes have been identified, they can be taken into account during the design of the products.

Quality control can also be implemented for manufacturing processes to minimise the amount of scrap produced (Kreith & Goswami, 2007). This reduces unnecessary operation, which reduces the energy consumed during the production done on the electric motors.

3.2.2.5 Intelligent Systems and Methods

Intelligent systems are capable of gathering data, interpreting the data and making decisions based on the interpretations (Hayes-Roth, 1995). These systems and methods could be set up also in order to take energy consumption into account as well. For example: data could be gathered on the KVA and kWh usage of different areas and processes and then used to monitor the energy consumption of these areas and processes.

3.2.3 Operation Management

Operation management mainly consists of three components, namely planning and control, team-based management and continuous improvement.

3.2.3.1 Planning and Control

Planning and control is required for all operations. IEs play a crucial role in the planning and controlling of operations. The usual focal points for planning and control revolve around productivity and profits. Energy efficiency can thus be included in the planning and control of operations to form part of the overall management in a company.

3.2.3.2 Team-based Management

Team-based management is built on the principle of involvement of the employees. Different departments in the facility form teams to manage their own department. This method of management can be employed to get employees involved with energy management programs by switching off equipment that is not in use, and by motivating employees to abide by the standard operating procedures (Du Toit, 2010).

3.2.3.3 Continuous Improvement

Continuous improvement is an overall management approach that helps companies to evolve in order to satisfy the changes in the needs of their customers and to improve their processes. This approach incorporates team-based management to assist with the implementation of the changes due to changes in customer needs or to eliminate fundamental error causes from processes.

Operations management can be applied to projects where cooperation is required from all of the employees. For example, a project to shut down all unnecessary equipment during production as well as during the shut down of the facility can be implemented. Most of the ECMs and O&Ms require the cooperation of the employees. Therefore, operations management can play a key role in the successful implementation of the ECMs and O&Ms.

3.2.4 Maintenance

Maintenance is crucial in EMPs. By making use of proper maintenance programs, all the equipment and systems in the facility lasts longer and operates more efficiently (Al-Ghanim, 2003; Beggs, 2002; Kreith & Goswami, 2007). When equipment and systems operate more efficiently, they consume less energy and thus help to reduce the energy consumption of the facility.

3.2.5 Information Systems

Information systems play a key role in EMPs (Caudana et al., 1995). These systems provide the necessary feedback on energy consumption to assist the control of the equipment and systems that are consuming the energy. The data gathered can be stored in a database for use in further analysis of energy consumption (Granderson, Piette, & Ghatikar, 2011). Information systems can also be linked to automatic monitoring programs that monitor the energy consumption and can implement changes in the equipment or systems to reduce unnecessarily high energy consumption or KVA loads. Information systems also play a key role in increasing awareness of EMPs and help to keep employees motivated to participate in these programs.

3.2.6 Optimisation

The process of finding an optimal solution to a complex problem is known as optimisation. It is applied in situations where the problem is influenced by multiple factors and multiple solutions are available. To find the optimal solution with regard to the influencing factors, optimisation models are applied. This usually involves the minimising or maximising of a specific objective subject to certain constraints (Zandin, 2001).

Optimisation models can also be implemented in complex problems regarding different ECMs and O&Ms in opposition to factors such as productivity or ergonomic standards (Kreith & Goswami, 2007). An optimisation algorithm, using a heuristic, was implemented in Visual Basic for Applications (VBA) to find near optimal solutions for space lighting. The method uses multiple objectives of cost and luminance specifications as fitness of possible solutions. This is typically depicted as a xy-pareto front for the two objectives.

3.2.7 Statistical analysis

Statistical analysis is a tool that can be applied in a large portion of IE methods and is crucial to a successful energy audit. It can be used in the identification of areas where energy efficiency can be improved and to evaluate the impact of ECMs and O&Ms that have been implemented.

3.2.8 Project Management

Project management consists of multiple phases, including scheduling, financial planning and managing the completion of the project. Initiating an energy management system or improving energy efficiency has many of the same phases and will require many of the same skills. Applying project management tools to implementing energy management systems or to energy efficiency project is therefore a logical development.

3.2.9 Financial Management

The reduction of energy consumption is mainly done with financial savings as the goal. Managing the financial aspects of energy conservation projects is therefore important. The financial aspects would include the possible savings from implementing the ECMs and O&Ms compared to the costs involved with implementing. If the savings that are made do not justify the initial expense, the ECMs and O&Ms will probably not be implemented.

4. Content Analysis of literature on IE and Energy Efficiency fields

The objective of this study is to find possible correlations between IE and energy management and efficiency fields. One approach to uncovering these correlations, is through literature studies. A literature study requires an overview of both fields. This overview can be obtained by physically reading all the articles written in both fields or by applying a tool to assist with analysing the content of the fields. One such tool was made available for the purposes of this study, namely the Content Analysis Toolkit (CAT).

4.1 Content Analysis Toolkit

Content Analysis Toolkit (CAT) is a program developed by Indutech to assist with the analysis of large amounts of information (Indutech, 2012). The information is contained in electronic documents and CAT is able to extract relevant information from the collection of documents, also known as a corpus. The information that is extracted includes the following (Uys, 2010; Indutech, 2012):

- Topics identified from the corpus, described by key terms with relevant scores
- For each topic:
    - Words most strongly related to the topic
    - Documents most strongly related to the topic
    - How the other topics relate to this topic
- For each document in the corpus:
    - Words most strongly related to the document
    - Topics most strongly related to the document
    - Documents most strongly related to the document
- A vocabulary of the key terms in the corpus
- For each word in the vocabulary:
    - Topics the word related to the strongest
    - Documents the word occurs in the most
    - How other words relate to this word
- A profile of an individual based on the documents associated with that individual
- Duplicates of documents

This information can be used in various ways to assist research. It enables the user to gain knowledge about the corpus without having to read all the documents contained in it. The topics give a basic guideline of what the documents in the corpus are about. The associations of the topics with documents and words further expand the window the user has to see into the corpus. From the topics and associations between the documents the user can easily find relevant documentation to his/her search.

CAT uses the Latent Dirichlet Allocation topic modelling technique to extract the relevant information [ii, iii]. This is done by extracting all the unique words from the documents in the corpus to create a vocabulary. Unique words are identified by eliminating words included in a “stoplist”. The “stoplist” consist of various words identified by the user as non-essential, including articles, prepositions, conjunctions, adverbs, pronouns and the names of the journals in which the documents are published.

The user also decides whether numbers must be included in the vocabulary. The number of occurrences of each unique word, from the vocabulary, in all the documents is then counted to calculate the frequency of the word. These frequencies are then included in a word-to-document matrix, which forms the basis of all the extracted information supplied by CAT.

The similarities or correlations calculated between the topics identified in the CAT analyses are based on correlation coefficients. Montgomery and Runger define correlation as dimensionless quantity used to compare linear relationships between pairs of variables (D.C. Montgomery, 2007). The correlations between topics are calculated using the frequency of occurrence of words in the topics.

4.2 CAT Analyses

Analyses with Content Analysis Toolkit (CAT) were done on three corpora. Firstly, an analysis was done on a collection of journal articles in the Industrial Engineering field. The articles were gathered from the South African Journal of Industrial Engineering (SAJIE) and from the Elsevier Industrial Engineering and Computers journal. Secondly, an analysis was done on a collection of journal articles pertaining to energy and more specifically, energy in buildings. These articles were retrieved from two Elsevier journals, namely the Energy journal and the Energy and Buildings journal. The third corpus was a combination of the first two corpora. This combined corpus was analysed to show possible overlapping between the Industrial Engineering and Energy fields.

Only the articles published during the last five years were used for the analyses. Ten topics were extracted by CAT and the analysis required a minimum frequency of 5 for a word to be included. Unigrams and bigrams were included in the analysis vocabulary, but numbers were excluded. An unigram is a single word like ‘Project’ and a bigram is a two-word term such as ‘Project Management’ (Uys, 2010).

A label was assigned to each topic by evaluating the top five words and documents related to the topic. The abstract of the top 5 documents were read to give an indication of the content of the topic. This abstract, in combination with the words related to the topic, allows the user to assign a suitable label to the topic. Once a label was assigned, spot checks were done within the highest related documents in order to validate the assigned labels.

4.3 Discussion of CAT Analyses Results

The results of the three analyses run with CAT are summarised in tables and will be discussed in the next three sub-sections. The discussions will cover the labels assigned to the topics based on the top related words and documents, the topic coverage and the similarities between the topics.

4.3.1 IE Analysis

This analysis was done to identify current topics in the IE field. Two journals in the IE field were identified for the analysis, namely the SAJIE and the Elsevier Industrial Engineering and Computers. Table 3 contains the summarised results of this analysis.

CAT assigns a certainty or accuracy ranking to the topics. This rank shows the top five topics about which CAT has the highest certainty about the words related to the topics. The top five topics for this analysis are indicated in Table 3. The ranks are indicated with coloured cells. The highest ranked topic is indicated with a red cell. The lower the ranking, the closer the colour changes to green.

The topic coverage of each topic indicates the percentage of the corpus that is related to the topic. Large variations in these percentages can indicate possible noise topics. A noise topic contains unrelated documents and does not give a clear indication of underlying themes, making it difficult for further interpretation. For this analysis, the corpus coverage, shown in Table 3 and Figure 7, does not indicate major variations with the possible exception of "Project Management and Change Management" and "Data Envelope Analysis" that will be discussed later in this section.

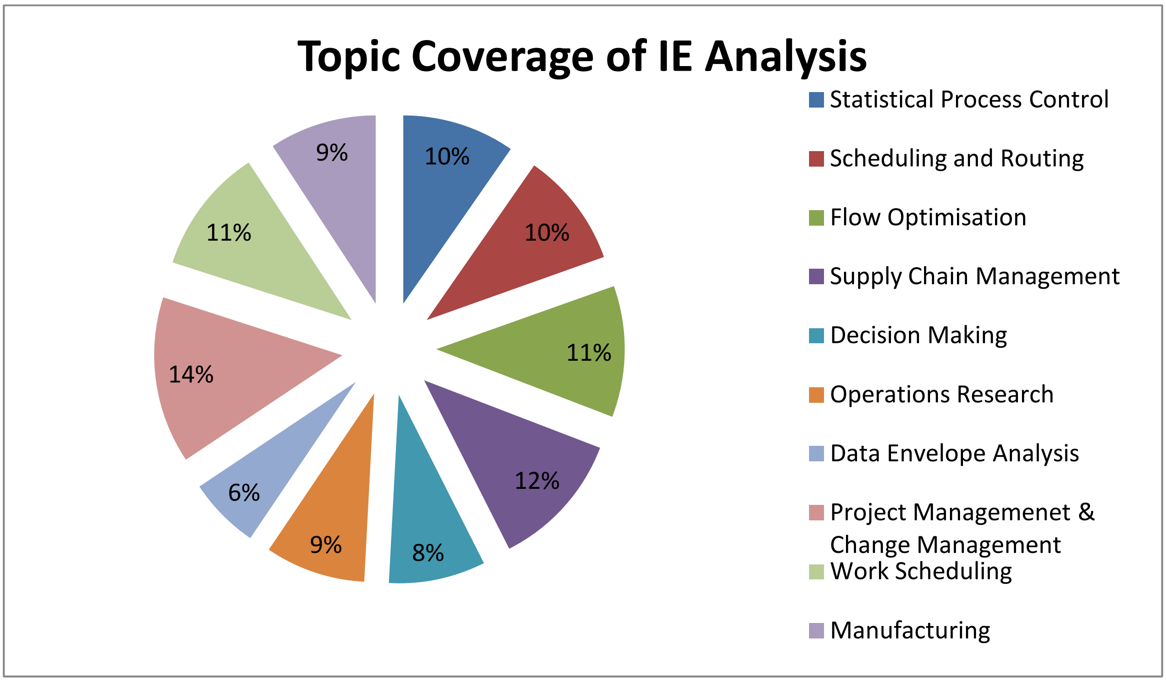


Figure 7 - Topic Coverage of IE Analysis

As mentioned previously, the relationship between the topic and the top five documents is important for the labelling of the topics and the interpretation of the results. Topic 1 was given the label of “Statistical Process Control”. This label was selected since it was the underlying field in the highest related documents as well as some randomly selected documents. The documents introduced different approaches and techniques applicable to statistical process control. Some of these include different types of control charts (Cheng & Cheng, 2011; Guh & Shiue, 2008; Guh, 2010; Haridy, Wu, Khoo, & Yu, 2011; Teh, Khoo, & Wu, 2011) neural networks (Cheng & Cheng, 2011; Guh & Shiue, 2008; Guh, 2010) , pattern recognition and feature extraction(Guh, 2010).

Topic 2 was given the label of “Scheduling and Routing”. Scheduling and routing of different vehicles were the main themes in all the top related documents. Different scheduling and routing problems for different types of vehicles are discussed in the top related documents. These include: car pooling problems [ie6], cash transportation vehicle routing problems (Yan, Wang, & Wu, 2012), delivery vehicle routing problem (Gulczynski, Golden, & Wasil, 2011), airline flight scheduling problems (C. H. Chen, Yan, & Chen, 2010) and vehicle routing problems with pick-up and delivery time constraints (Lin, 2008). This topic was given an above average ranking of fifth place for word-to-topic association. The top related words are: “time”, “problem”, “solution”, “vehicle” and “model”. These words relate with scheduling and routing; thus, the fifth place ranking is logical.

Table 3 - IE CAT Analysis results

Nr	Topic	Topic Coverage	Top 5 Rank	Top 5 Documents	Affinity	Top 5 Words	Probability
1	Statistical Process Control	9.66%		Using neural networks to detect the bivariate process variance shifts pattern	0.975162338	process	0.010612466
				Simultaneous process mean and variance monitoring using artificial neural networks	0.974721707	data	0.010610168
				A sum of squares double exponentially weighted moving average chart	0.972653566	control	0.00813237
				A combined synthetic and *np* scheme for detecting increases in fraction nonconforming	0.971705964	model	0.006371709
				An effective application of decision tree learning for on-line detection of mean shifts in multivariate control charts	0.970846075	chart	0.006325739
2	Scheduling and Routing	9.88%	5	A model and a solution algorithm for the car pooling problem with pre-matching information	0.975977735	time	0.01304256
				A model with a solution algorithm for the cash transportation vehicle routing and scheduling problem	0.961567732	problem	0.012164928
				The multi-depot split delivery vehicle routing problem: An integer programming-based heuristic, new test problems, and computational results	0.948798077	solution	0.008966548
				Applying Lagrangian relaxation-based algorithms for airline coordinated flight scheduling problems	0.948216735	vehicle	0.005772692
				A cooperative strategy for a vehicle routing problem with pickup and delivery time windows	0.947228381	model	0.005713881
3	Flow Optimisation	11.27%	3	A concurrent solution for intra-cell flow path layouts and I/O point locations of cells in a cellular manufacturing system	0.958277405	algorithm	0.014230469
				Estimation of distribution algorithm for permutation flow shops with total flow time minimization	0.930439521	problem	0.01244454
				A discrete differential evolution algorithm for the permutation flow shop scheduling problem	0.918411867	solution	0.011596913
				Parallel Simulated Annealing with Genetic Enhancement for flow shop problem with C_{sum}	0.910481444	search	0.008295111
				A mimetic random-key genetic algorithm for a symmetric multi-objective travelling salesman problem	0.908523909	solutions	0.007514506
4	Supply Chain Management	11.73%	2	Coordinating orders in a two echelon supply chain with controllable lead time and ordering cost using the credit period	0.983484027	cost	0.018998906
				Pricing and production decisions in dual-channel supply chains with demand disruptions	0.976937426	inventory	0.012629858
				The optimal integrated inventory policy with price-and-credit-linked demand under two-level trade credit	0.970487484	production	0.012143814
				Two-echelon supply chain inventory model with controllable lead time and service level constraint	0.970359152	demand	0.01168768
				Ordering, wholesale pricing and lead-time decisions in a three-stage supply chain under demand uncertainty	0.970164788	model	0.009214463
5	Decision Making	8.29%	4	Induced and uncertain heavy OWA operators	0.982085274	fuzzy	0.02532491
				Decision-making with distance measures and induced aggregation operators	0.980280133	decision	0.009550888
				The induced continuous ordered weighted geometric operators and their application in group decision making	0.976275862	model	0.007448051
				Generalized power aggregation operators and their applications in group decision making	0.976247505	criteria	0.006144072
				Some generalized aggregating operators with linguistic information and their application to multiple attribute group decision making	0.975179261	method	0.005474239
6	Operations Research	8.62%		Steady state analysis and computation of the GI[x]/Mb/1/L queue with multiple working vacations and partial batch rejection	0.961290323	system	0.015448301
				A discrete-time retrial queue with negative customers and unreliable server	0.961278195	maintenance	0.009273713
				Queuing analysis and optimal control of BMAP/G(a;b)/1/N and BMAP/MSP(a;b)/1/N systems	0.951862704	time	0.008431199
				A class of multi-server queuing system with server failures	0.950622407	cost	0.007282841
				A multi-criteria optimal replacement policy for a system subject to shocks	0.950473011	model	0.006913519

Nr	Topic	Topic Coverage	Top 5 Rank	Top 5 Documents	Affinity	Top 5 Words	Probability
7	Data Envelope Analysis	6.18%		Measurement of overall performances of decision-making units using ideal and anti-ideal decision-making units	0.945441746	model	0.012290563
				Minimax and maximin formulations of cross-efficiency in DEA	0.934677118	data	0.007248128
				An output oriented super-efficiency measure in stochastic data envelopment analysis: Considering Iranian electricity distribution companies	0.929298487	efficiency	0.005874076
				A new method based on the dispersion of weights in data envelopment analysis	0.921887714	dea	0.005814703
				Weight determination in the cross-efficiency evaluation	0.919693095	output	0.004623009
8	Project Management & Change Management	14.32%		PROJECT MANAGEMENT MATURITY: AN ASSESSMENT OF MATURITY FOR DEVELOPING PILOT PLANTS	0.97021044	management	0.011222908
				CONVERGENCE OF TECHNOLOGIES	0.969162996	project	0.007114782
				SUSTAINABLE DEVELOPMENT: A CONCEPTUAL FRAMEWORK FOR THE TECHNOLOGY MANAGEMENT FIELD OF KNOWLEDGE AND A DEPARTURE FOR FURTHER RESEARCH	0.967956934	service	0.005845558
				AN INVESTIGATION INTO THE STATUS OF PROJECT MANAGEMENT IN SOUTH AFRICA	0.967870257	quality	0.005676071
				PHASING TECHNOLOGY TRANSFER PROJECTS FOR SUSTAINABLE SOCIO-ECONOMIC DEVELOPMENT	0.966744457	process	0.005161833
9	Work Scheduling	10.8%	1	Flowshop scheduling of deteriorating jobs on dominating machines	0.976858154	scheduling	0.019426278
				Single-machine scheduling with learning effect and deteriorating jobs	0.975938967	time	0.018955288
				Single-machine group scheduling problems under the effects of deterioration and learning	0.975832597	job	0.017470744
				Two-agent scheduling with learning consideration	0.975401346	problem	0.014979574
				Single machine scheduling with time-dependent deterioration and exponential learning effect	0.975316661	jobs	0.014416233
10	Manufacturing	9.24%		A partial mesh replacement technique for design modification in rapid prototyping	0.967017035	time	0.009728998
				A knowledge base model for complex forging die machining	0.957438424	manufacturing	0.00883277
				Order-batching methods for an order-picking warehouse with two cross aisles	0.94759887	system	0.008409885
				Tool-path generation for sidewall machining	0.945544554	simulation	0.007191688
				Performance modelling, real-time dispatching and simulation of wafer fabrication systems using timed extended object-oriented Petri nets	0.939144515	production	0.006475667

Topic 3 was given the label of “Flow Optimisation”. The flow refers to work flow in different manufacturing set-ups. Different algorithms and approaches are discussed in the top related documents, including solutions for cellular manufacturing(Y. C. Ho & Liao, 2011), distribution and discrete evolution algorithms for permutation flow shops(Pan, Tasgetiren, & Liang, 2008; Y. Zhang & Li, 2011), simulated annealing for flow shop problems(Czapinski, 2010) and genetic algorithms for a travelling salesman problem (Samanlioglu, Ferrell, & Kurz, 2008).Flow optimisation was ranked as the third best defined topic with a 11,27% coverage of the corpus. This indicates that flow optimisation is a prominent theme in the IE corpus.

Topic 4 was given the label of “Supply Chain Management”. The documents related to this topic covered a wide range of supply chain aspects and different approaches to the aspects. Some of these aspects covered in the top related documents include: echelon supply chain problems (Arkan & Hejazi, 2011; Jha & Shanker, 2009), dual-channel supply chain problems (S. Huang, Yang, & Zhang, 2011), integrated inventory policies (C. H. Ho, 2011) and inventory management (Xiao, Jin, Chen, Shi, & Xie, 2010). CAT ranked supply chain management as the second best defined topic, with a strong association with the top related words (“cost”, “inventory”, “production”, “demand” and “model”). It also covers the second largest percentage of the corpus. The rating and the corpus coverage together reflect the importance of supply chain management in the IE field.

Topic 5 was given the label of “Decision Making”. Different decision making methods are discussed in the top related documents, with special attention being given to different approaches to ordered weighted averaging(Merigó & Casanovas, 2011a; Merigó & Casanovas, 2011b; Wei, 2011; J. Wu, Li, Li, & Duan, 2009; Zhou, Chen, & Liu, 2011). Decision making was given the fourth highest word-to-topic association rank. The top related words include: “fuzzy”, “decision”, “model”, “criteria” and “method”. Although this topic only covers 8,29% of the corpus, it is a well define topic based on the word-to-topic ranking.

Topic 6 was given the label “Operations Research”. The top related documents all had queuing theory as their main theme. Different types of queuing problems and approaches were discussed by these documents. Some of the queues and systems discussed included a $GI^{[x]}/M^{b}/1/L$ queue (Yu, Tang, & Fu, 2009), a discrete-time retrial queue(J. Wang & Zhang, 2009), $BMAP/G^{(a,b)}/1/N$ and $BMAP/MSP^{(a,b)}/1/N$ queues (Banik, 2009) and multi-server queuing systems (X. Yang & Alfa, 2009). Also discussed in some of the top related documents, are optimal replacement policies (C. C. Chang, Sheu, Chen, & Zhang, 2011).

Topic 7 was given the label “Data Envelope Analysis”. Data envelope analysis and efficiency were the topics of all the top related documents. Different aspects of data envelope analysis were examined in these documents, including the measurement of the overall performances of decision-making units (Azizi & Ajirlu, 2010)], cross-efficiency (S. Lim, 2011; Y. M. Wang, Chin, & Jiang, 2011), stochastic data envelope analysis (Khodabakhshi, 2010) and new weight dispersion methods (Bal, Örkcü, & Celebioglu, 2008).

Topic 8 was given the label “Project Management and Change Management”. Different types of management fields are discussed in these documents, including project management (Barry & Uys, 2011; Mittermaier & Steyn, 2009), change management and technology management (Beukman & Steyn, 2011; Brent & Pretorius, 2007; Brent & Pretorius, 2007). This topic covers the largest percentage of the corpus and therefore covers a wider span of subjects resulting in the more generalised label.

Topic 9 was given the label “Work Scheduling”. Several scheduling problems and approaches are discussed in the top related documents. The top related documents highlight single machine scheduling (X. Huang, Wang, Wang, Gao, & Wang, 2010; J. B. Wang, 2009; S. J. Yang & Yang, 2010), flow shop scheduling (J. B. Wang & Xia, 2006) and two-agent scheduling (C. C. Wu, Huang, & Lee, 2011). This topic was ranked first with regards to the word-to-topic associations, which means that all the documents related to this topic have a strong work scheduling theme. The top related words are as follow: “scheduling”, “time”, “job”, “problem” and “jobs”.

Topic 10 was given the label “Manufacturing”. A variety of different manufacturing processes and aspects are covered by the related documents. Manufacturing is a wide field with many facets, from the simulation of manufacturing systems (Liu, Jiang, & Fung, 2009) all the way to machining (M. Chang, Kim, & Park, 2009; Mawussi & Tapie, 2011)and rapid prototyping (Lai & Lai, 2010).

Table 4 shows the top three related topics to each of the extracted topics. The different relationships between the topics will be discussed in the following section.

Statistical process control shows similarities with manufacturing, which is to be expected as process controls which are applicable manufacturing processes. Operations research also relates to statistical process control due to the overlapping statistical aspects of both topics. Data envelope analysis is a technique to assess efficiency, which in turn relates to the control of processes.

Scheduling and routing shows a similarity with flow optimisation and work scheduling. This can be explained by the overlapping of the basic scheduling and routing approaches. The aim of scheduling and routing is to find the most efficient schedule and route for the activity. Data envelope analysis is a technique that can be applied to assess efficiency in general. Therefore, it can also be applied to assess scheduling and routing efficiencies.

Flow optimisation again shows a similarity with scheduling and routing and work scheduling. A similarity is also shown with manufacturing, since the optimisation of the flow of materials products is crucial in manufacturing processes.

Table 4 -IE Analysis Topic Similarities

Nr	Topic	Top 3 Topics	Affinity/Similarity
1	Statistical Process Control	Manufacturing	0.669906
		Operations Research	0.655158
		Data Envelope Analysis	0.65148
2	Scheduling and Routing	Flow Optimisation	0.702258
		Work Scheduling	0.661079
		Data Envelope Analysis	0.65686
3	Flow Optimisation	Scheduling and Routing	0.702258
		Work Scheduling	0.664999
		Manufacturing	0.6604
4	Supply Chain Management	Operations Research	0.657325
		Scheduling and Routing	0.64769
		Manufacturing	0.620429
5	Decision Making	Data Envelope Analysis	0.639835
		Statistical Process Control	0.630685
		Flow Optimisation	0.627845
6	Operations Research	Manufacturing	0.658541
		Supply Chain Management	0.657325
		Statistical Process Control	0.655158
7	Data Envelope Analysis	Statistical Process Control	0.65686
		Statistical Process Control	0.65148
		Manufacturing	0.645849
8	Project Management& Change Management	Manufacturing	0.650212
		Statistical Process Control	0.626298
		Decision Making	0.611431
9	Work Scheduling	Flow Optimisation	0.664999
		Scheduling and Routing	0.661079
		Operations Research	0.606531
10	Manufacturing	Statistical Process Control	0.669906
		Flow Optimisation	0.6604
		Operations Research	0.658541

An interesting similarity is shown between supply chain management and operations research. Some of the problem solving techniques could be applicable to supply chain management problems. Scheduling and routing, as well as manufacturing, also show similarities with supply chain management. Both of these fields are components of supply chain management.

Decision making has an affinity with data envelope analysis and statistical process control. This affinity arises from the usefulness of results obtained from data envelope analysis and statistic process control for decision making.

Operations research is applicable in various fields for various problems. Manufacturing and supply chain management topics show affinities for operational research. These affinities arise from the applicability of operations research in these fields. Statistical process control shares a basis of statistics with operations research, which results in the similarity shown between these two topics.

As before, a similarity between data envelope analysis, statistical process control and scheduling and routing was emphasized. Manufacturing is also shown to have a similarity with data envelope analysis. Efficiency is of key importance in manufacturing. Data envelope analysis thus plays a significant role in improving the efficiency of manufacturing processes.

Project management and change management shows an affinity to manufacturing, statistical process control and decision making. The similarity to manufacturing relates to changes occurring and projects initiated within manufacturing settings. Statistical process control and decision making are tools used during management and therefore show an affinity for the project management and change management topic.

Work scheduling is the highest ranked topic identified by CAT. Flow optimisation, along with scheduling and routing, are tools which are applicable to the work scheduling process as indicated by the affinity shown between these topics. Operations research contributes an array of possible scenarios and solutions to assist with the scheduling of work, and therefore also showing an affinity in the CAT results.

As discussed with previous topics, manufacturing shows similarities with statistical process control, flow optimisation and operations research. All three of these topics can be applied in a manufacturing environment.

4.3.2 Energy Efficiency Analysis

This analysis was done to identify current topics in the energy and energy efficiency fields. Two journals were identified for the analysis, namely the Elsevier Energy journal and the Elsevier Energy and Buildings journal. Table 5 contains the summarised results of this analysis.

The top five ranked topics for the Energy and Energy Efficiency analysis are indicated in Table 5. As with the IE analysis, the top ranked topic is indicated with red. The greener the colour, the lower the rank of the topic.

The topic coverage of each topic indicates the percentage of the corpus that is related to the topic. Large variations in these percentages can indicate possible noise topics. A noise topic contains unrelated documents and does not give a clear indication of underlying themes, making it useless for further interpretation. For this analysis, the corpus coverage shown in Table 5 and Figure 8 does not indicate major variations. The lack of major variations in the corpus coverage reasonably eliminates the possibility of noise topics occurring in the identified list of topics. “Impacts of Emissions and Energy Consumption in Manufacturing” covers the largest percentage of the corpus and in the topic discussions, it will show that this topic covers a wide range of themes.

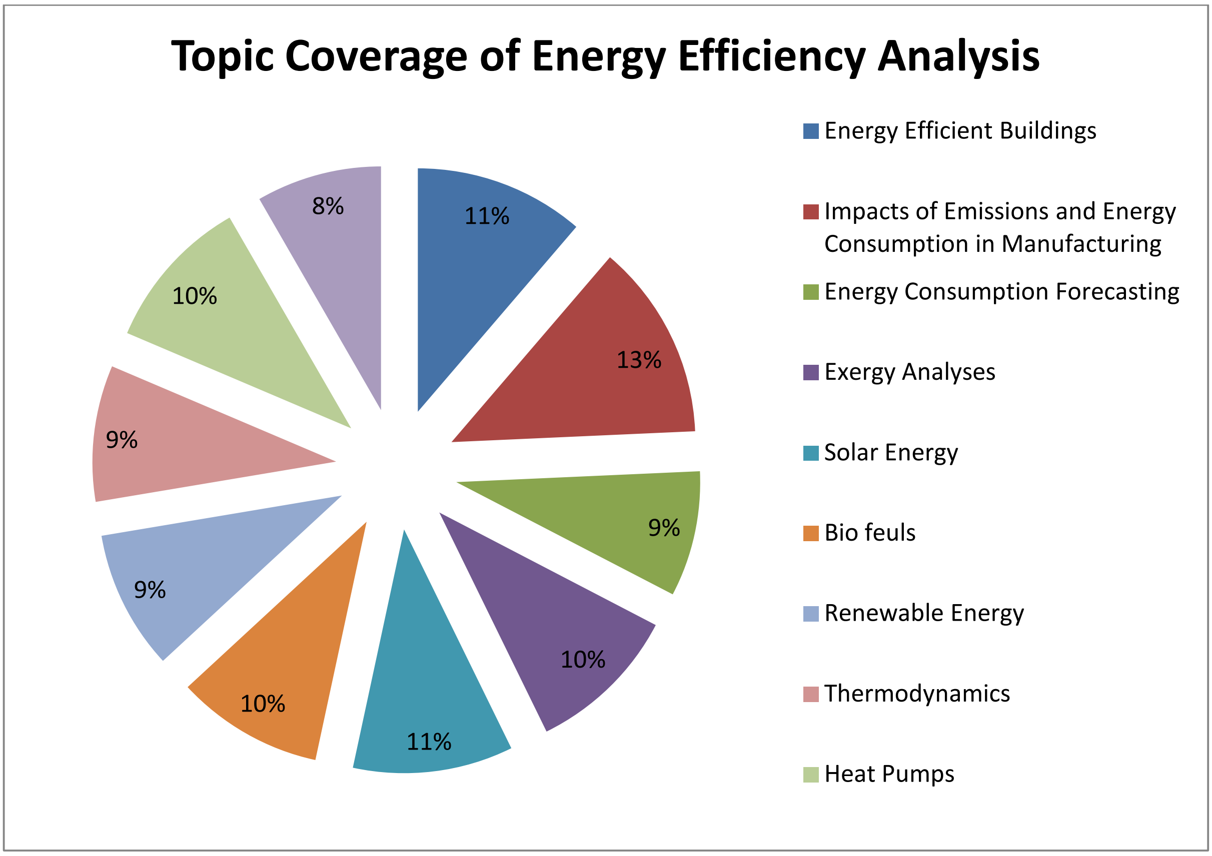


Figure 8 - Topic Coverage of Energy Efficiency Analysis

Table 5 - Energy Efficiency CAT Analysis Results

Nr	Topic	Topic Coverage	Top 5 Rank	Top 5 Documents	Affinity	Top 5 Words	Probability
1	Energy Efficient Buildings	11.26%	4	Do LEED-certified buildings save energy? Yes, but. . .	0.952919873	energy	0.038899339
				A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes	0.949004975	building	0.018017697
				Energy consumption and the potential of energy savings in Hellenic office buildings used as bank branches—A case study	0.945170814	buildings	0.013941825
				Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use	0.944094488	consumption	0.011424153
				Beyond the code: Energy, carbon, and cost savings using conventional technologies	0.932627722	heating	0.007890019
2	Impacts of Emissions and energy consumption in Manufacturing	13.02%		Bio fuels versus food production: Does bio fuels production increase food prices?	0.968424188	energy	0.030825201
				CO2 emissions structure of Indian economy	0.967168999	production	0.009040377
				Energy use in the Greek manufacturing sector: Amethodological framework based on physical indicators with aggregation and decomposition analysis	0.965790307	emissions	0.005802848
				Regional societal and ecosystem metabolism analysis in China: A multi-scale integrated analysis of societal metabolism(MSIASM) approach	0.964791851	oil	0.005546321
				Energy and economic analysis of different seed corn harvesting systems in Iran	0.961860855	electricity	0.005359166
3	Energy Consumption Forecasting	8.35%		An integrated fuzzy regression algorithm for energy consumption estimation with non-stationary data: A case study of Iran	0.969583778	model	0.015378893
				Minimum variance hedging with bivariate regime-switching model for WTI crude oil	0.949066214	data	0.008807615
				An adaptive fuzzy combination model based on self-organizing map and support vector regression for electric load forecasting	0.948225571	energy	0.008211941
				Electric load forecasting by seasonal recurrent SVR (support vector regression) with chaotic artificial bee colony algorithm	0.942826893	models	0.006472538
				Forecasting energy consumption in Taiwan using hybrid nonlinear models	0.939736347	time	0.006442889
4	Exergy Analyses	10.13%	3	A new approach to the exergy analysis of absorption refrigeration machines	0.978684531	exergy	0.014432006
				Exergy analysis of two cryogenic air separation processes	0.970203342	heat	0.012460888
				Conventional and advanced exergetic analyses applied to a combined cycle power plant	0.967404674	energy	0.012136266
				Comparative evaluation of LNG e based cogeneration systems using advanced exergetic analysis	0.965920156	efficiency	0.008973949
				Advanced exergetic evaluation of refrigeration machines using different working fluids	0.965340493	gas	0.008849465
5	Solar Energy	10.61%		Optical performance of inclined south-north axis three-positions tracked solar panels	0.957261029	solar	0.016168555
				Solar radiation on domed roofs	0.947843531	thermal	0.014567864
				Simplified correlations of global, direct and diffuse luminous efficacy on horizontal and vertical surfaces	0.94574064	energy	0.011863974
				Analysis of the influence of installation thermal bridges on windows performance: The case of clay block walls	0.942791005	heat	0.010811126
				Calculation of total solar fraction for different orientation of greenhouse using 3D-shadow analysis in Auto-CAD	0.939253777	temperature	0.009551615
6	Bio fuels	9.76%		Exhaust emissions from a light-duty diesel engine with Jatropha biodiesel fuel	0.969190351	fuel	0.009664232
				A comparative study of vegetable oil methyl esters (biodiesels)	0.965334793	combustion	0.008681277
				The effect of the addition of individual methyl esters on the combustion and emissions of ethanol and butanol -diesel blends	0.964746677	engine	0.007852742
				Co-liquefaction behaviour of a sub-bituminous coal and sawdust	0.963232859	gas	0.00730953
				Bio-crude production from secondary pulp/paper-mill sludge and waste newspaper via co-liquefaction in hot-compressed water	0.960676726	energy	0.005941702

Nr	Topic	Topic Coverage	Top 5 Rank	Top 5 Documents	Affinity	Top 5 Words	Probability
7	Renewable Energy	9.23%		Comparative study on the performance of control systems for doubly fed induction generator (DFIG) wind turbines operating with power regulation	0.979131886	power	0.023234373
				Performance evaluation of series compensated self-excited six-phase induction generator for stand-alone renewable energy generation	0.968862816	energy	0.017335652
				Metrics for evaluating the impacts of intermittent renewable generation on utility load-balancing	0.950320054	wind	0.013028292
				Hybrid solar-wind system with battery storage operating in grid–connected and standalone mode: Control and energy management e Experimental investigation	0.932330827	system	0.011694283
				Optimal retailer bidding in a DA market e a new method considering risk and demand elasticity	0.927831715	electricity	0.009498074
8	Thermodynamics	9.05%	5	Heat line based thermal management for natural convection within right-angled porous triangular enclosures with various thermal conditions of walls	0.978564878	heat	0.0174266
				Heat transfer and friction in solar air heater duct with W-shaped rib roughness on absorber plate	0.97810219	flow	0.012008435
				Heat transfer and friction factor correlations of solar air heater ducts artificially roughened with discrete V-down ribs	0.971545696	transfer	0.011183711
				Heat transfer and entropy generation analyses associated with mixed electro kinetically induced and pressure-driven power-law micro flows	0.965239295	temperature	0.009616229
				A numerical investigation of entropy generation in the entrance region of curved pipes at constant wall temperature	0.964512041	heat transfer	0.008063112
9	Heat Pumps	10.26%	1	Transient characteristics and performance analysis of a vapour compression air conditioning system with condensing heat recovery	0.940821256	heat	0.026043369
				Performance analysis of liquid desiccant based air-conditioning system under variable fresh air ratios	0.938342967	system	0.019134958
				Evaluation of alternative arrangements of a heat pump system for plume abatement in a large-scale chiller plant in a subtropical region	0.935313918	water	0.015956493
				Development and experimental validation of a novel indirect-expansion solar-assisted multifunctional heat pump	0.932216595	temperature	0.015721741
				Experimental investigation of a vapour compression heat pump used for cooling and heating applications	0.927330508	cooling	0.014843098
10	HVAC	8.32%	2	Performance analysis of supply and return fans for HVAC systems under different operating strategies of economizer dampers	0.956412021	air	0.024320095
				A robust CO2-based demand-controlled ventilation control strategy for multi-zone HVAC systems	0.953556731	temperature	0.017575974
				A new operating strategy for economizer dampers of VAV system	0.952145923	ventilation	0.011500448
				Thermal comfort for naturally ventilated residential buildings in Harbin	0.944818597	indoor	0.008953167
				The predictions of infection risk of indoor airborne transmission of diseases in high-rise hospitals: Tracer gas simulation	0.931701346	buildings	0.008752678

Topic 1 was given the label “Energy Efficient Buildings”. As one of the journals included in the corpus for this CAT analysis in Elsevier’s Energy and Buildings, a topic encompassing the relationship between energy and buildings is expected. The subject matter of top related documents include methods for decreasing the energy consumption of different types of buildings (Kneifel, 2011; Newsham, Mancini, & Birt, 2009; Spyropoulos & Balaras, 2011) as well as rating systems for evaluating the energy consumption of different types of buildings (Pérez-Lombard, Ortiz, González, & Maestre, 2009; Yohanis, Mondol, Wright, & Norton, 2008). Energy efficient buildings received the fourth highest rank for word-to-topic associations. The top five related words: “energy”, “building”, “buildings”, “consumption” and “heating”, which sum up the theme of the topic very nicely.

Topic 2 was given the label “Impact of Emissions and Energy Consumption in Manufacturing”. This topic covers a wide range of fields including emissions (Parikh, Panda, Ganesh-Kumar, & Singh, 2009), energy consumption (Salta, Polatidis, & Haralambopoulos, 2009), societal impact (Geng, Liu, Liu, Zhao, & Xue, 2011; Parikh et al., 2009) as well as energy and economic impact (Ajanovic, 2011; Pishgar-Komleh, Keyhani, Mostofi-Sarkari, & Jafari, 2012). The top related documents share a common field of interest, i.e. manufacturing.

Topic 3 was given the label “Energy Consumption Forecasting”. Different methods and tools for forecasting energy consumption for various situations are discussed in the top related documents. Some of these methods include fuzzy regression (Azadeh, Saberi, & Seraj, 2010), Markov switching and variance hedging (Hung, Wang, Chang, Shih, & Kao, 2011), support vector regression (Hong, 2011)and self-organising maps (Che, Wang, & Wang, 2011).

Topic 4 was given the label “Exergy Analysis”. According to Petrakopoulou et al, exergy analysis is the evaluation of energy conversion systems (Petrakopoulou, Tsatsaronis, Morosuk, & Carassai, 2011). The top related documents discuss exergy analyses on different types of conversion systems. This topic is ranked third for word-to-topic associations, which indicates that the top five related words (“exergy”, “heat”, “energy”, “efficiency” and “gas”) represent the theme of the topic effectively.

Topic 5 was labelled as “Solar Energy”. Different aspects of solar energy are discussed in the top related documents,including the effect of solar energy on existing structures and systems (Cappelletti, Gasparella, Romagnoni, & Baggio, 2011; De Rosa, Ferraro, Kaliakatsos, & Marinelli, 2008b; Faghih & Bahadori, 2009; Gupta, Tiwari, Kumar, & Gupta, 2011)as well as the applications of solar energy as a renewable energy source(Zhong, Li, Tang, & Dong, 2011).

Topic 6 was given the label “Bio fuels”. The studies discussed in the top related documents evaluate different aspect of bio fuels. Different types of bio fuels are compared(Satyanarayana & Muraleedharan, 2011).Evaluation of the emissions of certain bio fuels (Tan, Hu, Lou, & Li, 2012)as well as the production of bio fuels (Shui et al., 2011; L. Zhang, Champagne, & Xu, 2011) are covered by these documents.

Topic 7 was labelled as “Renewable Energy”. Sources of renewable energy are discussed (Fernandez, Garcia, & Jurado, 2008)in the top rated documents along with integrating these energy sources into the existing grid (Dali, Belhadj, & Roboam, 2010) and the effect this will have on the grid (Tarroja, Mueller, Eichman, & Samuelsen, 2012).

Topic 8 was given the label “Thermodynamics”. Various sub-topics relating to thermodynamics are covered by the top related documents. The sub-topics include entropy generation (Amani & Nobari, 2011; Shamshiri, Khazaeli, Ashrafizaadeh, & Mortazavi, 2012), heat transfer (Lanjewar, Bhagoria, & Sarviya, 2011; S. Singh, Chander, & Saini, 2011)and thermal management (Anandalakshmi, Kaluri, & Basak, 2011). Thermodynamics is ranked fifth for word-to-topic associations. The top five related words: “heat”, “flow”, “transfer”, “temperature” and “heat transfer” have a strong affiliation with thermodynamics, and therefore supporting the ranking given by CAT.

Topic 9 was given the label “Heat Pumps”. Different types of heat pumps are evaluated in the top related documents (Fatouh & Elgendy, 2011; J. Wang, Wang, Xu, & Xiao, 2009; Q. Wang et al., 2011) as well as other systems related to heat recovery (Jiang, Wu, Xu, & Wang, 2010). First rank was given to the heat pumps topic with regards to its word-to-topic association. This ranking thus indicates a strong association between heat pumps and the following words: “heat”, “system”, “water”, “temperature” and “cooling”.

Topic 10 was given the label “HVAC”. All the top related documents are about HVAC systems. Different aspects of HVAC systems for various facilities are discussed and special attention is given to ventilation in some of the documents (T. Lim, Cho, & Kim, 2010; Nassif, 2012; Z. Wang, Zhang, Zhao, & He, 2010). HVAC is short for heating, ventilation and air conditioning and therefore it has a significant association with the following words: “air”, “temperature”, “ventilation”, “indoors” and “buildings”. These are the top five words related to the HVAC topic and the association between these words. This topic has the second highest ranking.

Table 6 shows the top three related topics to each generated topic. Correlation coefficient values are shown for each pair of topics. The correlations between the topics will be discussed following after Table 6.

Table 6 - Energy Efficiency Analysis Topic Similarities

Nr	Topic	Top 3 Topics	Affinity/ Similarity
1	Energy Efficient Buildings	Emissions and energy consumption in production	0.708155871
		HVAC	0.691141538
		Renewable Energy	0.666808999
2	Impacts of Emissions and energy consumption in Manufacturing	Energy Efficient Buildings	0.708155871
		Renewable Energy	0.687203651
		Exergy Analyses	0.633542757
3	Energy Consumption Forecasting	Renewable Energy	0.64104444
		Energy Efficient Buildings	0.626035502
		Thermodynamics	0.614683818
4	Exergy Analyses	Heat Pumps	0.676040399
		Bio fuels	0.656152124
		Renewable Energy	0.650655798
5	Solar Energy	Thermodynamics	0.685362902
		HVAC	0.678897801
		Energy Efficient Buildings	0.659239599
6	Bio fuels	Exergy Analyses	0.656152124
		Thermodynamics	0.62677216
		Emissions and energy consumption in production	0.621261796
7	Renewable Energy	Emissions and energy consumption in production	0.687203651
		Energy Efficient Buildings	0.666808999
		Exergy Analyses	0.650655798
8	Thermodynamics	Solar Energy	0.685362902
		Heat Pumps	0.65658933
		Exergy Analyses	0.647267016
9	Heat Pumps	HVAC	0.676541256
		Exergy Analyses	0.676040399
		Thermodynamics	0.65658933
10	HVAC	Energy Efficient Buildings	0.691141538
		Solar Energy	0.678897801
		Heat Pumps	0.676541256

Energy efficient buildings show a strong relationship to impacts between the emissions and energy consumption in manufacturing. This relationship can stem from the important part reducing energy consumption plays in improving the energy efficiency of a building. HVAC is the highest energy consumption area in a facility (Stephen, 2009), which explains the strong affinity between the HVAC and energy efficient building topics. Renewable energy also shows a reasonably strong affinity to energy efficient buildings.

The impacts of emissions and energy consumption in manufacturing again show a strong relationship to energy efficient buildings. Renewable energy has a significant similarity with the impacts of emissions and energy consumption in manufacturing. This similarity can be based on a shared emissions theme in both topics. A reasonable affinity is also shown between exergy analysis and the impacts of emissions and energy consumption in manufacturing.

The similarities between energy consumption forecasting and renewable energy, energy efficient buildings as well as thermodynamics are not as strong as the previous two topic's topic-to-topic relationships between their top three related topics. Forecasting energy consumption can be useful for identifying a type of renewable energy and the scale of the renewable energy system required to meet the forecasted energy consumption. Improvements to increase the energy efficiency of a building could also be designed upon energy consumption forecasts.

Exergy analysis has the highest affinity with heat pumps. Since heat pumps are employed in energy conservation systems and exergy analysis is the analysis of energy conservation systems, this affinity is to be expected. Renewable energy and bio fuels are alternative energy sources in energy systems.Therefore, certain aspects of these topics would overlap with the analysis of energy conservation systems.

Solar energy has significant affinities for thermodynamics, HVAC and energy efficient buildings. Solar energy is reliant on the sun. The sun can impact on the indoor environment, and therefore impacting on the HVAC system and the energy efficiency of the building due to the counter measure that have to be taken to minimise the effect of the heat from the sun. Thermodynamics is concerned with the relationship of heat as a form of energy and how it interacts with other energy forms (Demirel, 2007). Some share themes may arise between heat as an energy form and solar energy due to the sun being a source of heat.

Once again, a similarity between bio fuels and exergy analysis is shown. Bio fuels also show an affinity towards the impact of emissions and energy consumption in manufacturing. Many of the documents related to bio fuels evaluate the emissions caused by using these fuel types, which is similar to the emissions component of the impact of emissions and energy consumption in manufacturing topic.

The similarities between renewable energy, the impact of emissions and energy consumption in manufacturing, energy efficient buildings and exergy analysis is shown again. These similarities have all been discussed shortly under previous topic-to-topic relationship discussions.

Heat pumps form part of thermal energy systems by transferring heat in the opposite direction of spontaneous heat flow (Harvey, 2009). This aspect can be used in HVAC systems, thus explaining the strong similarity between the two topics. Exergy analysis is focussed on energy conservation systems and heat pumps form part of energy systems and therefore a similarity between energy conservation systems and energy systems can explain the similarity between the two topics. Heat pumps form part of thermal energy systems and thermodynamics is the study of heat, or thermal energy. A similarity is thus bound to be identified between these two topics.

As before, the similarities between HVAC, energy efficient buildings and solar energy and heat pumps are confirmed. These similarities have all been discussed previously during the discussions of the topic showing the similarities to HVAC.

4.3.3 IE and Energy Efficiency Analysis

The third analysis that was done, combined the IE and Energy Efficiency corpora. The aim of this analysis was to identify possible correlations between IE and Energy Efficiency by evaluating the topics that CAT identified from the combined corpora. The results are shown in

Table 7.

The topic coverage of the IE and energy efficiency analysis is shown in Figure 9. Some variance can be observed in the topic coverage of the corpus, but the variance does not explicitly indicate noise topics with either very large or very small coverage percentages. The noticeable variances will be discussed shortly along with the labels of the different topics.

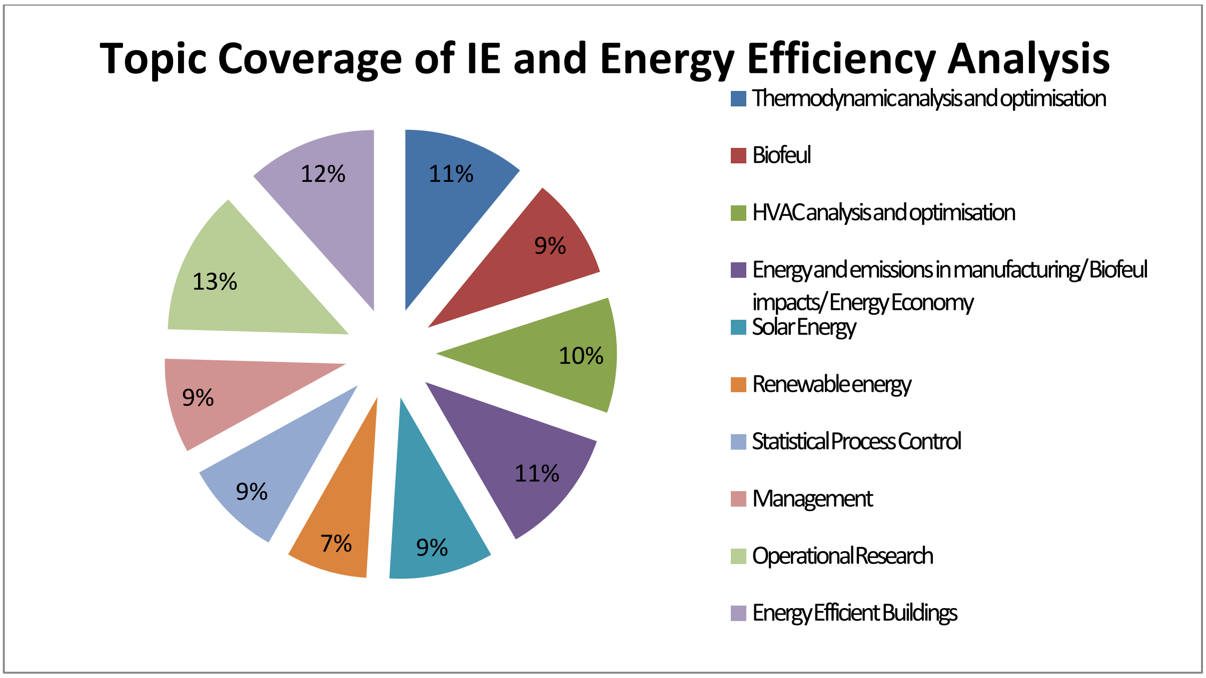


Figure 9 - Topic Coverage of IE and Energy Efficiency Analysis

Topic 1 was given the label "Thermodynamic analysis and optimisation". This topic focuses strongly on thermodynamic cycles such as Rankine cycles (Desai & Bandyopadhyay, 2009; Roy & Misra, 2012), refrigeration cycles (Morosuk & Tsatsaronis, 2008; J. Wang, Dai, Zhang, & Ma, 2009), and CO_2 cycles (Kim, Kim, & Favrat, 2012). The top related documents' subject matter includes the analysis and optimisation of these different cycles, which changes the focal point of the topic from the "Thermodynamics" topics identified in the energy efficiency analysis. Thermodynamics analysis and optimisation was identified as the topic with the highest word-to-topic association ranking. This indicates that the topic related strongly with the following words: "heat", "energy", "system", "exergy" and "water".

Topic 2 was given the label "Bio fuel". TH top related documents to this topic discuss various aspects of different types of bio fuel, specifically the emissions of these fuels (Park, Cha, Kim, & Lee, 2012; Sukjit, Herreros, Dearn, Garcia-Contreras, & Tsolakis, 2012; Tran, Sirjean, Glaude, Fournet, & Battin-Leclerc, 2011). Some of the types of bio fuels discussed by these documents include: bio ethanol blended diesel fuel (Park et al., 2012), butanol-diesel blends (Sukjit et al., 2012), methyl butanoate and methyl decanoate (Grana, Frassoldati, Saggese, Faravelli, & Ranzi, 2012) and acetylene mixtures (Esarte, Abián, Millera, Bilbao, & Alzueta, 2011).

Topic 3 was given the label “HVAC analysis and optimisation”. More detailed aspects of conditioning indoor environments are discussed by the op related documents. These aspects include: solar air heating (Lanjewar et al., 2011; S. Singh et al., 2011), analysis and optimisation of cooling systems (Q. Chen, Pan, & Guo, 2011; Lee, Rhee, Kim, Cho, & Moon, 2009), and thermal management (Anandalakshmi et al., 2011). This topic has the second highest word-to-topic ranking, which indicates a strong correlation between the topic and the top related words, i.e. “air”, “heat”, “temperature”, “flow” and “transfer”.

Topic 4 was labelled “Energy and Emissions in Manufacturing/ Bio Fuels Impacts/ Energy Economy”. This topic is not well defined by the top words and documents related to it; thus resulting in a combination of themes in the topic. The themes covered in the top related documents include: energy consumption in manufacturing (Salta et al., 2009), the impact of increased usage of bio fuels (Ajanovic, 2011; Nonhebel, 2011), emissions (Kythreotou, Tassou, & Florides, 2011) and economic impact of bio fuel usage.

Table 7 - IE and Energy Efficiency CAT Analysis Results

Nr	Topic	Topic Coverage	Top 5 Rank	Top 5 Documents	Affinity	Top 5 Words	Probability
1	Thermodynamic analysis and optimisation	10.89%	1	A new approach to the exergy analysis of absorption refrigeration machines	0.976513464	heat	0.0205834
				Transcritical or supercritical CO2 cycles using both low- and high-temperature heat sources	0.971226111	energy	0.013998556
				Process integration of organic Rankine cycle	0.971060526	system	0.013333712
				Parametric analysis for a new combined power and ejector–absorption refrigeration cycle	0.965699944	exergy	0.010451725
				Parametric optimization and performance analysis of a regenerative Organic Rankine Cycle using R-123 for waste heat recovery	0.965339671	water	0.00942365
2	Biofuel	9.1%		Effect of early injection strategy on spray atomization and emission reduction characteristics in bio-ethanol blended diesel fuelled engine	0.974833974	fuel	0.009925547
				Progress in detailed kinetic modelling of the combustion of oxygenated components of bio fuels	0.970644457	gas	0.008165494
				Gas and soot products formed in the pyrolysis of acetylene mixed with methanol, ethanol, isopropanol or n-butanol	0.970534491	combustion	0.007393029
				The effect of the addition of individual methyl esters on the combustion and emissions of ethanol and butanol – diesel blends	0.968070783	energy	0.006252932
				A wide range kinetic modelling study of pyrolysis and oxidation of methyl butanoate and methyl decanoate. Note I: Lumped kinetic model of methyl butanoate and small methyl esters	0.967770498	engine	0.005622437
3	HVAC analysis and optimisation	10.31%	2	Heat line based thermal management for natural convection within right-angled porous triangular enclosures with various thermal conditions of walls	0.977490859	air	0.02373314
				Detailed measurement of heat/mass transfer with continuous and multiple V-shaped ribs in rectangular channel	0.967060115	heat	0.016754379
				A new approach to analysis and optimization of evaporative cooling system II: Applications	0.966634708	temperature	0.016619749
				Heat transfer and friction factor correlations of solar air heater ducts artificially roughened with discrete V-down ribs	0.964853154	flow	0.011009251
				Heat transfer and friction in solar air heater duct with W-shaped rib roughness on absorber plate	0.954545455	transfer	0.00755226
4	Energy and emissions in manufacturing/ Bio fuel impacts/ Energy Economy	11.41%		Energy use in the Greek manufacturing sector: A methodological framework based on physical indicators with aggregation and decomposition analysis	0.965822785	energy	0.033059132
				Global food supply and the impacts of increased use of bio fuels	0.964955426	production	0.008420187
				The contribution of direct energy use for livestock breeding to the greenhouse gases emissions of Cyprus	0.961144578	electricity	0.006397994
				Bio fuels versus food production: Does bio fuels production increase food prices?	0.960650888	emissions	0.005779517
				Economic challenges for the future relevance of bio fuels in transport in EU countries	0.958490566	consumption	0.005507026
5	Solar Energy	9.29%	4	Optimal tilt-angles of all-glass evacuated tube solar collectors	0.96097561	solar	0.018214112
				Simplified correlations of global, direct and diffuse luminous efficacy on horizontal and vertical surfaces	0.960444324	thermal	0.013499018
				Calculating diffuse illuminance on vertical surfaces in different sky conditions	0.960268607	heat	0.01178196
				Solar radiation on domed roofs	0.957929883	energy	0.011707334
				Optical performance of inclined south-north axis three-positions tracked solar panels	0.957788484	temperature	0.010733296
6	Renewable energy	7.22%		Comparative study on the performance of control systems for doubly fed induction generator (DFIG) wind turbines operating with power regulation	0.982923782	power	0.022971222
				Performance evaluation of series compensated self-excited six-phase induction generator for stand-alone renewable energy generation	0.975955056	energy	0.0177082
				A six-phase synchronous generator for stand-alone renewable energy generation: Experimental analysis	0.944668008	wind	0.013623727
				Hybrid solar-wind system with battery storage operating in grid–connected and standalone mode: Control and energy management e Experimental investigation	0.937321937	system	0.010287783
				Integrated battery controller for distributed energy system	0.936943112	electricity	0.008146424

Nr	Topic	Topic Coverage	Top 5 Rank	Top 5 Documents	Affinity	Top 5 Words	Probability
7	Statistical Process Control	8.79%		Simultaneous process mean and variance monitoring using artificial neural networks	0.981322225	model	0.012900221
				Induced and uncertain heavy OWA operators	0.981165601	data	0.0093813
				Using neural networks to detect the bivariate process variance shifts pattern	0.979014599	fuzzy	0.006677529
				Recognition of control chart patterns using improved selection of features	0.976577438	control	0.0053974
				A combined synthetic and np scheme for detecting increases in fraction nonconforming	0.976565657	models	0.005377627
8	Management	8.45%		State of the art literature review on performance measurement	0.980165506	management	0.006003122
				A process-oriented multi-agent system development approach to support the cooperation-activities of concurrent new product development	0.979045607	process	0.004850279
				PROPOSED BUSINESS PROCESS IMPROVEMENT MODEL WITH INTEGRATED CUSTOMER EXPERIENCE MANAGEMENT	0.97745013	system	0.004604099
				A framework for measuring the performance of service supply chain management	0.977328599	information	0.004367259
				Linkages between manufacturing strategy, benchmarking, performance measurement and business process reengineering	0.975383255	product	0.004332567
9	Operational Research	12.93%	5	A survey of scheduling with deterministic machine availability constraints	0.990497624	time	0.011265474
				Common due date assignment and scheduling with a rate-modifying activity to minimize the due date, earliness, tardiness, holding, and batch delivery cost	0.986101083	problem	0.009950923
				Evaluation of mixed integer programming formulations for non-pre-emptive parallel machine scheduling problems	0.984362362	cost	0.006848686
				Coordination of split deliveries in one-warehouse multi-retailer distribution systems	0.983903421	solution	0.006615771
				Heuristics for scheduling problems with an unavailability constraint and position-dependent processing times	0.983220694	algorithm	0.006594284
10	Energy Efficient Buildings	11.62%	3	Thermostat strategies impact on energy consumption in residential buildings	0.952288218	energy	0.03101499
				Evaluation of the corrected seasonal energy demand, for buildings classification, to be compared with a standard performance scale	0.940621194	building	0.019014966
				Effects of occupancy and lighting use patterns on lighting energy consumption	0.9354215	buildings	0.015571562
				Energy consumption and the potential of energy savings in Hellenic office buildings used as bank branches—A case study	0.935395623	consumption	0.009792197
				Energy performance and indoor environmental quality in Hellenic schools	0.93470437	heating	0.008305167

Topic 5 was given the label “Solar Energy”. This topic is similar to the solar energy topic identified in the energy efficiency analysis and shares many of the top related documents. The top related documents cover the following subject matter: analysis of tube solar collectors (Tang, Gao, Yu, & Chen, 2009), luminous efficacy on different surfaces (De Rosa, Ferraro, Kaliakatsos, & Marinelli, 2008b), diffuse luminance in different sky conditions (De Rosa, Ferraro, Kaliakatsos, & Marinelli, 2008a), solar radiation (Faghih & Bahadori, 2009) and performance evaluation of solar panels(Zhong et al., 2011). The correlation of the topic with the top related words (“solar”, “thermal”, “heat”, “energy” and “temperature”) is ranked as the fourth highest.

Topic 6 was given the label “Renewable Energy”. This topic is similar to the renewable energy topic that was identified in the energy efficiency analysis and also shares some of the top related documents. Wind power (Fernandez et al., 2008), induction generators (G. Singh, Kumar, & Saini, 2010), synchronous generators (G. Singh, 2011), hybrid solar-wind power systems (Dali et al., 2010) and energy storage systems (Virulkar, Aware, & Kolhe, 2011) are the subjects discussed in the top related documents. All of these subjects relate either with sources of renewable energy or the integration and control of these types of energies.

Topic 7 was labelled “Statistical Process Control”. Statistical process control was also a topic identified in the IE analysis and these two topics share some of their top related documents. The main themes included in the top related documents are: mean and variance monitoring (Guh, 2010), ordered weighted averaging (Merigó & Casanovas, 2011b), detecting process variance shift patterns (Cheng & Cheng, 2011) and control charts (Cheng & Cheng, 2011; Gauri & Chakraborty, 2009; Guh, 2010; Haridy et al., 2011).

Topic 8 was given the label “Management”. This topic is unique to this analysis and covers a wide array of business processes and areas. The similar theme in most of the top related documents is management. The different processes and areas managed, discussed in the top related documents, include information management (Nudurupati, Bititci, Kumar, & Chan, 2011), product development (Juan, Ou-Yang, & Lin, 2009), customer experience management (Botha & Van Rensburg, 2010), service supply chain management (Cho, Lee, Ahn, & Hwang, 2011) and manufacturing strategies and performance measurement (Herzog, Tonchia, & Polajnar, 2009).

Topic 9 was given the label “Scheduling”. Although this topic shares a label with a topic that was identified in the IE analysis, it does not share any of its top related documents with the similarly labelled topic. This topic’s top related documents cover the following subjects: scheduling (Ma, Chu, & Zuo, 2010; Unlu & Mason, 2010; Yin, Cheng, Xu, & Wu, 2012), distribution systems (Li, Chu, & Chen, 2011) and the application of heuristics for scheduling problems (Mor & Mosheiov, 2011).

Topic 10 was given the label "Energy Efficient Buildings". This topic share a label with the energy efficient buildings topic identified in the energy efficiency analysis. The two topics, however, only share one of their top related documents. This energy efficient buildings topic's top related documents discuss the following: thermostat strategies (Moon & Han, 2011), building classification (Barelli, Bidini, & Pinchi, 2009), lighting energy consumption (Yun, Kim, & Kim, 2011), overall energy consumption and potential savings in buildings (Spyropoulos & Balaras, 2011) and energy conservation versus the indoor environmental quality (Dascalaki & Sermpetzoglou, 2011).

Table 8 shows the similarities between different topics identified in the IE and energy efficiency analysis. These similarities will be discussed shortly.

Thermodynamic analysis and optimisation shows a strong affinity to HVAC analysis and optimisation. This affinity is based on the important role thermal energy plays in HVAC systems. Thermodynamic analysis and optimisation also shows an affinity to renewable energy, more specifically to solar energy that consists of thermal and light energy. A similarity with bio fuels is also identified based on the thermal output aspects of bio fuels.

Bio fuel's strongest similarity is with thermodynamic analysis and optimisation, as discussed previously. As would be expected, bio fuels show a similarity between the energy and emissions in manufacturing/bio fuel impacts/energy economy topic. The similarity is not the strongest with bio fuel, due to the wide subject span of the energy and emissions in manufacturing/bio fuel impacts/energy economy topic. Bio fuels also show affinities to HVAC analysis and optimisation.

HVAC analysis and optimisation has a significant affinity to solar energy. This is due to the impact that the sun, the source of solar energy, has on HVAC systems. The similarity between HVAC analysis and optimisation and thermodynamic analysis and optimisation is shown again. The third strongest similarity is to energy efficient buildings. This similarity is understandable when considering that HVAC systems are the largest contributors to energy consumption in buildings.

Table 8 - IE and Energy Efficiency Analysis Topic Similarities

Nr	Topic	Top 3 Topics	Affinity/ Similarity
1	Thermodynamic analysis and optimisation	HVAC analysis and optimisation	0.68196164
		Renewable energy	0.65056168
		Bio fuel	0.64118484
2	Bio fuel	Thermodynamic analysis and optimisation	0.64118484
		HVAC analysis and optimisation	0.6258695
		Energy and emissions in manufacturing/ Bio fuel impacts/ Energy Economy	0.62553842
3	HVAC analysis and optimisation	Solar Energy	0.70396809
		Thermodynamic analysis and optimisation	0.68196164
		Energy Efficient Buildings	0.6440862
4	Energy and emissions in manufacturing/ Bio fuel impacts/ Energy Economy	Renewable energy	0.67597134
		Energy Efficient Buildings	0.66100132
		Management	0.64863609
5	Solar Energy	HVAC analysis and optimisation	0.70396809
		Energy Efficient Buildings	0.6767042
		Thermodynamic analysis and optimisation	0.61835396
6	Renewable energy	Energy and emissions in manufacturing/ Bio fuel impacts/ Energy Economy	0.67597134
		Thermodynamic analysis and optimisation	0.65056168
		Energy Efficient Buildings	0.64678107
7	Statistical Process Control	Operational Research	0.69794613
		Management	0.68813406
		Renewable energy	0.6180948
8	Management	Statistical Process Control	0.68813406
		Operational Research	0.68201129
		Energy and emissions in manufacturing/ Bio fuel impacts/ Energy Economy	0.64863609
9	Operational Research	Statistical Process Control	0.69794613
		Management	0.68201129
		Renewable energy	0.61693694
10	Energy Efficient Buildings	Solar Energy	0.6767042
		Energy and emissions in manufacturing/ Bio fuel impacts/ Energy Economy	0.66100132
		Renewable energy	0.64678107

Energy and emissions in manufacturing/ bio fuel impacts/ energy economy has a strong affinity to renewable energy, which is based on the bio fuel and energy economy aspects of the topic. Energy efficient buildings shows similarities with this topic, due to the manufacturing aspect of the topic and the economic impact energy efficient buildings can have. Energy and emissions in manufacturing/ bio fuel impacts/ energy economy also has an affinity to management, which is a topic from the IE field. This could point to the importance of managing energy and emissions in manufacturing and managing bio fuel impacts.

Solar energy has the strongest affinity to HVAC analysis and optimisation as discussed previously. It also shows similarities to energy efficient buildings, based on the impact that the use of solar energy can have on the non-renewable energy consumption. Thermodynamic analysis and optimisation also shows a similarity to solar energy. This is due to the thermal energy that forms part of solar energy.

Renewable energy shows an affinity to energy and emissions in manufacturing/ bio fuel impacts/ energy economy, as discussed previously. It also shows an affinity to thermodynamic analysis and optimisation as discussed previously. The third similarity is with energy efficient buildings. This similarity arises from the impact that the use of renewable energy can have on the energy consumption of non-renewable energy.

Statistical process control is a decidedly IE oriented topic. It shows similarities with operational research and management based on share statistical approaches and the use of the process controlling for the management of the processes. However, it also shows an affinity to renewable energy, which is an energy efficiency topic. This affinity can indicate the possible implementation of statistical process control techniques in the field of renewable energy.

Management is also a topic in the IE field. Its strongest similarity is to statistical process control as discussed earlier. It also shows a strong affinity to operations research, which is based on the application of solutions derived through operational research techniques. The third similarity of management is to energy and emissions in manufacturing/ bio fuel impacts/ energy economy. Energy and emissions in manufacturing/ bio fuel impacts/ energy economy is a topic in the energy efficiency field and the similarity between it and management can indicate the applicability of some management techniques in the energy efficiency field.

Energy efficient buildings once again show the similarities to solar energy, energy and emissions in manufacturing/ bio fuel impacts/ energy economy and renewable energy. All of these similarities have been discussed previously and all occur within the energy efficiency field.

4.4 Comparison of IE Analysis and Energy Efficiency Analysis

The final processing of the CAT analyses results were done to identify correlations between topics that were identified in the IE analysis and the energy efficiency analysis. This was done by calculating the correlation coefficient between each of the twenty topics based on the vocabulary of each topic. The correlation coefficient between these two sets of results was not calculated with CAT. Dr. J.W. Uys described a method for identifying similarities between research interest areas (Uys, 2010). This same method was applied to the IE and energy efficiency fields. The process consists of three main steps:

1. Creating the corpus vocabulary
2. Calculating the frequency of occurrence of each word in the corpus vocabulary
3. Calculating the correlation coefficient between each pair of topics

To create the corpus vocabulary, the vocabularies of all the topics (for both fields) were combined. The recurring words were then removed from the combined vocabulary to leave the corpus vocabulary populated with the unique words extracted from the two CAT analyses.

The frequency of occurrence of each word in the corpus vocabulary was calculated by comparing each topic's vocabulary with the corpus vocabulary. This comparison resulted in a binary-valued vector indicating the words from the corpus vocabulary present in each topic with a "1". Adding all the occurrences of each word in all the topics will result in the word's occurrence frequency value.

The correlation coefficient was calculated using a MS Excel formula, namely "CORREL". The correlation coefficient was calculated for each topic pair by using the binary-valued vector for the topics as input for the "CORREL" function. The results were accumulated in a symmetrical matrix that shows all the topics in the rows and columns. The correlation coefficients between the corresponding row and column's topics were shown in the cells. The cells in this matrix were formatted to show higher correlation coefficients with green and lower correlations with red. This matrix is shown in Table 9. The topics were given numbers to represent the labels to decrease the size of the matrix for inclusion in this document. The number assigned to each topic is shown in Table 10.

The highest correlation values are shown for the comparison of each topic with itself. These values make up the diagonal line of cells in bright green. Looking at the general colours of the cells in the matrix it can be deduced that the topics extracted from the IE corpus related stronger with other IE topics than with energy efficiency topics. The same can be seen for the energy efficiency topics.

Table 9 - Topic Pairs' Correlation Coefficients

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1.00000	0.18966	0.22343	0.20092	0.22343	0.25719	0.23468	0.13339	0.12213	0.26844	0.09962	0.03210	0.43726	0.06586	0.05460	-0.01292	0.06586	0.09962	0.06586	0.09962
2		1.00000	0.38099	0.25719	0.20092	0.22343	0.25719	0.09962	0.33597	0.16715	0.04335	0.04335	0.29095	-0.00167	-0.00167	-0.05794	0.11088	0.05460	0.02084	0.04335
3			1.00000	0.16715	0.23468	0.21217	0.20092	0.08837	0.25719	0.25719	0.03210	0.00959	0.29095	0.05460	-0.02418	-0.01292	0.05460	0.09962	0.02084	0.00959
4				1.00000	0.22343	0.29095	0.21217	0.17841	0.17841	0.20092	0.05460	0.17841	0.21217	0.06586	-0.01292	-0.03543	0.17841	0.08837	0.05460	0.04335
5					1.00000	0.17841	0.27970	0.13339	0.17841	0.22343	0.02084	0.00959	0.29095	0.02084	-0.03543	-0.04669	-0.01292	0.03210	-0.01292	-0.01292
6						1.00000	0.22343	0.13339	0.15590	0.22343	0.07711	0.08837	0.26844	0.12213	0.02084	-0.02418	0.12213	0.12213	0.07711	0.08837
7							1.00000	0.06586	0.25719	0.21217	0.06586	0.03210	0.27970	0.04335	0.03210	-0.02418	0.07711	0.08837	0.05460	0.04335
8								1.00000	0.02084	0.17841	0.14464	0.20092	0.12213	0.08837	0.02084	-0.01292	0.12213	0.03210	0.04335	0.07711
9									1.00000	0.15590	-0.02418	-0.03543	0.14464	-0.02418	-0.01292	-0.03543	0.00959	0.05460	-0.00167	0.03210
10										1.00000	0.08837	0.05460	0.21217	0.09962	0.04335	-0.05794	0.07711	0.06586	0.08837	0.04335
11											1.00000	0.26844	0.15590	0.13339	0.22343	0.07711	0.24593	0.11088	0.21217	0.29095
12												1.00000	0.12213	0.20092	0.02084	0.14464	0.36974	0.04335	0.09962	0.09962
13													1.00000	0.09962	0.07711	-0.00167	0.18966	0.12213	0.12213	0.13339
14														1.00000	0.07711	0.24593	0.25719	0.23468	0.34723	0.13339
15															1.00000	0.13339	0.11088	0.33597	0.25719	0.30221
16																1.00000	0.12213	0.16715	0.14464	0.13339
17																	1.00000	0.15590	0.21217	0.18966
18																		1.00000	0.29095	0.18966
19																			1.00000	0.29095
20																				1.00000

Table 10 - Number Assignment to Topics

Number	Corresponding Topic	Number	Corresponding Topic	Number	Corresponding Topic	Number	Corresponding Topic
1	Statistical Process Control	6	Operations Research	11	Energy Efficient Buildings	16	Biofuels
2	Scheduling and Routing	7	Data Envelope Analysis	12	Emissions and energy consumption in production	17	Renewable Energy
3	Flow Optimisation	8	Project Management & Change Management	13	Energy Consumption Forecasting	18	Thermodynamics
4	Supply Chain Management	9	Work Scheduling	14	Exergy Analyses	19	Heat Pumps
5	Decision Making	10	Manufacturing	15	Solar Energy	20	HVAC

Topic 13 (Energy Consumption Forecasting), which is an energy efficiency topic shows stronger correlations with most IE topics than the other energy efficiency topics. The correlation between energy consumption forecasting and statistical process control is the highest of these correlations at 0.43726. This correlation is most probably based on the mutual subject of statistics that is utilised for forecasting as well as statistical process control.

The second highest correlation is between energy consumption forecasting and the scheduling and routing topic from the IE corpus. These two topics also share a fundamental basis of statistics, which probably explains the correlation. Similar correlations are shown to flow optimisation and decision making. Statistical methods are applicable in both these topics, therefore overlapping with the statistical element of energy consumption forecasting.

The correlations discussed all share statistics as a basis. This similarity between all these topics, both in the IE and energy efficiency fields, indicates the importance of statistical methods. Statistical methods were mentioned in Section3.2, but are not seen as a focal point. From the results of the CAT analyses and the correlation calculations, it can be seen that more focus should be placed on the impact statistical methods can have in both these fields.

5. Case study

A case study was conducted at a company in the Western Cape that manufactures electronic and integrated circuit products. They requested that an energy audit be done of the facility and possible ECMs and O&Ms be identified for implementation at the facility to reduce the energy consumption.

The energy audit was conducted throughout the whole facility, but the ECMs and O&Ms focused mainly on the production floor. The company is in the process of planning an upgrade of the production floor and therefore the ECMs and O&Ms were limited to the same area as the upgrade.

The company requested that their name remain confidential. Therefore no direct reference will be made to the company.

5.1 Energy Audit

In order to reduce the energy costs, assessments of the facility and the current energy consumption of the facility were done to identify areas where possible improvements can be made. After the current energy consumption was assessed, a study commenced to find methods for reducing the energy costs at the identified energy consumption problem areas.

The assessment of the facility and its current energy consumption was done in the form of a Standard energy audit (see section 2.3.1.2). This audit consisted of the following components:

- Assessment of the electricity bills
- Energy consumption profile analysis
- Load profile analysis
- Analysis of shut down energy saving
- Identification of possible energy conservation methods

5.1.1 Assessment of Electricity Utility Bills

An assessment of the electricity utility bills of the facility was done from the beginning of 2009 up to the latest available bills for 2010. This assessment was done to identify patterns in the electricity usage of the facility and to discover deviations from these patterns.

The utility bills were separated into the two main sections of the tariff structure, namely the kWh usage over the measured number of days and the highest KVA peak measured every half an hour over the number of days of the billing period.

5.1.2 Energy Consumption Profile of Factory and the Identification of Problem Areas

To facilitate the identification of problem areas with regard to energy consumption of the facility, a study must first be done on the energy consumption of the different areas in the facility. This was done by constructing an energy consumption profile for the facility.

The energy consumption profile lists the energy dependent equipment in all the different areas of the facility, obtaining the energy usage ratings for all the equipment and estimating the time of use per day. A spread sheet was constructed that indicates the monthly kWh usage of all the energy dependent equipment and areas in the facility which was integrated into a monthly energy profile for the whole facility.

Since the commencement of this case study, new equipment has been installed at the facility. The new equipment is, however, not included in the initial energy consumption profile of the facility. This energy consumption profile focuses on the initial profile before any changes were implemented.

5.1.3 Load Profiles of the Facility

The data gathered from an electricity utility bill is not very specific. The kWh and KVA measurements are not shown in detail on the utility bills, which makes a detailed analysis of this data impossible. Therefore, a comprehensive analysis of the energy consumption of the facility was done by constructing a more detailed load profile. A meter was installed at the facility to measure the overall energy consumption of the facility. From this data it was possible to construct a detailed Load Profile.

The meter was only installed in June and some problems were encountered with the collection of the data, and therefore only two periods of data were collected successfully. These two periods were used to construct the load profile. Firstly, two-and-a-half weeks' energy usage data was collected from 11 - 30 June 2010 and the second set of data was collected from 27 July until 6 August 2010. At the time of the initial energy audit, only these sets of data were available and thus used for the analysis

5.1.4 Shut Down Energy Savings

From the load profile graphs an irregularity was discovered. The energy usage after shut down procedure was higher than the energy usage during weekends. The energy consumption should be at the same minimum value after hours and over weekends. On further investigation it was found that some of the lights and equipment on the production floor was left on after shut down. This discovery led to an experiment to be conducted to quantify the unnecessary energy consumed by this undesirable practice.

5.1.5 Lighting Audit

An audit of the lighting on the production floor and the store was done to ascertain the current lighting levels. The measurements of the current lighting system was compared to the required lighting in order to establish areas where the lighting was inadequate and improvements needed to be made.

The company requested special attention to be given to the lighting for the production floor and storage area. An upgrade of the facility was planned and as part of the upgrade, this lighting system would also be improved. Optimisation of the lighting system for the production floor is done in chapter 6.

5.2 Analysis of Data

Data was gathered from the electricity bills of the company, information was gathered about the current energy consumption profile of all the equipment in the facility and initial readings were taken with the electricity meter installed at the facility. This data and information was then evaluated in order to identify possible areas where energy efficiency can be improved.

5.2.1 Results of Assessment of Electricity Utility Bills

In order to compare the electricity utility bills, the utility bills were separated into the kWh usage and the peak KVA reading per billing period. Figure 10 shows the kWh usage compared for 2009 and 2010. The billing periods do not coincide with calendar months, but rather run from the middle of one month to the middle of the next month. For example: billing period 1 run from 17 January to 16 February.

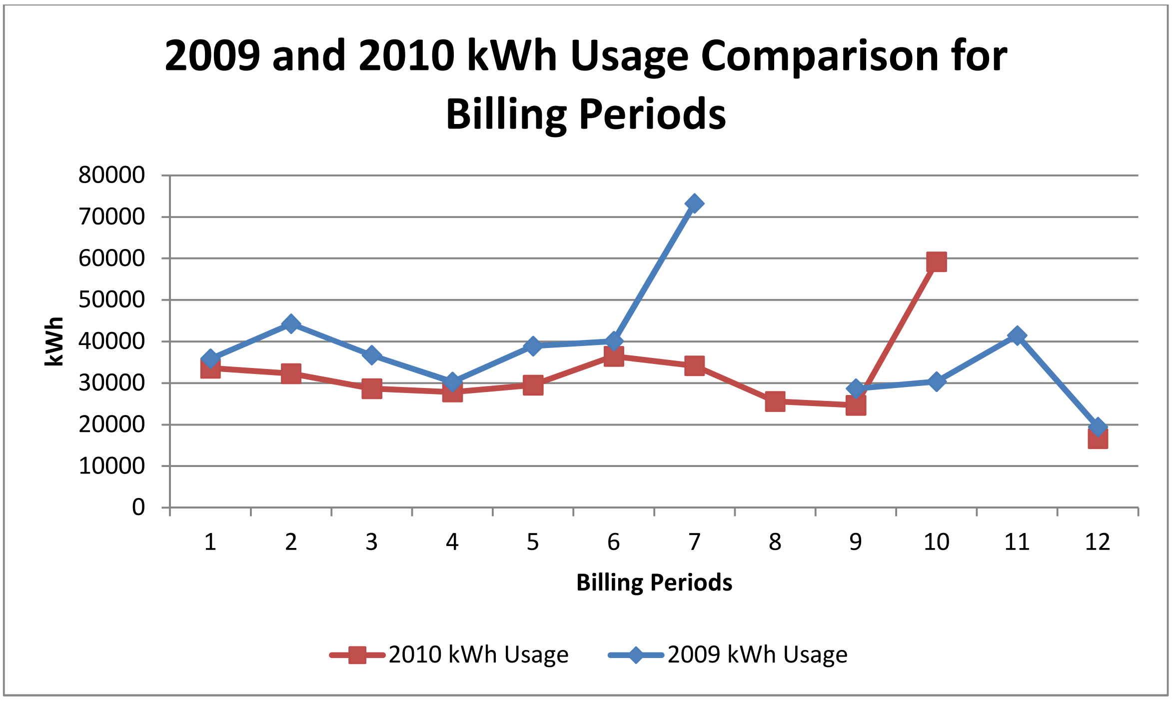


Figure 10 - kWh Usage Comparison between 2009 and 2010

In 2009, the utility bills for the seventh and eight periods were combined resulting in the higher kWh reported for the seventh billing period of 2009. Similarly, the tenth and eleventh billing periods for 2010 were combined on the utility bills resulting in a increased kWh usage for the tenth billing period.

In both 2009 and 2010 there is a decrease in the kWh usage from the second billing period to the fourth followed by an increase towards the sixth period. This indicates a pattern for the first half of the year, but due to the combined and missing electricity bills. it is difficult to identify a further pattern for the year.

Figure 11 shows the monthly production totals for 2009 and 2010. The production totals were calculated from the beginning to the end of each month. The difference between the billing periods and the calendar months makes it difficult to correlate the kWh usage and KVA peaks directly with the production. The general trends for the production totals do shadow the pattern identified in the kWh usage during the first half of the year.

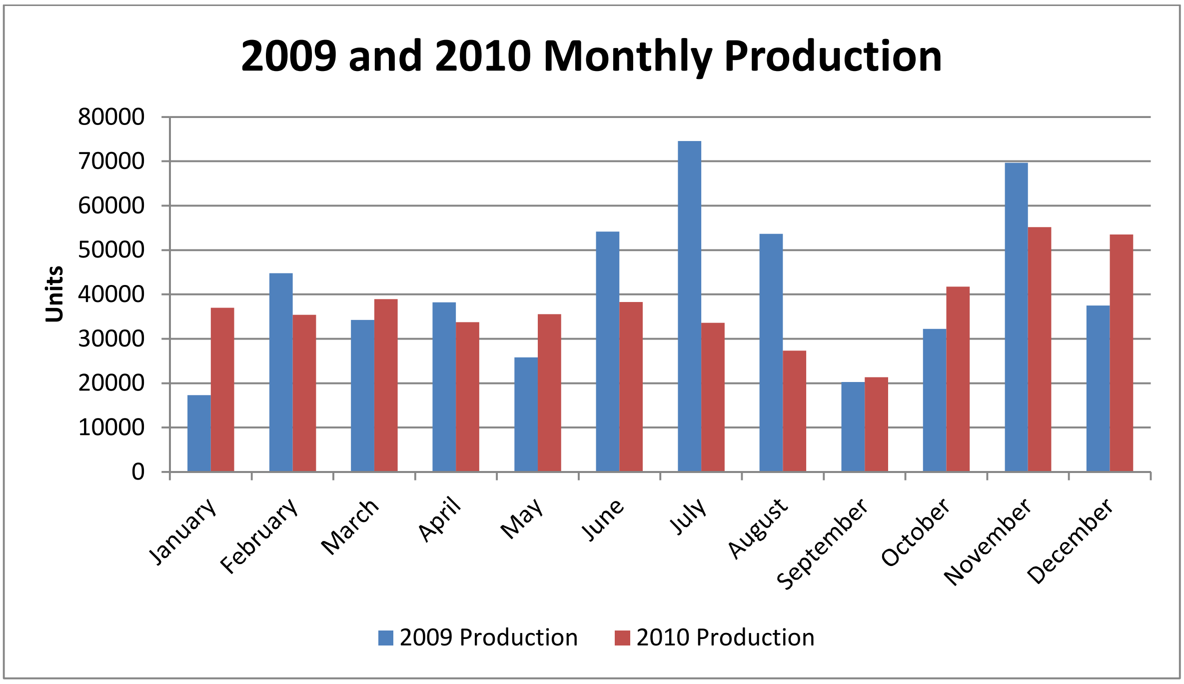


Figure 11 - Monthly Production totals for 2009 and 2010

Figure 12 shows the comparison between the KVA peaks for 2009 and 2010, as indicated on the electricity bills. A distinct pattern cannot be identified from the KVA peaks. With the exception of the increase of the KVA peaks from the fifth to the sixth period. No other prominent patterns emerge from the data.

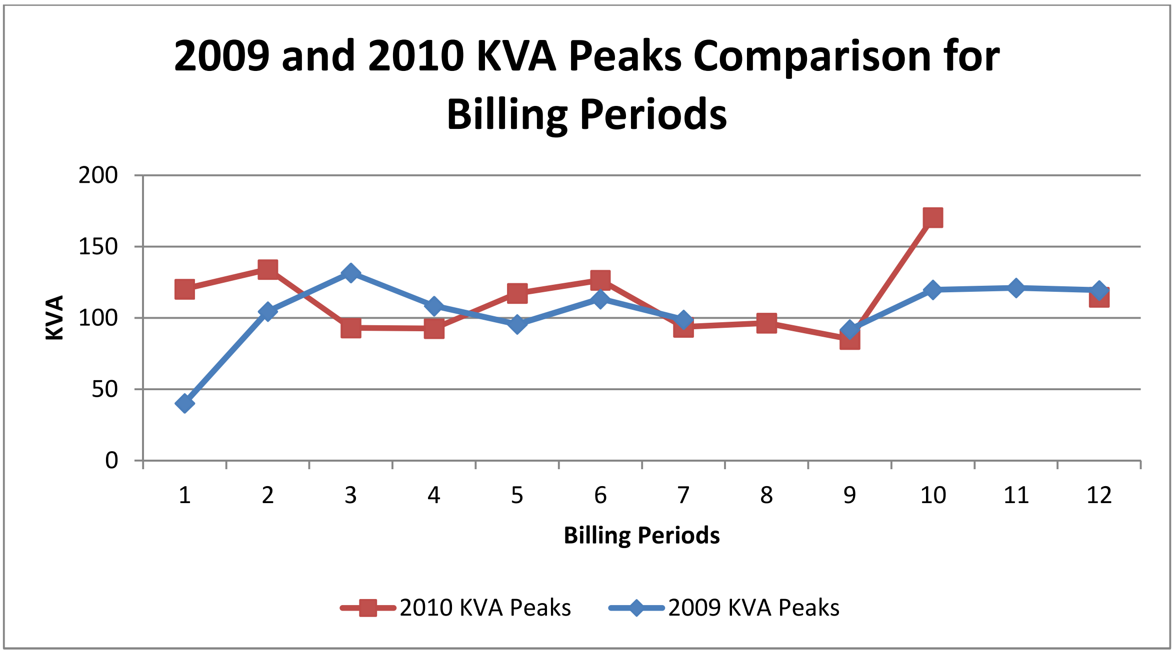


Figure 12 - KVA Peaks Comparison between 2009 and 2010

Other factors can also influence the kWh usage and KVA peaks. These factors include the climate or weather and the employees of the company. If the weather is extreme, it can lead to an increased use of the HVAC system. If employees are not vigilant about switching off unnecessary equipment or are not following the most energy efficient operating procedures, it can increase the energy usage.

From the kWh usage and KVA peak graphs, it is difficult to identify exact areas where energy efficiency can be improved. The inconsistency of the available data makes it difficult to discover obvious problem areas. It is therefore important to do further analyses on the actual energy consumption of the facility in order to discover possible areas of improvement.

5.2.2 Results of Energy Consumption Profile

The energy consumption profile of the facility was divided into four sections according to different areas and equipment in the facility as shown in Figure 13. These sections are the ‘Production floor’, ‘Outside facility’, ‘Rest of facility’ and ‘Lights’. The Production floor section consists of all the production lines. The Outside facility section includes the air conditioners and the compressors. The Rest of the facility section includes all the offices, the store and the Water lab.

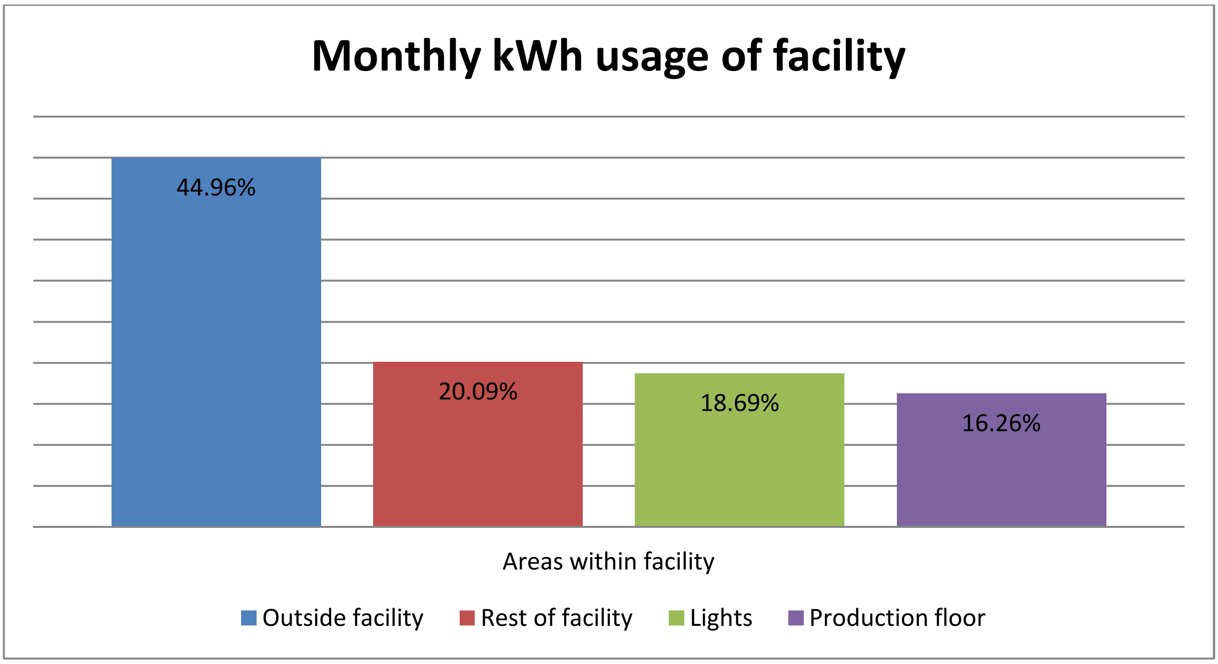


Figure 13 - Monthly kWh profile for areas within facility

Since the “Rest of facility” area consists of a combination of many areas and smaller equipment which is not part of the production floor, it was not taken directly into account during the energy audit. The other three areas indicated in Figure 13 are the main focal points for improving energy efficiency. The identified areas were examined further by looking at the different energy dependent equipment within each area.

5.2.2.1 Production Floor Energy Consumption Results

The Energy profile of the Production floor consists of the energy consumption of all the different production lines on the production floor. Comparing these production lines, Figure 14 shows that the production line producing Product G has visibly higher energy consumption than the other lines. A closer look at the equipment used on that line is thus required.

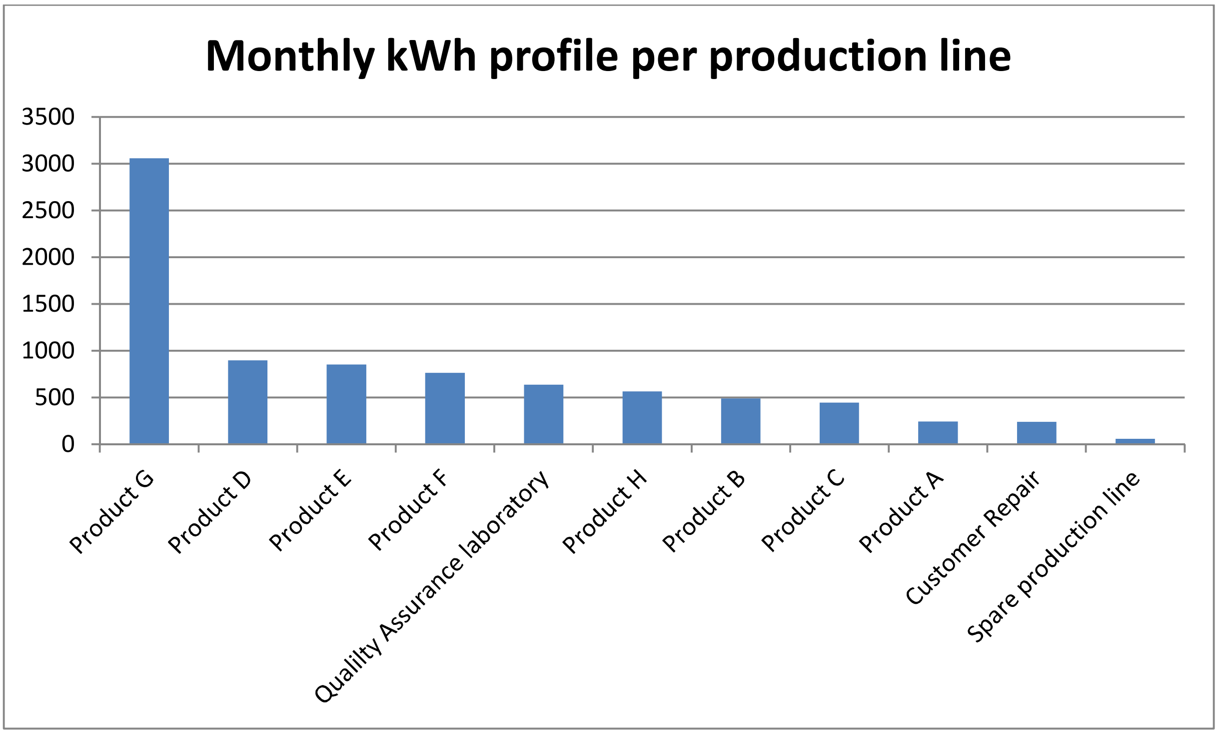


Figure 14 - Energy consumption profile of Production floor

In Figure 15 the energy consumption of the equipment used in the production line for Product G is shown. The piece of equipment that consumes noticeably more energy than the other equipment is the spot welder. This indicates that a study of the energy usage and operating hours of the spot welder should be initiated. Products may be redesigned to utilise a ‘snap fit’ or another energy efficient assembly method.

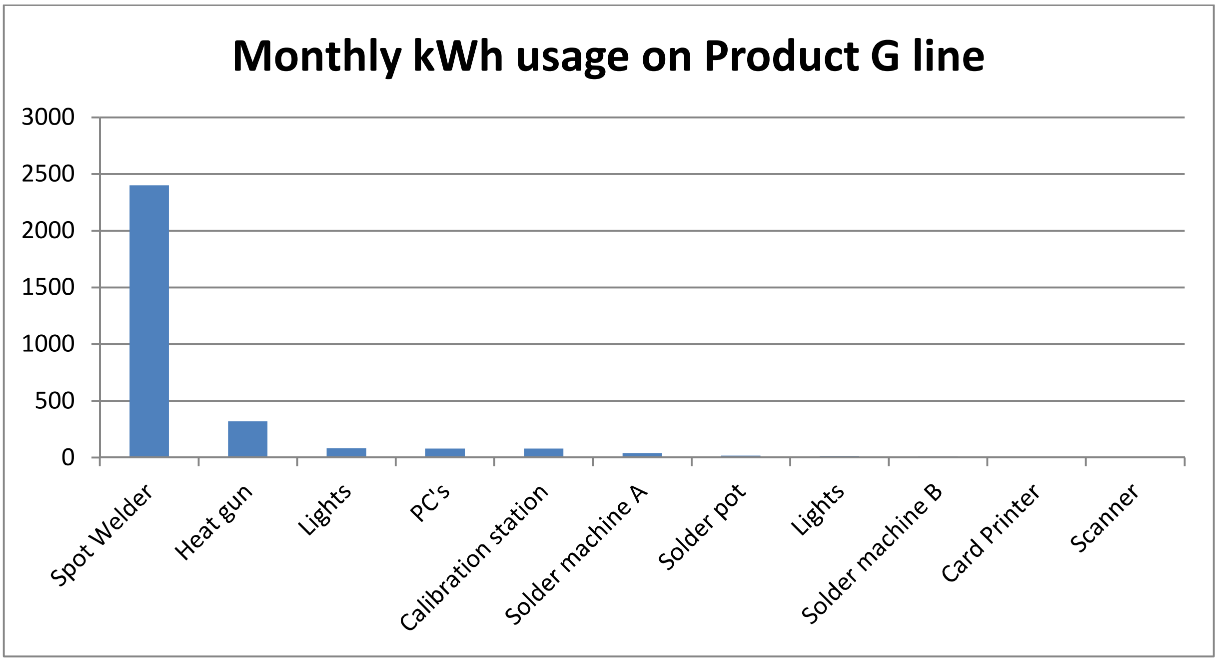


Figure 15 - Energy profile of Product G Production line

5.2.2.2 Outside the Facility Energy Consumption Results

In Figure 13 it can clearly be seen that the energy consumption on the outside of the facility is extremely high. Therefore, it is imperative that a study must be done to find ways to reduce the effect that the equipment on the outside of the facility has on the facility's energy consumption.

Figure 16 was constructed by splitting the air conditioners into two groups. The first group shown in the graph, "Large Air Conditioners", refers to the Air conditioners for the entire production floor. These air conditioners are situated outside the facility and the air is supplied to the production floor through a series of ducts.

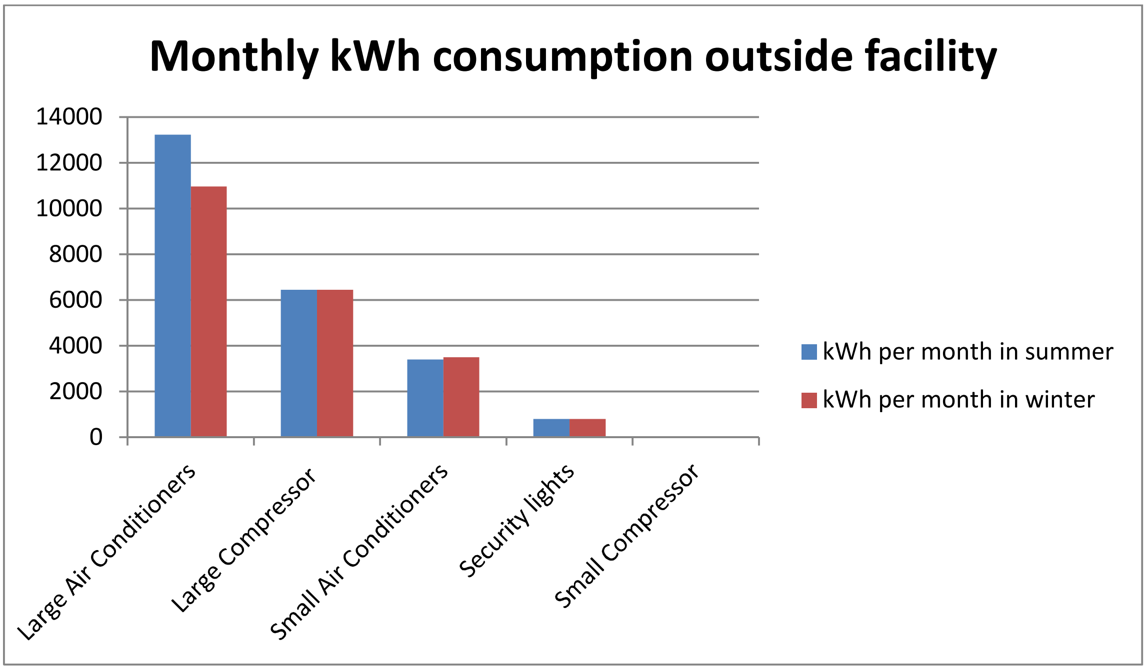


Figure 16 - Energy Consumption Profile of Outside of Facility

The third group is referred to as the "Small Air Conditioners". This group includes all the Air conditioners used in the offices. While gathering the data for the energy profile, inquiries were made as to the usage of the air conditioners in the offices. Most of these Air conditioners were seldom used for more than a couple of hours per day and all were switched off after shut down. This would explain the lower energy consumption of this group of air conditioners.

A further observation that was made when Figure 16 was constructed was the correlation of the energy consumption of the air conditioners with the seasons. During summer, the air conditioners are used to cool the air and during winter, to warm the air. As can be discerned from the graph in Figure 16, the season has an impact on the energy usage of the production floor air conditioners. During summer months, the "Large Air Conditioners" consume more energy than during winter months.

Currently, the production floor air conditioners are switched on when the first worker arrives at the facility and are switched off when the last workers leave. Methods will be investigated that could reduce the time the air conditioners have to work per day and the effect they have on the peak demands.

Apart from the production floor air conditioners, the large compressor also has significant energy consumption, as seen in Figure 16. The compressor is used to build up pressurised air for the air-tools used in production. The pressure is reduced throughout the day due to the usage of the air-tools, which then necessitates the compressor to start running in order to keep the pressure at the required level. These unscheduled start-ups also contribute to the high energy consumption and KVA peaks of the facility.

The actual energy consumptions of the compressors are unknown, because there is no schedule for their start-ups. This uncertainty reveals that it would be beneficial to gather more detailed data on the compressors' operating times and energy consumptions.

5.2.2.3 Results of Energy Consumption by the Lighting Systems

The lighting system is a major contributor to the energy consumption in a facility. Therefore, during the construction of the facility's energy consumption profile, the lighting system was separated from the other areas and equipment of the facility and profiled individually. A breakdown of the total lighting system energy consumption into different areas of the lighting system is shown in Figure 17. The lights of the facility were divided into five main areas:

- Production Bench lights
- Security lights
- Office lights
- Stores lights
- Production floor ceiling lights

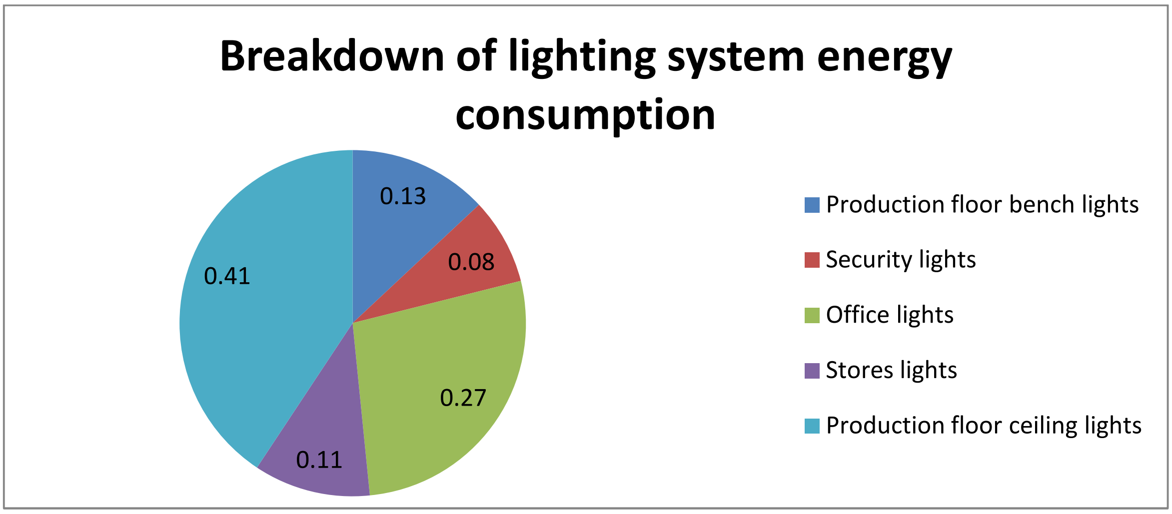


Figure 17 - Breakdown of lighting system energy consumption

The values shown in Figure 17 were calculated by normalising the percentage that each area contributed to the total lighting system's energy consumption. As seen in Figure 17, the production floor ceiling lights use more than 40% of the energy consumed by the lighting system. Therefore, it is a focal point for energy conservation measures.

5.2.3 Factory Load Profile Results

From the data gathered by the energy meter installed, the graphs in Figure 18, Figure 19 andFigure 20 were constructed. The longest period of data gathered was from 11 - 30 June 2010. This two-and-a-half week period was thus used to evaluate the load profiles.

In Figure 18, the kWh energy use per day is shown. From the graph, a weekly kWh usage pattern can be identified. The kWh usage during the week is higher than the kWh usage over weekends. Looking at the weighted average over the days of the week, the fluctuation from the average is not significant.

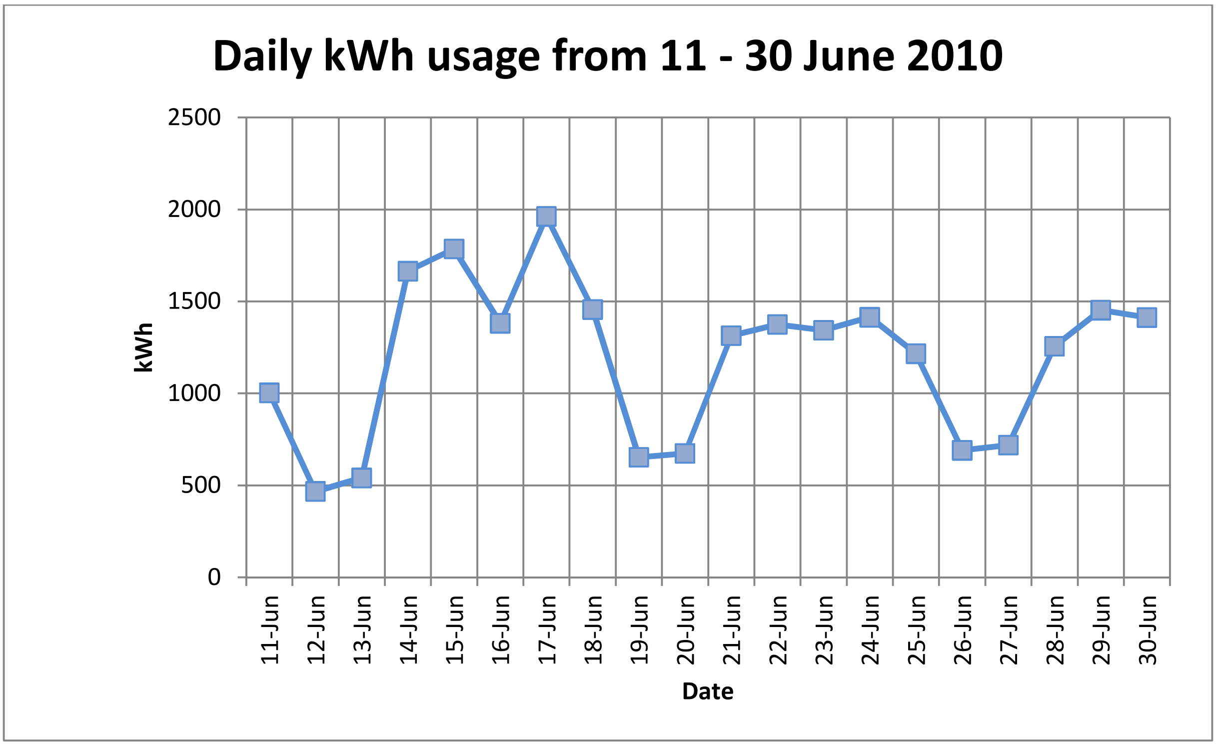


Figure 18 - Daily kWh usage from 11 - 30 June

Figure 19 shows the maximum KVA measured at the facility per day. The maximum KVA is very important, because the facility is being billed by the utility supplier for their highest maximum KVA drawn per month. Similar to Figure 18, the fluctuation in the KVA peaks during the week is not significant. A change in the scheduling of the start-up times of the high energy consuming equipment, such as the air conditioners and the compressor, can reduce the maximum KVA reached per day.

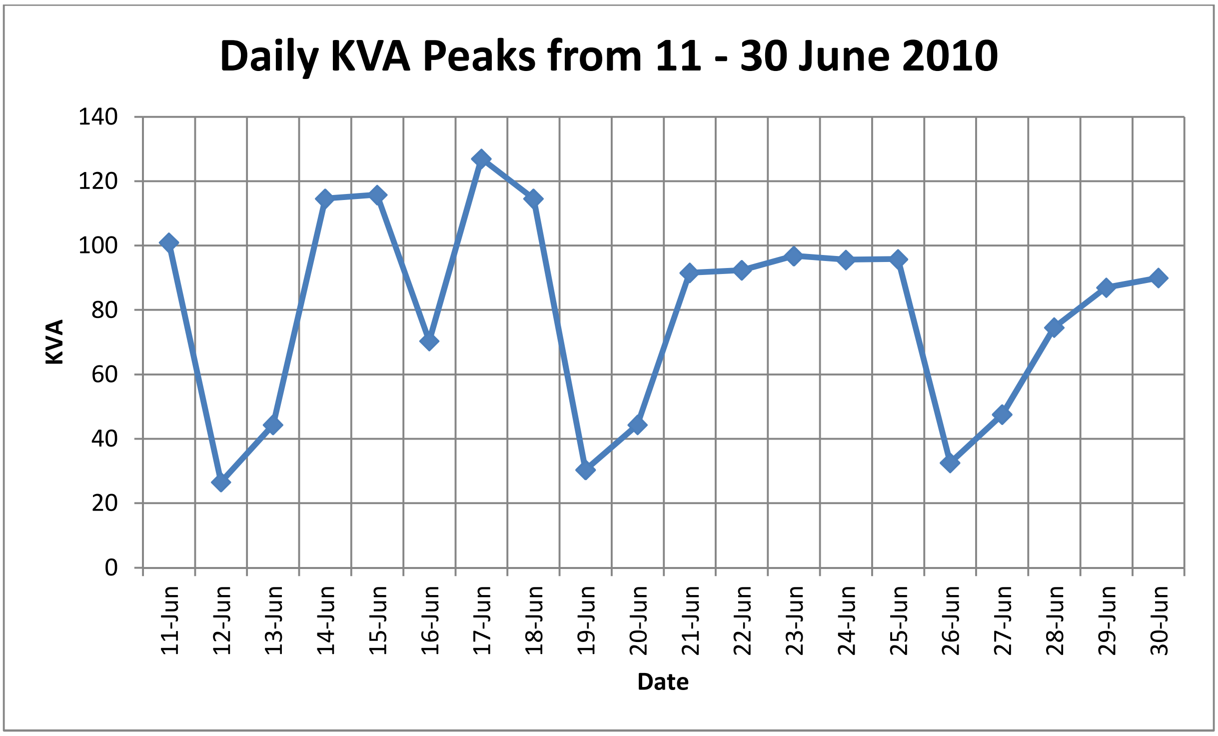


Figure 19 - Maximum KVA per day from 11 - 30 June

A further concern when looking at the kWh measurements per day, is the high amount of kWh drawn during the shutdown periods. This is shown by Figure 20, which was constructed from the meter readings of one week. These readings are taken over 15 minute intervals over the span of the day. One week's data is plotted in order to show the difference between the kWh consumption during the week and over weekends.

Over weekends the energy usage drops to well below 10kWh, but during week days the energy consumption during the shutdown period is much higher than 10kWh per day. This indicates that all equipment is not properly switched off when the production floor is shut down on week days. A small change in the shut down procedure and control should reduce the energy consumption to similar levels as over weekends.

The energy consumption data gathered by the electricity meter indicate a predictable usage pattern. It would thus be practical to study the energy usage of the facility more in depth.

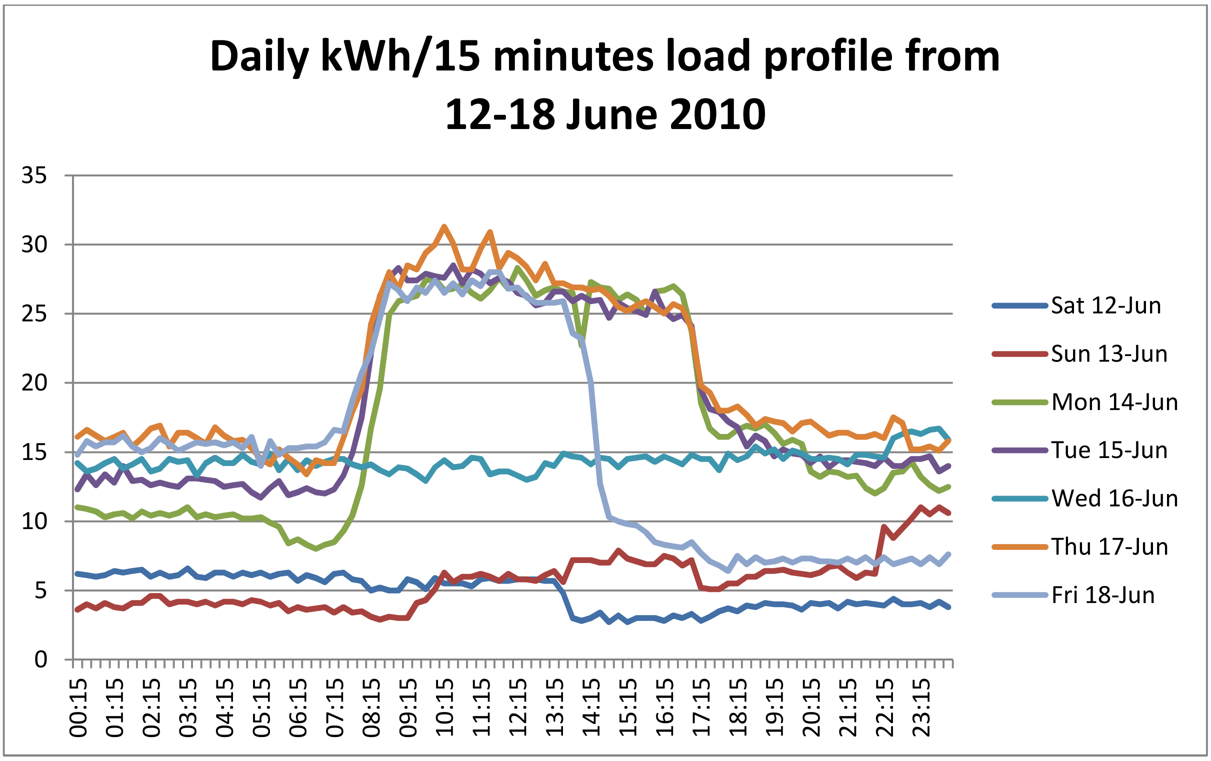


Figure 20 - Daily kWh load profile for one week

5.2.4 Shut Down Savings Results

During the evaluation of the load profiles of the facility during the week compared to the weekend, it was observed that there is an energy conservation opportunity during shutdown periods. An experiment was done to see the energy cost savings that could be made if the equipment on the production floor was properly switched off every day. Table 11 shows the savings that are possible when calculating the energy costs with the 2010 tariff structure.

Table 11 - Shut down experiment results

Shut down phase	Meter measurement (Wh)	kWh	Equivalent kWh saving	Equivalent cost saving per month
Production	48000	48		
+Air conditioners	33500	33.5	6844	R 2,786.88
+Production floor lighting	29000	29	2124	R 864.89
+Store lighting	20000	20	4248	R 1,729.79
+ All possible production equipment	17000	17	1416	R 576.60
				R 5,958.15

The experiment was done by documenting the kWh measured by the meter after each of the listed groups of equipment was switched off. This cumulated to a saving of just below R6 000 per month, which is approximately a quarter of the current energy costs of the facility. This indicates that a Shut Down Management initiative should be put into practice to capitalise on these possible savings.

Table 12 - Assumption made for shut down experiment

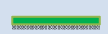
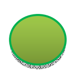
2010 Tariff (R/kWh)	R 0.41
Total hours per month	672
Working days per month	20
Working hours per day	10
Working hours per month	200
Non-working hours per month	472

5.2.5 Results of Lighting Audit

The lighting audit was conducted by taking lighting measurements with a Lux meter on the production floor and in the store. These lux values were then compiled into a visual representation of the current lighting levels. The diagram is based on the facility floor plan and the lux values were filled in on the floor plan. The lux values were then scaled using a colour scale to indicate whether the lux level meets the requirements or whether improvements need to be made.

Figure 21 shows the lux value diagram and also indicates the air conditioning ducts, the natural lighting, exactly where the lights are situated on the ceiling and which of the lamps are working properly. A key for the different objects included in the diagram is shown in Table 13. The influence of the objects can be seen in the patterns formed by the lux levels.

Table 13 – Lux value diagram key

Object	Description
	Working lamp
	Blown or missing lamp
	Window
	Air conditioning duct
	Shelf in store
	Working lamp in store

The colour scale used in the lux value diagram ranges from green to red. Higher lux levels are indicated by the greener areas. A lower lux level is indicated by more red areas, which indicates how far away the lux level is from the required level. The orange and red areas indicate where the lux values need to be increased. A floor plan of the facility is included in Appendix A.

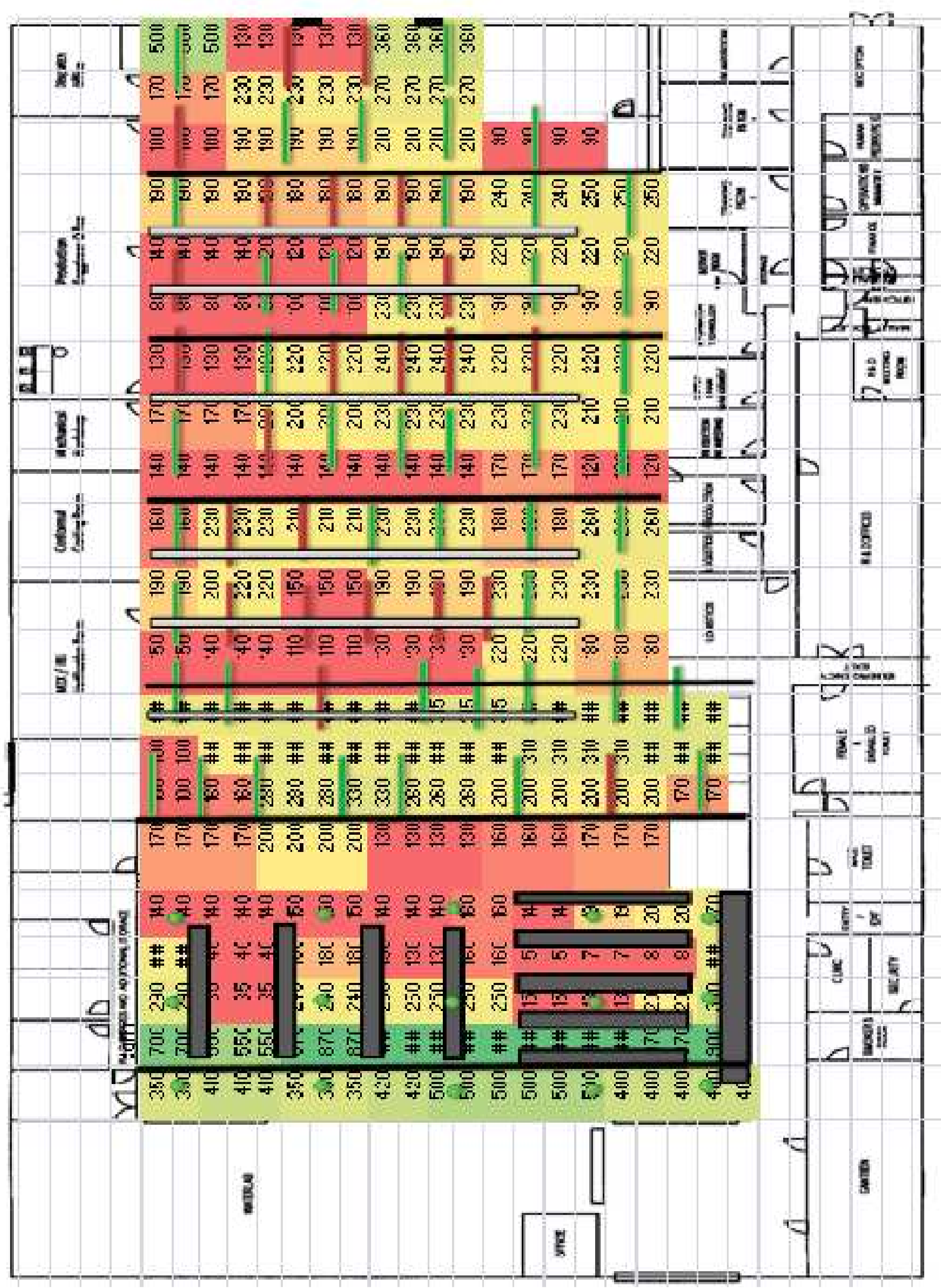


Figure 21 - Lux value diagram

5.3 Proposed ECMs and O&Ms

The main problem areas that were identified through the energy audit are the air conditioners, the lights, the compressor and the spot welder. In this chapter, recommendations are made to reduce the energy consumption at the specific areas as well as the overall facility.

5.3.1 Air Conditioners

The air conditioners are switched on at the same time as production starts up, leading to a higher than necessary peak in KVA usage at start-up time. To reduce the impact the air conditioners have on the start-up peak, they could be switched on before production starts. Further studies must be completed on the start-up times of the air conditioners and how often they must run in order to keep the ambient temperature at the preferred level.

Other measures that can be implemented are to set specific air conditioner guidelines. These guidelines should state at what temperature the air conditioners may be set, depending on the outside temperature. A tampering rule should be implemented where only a designated person may set the thermostat of the air conditioners. In order to implement the tampering rule, the controllers should be placed at one central point. Centralised controls can help with the management of the air conditioning settings by easing the monitoring of the controls.

Another factor that influences the ambient temperature of the production floor is the intake of air from outside the facility through open doors. This impact can be eliminated by creating buffer areas between doors and the production floor. A reduction in the amount of air flowing in from the outside will reduce the fluctuation of the ambient temperature and therefore reduce the running time of the air conditioners.

The installation of insulation for the production area should be considered in order to reduce the impact the outside temperature has on the ambient temperature. This can have a significant impact on the energy consumed by the air conditioning system.

5.3.2 Compressor

The compressor also contributes to the start-up peak, and thus a similar principle as with the air conditioners can be followed. The compressor may also be started before production in order to build up pressure to ensure that it does not need to run again until after the start-up.

In order to compile a schedule for the compressor, a study must be done on the running time required to build up pressure and how long it takes the pressure to be depleted during production before it must build up pressure again. Once more, data has been gathered on the operation times of the compressor and further evaluations can be done to find measures to conserve energy.

The major problem encountered with a compressed air system is a loss of pressure due to leakages. The compressed air system (the lines as well as the equipment) must therefore be checked for air leakages. An active leakage maintenance plan should be implemented to reduce the leaks in the system which causes losses in pressure and leads to unnecessary operation of the compressor.

5.3.3 Lights

The identified groups of lights in the facility that have the most significant impact on the energy consumption are the production floor ceiling lights, the store lights and the security lights. Recommendations on how to manage the effect these groups of lights have are discussed in this sub-section.

5.3.3.1 Production Floor Ceiling Lights

The lights used in the ceiling of the production floor are 75W fluorescent tubes. Maintenance should be performed on these lights to check which tubes are still in working order and which need replacing. Similarly, the tubes should also be tested and replaced if necessary.

Possible ways to reduce the energy consumed by the production ceiling lights are to reduce the number of lights by identifying the paths on the production floor and lighting only those areas, since the production lines have bench-lights. Another suggestion is to connect the ceiling lights in groups to allow selective lighting of the production floor. The plausibility of these suggestions depends on the flexibility that is required with respect to the layout of the production floor.

Currently, the lighting is fixed to the inclining roof of the production floor. A measure that would increase and even out the lighting level is to lower the lights to a horizontal position above the production floor. This can be done at a reasonable cost and would not require the current light fittings and bulbs to be replaced. Lowering the light fittings will also eliminate the effect the air conditioning ducts have on the lighting levels.

Natural lighting is another option to reduce the number of lights needed for the production floor and the amount of time that these lights must be switched on. Tubular skylights can be installed to utilise natural light and the lights installed in the ceiling of the production floor will then only be used when the natural light is not sufficient. The impact these skylights will have on the ambient temperature must be taken into account, since a certain amount of heat loss in the winter and heat gain in the summer is inevitable. The amount of heat loss or gain can be minimised by installing the correct type of skylight and ensuring that the glass has the necessary treatments.

5.3.3.2 Store Lights

The store lights use 400W metal halide bulbs, which can be replaced with more energy efficient bulbs. The replacement is dependent on the quality of the lighting required in the store. As with the production floor lighting, a maintenance program should be set in place to replace lamps that have blown.

5.3.3.3 Security Lights

The security lights consume the smallest percentage of the energy consumed by the lighting system, but energy conservation opportunities exist for this part of the lighting system as well. Security lights can be set on a timer; so they are switched off during daylight hours. This may vary depending on the season.

5.3.3.4 General Lighting

In general, the lights should work according to a schedule, whether they be set to their own timer or be connected to the alarm system to switch off when the alarm is activated. By setting the lights to a schedule, human error (which results in lights being left on during shut down periods) can be eliminated. An occupancy sensor could also be installed to determine whether a space is occupied and requires lighting.

5.3.4 Spot Welder

Data must be gathered on the production times of the spot welder. This study should investigate the actual time per day that the spot welder is in use. In order to gather data about the actual quantity of hours worked by the spot welder per day, an energy meter should be installed at the production line for Product G.

Once real time data has been gathered and the usage schedule of the spot welder is constructed, a schedule can be developed to eliminate the effect the spot welder has on the KVA peaks.

The operating time of the spot welder can be reduced and possibly eliminated, by redesigning the products that require spot welding as part of their production. A study can be done to evaluate the need of the spot welder and to identify possible ways to minimise and eventually eliminate the need for it.

5.3.5 General Recommendations

The energy consumption of the facility needs to be monitored closely to assist with the management thereof. Meters should be installed at different areas of the facility to gather real time data of the energy consumption. With this data in hand, real time management can be done according to the energy consumption.

To assist with the real time management, certain limits need to be set for the KVA peaks and possibly even for the kWh usage per day. When the energy consumption rises too close to these limits, decisions regarding the production and certain equipment can be made in order to stay below the limits.

A central control area is necessary in order to have all the real time energy usage data of the facility together. Central control will enable monitoring of the energy consumption of different areas in the facility. Software can be used to create a user friendly display of the energy usage data, similar to a dashboard. An alarm or warning system can be added to indicate when the KVA usage approaches the peak limit and if an inefficient combination of equipment is running.

If the kWh usage is also monitored, areas with high kWh usage can be identified as they arise during production. Once these areas have been identified, decisions can be made on possible actions to take to reduce the kWh used.

The results of the Shut Down Management initiative experiment show that it is imperative to emphasise the importance of switching off all equipment at shut down to the employees. Through the implementation of the Shut Down Management initiative, savings of around R6000 per month are possible. These savings depend on the amount of over-time worked and the successful implementation of the Shut Down Management initiative.

Another measure that can be taken to reduce the energy costs incurred by the facility, is to change to a tariffs structure that is better suited to the facility's energy consumption patterns and levels. A comparison should be done between the current tariff structure and possible alternative tariff structures to see whether it is cost effective to change the tariff structure.

5.4 Implementation of ECMs and O&Ms

A summary of all the ECMs and O&Ms that were identified is shown in Table 14. The ECMs and O&Ms were grouped according to the equipment or system to which they apply. Table 14 also indicates whether it was decided to implement the ECM or O&M at the facility.

Not all of the proposed ECMs and O&Ms were implemented at the facility. The following section will discuss which ECMs and O&Ms were implemented and give motivation for implementing or not implementing an ECM or O&M.

Table 14 also indicates when the ECM or O&M was implemented at the facility. The ECMs and O&Ms that are in progress are either in the process of being implemented or are ongoing processes. The ECMs and O&Ms that will be implemented as part of the facility upgrade are not implemented yet but will be implemented during the upgrade of the facility. The planned upgrade of the facility has not been started yet and the starting date is still unknown.

Table 14 - Summary of ECMs and O&Ms

Equipment and systems	ECM and O&M	To be implemented	Date Implemented
Air conditioning system	• Operating guidelines:		
	- Earlier start-up	Y	January 2012
	- Temperature settings	Y	January 2012
	• Centralised controls	Y	With Upgrade
	• Reduce heat loss and gain through building envelope:		
	- Seal doors and windows	Y	July 2011
	- Insulate building	Y	With Upgrade
Compressor	❖ Earlier start-up	N	
	❖ Study operating times	N	
	❖ Leak maintenance	Y	June 2011
Lighting system	❖ Production floor ceiling lighting:		
	- Replace blown lamps	Y	August 2011
	- Reduce number of lights	Y	With Upgrade
	- Task lighting	N	
	- Group lights for control	Y	With Upgrade
	- Lowering of lights	Y	With Upgrade
	- Natural lighting	N	
	❖ Store lighting:		
	- Replace existing lamps with energy efficient lamps	N	
	- Replace blown lamps	Y	August 2011
	❖ Security lighting:		
	- Replace blown lamps	Y	August 2011
	- Place light on seasonal timer	Y	July 2011
	❖ General lighting:		
	- Set lights on timer	N	
	- Link lights to alarm system	Y	July 2011
	- Install occupancy sensors	N	
General	❖ Monitor energy consumption in real time	Y	In Progress
	❖ Set KVA and kWh limits	Y	In Progress
	❖ Centralised controls	Y	With Upgrade
	❖ Shut Down Management	Y	In Process
	❖ Utility tariffs structure comparison	N	

5.4.1 Air Conditioning System

During the facility upgrade, the air conditioning ducts will be upgraded as well and the ducts will be installed above the ceiling. The decision was made to keep the air conditioners switched on 24 hours a day for 7 days a week. This decision was based on the elimination of the air conditioners' contribution to the start-up KVA peak as well as the reduction in the fluctuation of the temperature of the air. The air conditioners will only start cooling the air if it reaches a certain temperature. Therefore, the constant air conditioning will in fact reduce the amount of cooling that is necessary at a given time, because the air stays cooler throughout the day.

Most of the air conditioners were broken at the time of the final facility evaluation. The repairs of these air conditioners are underway and should be completed in time for the facility upgrade.

The sealing of the doors and windows was completed which reduced the fluctuation in the temperature inside the facility. The installation of the centralised controls will be done during the upgrade. The ceiling that will be installed will be constructed from an insulating material, which will eliminate the need for further insulation. The operating guidelines will be set in place after the upgrade of the air conditioning system has been completed.

5.4.2 Compressor

The compressor has been fitted with a timer to schedule its operating times, but the timer is not functional yet. A study of the operating times of the compressor would require the installation of an electricity meter at the compressor. The meter was not installed. A thorough study of the compressor's operations could thus not be completed.

Leak maintenance has been completed and it has been included in the maintenance program. The whole compressed air system was checked for leakages and any that were found were sealed.

5.4.3 Lighting System

The discussion of the lighting system will be done according to the different lighting areas and in general.

5.4.3.1 Production Floor Ceiling Lighting

The first ECM that was implemented was the replacement of the blown lamps in the production floor's ceiling. The working lamps and the fittings were cleaned simultaneously. Cleaning the lamps eliminate the reduction in light radiance caused by a build up of dust.

The grouping of the lights will be implemented during the facility upgrade. The lights will be grouped together in several groups that can be controlled separately. This will allow some sections of lights to be switched off if that particular area is not occupied.

Reducing the number of lights relates to the height of the lights above the working areas. With the lowering of the lights to a horizontal position above the working areas it is automatically moved closer as well. Since a ceiling will be installed during the facility upgrade, the lights will be moved horizontally and closer to the working area.

A test was conducted to try and measure the increase in the lighting level due to the lower lights. For the test, a section of the production floor’s ceiling lights were lowered to the level of the ceiling and measurements were taken with the lux meter. The measurements were then compiled into a second lux value diagram. This diagram is shown in Figure 22. The measurements were taken at night to simulate the effect the ceiling will have by blocking out the natural light that shines in through the windows in the roof.

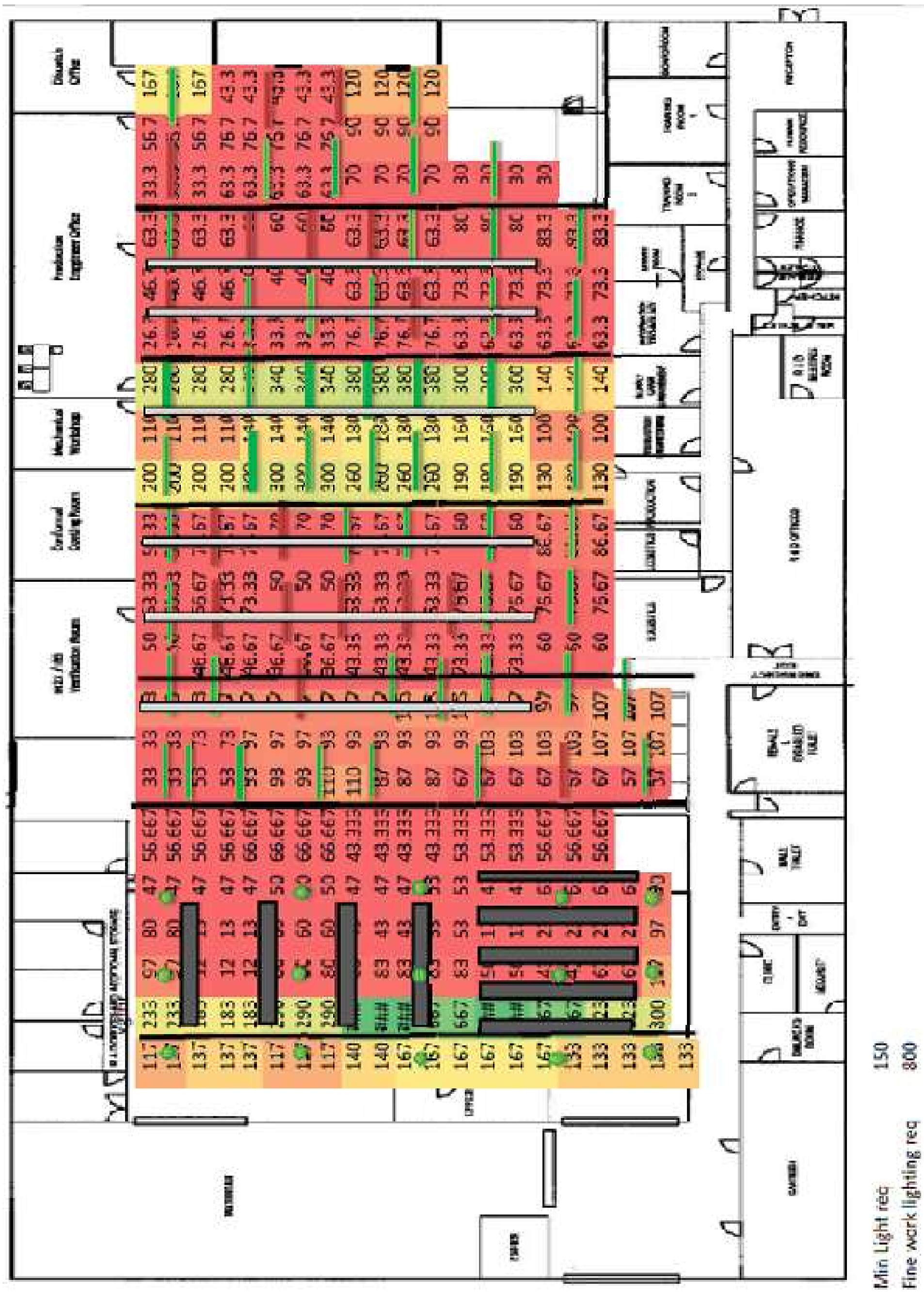


Figure 22 - Lux value diagram with lowered lighting section

Figure 21 shows the lux values of the lighting measured during the day. When comparing Figure 22 with Figure 21, it is noticed that the lighting is inadequate in most of the areas on the production floor. The only area where the lighting is acceptable is the area where the lights had been lowered. This indicates that the lowering of the lights will produce the required lighting level for the production floor, and therefore eliminating the necessity for additional lighting.

5.4.3.2 Store Lighting

The only ECM that was implemented in the store was the replacement of the blown lamps accompanied by the cleaning of all the lights in the store. The replacement of the current 400W metal halide lamps with other more energy efficient lamps was not done. The decision was made by the company to keep the current metal halide lamps due to their relative efficiency. Metal halide lamps efficiencies range anywhere between 45 -100 Lumens per Watt (LPW) (Hordeski, 2003; Kreith & Goswami, 2007). Metal halide lamps make a suitable choice compared to Light Emitting Diodes (LED) with efficiencies of up to 30LPW (Kreith & Goswami, 2007).

5.4.3.3 Security Lighting

The security lights are on a timer to prevent unnecessary operating time. The timer eliminates the possibility of human error. If the security lights switch off automatically, they cannot be left on unnecessarily.

5.4.3.4 General Lighting

To ensure that the lights are all switched off when the facility is locked up, the lighting system was linked to the alarm system and the lights will thus switch off when the alarm is activated. This eliminates the human error factor. Since the lighting system was linked to the alarm system, it was not necessary to install timers or occupancy sensors to switch off the lights.

5.4.4 Spot Welder

The product that is produced on the production line using the spot welder is systematically being phased out of production due to the development of new products. A detailed study in order to identify measures to reduce the operating times of the spot welder is thus unnecessary.

5.4.5 General

A meter was installed at the facility that measured the total electricity consumption of the facility. This meter is currently in the process of being connected to a web based interface to log the data in real time. Once this process has been completed, the monitoring of the KVA peaks and kWh usage can commence and limits can be set in place for real time management. The real time management is coupled with the centralisation of some of the controls to allow an appointed manager to control some of the major systems and equipment quickly and easily.

The Shut Down Management initiative is being implemented. Reminders are being sent to the employees to remember to switch off their equipment when they are finished with a shift. Reminders are also being sent to managers to remember to switch off their office equipment as well. An information system can assist with the monitoring of energy usage and assist with the raising of awareness of ECMs that are being implemented.

5.4.6 Utility tariff structure evaluation

One of the possible ways to reduce energy costs at the facility is to change from a fixed rate tariff structure to a Time of Use (TOU) tariff structure. A TOU tariff structure charges different rates depending on the time of day that the energy is used. A day is divided into three periods, namely Peak Times, Standard Times and Off-peak Times.

A comparison was made between the tariff structure that is currently being used by the facility and the possibility of switching to a TOU tariff structure. The company buys electricity through the Municipality of Cape Town and not directly from Eskom. Enquiries were made to Eskom to ascertain whether the company could buy electricity directly from Eskom. The answer received from Eskom indicated that the company has to buy electricity through the local municipality.

The comparison was done on a monthly basis for one year. The kWh usage and peak KVA values were comprised of data measured by the meter installed at the facility and averages were used where data was missing.

In Table 15, the energy costs incurred using the current tariff structure is shown. The tariffs were broken down into the different components, namely the Energy charge (R/kWh), the Demand charge (R/KVA) and the Service charge (R/day) in order to show the electricity costs incurred by each of the components. This allowed for a more detailed comparison to be done. Over the course of this case study, the electricity tariffs increased two times. The tariffs for all three years were included in this analysis.

Table 15 - Energy costs incurred on increased current tariff structure

	2010	2011	2012
Energy Charge R/kWh	R 0.41	R0.49	R0.54
Demand Charge R/KVA	R 121.16	R145.32	R161.31
Service Charge R/day	R 23.90	R28.67	R31.91

For the calculation of the energy costs incurred with the TOU tariff structure, the energy usage was grouped into time intervals. Peak times fall between 07h00 and 10h00 in the morning and 18h00 and 20h00 in the evenings. Standard times fall in between the Peak times, i.e. from 06h00 until 07h00, 10h00 until 18h00 and 20h00 until 22h00. Off-peak times are between 22h00 and 06h00.

The TOU tariff structure identifies a difference in the demand, based on the seasons. High Demand season is from June to August, Low Demand season is from September to May. Table 16 shows the breakdown of the TOU tariff structure obtained from the Municipality of Cape Town (*Tariffs 2011*).

Table 16–Breakdown of TOU tariff structure

TOU Tariffs		2010	2011	2012
Energy Charge - High Demand (c/kWh)	Peak	R 1.92	R2.30	R2.55
	Standard	R 0.51	R0.61	R0.68
	Off Peak	R 0.28	R0.33	R0.37
Energy Charge - Low Demand (c/kWh)	Peak	R 0.54	R0.65	R0.73
	Standard	R 0.34	R0.41	R0.45
	Off Peak	R 0.24	R0.29	R0.32
Demand Charge (R/KVA)		R 60.87	R73.00	R81.03
Service Charge (Rand per day)		R 3,900.00	R4680.00	R5210.00

It is important to notice the exceptionally high service charge per day connected with the TOU structure. This is likely due to the more detailed metering that the utility will be required to do in order to gather the electricity consumption data in relation to the times that the electricity was consumed. The very high municipal TOU service charge prompted further investigation and a comparison to Eskom's similar TOU tariffs structure's service charge. Eskom's Miniflex TOU tariffs structure has a variable service charge that is dependent on the monthly utilised capacity (Eskom, 2011). Enquiries were made to Eskom to ascertain whether the company could buy electricity directly from Eskom. The answer received from Eskom indicated that the company has to buy electricity through the local municipality.

An enquiry was made to the Municipality with regards to the service charge of the TOU tariffs structure and the correct method for calculating this charge. The answer received from the municipality confirmed that the service charge is charged per day and that the charge stays constant for any amount of electricity usage. The instructions from the tariffs structure information page were therefore followed.

Figure 23 shows the comparison between the total energy costs incurred per month for the current tariff structure and the TOU tariff structure in 2012. From the graph it can be seen that the TOU energy costs are significantly higher than the current tariffs structure's.

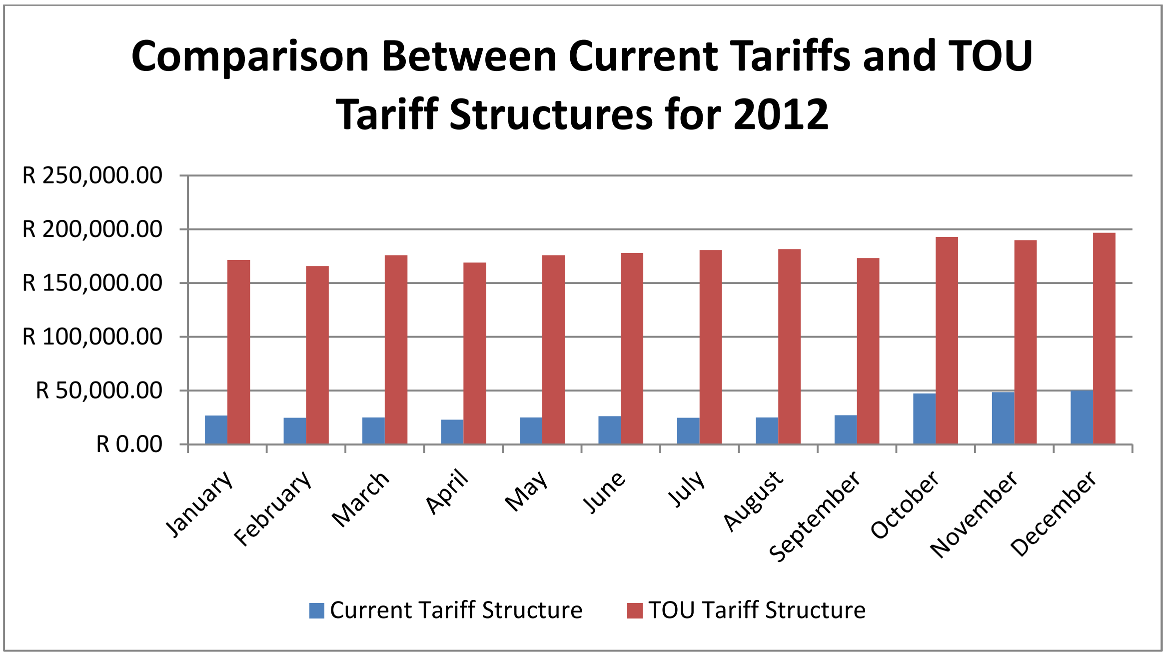


Figure 23 - Comparison between current and TOU tariff structures

The electricity charges were broken down into the three types of charges in Figure 24 in order to identify the charge that impacts on the total electricity charges the most. The comparison was done using the average annual charges of the two tariff structures. From this breakdown it can clearly be seen that the daily service charge of the TOU tariff structure contributes the most to the high total TOU electricity charge.

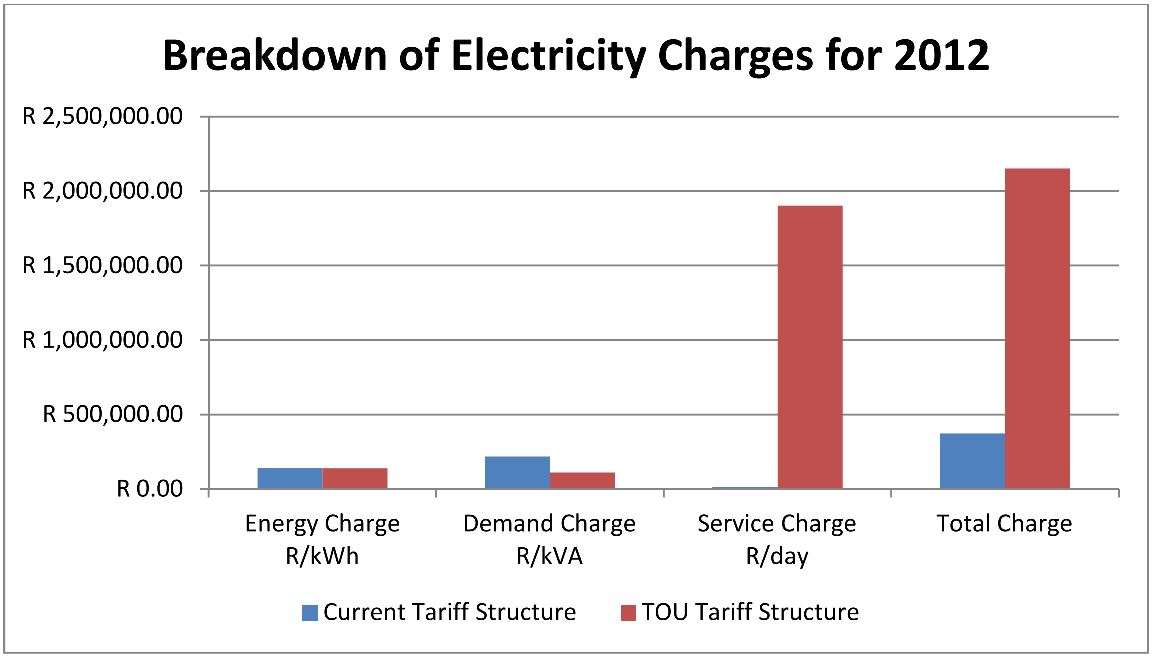


Figure 24 - Breakdown of average annual electricity charges

This significant increase in the service charge for the TOU tariff structures overshadows the savings that could be obtained in the energy and demand charges. This makes the TOU tariffs structures considerably more expensive than the current tariff structures. A change in tariff structure is therefore not recommended for the company.

5.5 Evaluation of Reduction in Energy Consumption

The final component of the energy audit case study was the evaluation of the energy consumption of the facility to establish whether the ECMs and O&Ms that were implemented reduced the energy consumption of the facility. The evaluation was done by comparing the electricity bills of previous years with the latest bills and comparing the kWh and KVA readings taken by the meter at the facility from before the implementation of the ECMs and O&Ms and after.

The ECMs and O&Ms that have been implemented up to date were only implemented from middle 2011 at the earliest, as shown in Table 14. This means that these ECMs and O&Ms could only impact on the energy consumption from middle 2011 onwards.

5.5.1 Evaluation of Electricity Utility Bills

Comparisons were done between the monthly overall electricity costs incurred, the total monthly kWh usage and the monthly KVA peaks. Graphs were drawn up to enable the comparisons. Figure 25 shows the monthly production values for 2009to 2012. Although the billing periods do not coincide precisely with the calendar months, a general indication of the impact of production on the energy consumption can be made.

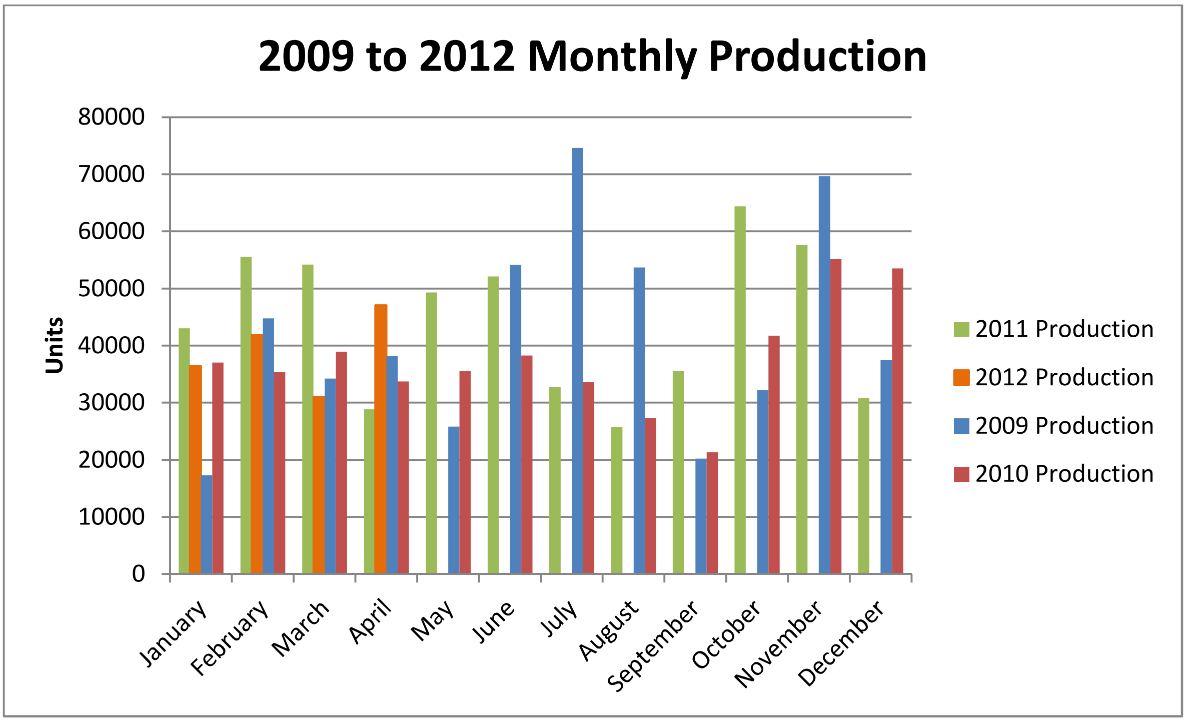


Figure 25 - 2009to 2012 Monthly Production Values

Figure 26 shows the comparison between the monthly electricity utility bills from 2008 to 2012. These values were taken from the actual electricity utility bills, but unfortunately not all of the bills were available, leading to some gaps in the data. The current data is, however, sufficient to draw a comparison between the four consecutive years.

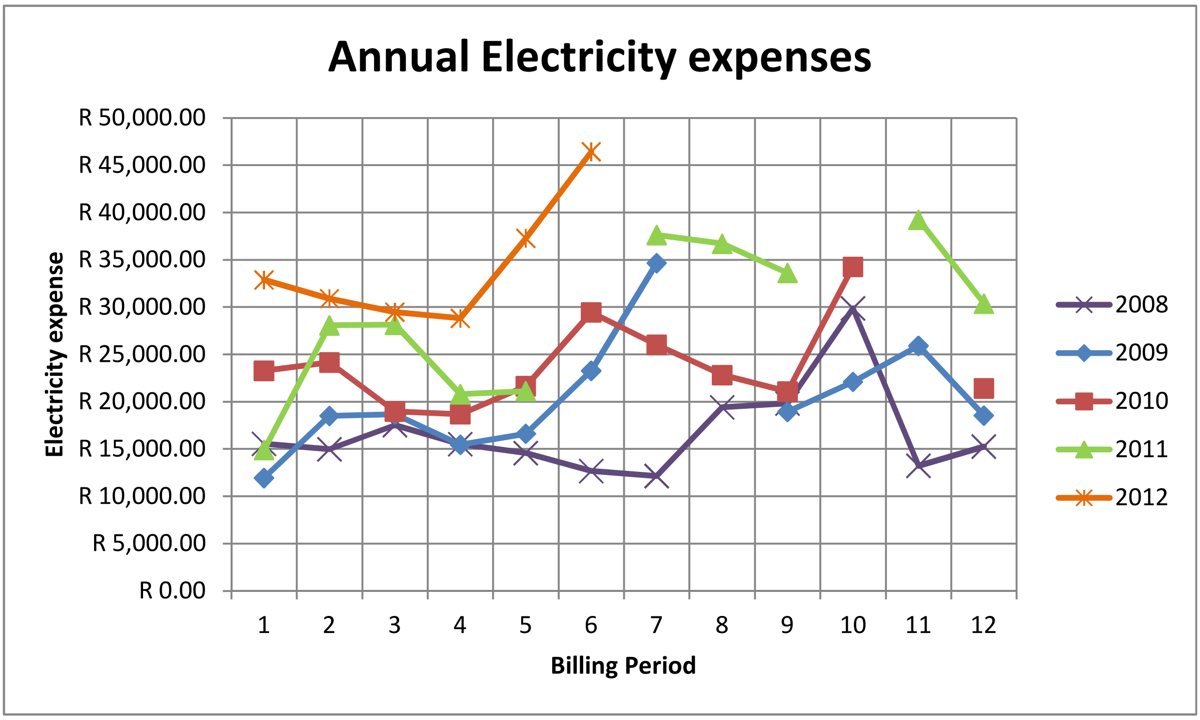


Figure 26 - Annual comparison of electricity expenses

When comparing the total electricity expenses, it is difficult to ascertain the actual savings, since the cost of electricity has increased annually over the last couple of years. This causes the electricity expenses to increase annually as well.

An alternative approach to the comparison is to break the electricity utility bills down into the KVA peaks and the kWh usage. This was done in Figure 27 and Figure 28, respectively. Only the electricity utility bills for 2009, 2010, 2011 and 2012 were available. The breakdown of the bills could thus not be completed for 2008.

In Figure 27 the KVA peaks measured by the electricity utility for 2009 to 2012 is shown graphically. The KVA peaks measure in the second half of 2011 and in 2012 vary less than all three previous years, even though the peaks are higher than the previous years.

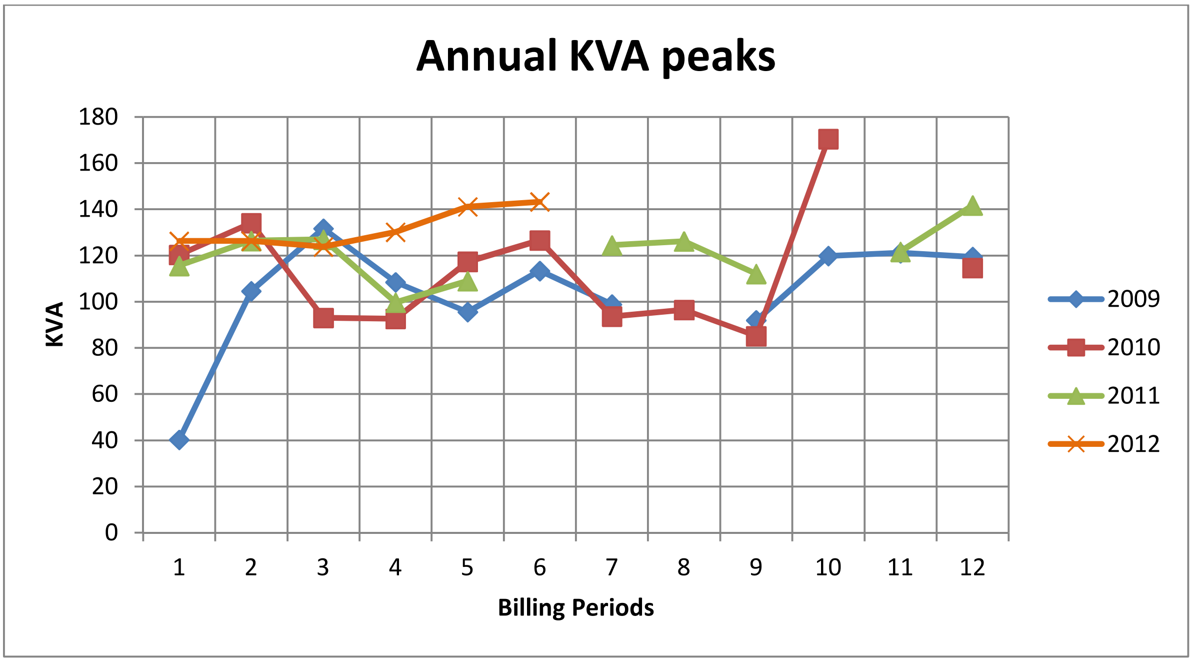


Figure 27 - Annual comparison of monthly KVA peaks

The maximum and minimum KVA peaks measured during 2011 are 126 KVA, and 99.68 KVA, respectively as shown in Table 17. The difference between the maximum and minimum KVA peaks in 2012 is even less than that of 2011. Less variation in the KVA peaks indicate that some improvements have been made with regards to the management of the KVA peaks.

When comparing the minimum and maximum KVA peaks of 2011 to that of 2010 and 2009, a reduction in the maximum KVA peaks can be distinguished in 2011. The maximum KVA peak measured in 2011 is lower than both the previous years'. However, the minimum KVA peak measured for 2011 is higher than both the minimum KVA peaks measured during 2010 and 2009. The maximum and minimum KVA peaks measures during 2012 are higher than all the previous years. This indicates that more can still be done to reduce the KVA peaks measured by the utility.

Table 17 - Minimum and maximum KVA peaks from 2009 to 2012

	2009	2010	2011	2012
Minimum KVA peak	40.32	85.12	99.68	124
Maximum KVA peak	136.32	170.48	126.96	143

Figure 28 shows the kWh usage measured by the utility for 2009 to 2012. The kWh usage for 2011 is lower than the previous two years during the first half of each year. In the second half, the kWh usage increases slightly, but still remains lower than the highest kWh usages recorded for 2009 and 2010. The increased kWh usage at the end of 2011 is also reflected by the production for that period. The kWh usage during the first quarter of 2012 is lower than the previous years in most periods. It is interesting to note that the production in 2012 is only the smallest during February and not for the rest of the first quarter. This reduction in kWh usage during the first quarter of 2012 indicates that some progress has been made in the reduction of the energy consumption of the facility.

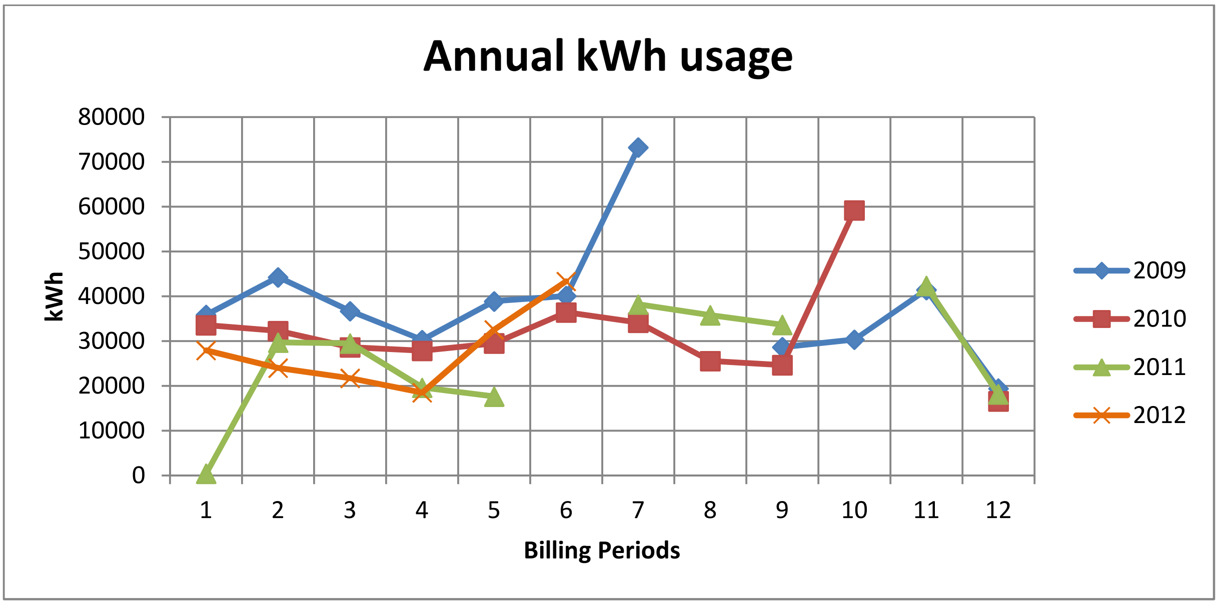


Figure 28 - Annual comparison of kWh consumption

In general, the reduction in electricity consumption has not been sufficient. Therefore, the currently implemented ECMs and O&Ms should be enforced more strictly and further energy conservation opportunities should be identified and taken advantage of.

A number of the proposed ECMs and O&Ms could not be implemented during the course of the case study due to an extended upgrade project period. The implementation of these ECMs and O&Ms could reduce the kWh usage and KVA peaks even more and therefore further evaluation of the reduction in energy consumption should be done once all the ECMs and O&Ms have been implemented.

5.5.2 Evaluation of Electricity Load Measurements

The meter, that measures the total facility kWh usage in 15 minute intervals, was installed mid 2010. Therefore, kWh usage data from the meter is only available from June 2010. Unfortunately, the meter had problems at its start-up and problems occurred while linking the meter to the data capturing website. This resulted in the loss of some of the data captured by the meter.

A comparison between the number of units produced at the facility and the kWh usage for 2011 and 2012 is shown in Figure 29 and Figure 30, respectively. This comparison is done with the monthly production and kWh usage data gathered at the facility by the meter. As previously mentioned, the kWh usage data that was gathered is not complete and thus only certain months were included in this comparison. The months that were included are the complete months of kWh usage metering which correlate with the production months.

Comparing the monthly production with the correlating monthly kWh usage is done to establish the relationship between fluctuations in the production and in the kWh usage. The fluctuation in the monthly kWh usage does show correlations with the fluctuations in the monthly production for 2011, with the exception of September. The kWh usage for July is very similar to May but the production in May is distinctly higher than in July.

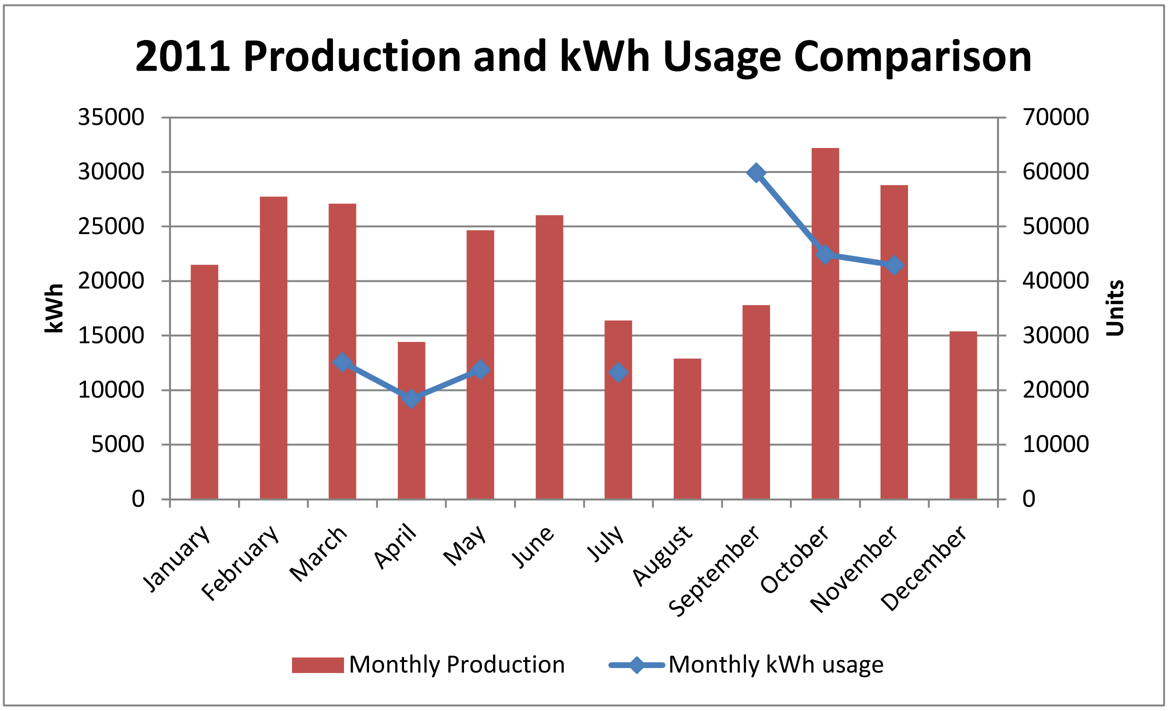


Figure 29 - Comparison between Production and kWh Usage for 2011

During 2012 more problems were encountered with the software used to log the electricity usage data captured by the meter. This resulted in only two complete months' worth of kWh usage data, i.e. March and April. Figure 30 shows that the kWh usage decreases while the production increases and the kWh usage for March is noticeably higher than the production.

The inconsistent fluctuation of the kWh usage compared to the production indicates that there are other factors influencing the kWh usage of the facility. These factors may include outside factors like the weather, variations in the air conditioning settings or it may be the impact that the type of product produced has on the energy efficiency of the production lines.

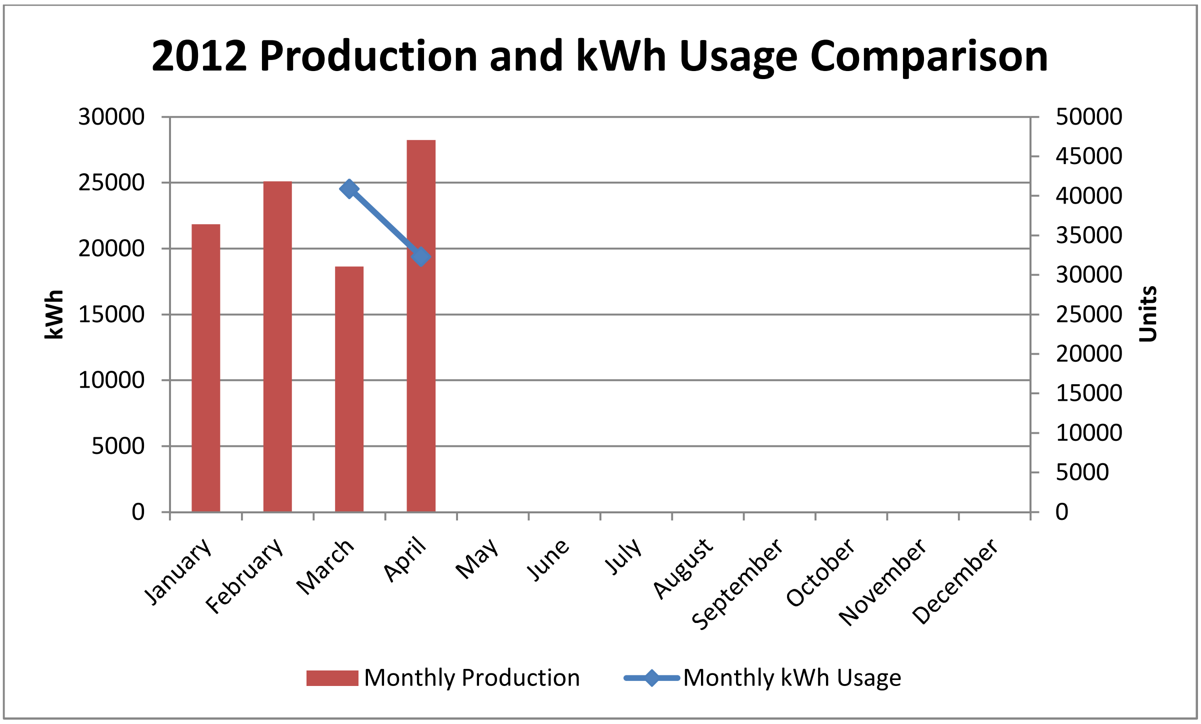


Figure 30 - Comparison between Production and kWh Usage for 2012

The evaluations of the overall load measurements were done to determine the impact that the ECMs and O&Ms have had on the energy usage of the facility. A more detailed evaluation of the load measurements for specific days can yield more detailed impacts. The impact that the Shut down Management ECM had on the energy usage of the facility can be identified by comparing the load profile in Figure 18 to the latest available load profile from 2012, as shown in Figure 31.

The initial problem that was identified in Figure 18 was the unusually high kWh usage after hours compared to weekends. This problem was addressed by implementing a strict Shut Down Management program. The program reminds employees of the correct shut down procedure and requires floor managers to check for unnecessary equipment not being shut down. Figure 31 shows clearly that the afterhours kWh usage is now similar to the kWh usage over weekends.

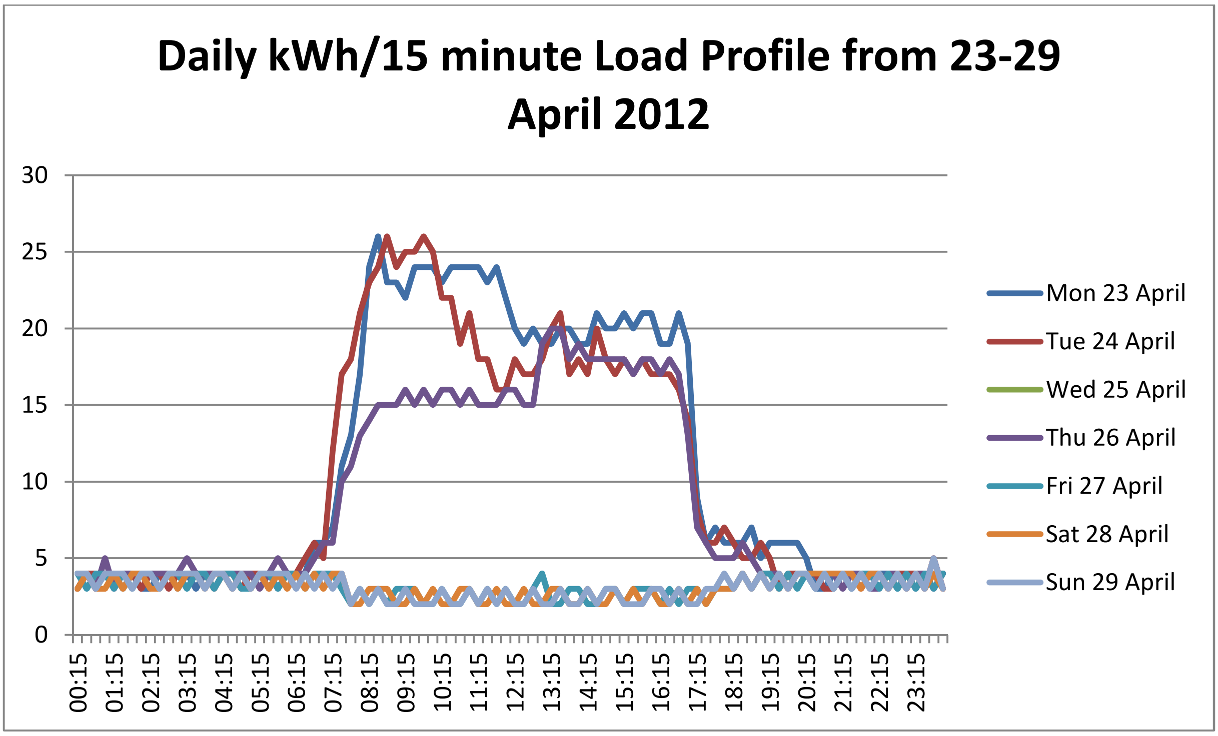


Figure 31 - Daily 15 minute interval kWh load profile for 23-29 April 2012

5.5.3 Overall Evaluation of Reduction in Energy Consumption

Overall it was difficult to determine the precise impact of the ECMs and O&Ms on the facility's energy consumption. Some improvements in the fluctuation of the KVA peaks were identified and there was a reduction in the kWh usage during the first quarter of 2012. These improvements can be linked to the ECMs and O&Ms that were already implemented at the facility. The ECMs and O&Ms that were implemented at the facility include the following:

- Continuous running of air conditioners
- Seals at the delivery doors
- Leak maintenance for the compressed air system
- Replacement of all blown lamps
- Connecting the lights to the alarm
- Shut Down Management

The continuous running of the air conditioners could have impacted on the KVA peaks, but probably did not reduce the kWh usage of the facility. It may have increased the kWh usage of the facility. Without further data retrieved from the air conditioners, it will be difficult to prove the impact the continuous running has had on the kWh usage.

The impact the implementation of the Shut Down Management program had on the after hour kWh usage is clear from the evaluation of the daily load measurements. Management was identified by CAT as one of the top ten topics in the IE field in the last five years. The successful implementation of a management program to reduce energy consumption at the facility indicates the correlation between energy management and management as an IE topic. This correlation is also shown in section4.3.3 between the “Management” topic and the “Energy and emissions in manufacturing/Bio fuel Impacts/Energy Economy” topic.

It is proposed that more energy meters should be installed at the facility to enable more specific monitoring of the energy consumption of specific areas in the facility and of high energy consumption equipment. The more detailed monitoring will also allow the identification of the most effective ECMs and O&Ms.

Due to the fact that all the proposed ECMs and O&Ms could not be implemented immediately at the facility, it is difficult to establish a definitive relationship between the ECMs and O&Ms and the reduction in the measured kWh usage of the facility from 2010 to 2012. Only once the facility upgrade has been completed and all the accepted ECMs and O&Ms have been implemented, will it be possible to perform a more definitive evaluation.

Another factor that influenced the level of detail of the evaluation is the number of meters that are installed at the facility to monitor the energy consumption. At the time of this evaluation only one meter was installed at the facility to record the total kWh usage of the facility. From the data recorded by this meter it is not possible to evaluate specific areas or equipment in the facility. This makes it impossible to pinpoint the specific areas were savings where made or areas where the ECMs and O&Ms were not successful in reducing the energy consumption.

6. Lighting Design Genetic Algorithm

As part of the case study, the company requested specific research to be done on their lighting and how to improve the lighting system for the production area during the facility upgrade. This request led to an investigation into lighting design and ways to optimise the design of lighting systems.

An energy efficient lighting system forms part of an energy efficient building, which is one of the top ten topics identified by CAT in the energy efficiency field. The optimisation of a lighting system, with regards to cost and energy efficiency, applies a part of the operational research section of the IE field. Operational research was identified by CAT as one of the top ten topics in the IE field. CAT did not recognize a significant correlation between energy efficient buildings and operational research, but the analysis and optimisation of HVAC systems show that operational research is applicable in energy efficient buildings (Wright, 1996). This study will try to demonstrate the potential correlation between energy efficient buildings and operational research through the optimisation of the design of lighting systems.

Lighting design is the process of designing the lighting system of a facility to meet the required lighting levels and reduce the overall costs associated with the lighting system. This entails determining the number of lights as well as the placement of the lights in the ceiling.

Optimising lighting design is a multi-objective problem with unique factors that influence the solutions. The minimum required lighting must be met for the area but the minimum number of lights needs to be installed. Therefore, a multi-objective optimisation solution method has to be applied to this problem. Several methods exist to find the optimal solution to a multi-objective problem. Three major types of multi-objective optimisation methods exist, namely evolutionary methods, simulated annealing methods and particle swarm methods.

Genetic algorithms are one of the most basic evolutionary methods that have been applied successfully to multi-objective design problems in various fields. These fields include the optimisation of green building design (F. Wang et al., 2009), general design optimisation (Caldas & Norford, 2002), Lighting arrangements for night time construction projects (Hyari, 2005), design of plant lighting systems (Ferentinos & Albright, 2005) and 3-dimensional computer graphics lighting design (Aoki & Takagi, 1997). A genetic algorithm poses fundamental flexibility that allows for the selections of optima with regards to the specifications (Man, Tang, & Kwong, 1999). The flexibility and wide range of application of the genetic algorithm served as the grounds for selecting genetic algorithms as the optimisation method for the lighting design.

This chapter applies a Genetic Algorithm (GA) to the lighting design problem. The GA that was applied was constructed specifically for lighting design. The GA takes into account the difference between the actual and required lighting in facility areas, ceiling heights and lighting requirement. It also allows the user to choose the lighting type to evaluate as well as the required lighting for that specific facility.

The evaluation of the possible solutions was based on the number of lights and the amount of unnecessary lighting measured on the floor area. It was done by comparing the amount of unnecessary lighting of solutions that have the same number of lights. A unique method was used for the replacement of solutions into the population, which is based on the evaluation discussed above.

In this chapter an overview of GAs was included to explain their application and structure. A section on lighting design and important lighting definitions was included in this chapter to aid with the lighting design aspects of the Lighting Design GA. Once GAs and basic lighting and lighting design concept have been described, details of the Lighting Design GA are discussed.

6.1 Background on Genetic Algorithms

In the real world, complex problems are encountered that have various factors and constraints influencing the problem and multiple feasible solutions exist. When faced with such problems, an optimisation approach should be taken to find the best possible solution, given the factors and constraints (Zandin, 2001).

Optimisation, in the field op metaheuristics, is defined as the process of finding the optimal value for an objective function with regards to its parameters (Dréo, 2006). The objective function is a mathematical function that represents the output of a process that is to be maximised or minimised (Winston, 2004). The objective function comprises of parameters, also known as decision variables, which influence the performance of the process and are controllable (Winston, 2004). The parameters of an objective function must satisfy the constraints of the problem (Dréo, 2006).

Different optimisation methods are available, but this chapter will focus on metaheuristics. Metaheuristics utilises a degree of randomness to locate the most optimal solution to the problem (Luke, 1). A benefit of metaheuristics is its applicability in both discrete and continuous problems (Dréo, 2006). Several types of metaheuristics exist, some of which are Simulated Annealing, Tabu searches, Genetic and evolutionary algorithms as well as ant colony algorithms (Dréo, 2006).

Genetic Algorithms (GAs) are very similar to evolutionary algorithms. These algorithms are based upon the evolution of species (Dréo, 2006). Both types of algorithms follow the same sequence, as illustrated by the flow chart in Figure 32 (Dréo, 2006):

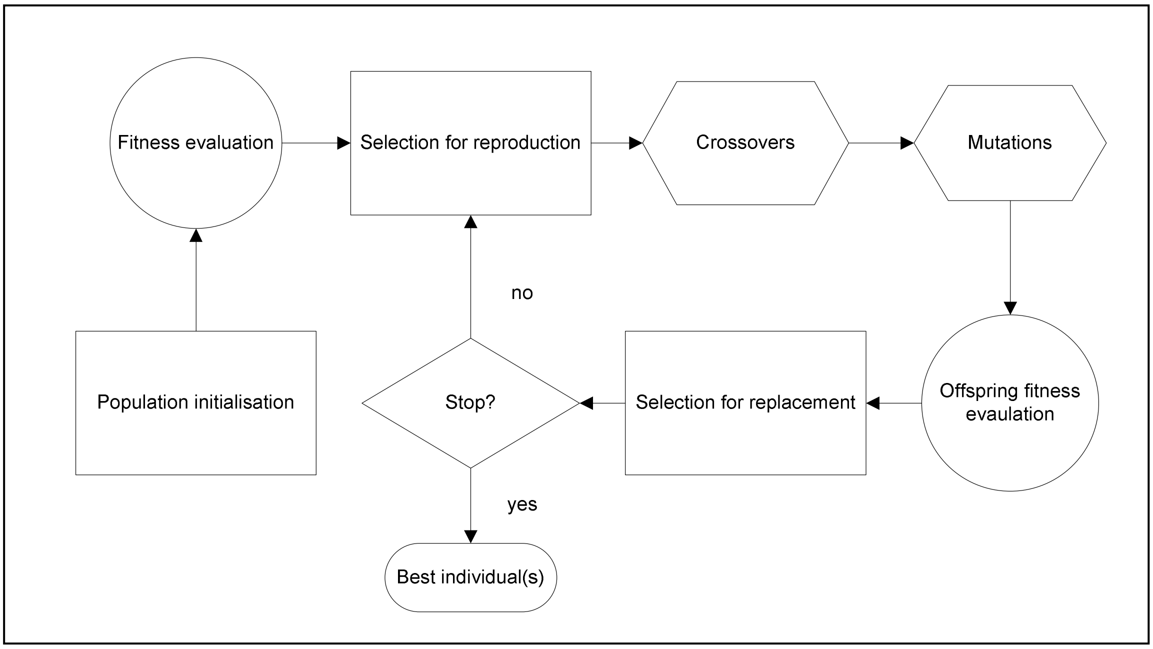


Figure 32 - Evolutionary algorithm principle

GAs have advantages over more traditional numerical optimisation methods. These advantages include (Haupt R.L., 2007):

- Optimises with continuous or discrete parameters
- Does not require derivative information
- Simultaneously searches from a wide sampling of cost surfaces
- Works with a large number of variables
- Is well suited for parallel computers
- Optimises variables with extremely complex cost surfaces
- Provides a list of optimum parameters, not merely a single solution
- May encode the parameters and complete optimisation with encoded parameters
- Works with numerically generated data, experimental data or analytical functions

6.1.1 Population Initialisation

The first step of a GA is to generate the population that is to be used for optimisation. The population is made up of individuals representing possible solutions to the problem. An individual consists of a set of values for the parameter of the problem, usually stored in the form of a chromosome. When these parameters are entered into the objective function, a possible solution is calculated. This solution is known as the fitness of the individual.

6.1.2 Fitness Evaluation

The second step entails that the individuals in the population are compared with one another based on their fitness. This comparison is done by first calculating each individual's fitness and then comparing the individuals until the fittest are identified.

6.1.3 Selection for Reproduction

In order to reproduce, two parent individuals must first be selected from the population. Four types of selection methods can be used. The most basic selection method is simply to select the parents randomly from the population. Random selection is, however, not ideal since it does not take the fitness of the individuals in the population into account.

The next two selection methods are Fitness-proportionate selection (F-PS) and Stochastic Universal Sampling (SUS) (Luke, 2010). Both of these selection methods take the fitness of the individuals into account. The F-PS, also known as Roulette selection, and SUS are based on natural selection. They use the principle that the fitter an individual is, the more often that individual should be selected as a parent and that fit individuals should be selected at least once (Coley, 1999; Dréo, 2006; Haupt R.L., 2007; Luke, 2010). For both selection methods individuals in the population must first be sized according to their fitness. An illustration of this sizing is shown in Figure 33 (Luke, 2010):

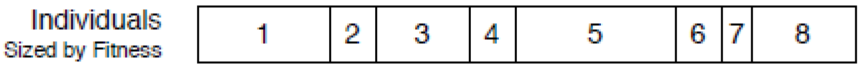


Figure 33 - Representation of sized individuals in population

Once the individuals have been sized according to their fitness, the selection process can begin. F-PS generates a random number between 0 and the total fitness of all the individuals (s). The individual's range in which the random number falls is then selected (Luke, 2010). Individuals with larger ranges are thus likely to be selected more often. SUS first selects a random starting point between 0 and the total fitness of the population divided by the number of individuals in the population (n). Once the starting position has been determined, the selection occurs at intervals of s/n, as shown in Figure 34 (Luke, 2010). SUS selects more than one individual from the population. The number of individuals selected is equal to the number of offspring (Dréo, 2006).

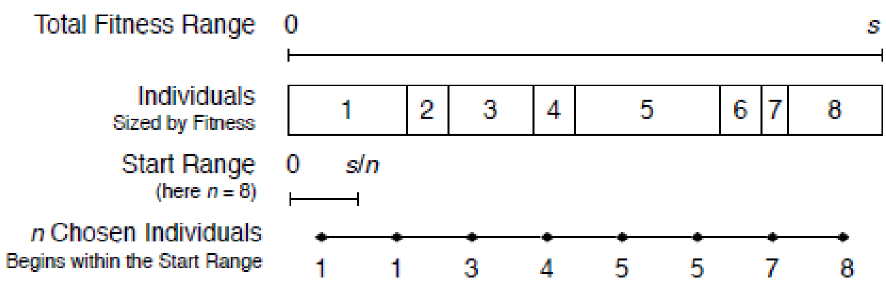


Figure 34 - Illustration of SUS

The final selection method is tournament selection. Two groups, consisting of two or three individuals, are randomly selected from the population. The fittest individual in each of the two groups are then selected as the parents. Figure 35 gives a graphical representation of tournament selection (Haupt R.L., 2007):

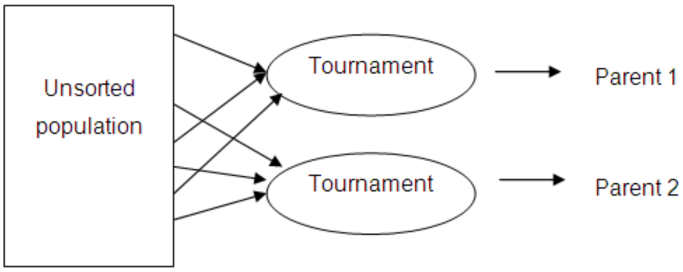


Figure 35 - Tournament selection

6.1.4 Crossover

The production of offspring is done through a process named crossover. Crossover entails swopping some of the parameters stored in the chromosome of the parent individuals to create child individuals with chromosomes consisting of parameters from both parents. The parameters of the chromosome can be represented by integers, binary digits or even more complex structures, depending on the type of problem (Dréo, 2006).

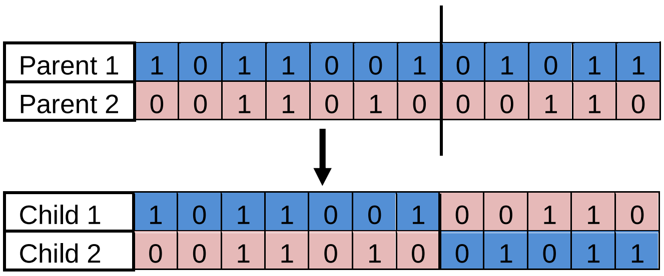


Figure 36 - One-point crossover

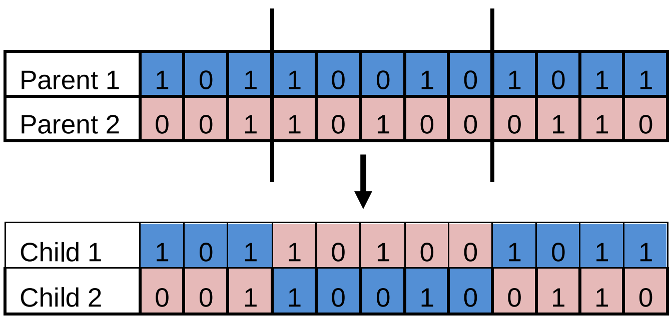


Figure 37 - Two-point crossover

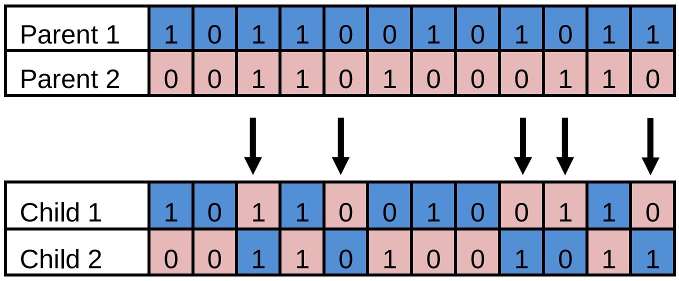


Figure 38 - Uniform crossover

Three methods are used for crossovers which differ with respect to the selection method used to select the parameters for the crossover. The first method randomly selects one point on the chromosome from where the swop-over is done, as illustrated in Figure 36. The second crossover method selects two points between which the swop-over is done, as illustrated in Figure 37. The final method is called uniform crossover. This method moves along the chromosome and does a coin toss random selection to determine whether the parameter should be swopped over. Uniform crossover is illustrated in Figure 38.

One-point and two-point crossover methods assume that certain attributes of the individual is enclosed in consecutive parameters. Therefore, a group of consecutive parameters are swopped over to keep the attribute intact (Luke, 2010). The uniform crossover method does not make the assumption that attributes are enclosed in consecutive parameters, thus allowing uniform crossover to be used more widely.

6.1.5 Mutation

Mutation forms part of GAs to bring about random variations in the population (Haupt R.L., 2007). As in real life, mutations do not occur frequently (Coley, 1999). A probability is used to determine whether a mutation will occur during that iteration of a GA. The mutation probability is usually set as the inverse of the number of parameters in the chromosome (Luke, 2010). Similar to the uniform crossover, each of the parameters are evaluated individually by comparing a randomly generated number between 0 and 1 to the mutation probability. If the mutation probability is larger than the random value, that parameter is changed.

6.1.6 Offspring Fitness Evaluation and Replacement

Once the offspring (children) has been produced, they are also evaluated based on their fitness calculated with the objective function using their parameters. Now the offspring has to be replaced back into the population. The general replacement approach used is to replace the least fit individuals in the population with the offspring (Dréo, 2006).

6.1.7 Optimisation

The final part of a GA is the determination of the optimal solution to the problem represented by the GA. This is done by evaluating the entire population, after crossover and mutation, based on each individual's fitness. An evaluation is done to identify the fittest individual. This individual is a possible solution. The next iteration of the parent selection, crossover and mutation is then started in order to produce more offspring and more possible solutions to the problem.

6.2 Lighting Definitions and Background on Lighting Design

This section will discuss some basic definitions of lighting terminology that explains the basic concepts of lighting and lighting design. The lighting design process is also described to assist with the logic behind the application of a GA to the lighting design process.

6.2.1 Lighting Terminology Definitions

A lighting system consists of a number of components. The most basic components are the lamps and ballasts. A lamp is defined as a man-made source of light, while a ballast is the device that provides the necessary volt and current to start and operate the lamp. A lamp and ballast together is known as a luminaire (Institute of Electric and Electronic Engineers, 1996).

A light that is switched on emits a luminous flux in all directions. Luminous flux is measured in lumens (lm). Lumen does not give any information on the direction of the light. Luminous intensity is the intensity of luminous flux in any three-dimensional direction. It is measured in candela (cd), which is equal to the amount of lumen per steradian (Beggs, 2002).

Steradians are the solid angles, with the vortex of the angle situated at the centre of the sphere, which cut off a spherical surface from a sphere. This is indicated by the cone shape in Figure 39.

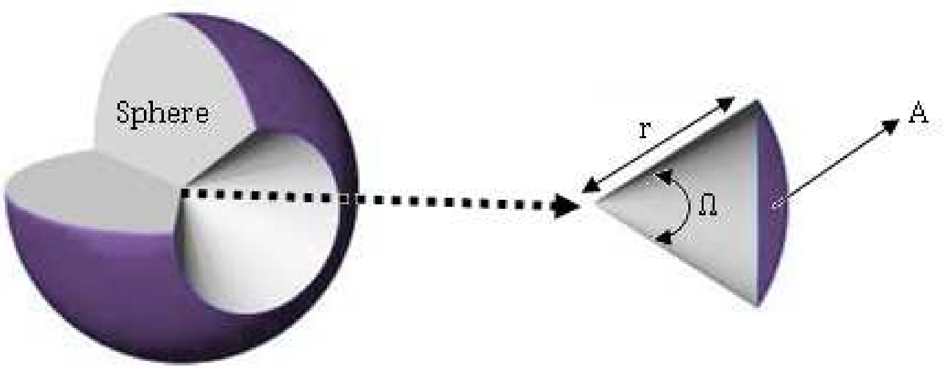


Figure 39 - Steradian illustration

Listed below are some definitions of different measures of power (Ryer, 1997):

- Flux is the measure of rate of energy flow in watts (watts = joule per second)
- Radiant flux is the measure of radiometric power
- Luminous flux is the measure of power of visible light
- Photopic flux is the measure of power weighted to responsiveness of the human eye
- Scotopic flux is the measure of power weighted to sensitivity of the human eye in dark adapted state
- Irradiance is the measure of radiometric flux per unit area (Measured facing the light source)

Luminance is the measure used for light flux (lumen) per unit area either reflected from or transmitted through a surface. The contrast between the luminance of an object and the luminance of the background behind the object is known as the luminance contrast. Luminance efficacy measures the efficacy of a lamp in terms of the light output per unit of electrical input. The unit for luminance efficacy is lumens per watt. The equation for luminance contrast is (Institute of Electric and Electronic Engineers, 1996):

$$Luminance\ contrast = \frac{background\ luminance - object\ luminance}{background\ luminance} \quad (2)$$

The action of light radiating from the light source and falling on a surface of an object is called illumination(Institute of Electric and Electronic Engineers, 1996).The amount of visible light that falls on the surface of the object is therefore called illuminance, and it is measured in lux (lx) (Beggs, 2002; Institute of Electric and Electronic Engineers, 1996; Ryer, 1997). Lux is equal to the lumen per square meter of area (Ryer, 1997). Light is a radiant energy type. Its illuminance thus varies inversely with the distance between the light source and the surface. This inverse relationship is known as the inverse square law (Beggs, 2002).

Another important factor that influences illumination is the angle with which the light hits the surface. When a surface is illuminated at an angle, the light is spread over a larger area which decreases the illuminance. Combining this information with the inverse square law generates the cosine law (Beggs, 2002):

$$Eh = \frac{I\theta}{d^2} \times cos\theta \quad (3)$$

With Eh referring to the illuminance on the horizontal surface, I_θ is the illuminous intensity in the θ direction, d is the distance between the light source and the surface and θ is the angle at which the light hits the surface (Beggs, 2002).

Candela is a base unit in light measurement. A light source that is 1 candela strong emits 1 lumen per steradian in all directions. When a light source emits light in all directions, it is known as an isotropic light source. An isotropic 1 candela light source produces 1 lumen per square meter at a distance of one meter. An illustration of this concept is shown in Figure 40 (Ryer, 1997) .

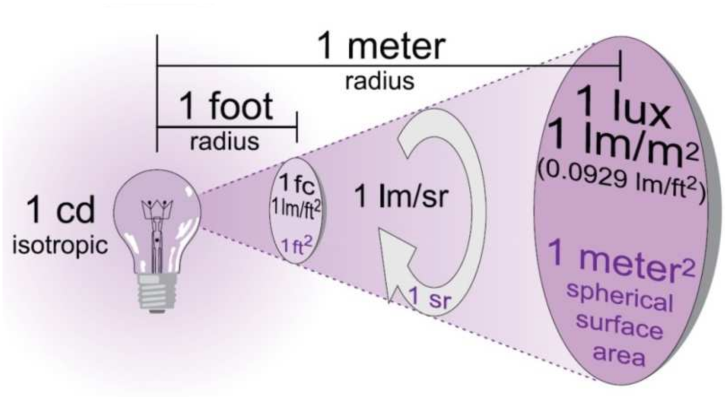


Figure 40 - Candela illustration

Glare is defined as the sensation that is produced by a brightness that is greater than the current adapted light of the human eye. This sensation can cause annoyance, discomfort or even a loss in visual performance and visibility. Therefore, it should be kept to a minimum (Institute of Electric and Electronic Engineers, 1996).

6.2.2 Lighting Design

When designing a lighting scheme, there are certain factors that influence the efficiency of the lighting scheme that need to be taken into account. These factors are:

- The efficacy of the lamps
- Luminaire performance
- Layout of fittings
- Surface reflectance of décor and furniture
- The size and shape of the space

A popular designing method that incorporates all of these factors is the Lumen Design method. This method is fast and is used to design regular lighting schemes. It consists of two steps. Firstly, the number or luminaires required is calculated and secondly, the spacing of the calculated number of luminaires is determined (Beggs, 2002; *Cooper Lighting & Safety, 2010*).

The number of luminaires (n) can be calculated with the following equation:

$$n = \frac{Eav \times A}{\emptyset \times UF \times MF} \tag{4}$$

Eav is the average illuminance that is required in the space and is measured in lux. The required illuminance depends on the visual tasks that have to be performed in the space. Higher illuminance is required for more demanding visual tasks. The lighting designed lumen per fitting (Ø) value is the total lumen output of a specific lamp in a specific luminaire fitting. A variety of lamps might fit in a specific fitting and produce different amounts of lumen and it is thus important to know the different types of lamps (Beggs, 2002).

The Utilisation Factor (UF) takes into account the direct luminous flux as well as the reflected flux reaching the work plane from the light source. The equation below can be used to calculate the Utilisation Factor:

$$UF = \frac{Total\ flux\ reaching\ the\ work\ plane}{Total\ light\ source\ flux} \tag{5}$$

The UF is influenced by the type of luminaire used, the dimensions of the space and the reflectance of surfaces in the room. Manufacturers of lamps often construct tables with UFs for different reflectance values for the walls and ceiling in a room as well as different room dimensions.

The room dimensions are combined into a room index, which is calculated as shown in the equation below:

$$Room\ Index = \frac{L \times W}{Hm \times (L + W)} \tag{6}$$

$L\ is$ equal to the length of the room, W is equal to the width of the room and Hm is the mounting height of the ceiling above the work plane. Table 18 is an example of an UF table created by a manufacturer (Beggs, 2002).

Table 18 – Luminaire Utilisation Factor

		Room Index					
		1.00	1.25	1.50	2.00	2.50	3.00
Room Reflectance	**50[50]**	0.50	0.54	0.57	0.61	0.63	0.65
Ceiling (%)	**50[30]**	0.47	0.51	0.54	0.58	0.61	0.63
Wall [%]	**50[10]**	0.44	0.48	0.51	0.56	0.59	0.61

The Maintenance Factor (MF) included in the calculation of the number of luminaires takes into account factors that reduce the light output of luminaires. These factors include the reduction in lamp output over its lifetime, the build-up of dirt on reflectors, diffusers and surfaces in the room over time and the reduction in light due to failed lamps that remain unattended. The Maintenance Factor is calculated as shown below (Beggs, 2002):

$$MF = LLMF \times LSF \times LMF \times RSMF \tag{7}$$

$LLMF$ is a Lumen Maintenance Factor that is equal to the remaining percentage of the original lumens of a lamp after a certain period of time. LSF is the Lamp Survival Factor which is the number of lamps that have not failed after a given period of time. Both $LLMF$ and LSF can depend on the type of lamps that are installed and the operating hours that have to pass before lamps are replaced (Beggs, 2002).

Luminaire Maintenance Factor (LMF) measures the impact of different maintenance practices on different luminaires in different environments. The maintenance practices refer to the interval between cleaning sessions of the luminaires and any reflective surfaces in the space. The different environments are classified as either clean, normal or dirty (Beggs, 2002).

The Room Surface Maintenance Factor ($RSMF$) quantifies the extent to which different cleaning regimes have an impact on the reflectance of surfaces in the space. RSMF depends on the Room Index, the distribution type of the luminaire (direct, general or indirect), the cleaning regime and the cleanliness of the environment (clean, normal or dirty) (Beggs, 2002).

The second step in the Lumen Design Method is to calculate the spacing of the luminaires. The spacing is calculated by dividing the area by the number of luminaires (n) calculated in the first step and then taking the square root of that fraction:

$$Spacing = \sqrt{\frac{Area}{n}} \tag{8}$$

A mounting height ratio which should not be exceeded when designing a lighting scheme is usually given by the manufacturers of lamps and ballasts (Beggs, 2002).

Other lighting design methods exist. These methods are:

- Zonal Cavity method
- Point-by-point method
- Design by incorporating photometric data

The Zonal Cavity lighting design method is used to calculate the number and replacement of luminaires to meet required lighting levels. The basic lumen method is used as a base and other factors that influence the output of the luminaires are incorporated (Institute of Electric and Electronic Engineers, 1996).

The Basic lumen method:

$$foorcandle = \frac{lumens\ striking\ an\ area}{square\ feet\ of\ area} \tag{9}$$

The Zonal Cavity method:

$$footcandle = \frac{lamps/luminaire\ \times\ lumens/lamp\ \times coefficient\ of\ utilisation\ \times LLF}{area/luminaire} \tag{10}$$

with LLF referring to the Light Loss Factor, which is used to calculate the illuminance after a certain period of time and under certain conditions (Institute of Electric and Electronic Engineers, 1996) .

The Point-by-Point method is a very detailed and time consuming method. It is usually conducted by a computer and several computer programs have been written to utilise this method. The total contributions from all luminaires at work level, both the direct and the indirect illumination components, are summed for points in the space. The information that is required in order to implement this method is (Institute of Electric and Electronic Engineers, 1996):

- The geometry of the lighting installation
- Details of the room
- Surface reflectance
- Candlepower data for the specific luminaires

Photometric data types convey different sets of information about the distribution of candlepower from luminaires. Four types of photometric data formats will be discussed:

- Polar intensity curves
- Cartesian diagrams
- Illuminance cone diagram

- Isolex diagrams

The polar curves illustrate the luminous intensity distribution in candelas per 1000 lumen (cd/1000lm) for transverse and axial planes of the luminaire. It shows different types of distributions, such as wide, narrow, direct or indirect as well as the intensity. Cartesian diagrams indicate the distribution of luminous intensity (cd/1000lm) for horizontal and vertical planes of luminaire. It serves as a visual guide for determining the type of distribution (Cooper Lighting & Safety, 2010).

Illuminance cone diagrams indicate the maximum illuminance (Elux) at different distances and beam angles. This data is usually used for spotlights and lamps with reflectors. Isolux diagrams are used to assess the distribution and characteristics of luminaire and also to determine lighting levels. The diagrams show points of equal illuminance, in lux, on the floor or wall pane from a mounted light source (Cooper Lighting & Safety, 2010).

6.3 Genetic Algorithm Application for Lighting Design

In this chapter a GA was applied to lighting designing. The aim of lighting design is finding a suitable number for lights and layout for those lights in a facility. It is a complex problem with multiple possible solutions and therefore a GA was developed to find near optimal solutions for lighting design. The goal of the Lighting Design Genetic Algorithm (LDGA) is to determine the near optimal arrangement and number of lights at the lowest cost and energy consumption.

The cost of the lighting design depends on the number and types of lights. The number of lights influences the installation, maintenance, replacement as well as the energy costs incurred by the lighting system. The energy cost is also influenced by the type of lamp installed. Therefore, the cost element of the objective function is evaluated based on the number of lights. This simplification is based on the knowledge that one specific type of light will be installed at the facility as a way to standardise the lighting. The lighting type is defined by the user of the LDGA.

The LDGA was constructed to minimise the deviation of the lighting from the required lighting levels. For the LDGA, the effect that a light, which is installed at a specific location on the ceiling, has on the floor was measured. This was done by dividing the ceiling and the floor into squares of 1 m x 1 m to create grids. The light effect in each of the squares on the floor was then calculated using the inverse square law and simple geometrics, as discussed in section 6.2.1. Figure 41 illustrates the meter by meter blocks on the ceiling and the floor as well as the angle used to calculate the light effect on a floor block. The lighting on each floor block was then compared to the required lighting for the block.

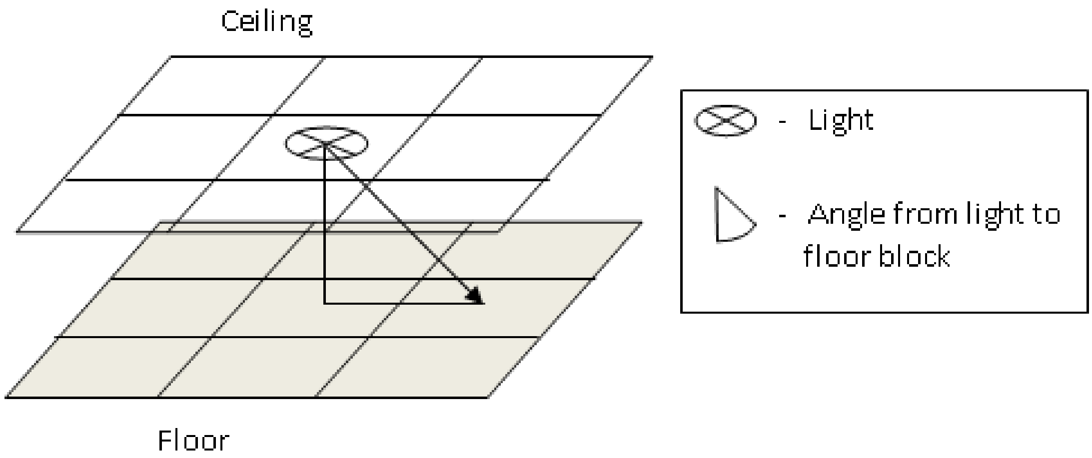


Figure 41 - Ceiling and floor blocks

The LDGA was developed to allow use in different size facilities. The dimensions of the area, entered by the user, were used to determine the number of blocks on the floor and ceiling. The height of the ceiling is used for the light effect calculations and it is also specified by the user. The parameters that influence the fitness of an individual are as follows:

- The number of lights
- The layout of the lights on the ceiling
- The floor (and ceiling) area of the facility
- The height of the ceiling above the floor

In order to optimise the lighting design, the LDGA has three objectives, i.e. to meet the minimum lighting requirement for each of the blocks on the floor as indicated by the user, to minimise the number of lights installed in the facility and to minimise the cost related to the lighting design. The cost related to the lighting design is directly proportionate to the number of lights, since only one type of light will be installed throughout the facility. Therefore, only the number of lights will be minimised with the LDGA.

6.3.1 Population Initialisation

The individuals in the population were defined as chromosomes containing binary strings. Each bit in the binary string refers to a block on the ceiling and a bit set as 1 indicates that a light has been installed in that block on the ceiling. The length of the chromosome differs according to the area of the ceiling, as illustrated in Figure 42.

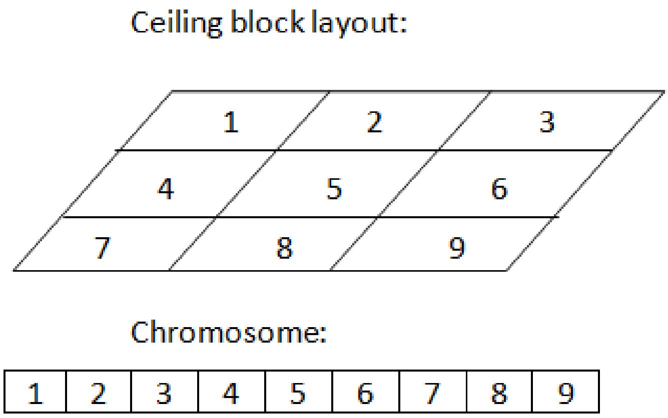


Figure 42 - Ceiling block to chromosome conversion

The binary strings for the chromosomes were generated by doing a coin toss and comparing the outcome of the coin toss to probability. Genetic algorithms are based on random generation of individuals which means that there is equal chance for a light to be installed or not. This probability is not ideal for the goal of this genetic algorithm, since the goal is to reduce the number of lights and therefore reducing the energy consumed by the lighting system. A 'manual logic' was incorporated into the code to eliminate the complete randomness.

The probability was constructed to assist the algorithm in minimising the amount of unnecessary lighting by making it less probable to install a light. This was done by dividing the required lighting with the lumen rating of the lights to be installed, which gives a small probability. Any number of lights could be placed in any position on the ceiling. In this way, it allows a wide range of possible lighting design solutions to be generated.

6.3.2 Fitness Evaluation and Selection

The fitness of an individual is based on two factors:

- The amount of unnecessary lighting
- The number of lights installed

The amount of lighting produced by an individual was calculated by adding up the effect that each light installed in the ceiling has on all the blocks on the floor. To simplify this calculation, a "Light Effect" table was first constructed. This table stores the effect that a light in each ceiling block has on each floor block. An example of the "Light Effect" table is shown in Table 19.

Table 19–"Light Effect" table

	Floor block 1	Floor block 2	Floor block 3	Etc.
Ceiling block 1	Light effect of light in ceiling block 1 on floor block 1	Light effect of light in ceiling block 1 on floor block 2	Light effect of light in ceiling block 1 on floor block 3	
Ceiling block 2	Light effect of light in ceiling block 2 on floor block 1	Light effect of light in ceiling block 2 on floor block 2	Light effect of light in ceiling block 2 on floor block 3	
Ceiling block 3	Light effect of light in ceiling block 3 on floor block 1	Light effect of light in ceiling block 3 on floor block 2	Light effect of light in ceiling block 3 on floor block 3	
Etc.				

This calculation was done by using the inverse square law and geometry to determine the angle and the distance that the light travels from the source to the floor. From the bits in the chromosome, the location of the lights was determined, as shown in Figure 42. Once the position was determined, it was compared to the position of each of the floor blocks to determine the exact distance. Figure 43 shows the height (h), the horizontal distance (b) and the actual distance travelled by the light.

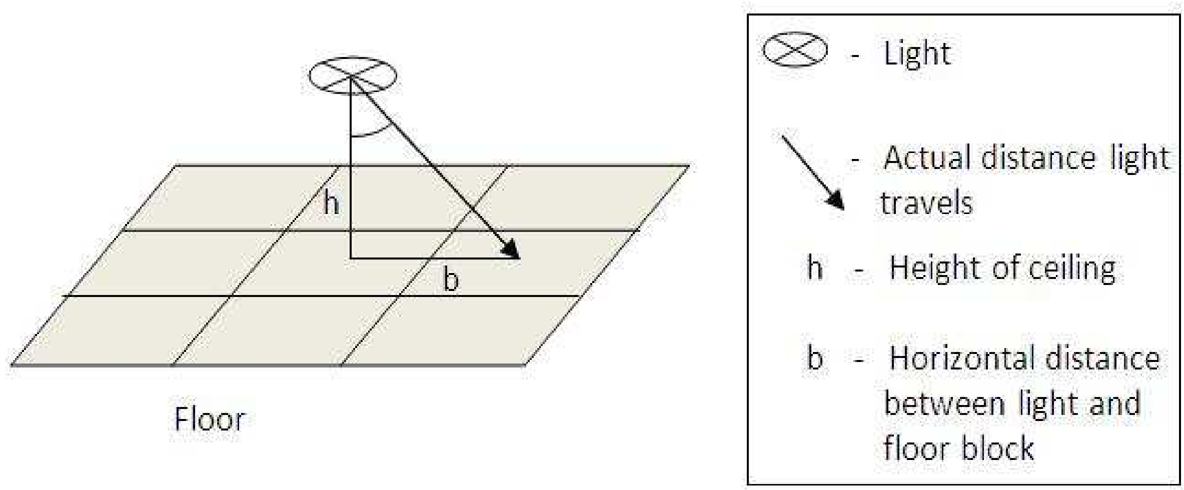


Figure 43 - Calculation of the actual distance light travels

To calculate the distance, the height of the ceiling and the horizontal distance between the light and the floor block was used in the Pythagorean formula:

$$Actual\ distance = \sqrt{(b^2 + h^2)} \quad (11)$$

From the Light Effect table the actual lighting provided by a specific individual's number and layout of light could be determined. This was done by summing the effects that the lights from a specific individual have on each of the floor blocks. These summed values, referred to as “Blockfitness” in the LDGA, were then stored in a separate array for use in the evaluation of the fitness of the individuals.

Once the “Blockfitness” for each floor block was calculated, these values were compared to the required lighting level. The required lighting level is prescribed by the user of the LDGA according to lighting standards for that specific facility. If the “Blockfitness” of each of the floor blocks do not meet the required lighting, the individual is rejected from the population and another individual is generated. This ensures that the population only contains feasible solutions.

To evaluate the fitness of the individuals with regard to the amount of unnecessary lighting, the total amount of unnecessary lighting is calculated for each solution. The total unnecessary lighting values were then compared to find the smallest difference between the required lighting and the light effect of the solutions. The smallest amount of unnecessary lighting indicated the fittest individual in the population.

The evaluation of the fitness based on the number of lights installed was done by documenting the number of lights installed for each individual and then finding the individual with the least amount of lights.

For fitness-proportionate selection (F-PS), a cumulative distribution function (CDF) first needs to be created in order to incorporate the fitness of the individuals into the selection process. For the LDGA, two CDFs were constructed. The first CDF was constructed using the maximum amount of unnecessary lighting on a floor block per individual. The second CDF was constructed from the number of lights installed per individual.

The selection process then chose one parent using the unnecessary lighting CDF and the other parent using the number of lights CDF. This method incorporated both of these objectives on an equal importance level with regards to the overall goal of the LDGA.

6.3.3 Crossover

The crossover of the two parent individuals was done using Uniform crossover, as discussed in section 6.1.4. The function runs through the chromosome and generates a random number at each of the bits. The random number is compared to the probability of the switch occurring. This probability is usually set very small and must be less than 0.5 (Luke, 2010).

6.3.4 Mutation

Mutation was done using the Bit-flip method. Similar to the Uniform crossover, the Bit-flip mutation method moves along the chromosome and generates a random number at each bit which is compared to the mutation probability. This method is discussed in more detail in section 6.1.5.

6.3.5 Offspring Fitness Evaluation and Replacement

The offspring created by crossover and after mutation were evaluated to establish their fitness levels. The same evaluation was done that was used to evaluate the fitness of the individuals in the population. Offspring then replaced the weakest solutions in the population that has the same cost as the offspring. This is a slightly different method than is normally used, and is only possible because the lights (and the cost) increase in discrete or whole numbers.

Replacement only takes place if the offspring are indeed fitter than the weakest individuals in the population. If the offspring are not fitter, they are discarded and a new iteration is started. Three approaches were taken, depending on the number of solutions that have the same number of lights as the offspring:

- ❖ If no solutions exists with the same number of lights as the offspring:
    - The most solutions that have the same amount of lights was found
    - The offspring was compared to the weakest of the above mentioned group of solutions
    - If the offspring was fitter than the weakest of the group it was replaced in the place of the weakest
- ❖ If only one solution exists with the same number of lights as the offspring:
    - The offspring is compared to that solution
    - If the offspring is fitter than that solution it is replaced in the place of that solution
- ❖ If more than one solutions exist with the same number of lights as the offspring:
    - The offspring is compared to the weakest of the group with the same number of lights
    - If the offspring is fitter that the weakest of the group it is replaced in the place of the weakest

6.3.6 Optimisation

The goal of the LDGA is to find possible solutions for the number and layout of lights in a facility. The solution must minimise the number of lights installed in order to minimise the installation cost as well as the overall maintenance and energy costs, and the lighting level must be kept as close to the required level as possible. The population, after the creation and replacement of the offspring, was evaluated on these criteria to determine the fittest individual in the population. This evaluation was repeated after each of the iterations to determine whether the fitness of the fittest individual was improved through the iteration.

Since the fitness of an individual is dependent on two factors, i.e. the amount of unnecessary lighting and the number of lights, the problem has two objectives. An optimal solution must have a minimum number of lights as well as the least amount of unnecessary lighting. Therefore, Pareto Optimality and Trade-Off curves were used to find the best feasible solutions.

A Pareto optimal is defined as the solution (defined as A) to a multi-objective problem, if no other feasible solution is at least as good as A with regards to every objective and better than A with regards to at least one objective (Winston, 2004). The trade-off curve is the curve formed by plotting the best feasible solutions to the multi-objective problem (Winston, 2004).

For the LDGA, the Pareto optimal will be found using trade-off curves. The trade-off curves will be constructed using the number of lights installed for each individual as one axis and the maximum amount of unnecessary lighting identified from all the floor blocks as the second axis.

6.4 Testing of LDGA

The genetic algorithm was first tested with a constant required lighting level throughout the whole area. A second test was conducted with variable lighting requirements over the area.

6.4.1 Testing of Combinations of Population Size and Number of Iterations

In order to evaluate the effectiveness of the LDGA at designing lighting, an evaluation of the LDGA was done. The LDGA was tested using the dimensions of the facility where the case study was conducted. The test was conducted using three lamps of different intensities, i.e. low, medium and high.

150lux was used as the required lighting level during the testing process. This value was derived from the South African National Standards (SANS) and Interior lighting standards. It was possible to work with such a low required lighting level, because the facility makes use of task lighting to increase the lighting levels where needed. The low lumen light sources were estimated at 450 lm and the medium and high lumen light sources were estimated at 1100 lm and 2600 lm, respectively.

The population size generated by the LDGA and the number of iterations run by the LDGA were set at different values for the tests in order to evaluate the relationship between those two variables in the LDGA. The population size values varied between 100, 250, 500 and 700 possible solutions. The number of iterations run by the LDGA varied between 100, 300, 500 and 700.

6.4.2 Discussion of Results of Constant Lighting Requirement Test

The test of the LDGA was conducted with 21 variations of population size, iterations and lumens of lights, as seen in Table 20. The near optimal solutions for each variation are also included in Table 20. The number of lights prescribed by the near optimal solution and the fitness of the solutions are shown.

For each of the tests, a Pareto front was constructed to show all the solutions generated during the test. The better solutions lie on the left of the graphed solution populations and is called the Pareto front, as shown in Figure 44. The near optimal solutions were then identified from the Pareto fronts. Only some of the Pareto fronts are included in this chapter. An evaluation of the results in Table 20 revealed that the lumens of the lights being used in the LDGA impacts directly on the fitness of the near optimal solution. An increase in the lumen of the lights leads to a decrease in the number of lights required in order to meet the lighting requirements. High lumen lights are therefore the better option to install at this facility because of the reduction in number of lights and unnecessary lighting.

Table 20 - Testing combinations and near optimal solutions

Combination reference (counter)(light intensity)	Population size	Number of iterations	Near optimal Solutions: Number of lights	Fitness [lux]
BL	100	100	254	843355
BM	100	100	89	703280
BH	100	100	33	611909
CL	250	100	253	831678
CM	250	100	89	714198
CH	250	100	32	579728
DL	500	100	246	802848
DM	500	100	87	689476
DH	500	100	26	439795
EL	700	100	248	826004
EM	700	100	88	667502
EH	700	100	27	504083
FL	500	300	243	821137
FM	500	300	90	711763
FH	500	300	29	532170
GL	500	500	247	810268
GM	500	500	93	731924
GH	500	500	30	515419
HL	500	700	246	811449
HM	500	700	88	707691
HH	500	700	28	465306

A further evaluation was done on the results of the tests to compare the impact of the population size and the number of iterations that was run. Since the best near optimal solutions were obtained during the test run with the high lumen lights, the evaluation was done only on the results of those tests. Table 21 shows the results from the test run with the high lumen lights.

The green row indicates the best near optimal solution that was generated. The results in Table 21 show that increasing the population size improves the fitness and number of lights of the solutions more than increasing the number of iterations.

Table 21 - Table of test results for high lumen lights

Combination reference (counter)(light intensity)			**Near optimal Solutions:**	
	Population size	**Number of iterations**	**Number of lights**	**Fitness [lux]**
BH	100	100	33	611909
CH	250	100	32	579728
DH	500	100	26	439795
EH	700	100	27	504083
FH	500	300	29	532170
GH	500	500	30	515419
HH	500	700	28	465306

In some cases the Pareto fronts revealed solutions worthy of further investigation. These cases were examined further by constructing diagrams of the ceiling and floor that indicate the lighting patterns on the ceiling and the light effect of the patterns, respectively. Three types of cases were observed during the testing procedure:

- Outlier solutions
- Two near optimal solutions with the same number of lights but different fitness values
- Two near optimal solutions with a trade-off between their number of lights and fitness values

6.4.2.1 Outlier Solutions

It is interesting to observe the layout of the light on the ceiling for an outlier solution since the solution has a significantly larger number of lights, but the fitness is equal to solutions containing fewer lights. Two tests were found with outlying solutions, namely the BH and GH tests. The Pareto fronts of these two tests are shown and the light layout and light effect diagrams were drawn up and included as well. The outlying solution can be identified clearly (Figure 44) at 89 lights and a fitness of 1102505 lux.

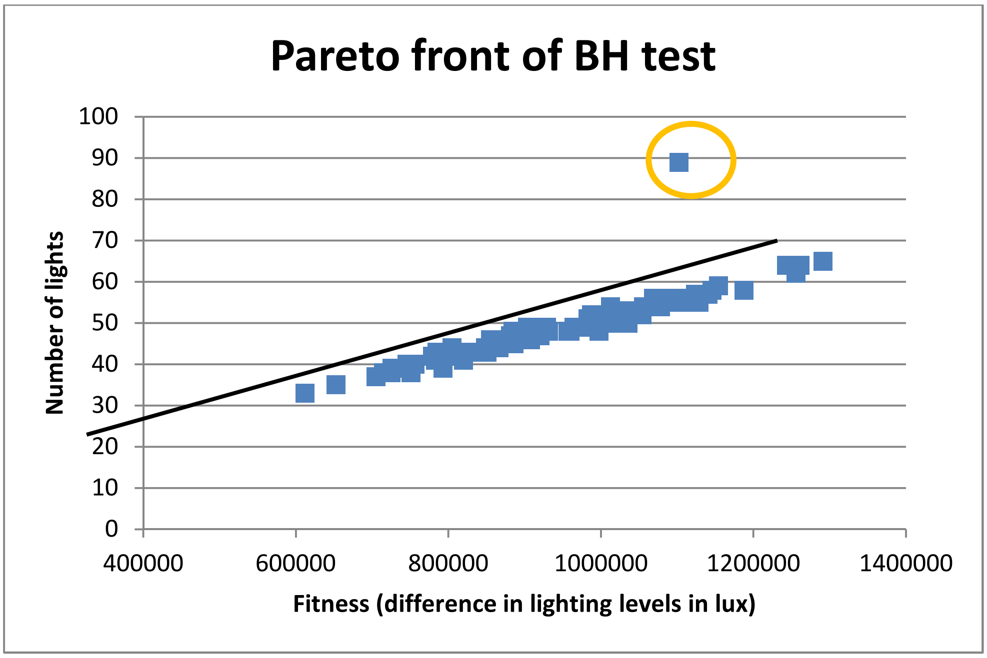


Figure 44 - Pareto front of BH test

The light layout and light effect diagrams in Figure 46 and Figure 45, respectively, indicate that the lighting layout is quite proportionate and therefore the light effect on the floor does not show very high lighting levels. The avoidance of high lighting effects, due to the close clustering of lights, on the floor decreases the total amount of unnecessary lighting and thus improves the fitness of the solution.

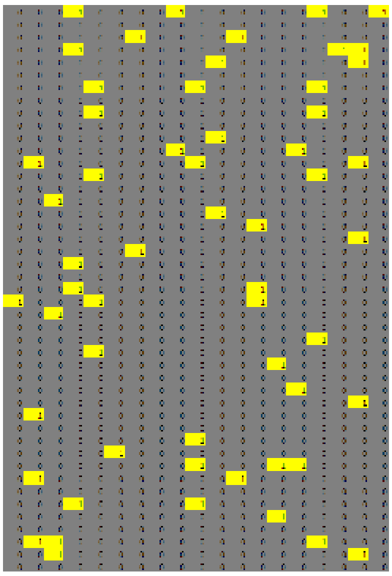


Figure 46 - Light layout diagram of outlying solution in BH test

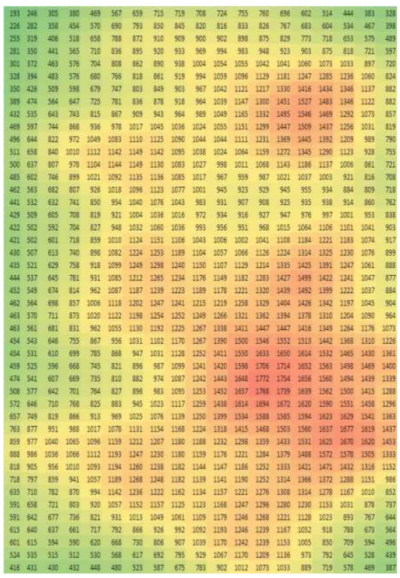


Figure 45 – Diagram of effect light pattern of outlying BH solution has on floor

A second outlying solution was found in the Pareto front of the GH test. This solution has 70 lights and a fitness of 850906 lux, compared to the approximate 45 lights of the other solutions around the same 85000 lux mark.

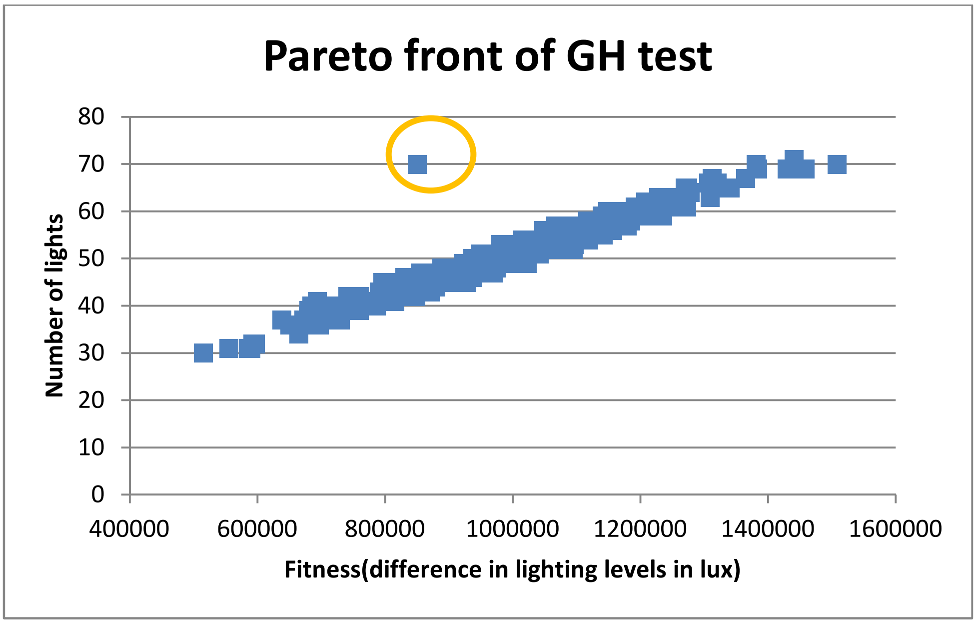


Figure 47 - Pareto front of GH test

The light layout diagram and light effect diagram shown in Figure 49 and Figure 48, respectively, show a similar proportionate design as the BH test's outlying solution. Once again, no significant clustering of the lights is visible. As mentioned before, the even scattering of the lights reduce the difference between the actual and required lux levels.

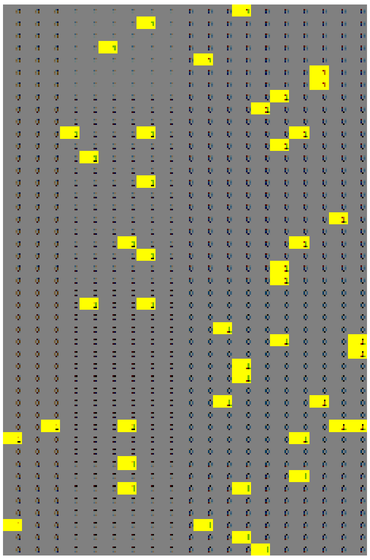


Figure 49 - Light layout diagram of outlying solution in GH test

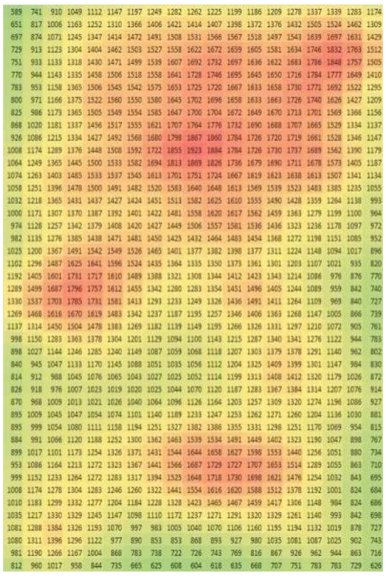


Figure 48 - Diagram of effect light pattern of outlying GH solution has on floor

6.4.2.2 Two near optimal solutions with the same number of lights but different fitness's

The second type of case that was observed in a Pareto front was two near optimal solutions with the same number of lights but different fitness's. It was observed in the CH test's Pareto front. For this case the solution with the best fitness was selected as the near optimal solution ahead of the other solution due to the objective to minimise the amount of unnecessary lighting. The light layout and light effect diagrams for both the solutions were constructed to facilitate a comparison between the two solutions.

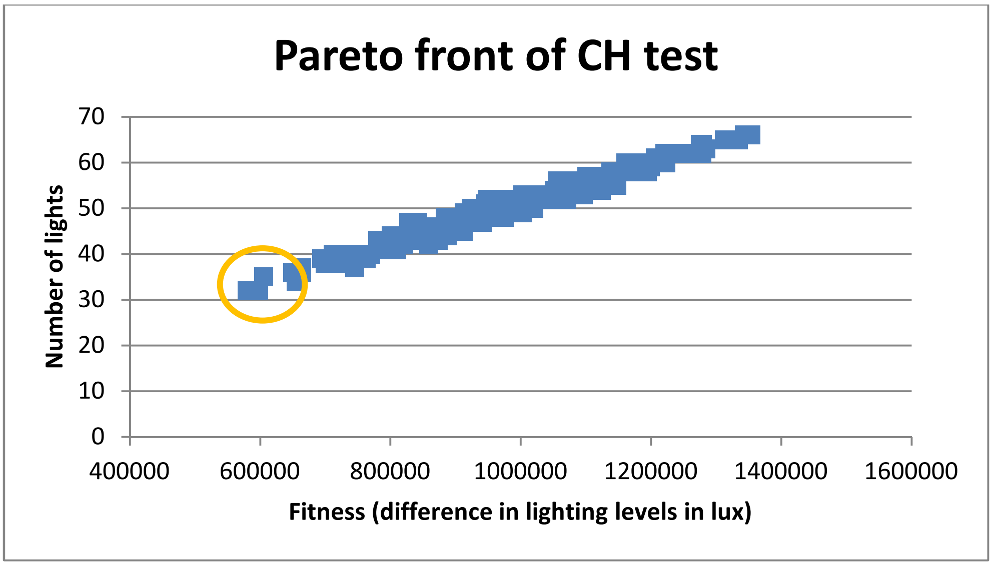


Figure 50 - Pareto front of CH test

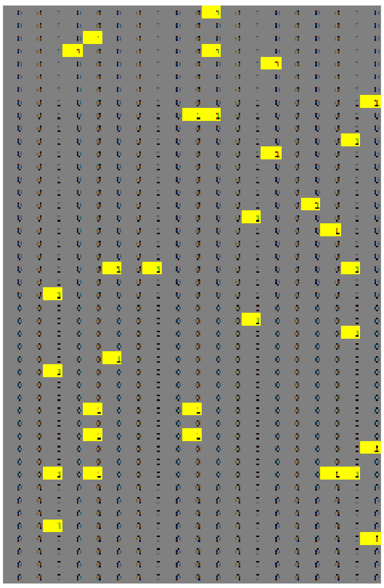


Figure 52 - Light layout diagram of fittest solution in CH test

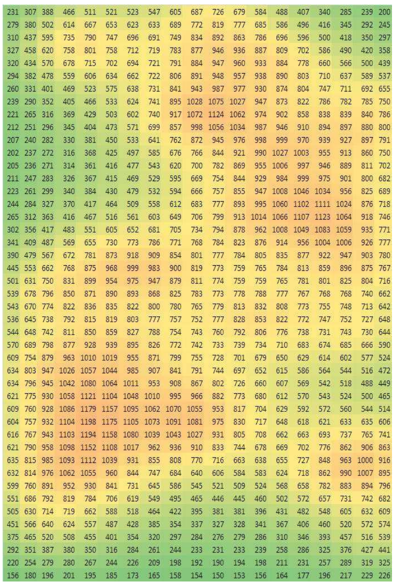


Figure 51 - Diagram of effect light pattern of fittest CH solution has on floor

By comparing the light effect diagrams in Figure 51 and Figure 54, a similar pattern is observed. The similarity in the number of lights and the pattern of the lights makes it more difficult to make a decision as to which lighting pattern is the fittest. Therefore, it is better to base the decision on the number of lights. The number and type of lights relate directly to the cost incurred by the installation and usage of the lighting system.

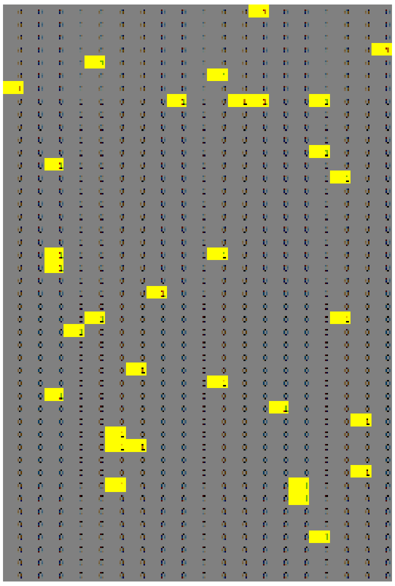


Figure 53 – Light layout diagram of solution in CH test with the same number of lights as the fittest solution

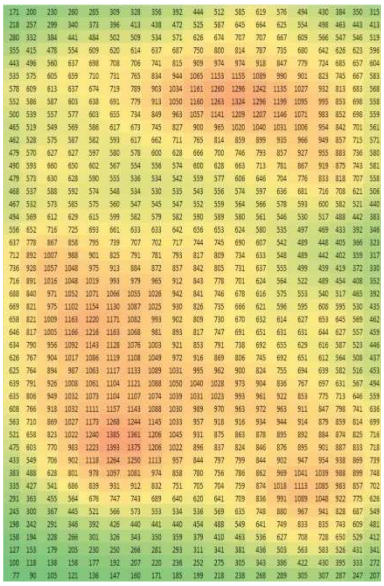


Figure 54 - Diagram of effect light pattern of CH solution with same number of lights as the fittest solution has on floor

6.4.2.3 Two Near Optimal Solutions with a Trade-Off Between Their Number of Lights and Fitness

The last type of case found in some tests' Pareto fronts were two near optimal solutions where one solution has fewer lights, but the other solution has a better fitness. In these cases the final decision between the two solutions was made based on the number of lights. The number of lights was given preference due to its direct relationship to the cost of the lighting system. To a certain extent, the increased light effect can be accepted due to the reduction in cost caused by the reduction in number of lights. This case was observed in three tests, namely EL, FL and FM.

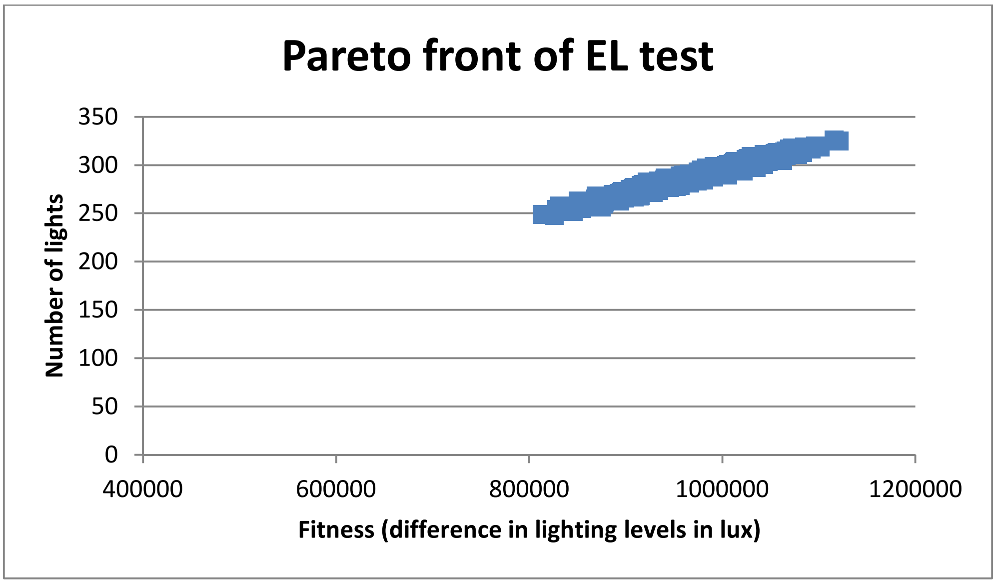


Figure 55 - Pareto front of EL test

The EL test's Pareto front shows that two near optimal solutions were generated. Comparing the two results show an interesting set of results. The one solution has a fitness of 813087 lux and uses 249 lights in the lighting design. The other solution has a fitness of 826004 lux and uses 248 lights in the lighting design.

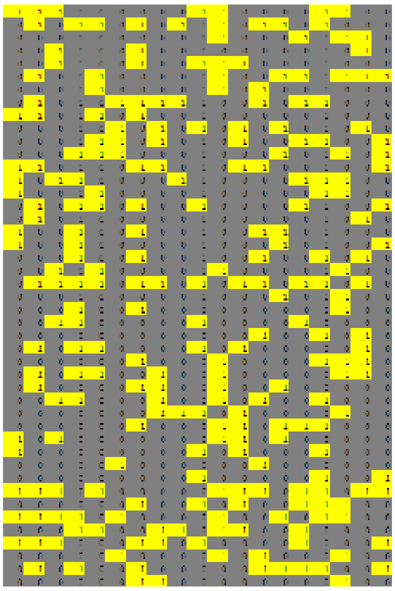


Figure 56 - Light layout diagram of fittest solution in EL test

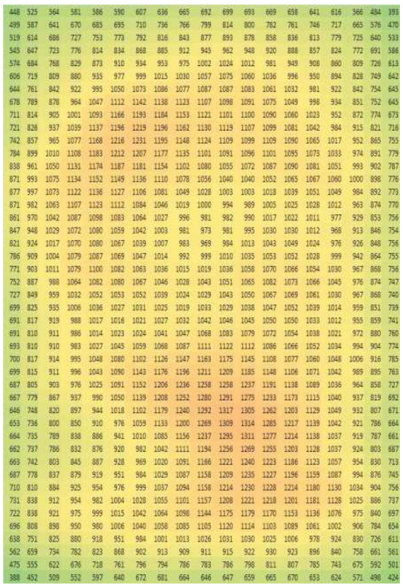


Figure 57 - Diagram of effect light pattern of fittest EL solution has on floor

A possible explanation for this occurrence is the specific patterns for each of the solutions. If a pattern groups a number of lights close together, it will result in a large increase in the effect these lights have together. The placement of lights close to the edge of the area can reduce the effect these lights have, since their effects are not combined with other lights.

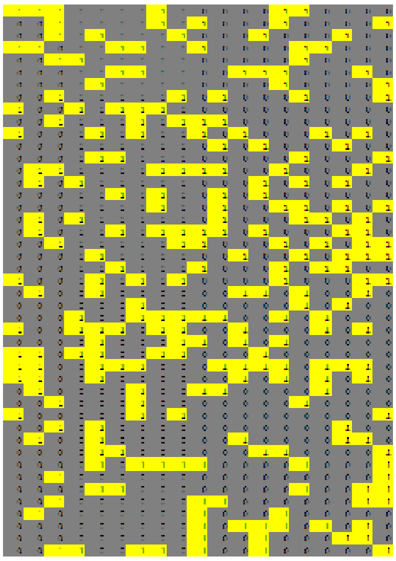


Figure 59 - Light layout diagram of alternate fittest solution in EL test

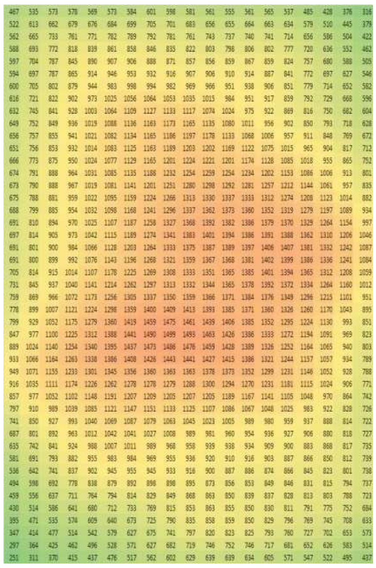


Figure 58 - Diagram of effect light pattern of alternate fittest EL solution has on floor

The FL test results are very similar to the results of the EL test. Again two near optimal solutions were generated. The first solution has a fitness of 821137 lux and uses 243 lights in the lighting design. The second solution has a fitness of 817638 lux and uses 245 lights in the lighting design. The same decision was made as with the EL test, i.e. to choose the solution with the lowest number of lights due to the immediate reduction in cost. It is difficult to interpret the actual lighting pattern because of the large area. The decisions are thus made based on the number of lights and the lighting effect of the solutions.

The FM test also generated two near optimal solutions. The first solution has a fitness of 711763 lux and uses 90 lights, while the second solution has a fitness of 704687 lux and uses 92 lights. Once again the number of lights contradicts the fitness of the solutions. The same decision making approach was taken and the solution with the least number of lights was selected as the better solution.

6.4.2.4 Conclusion to constant lighting requirement testing

The results of this test show that higher intensity lighting results in fewer lights are required to meet the lighting requirement. It was also found that the population size used in the algorithm has a larger impact on the resulting solutions than the number of iterations run.

From the results gathered through this test it is interesting to notice that the areas close to the edge have the least amount of unnecessary lighting, shown by the green areas on the lighting effect diagrams. This finding is due to the fact that the areas closer to the edges have less ceiling block where lights can possibly be placed. Therefore, the light effect on those areas is less since fewer lights impact on them.

6.4.3 Testing of LDGA with Variable Lighting Requirements

The second test done on the LDGA was based on variable lighting requirements. In many facilities the same level of lighting is not required throughout the whole facility, since different tasks are completed in different areas of the facility. Varying the required lighting level in a facility is a way to reduce the amount of unnecessary lighting installed at the facility. A test was therefore done to evaluate the applicability of the genetic algorithm to design a lighting system for variable lighting requirement levels.

The tests were done by running the LDGA with specific variable lighting requirement level patterns. The Population size and the number of iterations were kept constant. A smaller area was used for these tests to ease the interpretation of the resulting lighting patterns and lighting effects. Each variable lighting requirement level pattern was tested with high intensity lamps (2600 lumens) and low intensity lamps (450 lumens).

The variable lighting requirement level patterns comprised of different lighting requirement levels, namely a high lighting requirement of 500 lux for detailed work, a medium lighting requirement of 300 lux for relatively detailed work and a low lighting requirement of 150 for general activities. The three variable lighting requirement test patterns are shown in Figure 60Figure 61 and Figure 62.

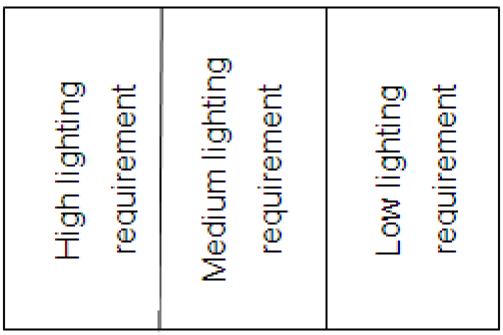


Figure 60 - Variable lighting requirement test pattern 1

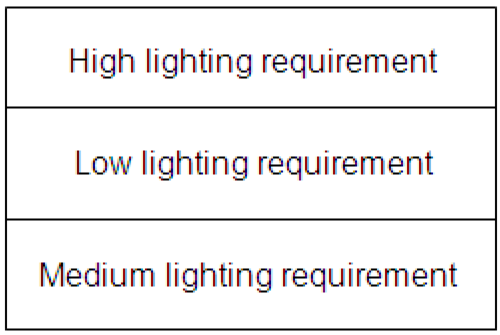


Figure 61 - Variable lighting requirement test pattern 2

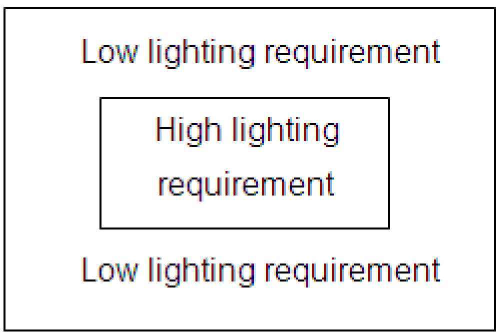


Figure 62 - Variable lighting requirement test pattern 3

6.4.3.1 Results of Variable Lighting Requirements Test

The results of the tests that were run with the variable lighting requirements are shown in Table 22. The “Var1” tests were done on the pattern shown in Figure 60 with the “L” referring to the lower lighting intensity lamps and the “H” referring to the high lighting intensity lamps. The pattern shown in Figure 61was tested with the “Var2” tests with both the low and high intensity lamps. The “Var3” tests were done on the pattern shown in Figure 62.

Table 22 – Summary of Variable Lighting Requirements Tests results

Test run	Fitness [lux]	Number of lights
Var1L	439362	192
Var1H	251537	23
Var2L	464528	201
Var2H	280540	25
Var3L	330000	146
Var3H	208093	18

A comparison can be made from Table 22 between the high and low intensity lamps tested on each required lighting pattern. The high light intensity lamps, similar to the constant required lighting test results, deliver the fitter results. The results in Table 22 cannot truly be compared with one another since the tests were done on different variable requirement lighting patterns. The better option is to compare the light effect diagrams.

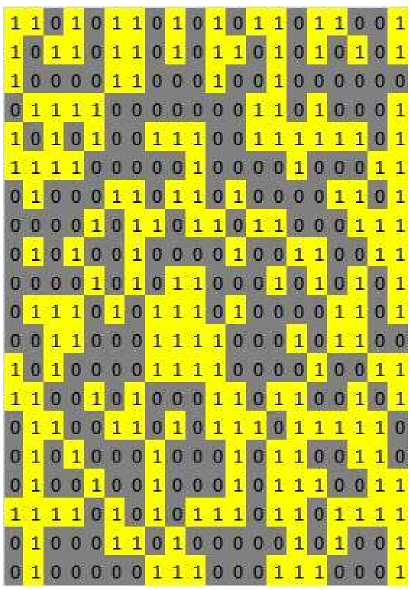


Figure 64 - Light layout diagram of Var1L test

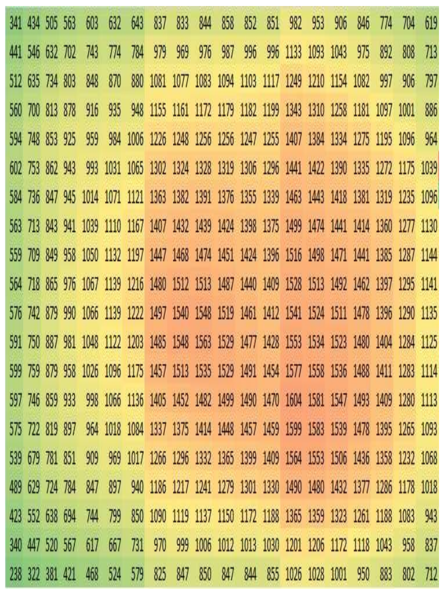


Figure 63 - Light effect diagram of Var1L test

The diagrams for the lighting pattern on the ceiling and the light effect on the ground for the Var1L test is shown in Figure 63 and Figure 64, respectively. The light effect diagram shows a large amount of unnecessary lighting at the area in the facility that has the lower required lighting level.

0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 66 - Light layout diagram for Var1H test

228	251	196	111	47	16	18	238	269	310	349	392	444	657	718	737	690	610	522	436
250	269	208	127	77	53	67	302	360	415	464	508	565	781	831	839	796	721	639	540
197	204	167	119	84	80	106	365	448	523	579	628	686	895	928	920	879	831	759	648
109	125	116	92	82	91	132	404	503	596	657	716	781	976	990	967	935	910	860	739
41	70	75	75	82	102	147	416	506	597	668	741	801	983	981	956	945	942	905	789
10	41	60	73	84	110	149	404	475	551	625	690	742	916	912	904	907	922	894	786
10	47	76	95	109	128	153	395	448	500	561	614	660	831	835	845	860	869	846	755
35	82	119	143	153	157	173	399	433	476	519	563	598	770	789	804	822	832	803	728
79	153	199	220	213	206	211	417	439	473	509	546	577	753	779	798	823	837	816	744
139	237	306	322	301	277	259	458	472	496	533	571	606	787	810	834	868	892	879	799
196	318	406	426	397	359	328	514	518	545	589	636	681	863	884	908	936	962	956	869
235	369	477	518	502	456	412	583	585	614	670	742	809	993	1008	1011	1017	1021	1003	917
266	410	540	616	614	569	513	664	653	692	773	880	974	1173	1178	1152	1111	1067	1015	918
299	453	600	701	723	683	605	735	717	761	867	1011	1145	1364	1368	1321	1220	1104	994	871
338	496	640	744	785	751	662	783	762	810	929	1100	1262	1511	1535	1465	1313	1125	954	800
371	532	658	749	786	746	661	788	772	827	948	1116	1283	1553	1589	1511	1334	1109	903	727
379	536	644	711	727	680	605	748	752	817	927	1058	1192	1448	1488	1414	1246	1037	825	649
340	486	582	625	619	570	513	683	707	777	873	954	1026	1238	1254	1191	1063	892	715	564
273	406	494	514	492	441	404	595	633	703	777	816	836	997	985	939	846	720	592	476
190	311	388	397	359	317	292	494	530	584	636	650	645	782	760	716	649	564	476	394

Figure 65 - Light effect diagram for Var1H test

Figure 66 shows the light layout for the fittest solution generated in the Var1H test. Figure 65 shows the light effect diagram for the same test. A similar effect is seen with respect to the unnecessary lighting as with the Var1L test in Figure 63.However, the amount of unnecessary lighting looks to be less. This is observed from the reduced red areas on the light effect diagram for the Var1H test.

The reduced number of lights and unnecessary lighting observed in the Var1H test results, compared to the Var1L test, shows that for this required lighting pattern the better results are obtained with higher lighting intensity lamps.

The light layout for the Var2L test is shown in Figure 68. The light effect for the Var2L test is shown in Figure 67. Figure 70 and Figure 69 show the light layout and light effect of the Var2H test, respectively. As seen with the “Var1” tests, the low required lighting areas result in large amounts of unnecessary lighting.

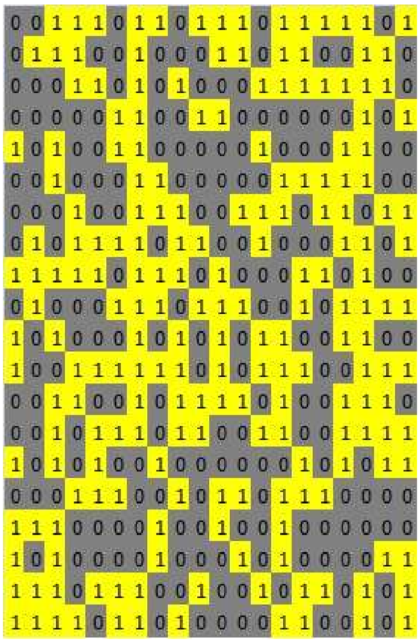


Figure 68 - Light layout diagram for Var2L test

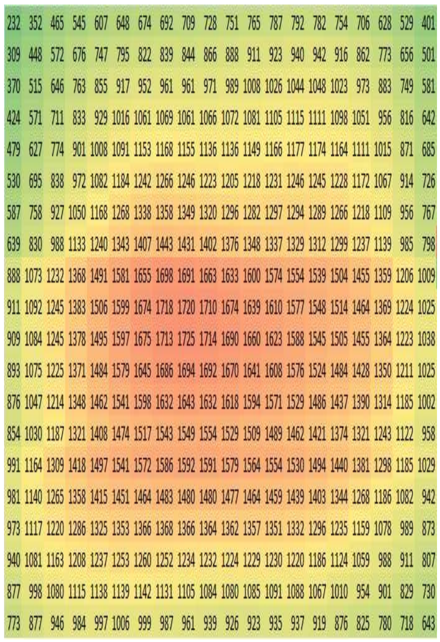


Figure 67 - Light effect diagram for Var2L test

Comparing the Var2L test results with those of the Var2H test, a similar deduction can be made with the “Var1” tests. The higher lighting intensity lamps give a better result using fewer lights. This can be observed from the darker red areas shown in the Var2L test result diagram, in comparison with the slightly lighter red areas in the Var2H test result diagram.

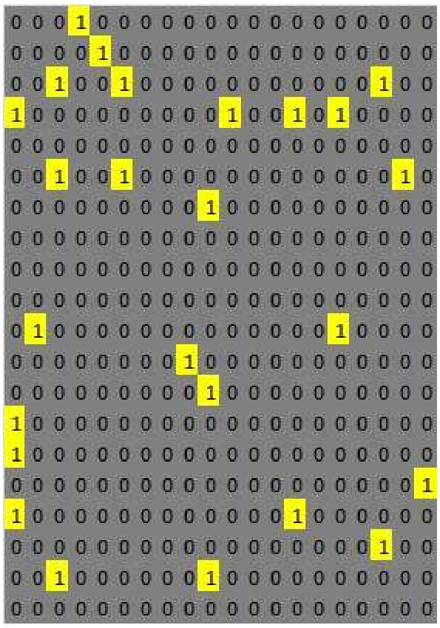


Figure 70 - Light layout diagram for Var2H test

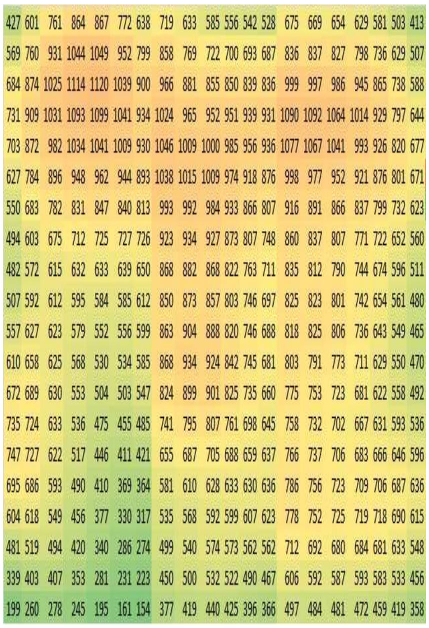


Figure 69 - Light effect diagram for Var2H test

The Light layout diagram for the Var3L test is shown in Figure 72 and the light effect diagram is shown in Figure 71. Figure 74 illustrates the light layout diagram of the Var3H test and Figure 73 illustrates the light effect diagram.

1	1	1	0	1	1	1	0	0	1	1	0	0	1	0	1	1	0	1	0
1	0	0	0	1	1	0	0	1	0	0	1	1	0	0	0	1	0	0	0
0	0	1	0	0	0	0	0	1	0	0	0	1	0	1	0	0	1	0	1
1	1	1	0	0	1	1	0	1	1	0	0	0	1	0	0	0	0	1	1
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1
1	1	0	0	1	0	1	0	1	1	1	1	0	1	0	0	0	0	0	1
1	1	1	1	0	1	0	0	1	0	0	0	0	1	0	0	1	0	1	1
0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	0	1	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	1	0	1	0	0	0	0	1	1	0	1	0	0	0	0	0
0	1	1	0	0	1	1	0	1	1	0	0	1	0	0	0	0	1	0	1
0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	1	0	0	0
0	0	0	1	0	1	0	0	1	1	1	1	0	0	0	0	1	1	0	0
1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0
1	1	0	1	1	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0
0	0	1	1	1	0	0	1	0	1	1	0	0	0	0	1	0	0	0	1
0	0	1	0	0	1	0	1	0	1	0	0	1	0	1	0	0	1	0	0
1	0	1	1	1	0	1	0	1	1	1	0	0	1	1	0	1	1	0	1
0	1	0	0	1	0	1	1	1	0	0	1	1	0	1	0	0	0	1	0

Figure 72 - Light layout diagram for Var3L test

535	607	664	698	729	743	743	737	734	732	725	715	707	687	670	650	619	574	510	434
605	694	751	791	820	839	837	836	832	838	821	811	804	787	767	740	706	665	593	504
659	758	819	854	879	895	899	900	903	898	894	887	874	857	829	801	770	731	667	572
703	807	867	902	916	927	937	949	954	952	935	928	922	902	874	849	818	772	714	622
730	835	903	927	945	955	966	975	983	980	968	964	959	939	913	879	844	802	743	652
753	866	930	962	974	633	638	651	661	671	666	651	642	628	593	902	863	819	754	662
773	885	959	998	1016	669	679	690	695	705	701	689	678	652	616	923	882	833	764	671
758	886	968	1025	1049	701	700	709	708	722	726	709	687	671	631	944	900	842	764	663
739	856	949	1018	1057	719	714	713	728	729	732	724	702	676	643	948	894	829	744	641
703	825	927	1011	1062	731	733	748	745	761	763	752	730	694	644	946	883	809	720	619
679	803	921	1003	1069	750	771	779	797	808	807	787	764	716	656	945	877	802	704	599
675	797	904	1003	1066	769	800	823	848	855	850	835	785	738	669	957	886	797	697	590
686	797	908	997	1076	779	822	859	884	900	897	860	807	739	680	970	888	794	692	578
692	811	916	1004	1081	801	833	881	905	920	900	857	805	733	673	963	881	780	669	562
705	823	938	1027	1101	810	856	882	905	910	889	841	783	722	660	944	864	757	655	548
708	842	957	1054	1117	1164	1204	1236	1242	1247	1218	1167	1111	1056	984	914	836	742	640	536
697	826	950	1037	1107	1151	1179	1206	1216	1206	1181	1130	1076	1018	961	887	808	727	632	535
658	787	901	993	1051	1093	1125	1151	1157	1148	1116	1070	1024	975	918	859	789	704	612	516
596	718	821	901	962	1004	1035	1060	1066	1053	1021	986	948	906	849	793	728	653	576	487
519	623	707	780	831	874	904	924	928	917	894	861	827	792	746	689	638	577	509	431

Figure 71 - Light affect diagram for Var3L test

As seen with the previous test results, the lower required lighting areas show higher amounts of unnecessary lighting than the higher required lighting areas. The "Var3" test show a smaller variance between the amount of unnecessary lighting in the high lighting intensity lamps and the low lighting intensity lamps, but the higher lighting intensity lamps deliver a light effect that is closer to the required lighting.

0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 74 - Light layout diagram for Var3H test

64	85	105	132	166	210	261	332	411	488	538	539	484	410	347	314	301	301	286	249
85	107	133	162	198	251	312	395	490	568	595	579	516	443	388	363	363	375	369	317
111	137	161	194	234	286	355	441	537	605	614	576	513	456	411	399	408	425	424	364
143	168	197	230	273	325	393	470	546	596	590	553	507	464	436	422	429	437	423	365
177	206	238	270	316	371	434	494	547	570	563	538	510	485	468	454	443	432	398	342
229	259	286	321	366	75	140	192	220	220	210	195	183	176	168	504	476	435	386	328
296	323	348	378	420	132	204	257	266	247	232	228	233	248	253	586	539	470	400	331
379	407	420	437	473	183	254	304	301	278	265	278	310	347	369	699	624	524	423	340
475	504	500	504	524	216	271	308	309	300	303	344	403	467	495	809	708	577	454	361
552	583	575	567	570	239	268	289	298	308	339	407	501	584	599	887	757	612	482	380
579	632	647	640	630	276	281	288	295	318	369	458	576	670	676	930	781	630	503	402
578	664	713	715	701	333	320	311	314	334	389	482	601	694	695	941	793	646	526	424
565	679	753	780	774	408	384	355	345	360	405	492	595	669	664	923	791	666	556	459
548	663	761	814	843	497	467	421	390	388	423	500	590	648	633	902	799	696	603	510
529	643	743	827	890	567	542	489	442	422	439	503	583	634	611	894	820	750	674	581
525	637	742	839	913	950	945	906	851	810	802	842	908	949	931	884	842	808	744	652
537	649	758	855	915	959	984	969	906	837	799	819	869	903	882	847	826	814	763	672
557	660	757	841	890	936	988	998	926	829	770	768	803	830	805	769	747	730	684	605
576	653	713	770	809	855	914	936	869	771	703	686	698	711	687	649	622	595	554	489
551	603	627	651	683	723	769	782	738	665	602	578	573	569	550	518	490	461	423	374

Figure 73 - Light effect diagram for Var3H test

6.4.3.2 *Interpretation of the Variable Required Lighting Test Results*

In all of the tests run for the variable required lighting tests, the same observations can be made. The higher lighting intensity lamps deliver the fitter solutions using fewer lights and the unnecessary lighting is mostly encountered in the areas with the lower required lighting.

The pattern of unnecessary lighting does not conform completely to the variable required lighting patterns as would be expected. In both the high as well as low required lighting areas, a variable amount of unnecessary lighting can be observed. This leads to the conclusion that the LDGA could recognise the patterns, but requires more optimisation to adhere more effectively to the patterns.

6.5 Interpretation of LDGA testing results

Two main observations were made during the testing of the LDGA. Firstly, it is the importance of the pattern of the lights as shown by the outliers in the results. These cases showed that it is important to disperse the lights sufficiently in order to avoid unnecessary spikes in the lux levels.

The second observation was the impact the luminance of the lights has on the design solutions. In both the constant and varying lighting requirement tests the higher luminance lights resulted in more optimal design solutions. The higher luminance lights result in fewer lights necessary to meet the required lighting level, but it also increases the fluctuation between the required lux levels and the actual lux levels. This unnecessary lighting then leads to increased energy usage costs which are unwanted.

Other programs exist for the manual design of lighting systems e.g. DAILux (*Lighting simulation software: Calculux and DIALux - philips*), RADIANCE (Ward, 1994) and Visual (*Visual*). These programs simulate the lighting effect obtained from a manually designed lighting system that is put in by the user. The study aimed to determine whether an optimal lighting design could be generated using a basic evolutionary algorithm.

Some success was achieved with meeting the required lighting levels of the optimisation problem, but irregular light installation patterns cause unnecessary high lighting at certain areas. With further specifications and restrictions given as input to the LDGA, more optimal light installation patterns could be generated.

The final conclusion can therefore be made that GAs can play a part in the optimisation of lighting designs, but that the Gas should be paired with additional rules and even other generative algorithms in order to obtain the best optimal results.

7. Conclusion

7.1 Introduction

Due to the constant increasing energy costs in South Africa, it is imperative to consume energy efficiently and to find new approaches to increasing the energy efficiency of facilities. This study viewed energy efficiency and energy conservation measures from an IE perspective and attempted to identify IE methods that can potentially be applied to assist existing energy conservation measures.

7.2 Methodology

- Research was done on EMPs, energy audits and current energy conservation measures to gather information on the methods employed during EMPs and energy audits.
- IE methods were researched and possible applications in ECMs were identified.
- IE and energy efficiency corpora were analysed using the CAT program to identify correlations between the two fields.
- A case study was completed at a facility where an energy audit was done and applicable energy conservation methods from the research were proposed for implementation.
- A Genetic Algorithm was written to find near optimal solutions to lighting design problems and prove the importance of optimisation for increasing energy efficiency.

7.3 Results

Possible applications for the IE methods in energy management and ECMs were identified. These possible applications can assist Industrial Engineers in facility management positions with energy managing at facilities. A specific IE method can be utilised for more than one ECM and therefore impact on the energy consumption at several areas in a facility, as shown in Figure 6. The applicability of the IE method depends on the type of facility that it is applied at. Each facility has a unique breakdown of energy consumption. The application of ECMs and IE methods will thus have to be adjusted to suite each specific facility. The results obtained will vary according to type of ECM and IE method applied and the impact that specific energy usage area has on the total energy usage.

The results of the case study are positive, but more improvements can be expected due to the fact that a number of the proposed energy conservation measures could not be implemented during the course of this project. A facility upgrade is planned for 2012 and the remainder of the energy conservation measures will be implemented as part of the upgrade. The evaluation of the current energy consumption compared to previous years has shown a reduction in the KVA peaks and a reduction in the daily kWh consumption. These reductions in energy consumption could, however be expanded with the implementation of the rest of the EMPs. The most significant improvement was in the daily kWh usage after hours. Successful implementation of a Shut Down Management program resulted in these improvements and highlights the importance of management in an energy conservation project.

The literature analyses that were done by using the CAT program, identified the ten most significant topics for the IE, energy efficiency and a combined corpus. The topics of the IE and energy efficiency corpora showed correlations within each corpus. Analysis of the combined corpus showed that the correlations identified were mostly within the two corpora. Some of the topics identified in this study showed a combination of IE and energy efficiency topics, but not significantly so.

The final CAT analysis that was done, was the calculation of the correlations between the IE and energy efficiency topics identified in the first two analyses. Correlations were calculated based on the word occurrences shared between topics. The results highlighted the correlation between statistical methods and different energy efficiency topics. Statistical methods play an important role in management, decision making and optimisation calculations, thus making it a vital tool in both the IE and energy efficiency fields.

The Lighting Design Genetic Algorithm was able to generate plausible lighting designs. The GA was expanded to incorporate the possibility of variable required lighting levels in an area. The results obtained from the tests of the GA on constant required lighting levels shows plausible solutions that meet the required lighting levels, but still results in high levels of unnecessary lighting. Similarly, the test done on variable required lighting levels also show unnecessary lighting and an inability for the GA to completely recognise the patterns of the variable required lighting. This indicated that the GA can be applied to design a lighting system, but that it requires further improvement and possible combination with other optimisation algorithms or tools.

A final summary of the results obtained through this study, shows that management, statistical methods and optimisation methods or algorithms can be successfully applied to improve energy efficiency. Other IE methods may also be applicable, but their successfulness must be proven practically.

7.4 Recommendations

There is an opportunity for elaborating on the relationship between Industrial Engineering methods and energy conservation measures in order to assist Industrial Engineers with the management of energy consumption. Using the CAT software, many possible IE methods of fields were identified that showed correlations with energy efficiency fields. Since many of these correlations have not been proven practically, an opportunity exists for further studies to be executed to prove these correlations practically in different situations and facilities.

As previously stated, the company where the case study was completed planned an upgrade of the facility in 2012, which includes a number of the proposed ECMs. Up to date, the upgrade has not been completed and the results from the implementations of all the proposed ECMs could not be included in this report. Once the upgrade has been completed, the energy consumption should be evaluated again to ascertain the impact the upgrade had. Further studies should also be completed on the compressor's operating times to complete the energy profile of the facility. More meters should be installed at the facility to enable closer monitoring of the energy consumption specifically. The energy monitoring system must be completed to assist with the overall management of the energy consumption.

The LDGA generated plausible solutions for the lighting design of the facility's production floor, but further improvement of the algorithm would result in more optimal results. These improvements include more specifications or rules for the GA and the possible combination of the GA with other optimisation algorithms to utilise more than one optimisation approach. The program could also be expanded to incorporate the different lighting patterns of different types of lights and the effect ballasts have on the lighting patterns. A visual representation of the near optimal lighting design generated by the LDGA will further contribute to the real world application of the algorithm as well as the user-friendliness of the program.

7.5 Concluding Remarks

The goal of this study was to identify areas in energy management where IE methods are applicable. During this study it was shown that IE does have applications in energy management fields. The different methods used in this study, i.e. literature reviews, content analyses and case studies, identified different IE methods and fields applicable to different energy management fields. All of the discovered applications would not have been identified with only a single method, thus indicating the importance of combining different methods for the identification of applicable IE methods and field.

This study has shown that there are various techniques and methods used by IEs that can impact on energy management, but also that a vast amount of research can still be done since IE and energy management are both such broad fields. Since it is known that energy usage is one of the major indicators for sustainability, further research of how IEs can manage energy usage in different industries is essential.

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9. Appendix A

Figure 75 shows the original floor plan of the facility. This floor plan of the facility shows the production area with the different production lines and the office spaces surrounding the production floor. This version of the floor plan is included to show the areas where the lux values were measured for the lux value diagrams.

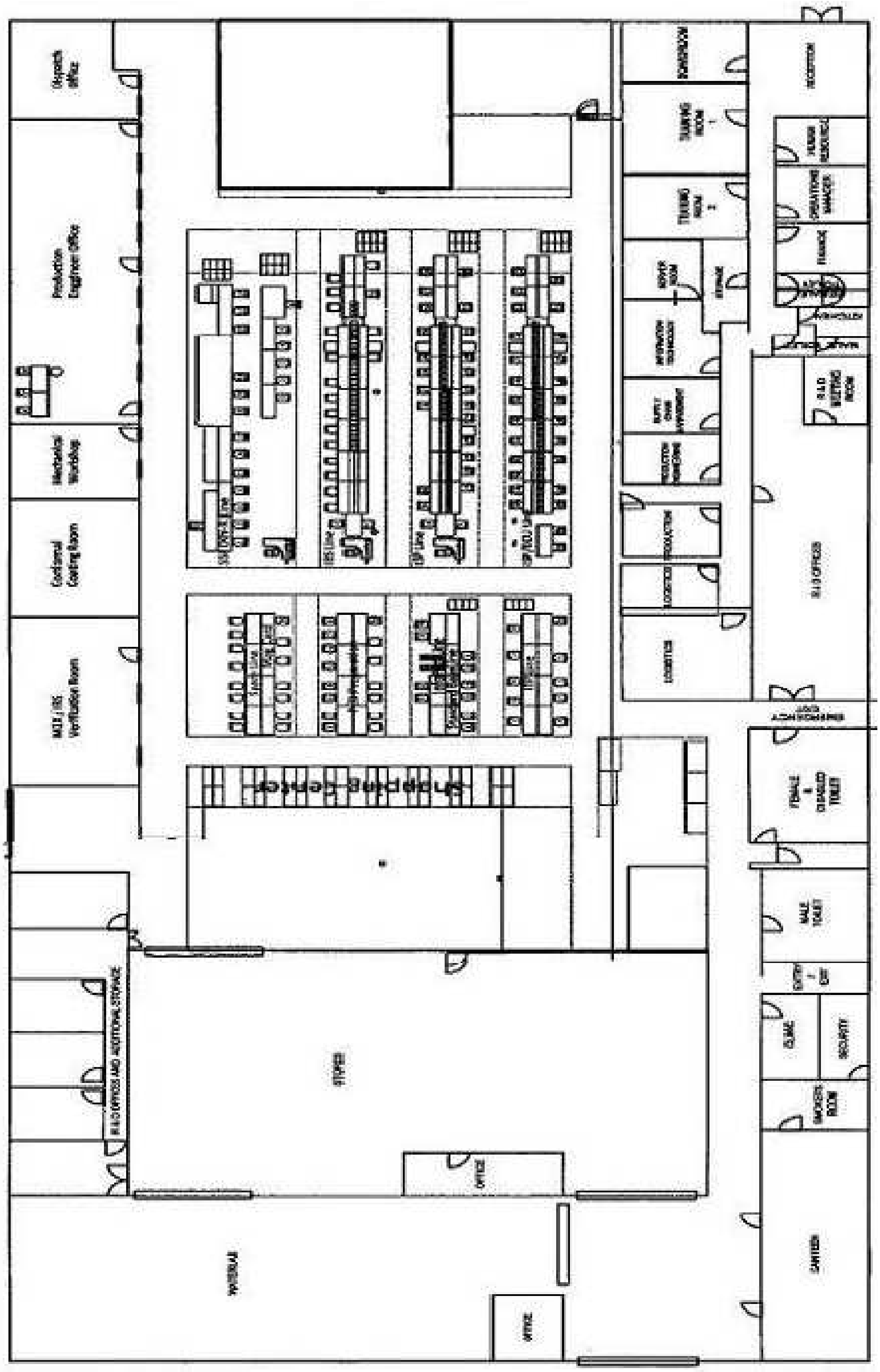

Figure 75 - Floor Plan of Facility