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Guiding Principles for Establishing Energy Consumption Reduction and Increase Production Performance in Manufacturing

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ABSTRACT

This study provides a review, framework and guiding principles for constructing energy consumption reduction disciplines, with examples of application to international industries. It reviews the work of agencies and governments in creating energy efficiency models that help policy makers to assess changes in energy efficiency. A possibility to reduce costs incurred in product manufacturing and energy consumption constitutes energy-efficient consumption at industrial enterprises. The study justifies the performance indicators of industrial enterprises' power supply systems. The estimates produced indicate that the largest portion of the potential energy savings is attributed to implementation of energy-saving projects. The study was performed at a manufacturing plant in South Africa with 489 respondents. It focused on energy usage in the manufacturing sector since this sector has always been the largest contributor to the GDP of South Africa. The results indicated that the proposed framework can not only reduce energy consumption but also increase production.

Keywords: Energy Consumption, Energy Efficiency, Framework
JEL Classifications: N77, N67, O14, P18

1. INTRODUCTION

Manufacturing companies are not only the main contributors to the South African economy, but also the main consumers of energy. South African manufacturers are experiencing multiple challenges including highly entangled and interconnected energy costs (Permin et al., 2016), mainly caused by the increase in global warming and the instability in the petroleum oil market.

The importance of oil to the world economy was highlighted as far back as 1973-1974. In this time an oil crisis hit the world when the price increased significantly. Not long after this price hike the oil suppliers introduced sanctions to several Western countries who were supporting Israel in the war against Egypt and Syria. The high dependence on oil or other fossil fuels and relating energy shortages became a worldwide concern. Vikhorev et al. (2013) reiterated the importance of industries becoming more energy efficient which will result in better competitiveness and will benefit the global environment.

Studies related to electricity usage found that implementing an energy optimisation framework is an effective tool to reduce consumption (Sobhani et al., 2014. p. 718). An energy optimisation framework is defined as a framework that identifies the highest energy consuming elements and replace it with lower energy consuming devices that deliver the same technical service to the environment (Méndez-Piñero and Colón-Vázquez, 2013. p. 149). The objective of this process is to find economic methods for the replacement of current equipment in order to reduce energy consumption. The savings collected during the lifetime of the equipment guarantee the recovery of the initial expenses. Baños et al. (2011. p. 1759) stipulated that most equipment is functional between 5 and 10 years and, therefore, recommended 2 years to realise the savings.

In the light of these energy efficiency matters the primary and secondary objectives of the study are:

- To develop and test a framework for the reduction of energy consumption in a manufacturing plant in South Africa.
- To determine the effectiveness of the framework on manufacturing performance in a South African manufacturing plant.

To fulfil the objectives of the study the following questions had to be answered:

- What effect does an energy reduction framework have on the energy consumption in a South African manufacturing plant?
- How is the production rate in the manufacturing plant effected by the implementation of an energy reduction framework?
- Which high energy consuming elements have the highest impact on the energy consumption at the manufacturing plant?

2. BACKGROUND TO ENERGY CONSUMPTION IN MANUFACTURING

Energy output in manufacturing has not kept up with the labour development and material productivity of the last 5 decades. The industrial sector consumed about 50% of the global energy during the 2010s, while this consumption almost doubled over the last 60 years (Fang et al., 2011. p. 234-240). In the United States of America, manufacturing accounts for more than 25% of the total energy usage and 28% of the CO_2 emissions. The global greenhouse gas emissions by manufacturing is approximately 19%. Energy production itself, largely contributes to the emission of CO_2 in the atmosphere

Production in emerging economies has shown a drastic increase in recent years. From 1979 to 2011, China's economy grew approximately 9.9% on average per year (National Bureau of Statistics, 2012). Simultaneously, between 1980 and 2007, China's main power usage increased by about 340% while CO_2 emissions grew by about 352% (Zhang and Cheng, 2009. p. 2706-2712). With such growth the pressure on the global resource markets is also increasing. This is specifically true for crude materials and the oil price as the main energy carrier (Brueske et al., 2012).

Crude oil, natural gas and coal form the basis of energy generation worldwide. Since these crude materials are diminishing fast, there is an increased focus on green energy like solar, wind and waste energy endeavours. Contributing to the need of alternative energy sources is the nuclear phase-out adopted by countries such as Germany and Japan. The phase-out decision followed the 2011-Fukushima disaster which moved Germany to close eight of its nuclear power stations with the goal of having all nuclear plants offline by 2022 (Appunn, 2015). Although striving to increase renewable energies to make up for the phase-out, fossil energy carriers are still essential to satisfy the needs (Putz et al., 2012. p. 482-487).

South Africa faces energy challenges similar to the rest of the world such as a stable energy supply, cleaner energy mix and better energy data-sharing. Based on these concerns, the IEA and the South African Department of Energy have been developing a close relationship, which led to the signing of a Memorandum of Understanding in July 2011. In this framework they agreed to create work plans for the identification of projects and directions for co-operation. In light of this agreement a joint Programme of Work was signed in October 2011 and renewed in October 2013 as well as in November 2015. South Africa further became an association country of the IEA in November 2018 (IEA, 2018).

3. ENERGY EFFICIENCY

Energy efficiency has grown in importance in many countries due to the shortages of energy sources, the impact of the use of fossil fuel on the environment and the need for ongoing growth (Gao et al., 2015). Energy efficiency refer to minimal energy consumption without reducing the standard of living, the production quality and profitability. Worldwide governments are implementing policies regarding energy efficiency and cleaner energy. The compiling of these policies requires accurate measuring of the efficiency in a specific region, yet there is no definitive or quantitative measurement thereof.

3.1. Energy Efficiency Indicators in Manufacturing

The energy efficiency of elements in manufacturing has been identified as a determining factor for cost reduction. Ang (2006) defined energy efficiency indicators as monetary-based, physical based and economy-wide or sectoral energy efficiency indicators. At macro-level, monetary or economic based indicators seem more suitable for energy efficiency studies. In contrast, traditional indicators such as energy intensity (energy input per GDP) consider energy as the only input to create GDP and omit other essential inputs such as capital and labour (Hu and Wang, 2006).

Seow (2011) categorised energy consumption into direct and indirect energy. The indirect energy includes the technical services not directly used by production. The direct energy refers to the energy needed for production and is subdivided into Value Added (VA) energy and Auxiliary (AU) energy. The methodology for calculating AU and VA electricity was tested on more than 20 different types of value streams (Mustafaraj et al., 2015). From these results the following steps were proposed for the calculation of AU and VA electricity:

- Selecting the assortment of the energy substance;
- Analysis of energy metres availability throughout each machine;
- Electricity usage and information assortment associated with each machine, over a pre-determined period;
- Collecting manufacturing information associated with each machine over a pre-determined period;
- Conversion of the manufacturing data with reference to a Probability Density Function. A batch manufactured by a particular machine in conjunction with the time it used to manufacture the batch should be recognisable;
- Conversion of the energy usage information with a Probability Density Function. This signified the unpredictability of energy

usage to manufacture a group of products with reference to a specific machine;

- Calculation of the total AU (kWh) and VA electricity (kWh) consumption for each machine over a pre-determined time.

3.2. Energy Efficiency Trends in the Building Industry

Assessment structures for the thorough management of building energy efficiency, have been incorporated globally. The rating system by Koo et al. (2014. p. 218-231) had two perspectives, namely the formulation of acceptable standards for the building energy efficiency rating system; and the introduction of reward and forfeit programs to stimulate the willing participation in the energy saving campaign.

Joining this worldwide campaign, the South Korean Ministry of Environment introduced a national carbon emissions reduction target (CERT). The set target is a 37% reduction in greenhouse gas emissions by 2030 and a 25.7% reduction for the domestic industry (Ministry of Environment, 2015). One policy supporting CERT, initiated in 2001 by the Ministry of Trade, Industry and Energy is an energy performance certificate (Hong et al., 2015. p. 671-707). Obtaining BEER certification, however, could incur additional construction costs (Koo et al., 2015. p. 410-425). It was, therefore, imperative to observe the possible cost reduction in implementing the BEER-certification and in defining its rank in the initial design phase.

3.2.1. The development of the BEER prediction model

One significant feature of the building sector is the high level of regulation. Building codes and policies often determine the standard of resources and products used that have an impact on energy efficiency. Addressing the EE in the sector, the BEER prediction model was developed in two major steps. The first step was the energy performance assessment of buildings with BEER certification. The second step was the estimation of the possible cost reduction for the BEER-certified buildings.

Abdelhady et al. (2016) set out to create a model to determine the potential cost saving when applying BEER certification. It involved life cycle cost analysis, real option valuation, and Monte Carlo simulation. The Monte Carlo simulation is a modelling technique for complex situations where many unplanned variables are involved, predicting the impact of risk. The calculation of potential cost saving through BEER certification include energy cost saving, lower CO_2 emission as well as extra building expenses (Abdelhady et al., 2016. p. 1-6). This model can assist investors to decide on the specific grade of BEER-certification in the early design phase (Diaz et al., 2011. p. 263-267).

The certification system further differentiates between residential and non-residential buildings. The residential buildings focus on the multi-family housing facilities. This accounts for more than 48% of the households in South Korea (Ministry of Land, Infrastructure and Transport, 2014). By investigating the BEER-certification, four areas of concern in the guidelines of standard housing, were identified, namely the heating elements, air outlets, house front and temperature distribution. The design of a residential house regulates the area exposed to the outdoors through the parameter walls and ceiling. To save energy the exposed area should be kept to a minimum. Based on these factors, a traditional multiple family housing unit, without the BEER-certification might still achieve a specific level of energy savings compared to the standard housing in BEER-certification (Majcen et al., 2013. p. 125-136).

3.2.2. BEER application in residential housing

The overall energy usage of multiple family housing complexes was computed by adding the energy used for water and space heating to the total electricity used. The equation used for the calculation was $p(t)= f(t)+X(t)$. The amount of CO_2 emissions was calculated by multiplying the amount of each energy consumption by the CO_2 conversion coefficients, using the equation $X(t)= \varphi X(t-1)+ \vartheta$.

The site EUI (kW h/m^{2}y) and CEI (kg-CO_2/m^{2}y) were calculated by dividing the total amount of energy consumption and the relevant CO_2 emissions by the total enclosed area (TEA). The TEA stands for the area excluding the mechanical facility spaces and the underground floor areas from the total gross area. The equations for these calculations were:

$$h(t)=\begin{cases}\sum_{j=1}^{D(t)} T_j^i(t)-T_j^o(t), if\ T_j^i(t)>T_j^o(t)\end{cases}$$

And

$$\pi_r(\tau)=\sum_{n=0}^{\infty}(1+i)^{-T_n}\, ce^{-\beta' T_n} 1_{\{T_n\le\tau\}} =\sum_{n=0}^{\infty} c\,((1+i)e^{\beta'})^{-T_n} 1_{\{T_n\le\tau\}}.$$

3.2.3. Comparative analysis

Comparative analysis between the non-certified and BEER-certified multiple family housing complexes was performed in order to establish the reduced energy usage through the BEER-certification application. These savings were also predicted by considering the actual saving of an end-use energy profile (Jeong et al., 2017. p. 257-270). This was used to institutionalise The Commercial Building Disclosure Program that requires most owners of office space of 1 000 m^2 or more to have a relevant BEER-certificate. This is necessary to comply with legal obligations under the Building Energy Efficiency Disclosure Act 2010.

3.2.4. Occupant influence on residential housing energy efficiency

Over and above the importance of certification and policy in ensuring the construction of energy efficient housing, the influence of occupant behaviour must be taken into account. Hu et al. (2020), in their review of occupant behavior in building energy policy, underline the fact that while occupant behavior has a significant effect on building energy policy and on the ongoing energy efficiency of structures, this has nevertheless been largely oversimplified and poorly understood. This is largely due to the diverse and complex nature of occupant behaviors, with the interdisciplinary research required forming a significant barrier to greater understanding. They propose a framework for understanding occupant behaviors, proposing a regulation, information and incentive structure for conceptualising and, in turn, influencing occupant behaviors. (Hu et al., 2020. p. 2). One of the insights that they detail is the importance of occupancy and use patterns which can vary both seasonally and culturally, impacting the energy efficiency of the building. The deployment of 5G and the use of big data collection strategies offer new opportunities which enable the use of tailored "informational" strategies aimed at altering occupant behavior (Hu et al., 2020. p. 9). These technologies furthermore remove a degree of uncertainty and inaccuracy in building energy use prediction, opening the path to a "outcome-orientated and data based" building energy policy, facilitating monitoring and assessment.

Alberini et al. (2020), in their recent study of the price elasticity of natural gas in the Ukrainian market from 2013 to 2017, reinforce the importance of occupant behavior for energy efficiency. While they report that natural gas price elasticity was low, it was nevertheless evident from their research that occupants are able to reduce consumption given an increase in gas prices (controlling for government subsidies). Wealthier households provide a notable exception in so far as their demand was essentially inelastic and Alberini et al. conclude that the increased tax revenue paid by the wealthiest households can be put to use in funding policies aimed at further increasing household energy efficiency and encouraging a switch to renewable heating sources (Wardman, 2001).

3.3. Operation Energy Saving Models

Houri and Khoury (2010) investigated the feasibility of the business model for the service provider using expected cost and value-at-risk criteria. They made use of a stochastic framework to identify the influencing factors for the selection of replacement technology that yields a lower expected cost of energy usage and replacement cost compared to another technology. The results indicated a significant financial benefit for the service provider and the customer. The customer benefits financially from the reduction in energy usage and replacement costs as well as from additional revenue obtained through selling carbon offsets. Since this business plan is based on increasing energy efficiency, the proposed approach decreases energy consumption and therefore CO_2 emissions, proving beneficial to all stakeholders (Liu et al., 2012).

A one-of-a-kind framework is presented by Chih-Lin et al. (2014). Their study developed a comprehensive analytical framework for the management of energy-saving companies to deliver improved energy efficiencies and reduced costs of technologies. They included the change in energy consumption, volatile energy unit price and useful life of a technology as well as the revenue from carbon offsets simultaneously in a stochastic setting to analyse a business plan that offers energy-saving technologies as a service.

3.4. Alternative Approaches to Energy Efficiency

Having identified the three main challenges to energy efficiency, researchers set out to find suitable solutions to these challenges:

- The maximising of electrical energy set against the maximisation of the production structure;
- The instability in energy accessibility, energy sources and financial implications; and
- The use of modelling mechanisms for changing measures with relation to diverse sub-systems.

3.4.1. Sequencing of machinery

In an effort of solving the challenge of energy efficiency versus manufacturing-system effectiveness, Mikhaylidi et al. (2015), anticipated that the power usage for the respective machines were unchanged. They considered a manufacturing operations control problem with known time-varying electricity prices in a finite planning result. Each was an individual process with its own hollow electricity consumption function. The model used a precise start-up cost and a set reservation cost for when the machine was idling. Their study identified reduced energy consumption in future production through a jointly manufacturing system design.

3.4.2. Energy feedback control

Lee and Prabhu (2015. p. 1-13) proposed an energy-aware feedback control model for production planning and volume control. They considered the costs of energy consumption, machine maintenance, production capacity and the penalty cost imposed by just-in-time production requirements. Computational experiments showed flexible capacity control delivered a 25-99% and 18-24% better system performance for production and energy cost, respectively. On the other hand, it generated an average of 37-50% higher upkeep expenses based on the increased production rate.

3.4.3. Technology improvement

An original approach was taken by Tan and Yavuz (2015. p. 1-18). Their model included improvement in energy efficiencies and costs of technologies with time, fluctuation in energy usage, volatility in energy cost, the lifespan of technology and income from carbon offsets all together. They developed a probability setting to examine a business plan offering energy-saving technology as a service. Through this approach, they addressed risk management by testing different effects and scenario in the context of uncertainties (e.g. energy pricing). Since they mainly work at a high business level, challenge #1 is addressed using a mono-criterion additive aggregation, while challenge #3 is addressed using a global linear regression of the day's temperature.

3.4.4. Technology replacement

In order to achieve energy efficiency, it is often necessary to replace existing apparatus with modern technology. Before a technology is replaced, however, the total cost of operation needs to be determined. This can be done by using the cost of the technology, its energy conversion efficiency, energy consumption, useful life span, electricity unit price and revenue from carbon offset (Zhu et al., 2009. p. 3169-3181).

In order to identify better technology, a comparison of the overall investment in two sets of equipment with varying power conversion efficiencies, expenses and number of problems over a specific time can be done. The aim is to identify the equipment that will operate at the most efficient cost. In comparing two technologies it is assumed that the lower cost and higher efficiency are similar for both sets of equipment. Tan and Yavuz (2015) further recommended that if one technology is operating more economically while another is more effective the overall estimated expenses should be compared to a baseline costing in order to select the best option.

Cui et al. (2014) proposed that once the framework parameters have been determined, the total cost can be determined. Total cost refers to the difference between the cost of replacement and energy usage and the revenue from the carbon offset markets in a specific time period. More efficient technology reduces the CO_2 emissions which can result in further monetary savings (Jeon et al., 2015. p. 7049-7059). Such benefits can help to fund the technology replacement.

3.4.5. Carbon offset

A carbon offset is a lower emission of CO_2 or greenhouse gases compensating for an emission made elsewhere. According to the Kyoto Protocol, businesses can trade the saved amount of CO_2 at a carbon offset market within the acceptable limits. The framework by Tan and Yavuz (2015) included this revenue generated from technology replacement. The limits set by the regulators are expected to decrease, however, with the improved technology. Lowering CO_2 emission will eventually be enforced, which will lower the monetary rewards as well (Dong et al., 2016).

Initiatives such as the energy-consuming right trading system in China, which as part of the Made in China 2025 roadmap, are examples of national efforts to increase energy efficiency. Yang et al. (2020) detail the construction of such a system which works in a similar fashion to carbon emission right trading and in which China, acting as the world's largest manufacturing country, has a particular interest. The energy-consuming right trading framework detailed by Yang et al. seeks to take into account the heterogeneity of manufacturing in China which is split across 18 sectors. Furthermore, by splitting energy resources into renewable and non-renewable, while taking the stark differences between energy intensive sectors and low energy consumption sectors into account, under the fairness principle of grandfathering, Yang et al. are able to yield both the optimal energy consuming right and the optimal energy consuming mix (Yang et al., 2020. p. 2). In conclusion, Yang et al. point to the fact that their work focuses solely on the setting of energy allocation, and not on the influence of CO_2 emissions opening up an avenue for further study which would seek to simultaneously set "control targets of energy and carbon emissions under the same collaboration framework" (2020. p. 8). They furthermore underline the importance of regulators in the creation of a compensation system which will encourage compliance across the heterogeneous manufacturing sectors all while compensating for deficiencies that arise out of energy efficiency loss (Yang et al., 2020. p. 8).

3.4.6. The payback method used to recover costs

Energy efficiency improvement projects require investments to address the various high consuming elements. The cost recovery of this investment is known as the pay back method and makes use of the savings to recover the financial outlay. In other words, the payback method refers to the economical savings per period to recover the initial investment by the company. The payback period in capital budgeting refers to the period of time required to recover the funds expended in an investment, or to reach the break-even point. The payback method of the framework proposed by Méndez-Piñero and Colón-Vázquez, (2013. p. 149) is to maximise the annual financial benefits. This is achieved by installing feasible replacements that use less energy in specifically identified areas. The net benefit is calculated by multiplying the total daily savings per area by the working days per year. The initial financial lay out of the suitable replacements is subtracted from the net benefits to calculate the net savings. This method of maximising the economic benefits per year is also confirmed by Rabi and Spadaro (2016. p. 6).

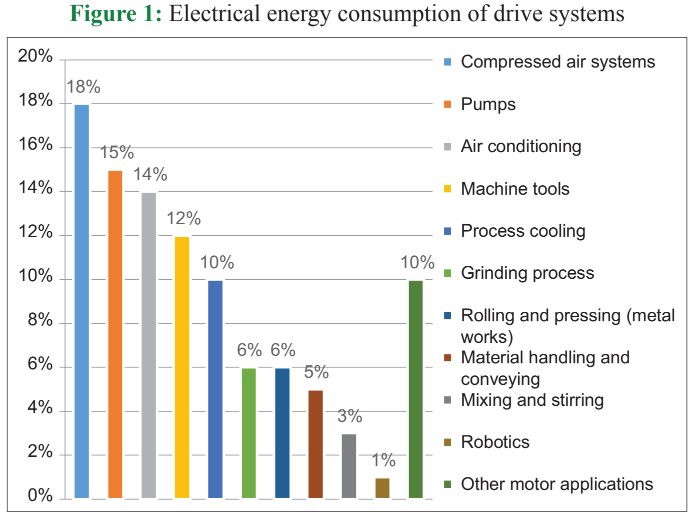
Sobhani et al. (2014. p. 710) are of the opinion that the recovery of the initial investment can be guaranteed when a feasible alternative is identified. Feasibility indicates that benefits are generated during the lifetime of the technology. The expected lifetime of the majority of this kind of equipment is between 5 and 10 years, therefore Baños et al. (2011. p. 1759) recommended between 1 and 2 years as an acceptable period to recover the investment.

3.5. High Energy Consuming Elements

An analysis by Javied et al. (2015) allocated the highest electric power consumption in the industry to a few dominant applications, namely pumping systems, compressed air systems and air conditioning systems. Other significant motor applications are cooling systems, manufacturing machine tools and heating elements. Figure 1 presents the elements' energy consumption in industry. A detailed analysis of these applications could lead to reduced energy wastage. Knowledge of the key energy consumers is vital for the industry, in order to improve their carbon footprint as well as reducing their energy costs. Becoming more energy efficient and green can also enhance market competitiveness.

Sebu (2016) identified five systems in manufacturing as the highest energy consuming elements, namely lighting, air conditioning, air compressors, production machines and heating elements. She proposed that each system should be evaluated individually to determine the feasibility of replacement. In order to simplify the evaluation process, the facility is divided into four areas: offices, production, warehouse and exterior which are not necessarily limited to a single building (Méndez-Piñero and Colón-Vázquez,

Figure 1: Electrical energy consumption of drive systems



Source: Javied et al. (2015)

2013. p. 152). The energy saving framework assess the facility by area and identifies the high energy consumption elements which negatively impact maximum financial benefits.

Cataldo and Scattolini (2014) suggested that energy consumption is calculated as the product between electric power and time. This calculation is not influenced by time and highlights the effect on energy consumption. This implies that the measure of energy hinges on the period in which the actuator is actively functioning, although the succeeding period hinges on the number of starting sequences of the actuator (Cataldo and Scattolini, 2014). The power used for the duration of which the actuator is actively functioning is then regarded as an equal value to the electric power.

3.5.1. Savings on HVAC systems

A model predictive control (MPC) algorithm for solidified water storage incorporated with HVAC system under a period reliant electricity price arrangement was proposed by Candanedo et al. (2013. p. 1032-1045). The algorithm includes the simple use of parameter models for the cooling machine and the ice bank. The calculation is then used to choose the ideal grouping of cooling machines and ice bank cooling power aids at specific time periods over the forecasted horizon. The findings indicated that the MPC algorithm can realise financial benefits of 5-20%. This is with regards to the improved storage importance approach which refers to the way the storage media of active CTES is melted to a maximum during the peak demand time. An additional saving of 20-30% is possible with regards to the cooling machine approach that is reliant on time, weather, electricity cost and required indoor construction heat luxury necessities.

3.5.2. Savings on lighting

In order to lower the electricity usage of the lighting system, Sebu (2016) suggested changing existing bulbs with energy efficient bulbs that consume less kWh. It is accepted that the quantity of bulbs per zone has been recorded and that the replacement bulbs will deliver the same quality of light required (Baños et al., 2011. p. 1759). Modern lamps available in the market can now produce more lumens so that fewer bulbs are actually needed (Méndez-Piñero and Colón-Vázquez, 2013. p. 151).

3.5.3. Savings on compressed air

Sebu (2016) showed that the number of air compressors in manufacturing companies varies according to the requirements of the company and the capacity of the equipment. To prevent a shortage of compressed air in the event of a breakdown, companies often rely on two or more systems (Permin et al., 2016). An air compressor uses constant power and the higher the pressure, the more energy is required. The relationship is, however, not linear but exponential therefore using two systems decreases the energy demand.

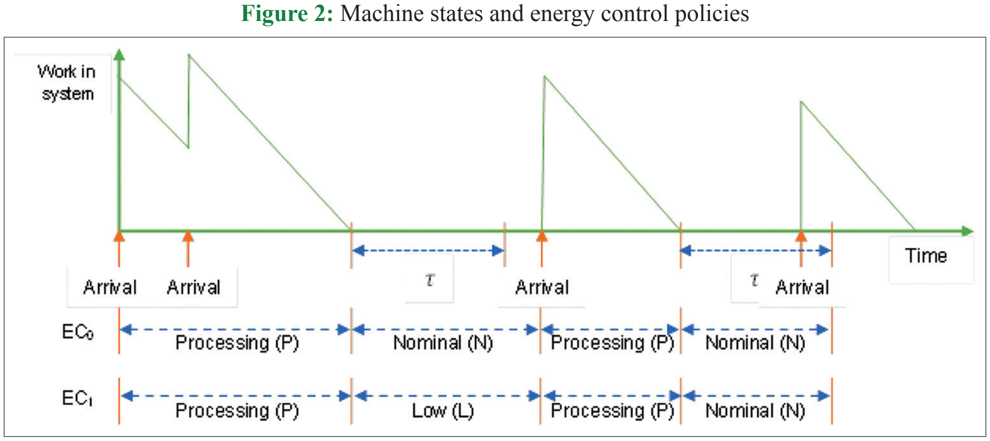
The application of machine learning to energy efficiency shows great promise, Cupek et al. (2018) detail such an application in the determination of energy consumption profiles in discrete production stations which make use of pneumatic systems. By using sophisticated data mining techniques (notably the *k*-means method) they illustrate both the manner in which clustering as a data mining method can be implemented in order to detect discrepancies, and the application of these techniques to energy efficiency monitoring in an industrial setting. The strength of the proposed solution lies in that it does require any changes in control procedures and is deployable in both green and brown production environments, allowing for the rapid and precise detection of energy efficiency and / or anomalies in reference to a given variant of production (Cupek et al., 2018. p. 538).

3.5.4. Savings on production machine energy

Bannat (2008) proved that classifying important appliance conditions at appliance level, appliance level power can be displayed. The progression can be supported by means of machines and cameras. They also established that satisfactory appliance level power management guidelines can be allocated to explain conditions once the appliance conditions have been demarcated. They proposed that a power consumption management procedure of turning off idle equipment must be taken into account. An individual appliance state can be showed with the processing power period and by following the procedure strategy established at product level.

Figure 2 depicts the appliance functional conditions and power management guidelines. The figure represents the relationship between the different states of a machine and conserving energy. For energy usage frameworks at an operational and functional

Figure 2: Machine states and energy control policies



Source: Prabhu et al. (2013)

level, three functional appliance conditions and two operational level power management strategies were defined (Prabhu et al., 2013). The common operational position of an appliance is referred to as P and is an appliance producing incisions on solids represents an operational period and an idle period is considered an N state.

The lower energy consumption state is also known as the additional idle state. Less power is consumed than the N position, however it is only well-defined under the functioning power control procedure. If a less functioning period is longer than the time verge, an appliance is expected to remain in the less functioning period. The less functioning positions L and N are approximately similar to the energy saving and less functioning types in moveable equipment. The initial power management procedure does not take into account any operational level power management (Gloy et al., 2015. p. 88-96). The P and N functional conditions are simply presented because the equipment is either working or idling. Should idle stages be lengthier, L positions are acceptable by appliances in other power management guidelines. Figure 2 demonstrates in what way the P, N and L positions are demarcated. Appliance specific concerns are mandatory to apply the presented appliance conditions and power management guidelines. The N state is thus redefined as idle whereas the L condition is shown as switched off. The theory is that all appliances are in the active state. Power saving is possible by switching a less active appliance to an inactive position but the time to start-up must be considered. It is therefore possible to calculate the value of □ as the new position period of the appliance, while the manufacturing interruption is anticipated by EC1 not to be permitted.

3.5.4.1. Comparing production machine parameters with simulation

According to Prabhu et al. (2013) an association of the production power status in the production phase is possible by removing settings at the manufactured goods stage and relating the settings to appliance energy and manufacturing facility energy. The study further showed how measurements in each phase are used in a structured way as input information for the following phase. Mimicking the power usage of a theoretical production facility with administrative aspects, their study presented a complete power usage and the kWh used for each part and product in inclusive calculations. Through these calculations, they proved that the production power used with the aspects at diverse phases can be projected.

3.5.4.2. Energy saving using optimised milling and unconventional machining techniques

Significant energy efficiency is also possible using more advanced techniques related to milling, especially in so far as machine tools account for 12% of the electrical consumption of drive systems. To this end, Asrai et al. (2018) propose a novel mechanistic model of energy consumption in milling which, in considering the thermodynamic nature of the milling process, allows for a substantial reduction in energy consumption through the prediction and thus optimisation of energy use in milling operations (Asrai et al., 2018. p. 658). The model is furthermore applicable to a variety of machine tools in so far as it exhibits substantial generality. Similarly, Wang et al. (2018) propose a multi-objective mathematical model which enables the careful selection of cutting parameters, thereby minimising unit production cost and energy consumption for face milling operations. Their solution rests on an evolutionary strategy based method with the material removal rate found to play a key role in the optimisation of machine performance as far as energy efficiency is concerned (Wang et al., 2018. p. 2099). Guerra-Zubiaga et al. (2018) in turn offer an exploration of machining strategies using a Design of Experiments based analysis of energy consumption taking the material removal rate into consideration as they examine cut parameters. Their results show that feed rate is the primary influence, contributing 80% to the energy consumption of both linear and circular cutting trajectories (Guerra-Zubiaga et al., 2018. p. 1076). Over and above the direct applications to energy efficiency that their research holds, they suggest that further research should consider other materials (they focused on wood) including aluminium, steel and composites, while adjusting factors such as spindle speed, depth of cut per pass, and feed rates as related to these materials (Guerra-Zubiaga et al., 2018. p. 1076).

Given the increasing importance of unconventional machining, and the energy demands made by such processes (up to 1000 times that of traditional machining when removing the same volume of material), the review by Zheng et al. offers an important overview of efforts being made to address the energy efficiency of these processes. Unconventional machining refers to the use of electrical discharge machining in situations where the hardness of the materials, and the complex, high quality, shapes required preclude the use of traditional methods (Zheng et al., 2020. p. 2). Among the technologies currently in use for the machining of titanium, composite, metal matrix or ceramic materials is wire electrical discharge machining, which, due to its precision, occupies an essential market position, but for which relatively little research concerning its energy efficiency has been undertaken. The strategies highlighted by Zheng et al. focus on increasing the energy efficiency of wire electrical discharge machining and include the optimisation of the machine tool through the optimisation of the pulse system, the optimisation of the wire feeding and cooling systems, and the optimisation of the machine control system. Further improvements to energy efficiency can be achieved through improved process modelling, taking workpiece thickness and material into account (Zheng et al., 2020. p. 9). Further research into intelligent pulsed power supplies, improving the utilisation rate of pulse energy, coupled with the existing use of artificial intelligence algorithms in modelling and process parameter simulation of wire electrical discharge machining, optimisation of the cutting path and improved man-machine process design (reducing stand-by time and errors) can all contribute to increased energy efficiency (Zheng et al., 2020. p. 13).

3.5.4.3. Production machine energy saving using profiles

Thiede et al. (2013. p. 78-87) investigated less productive and full productive stages from machine profiles that indicated different energy usage at the different production phases. The AU (machine idle state) and VA ranges were divided with reference to the device's practical specifications and the gathered information. A profile was developed by Mustafaraj et al. (2015) for each individual machine. The results from the scrutiny on the appliance profiles verified the significance of AU and VA energy that confirmed that they were significantly close to the appliance characteristics. Originated from the appliance characteristics, the maximum period necessary to produce a component in the exact appliance was recorded as 56 minutes. In contrast, the findings indicated that the possible solidity of the logged sequence period for the appliance is greater (IEA, 2018).

Figure 3 illustrates the AU and VA energy dispersal in comparison of four machines. It is evident that Machine 1 has the maximum power concentration matched to the other three machines. Therefore, it is of high importance to pay attention on Machine 1 since it contains the maximum prospects for decrease in AU power usage.

3.5.4.4. Production machine energy saving by switching machines off

Research by Mustafaraj et al. (2015) also focused on the AU and VA energy usage. They offered an accurate and flexible methodology to apportion power usage at machine and revenue saving stages. It was evident that each machine varied between 10% and 26% in AU power usage. Information gathered over less productive periods were ignored from the complete manufacturing energy usage information leading to a 50% decreased AU energy usage. Consequently, by switching off apparatus in the period of non-production, AU power usage could be decreased significantly (Mustafaraj et al., 2015).

3.5.4.5. Production machine energy saving by use of simulation experiments

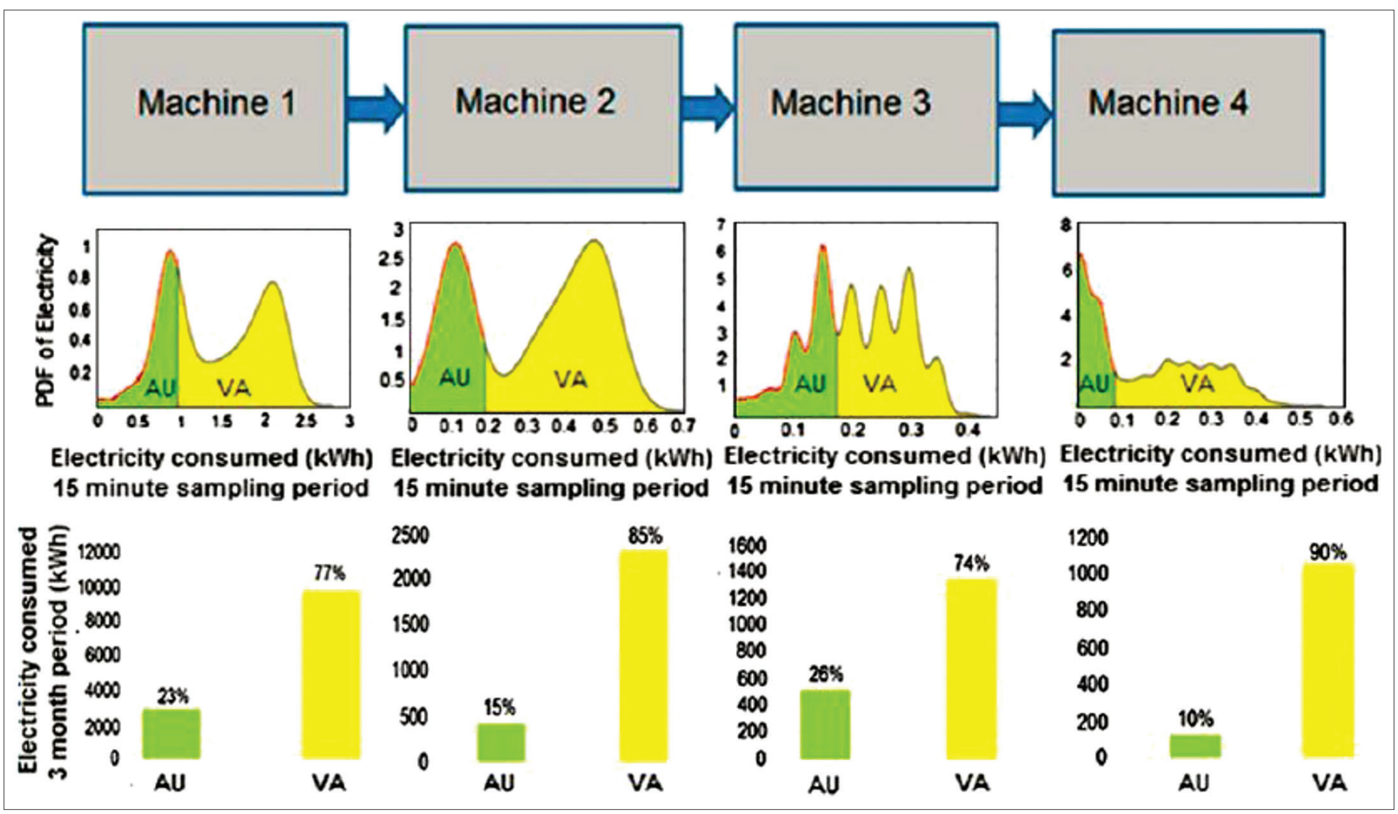
This model, using simulation experiments, starts by establishing the end result or consumable level components. Using a development strategy with the relevant components as production infrastructure level frameworks, in which appliances' functional condition, handling power and dispensation periods are demonstrated (Liu et al., 2012). The exploration at the manufacturing level recognises important aspects in power consumption characteristics and offers the industrial energy comparisons relating to aspects for executive choices by the use of replication experimentations based on production level frameworks.

4. METHODOLOGY OF THE STUDY

The main objective of this study was to test a proposed energy reduction framework at a manufacturing plant in South Africa. It was motivated by the challenges faced by manufacturers worldwide, of which reduced cost and increased production were prominent. All ethical considerations were adhered to and permission was obtained from the relevant stakeholders to conduct the study. This study is exploratory in nature and made use of quantitative analysis. A standardised questionnaire was used to define the influence of the improved energy efficiency of the manufacturing elements on the individual's performance. The quantitative approach was deemed suitable due to its offering of precision and control. Precision stems from the consistent quantitative measurement of data collected, while the sampling and design techniques offer control (Babbie and Mouton, 2006. p. 49).

The research was conducted at the nine plants of a manufacturing company in South Africa. The proposed framework was implemented and tested at these plants. The questionnaire was distributed to the different employment levels namely

Figure 3: AU and VA energy consumption using profiles



Source: Mustafaraj et al. (2015)

the manufacturing workers, the divisional managers, senior managers and certified energy managers, with an actual response of 489 participants. The questionnaire consisted of four sections addressing the geographical information of the participants, determining which high consuming elements were replace in the respective areas and sub divisions and determining the effect of the framework on the performance or production rate of the area or sub division. The last section consisted of 15 questions gathering critical data regarding the energy consumption measure before and after the implementation of the framework, as well as the total energy saved on the particular elements in the manufacturing plant.

With regards to the framework, the data was collected over a complete energy billing cycle. The primary focus of the investigation was the relevance of the facts regarding the reduction of energy in the manufacturing plants and the impact on the manufacturing performance. The data collected was based on measurements of energy before as well as after the implementation of the framework to determine the exact effect of the framework.

4.1. The Framework Construction

The framework adopted an algorithmic approach to enable a decision that designs a quantitative measure of evaluating the energy saving. This study intended to introduce a combination of optimisation and energy saving techniques that have not been applied in previous optimisation studies. The purpose of this framework was to detect the highest power consuming elements in a manufacturing plant and to replace these elements with more efficient technologies. It also aimed to determine the effect of these improved environmental factors on the production performance itself. The framework evaluated the alternative elements by area and identified the most beneficial replacements that complied with the limitations to maximise the obtained economic benefits. This was done by:

- Acquiring the building plans and office layouts in order to visualise of the logical separation of the functions of the plants.
- Dividing the offices into areas and sub divisions to ensure the measurement of the energy consumption to the smallest possible functional office space.
- Identifying the highest energy consuming elements in each office space.
- Applying the algorithm to determine the viability of replacing elements.
- Identifying of the applicable replacement technology based on specification to determine the maximum energy usage.
- Measuring of energy consumption before replacement with the new technology to determine the accuracy of the energy reduction framework.
- Replacing of the high consuming technology in order to reduce energy consumption in the manufacturing plant.
- Measuring the energy consumption after replacement to determine the impact and saving of energy in the area or sub division.
- Determining the energy consumption reduction.

4.2. Framework Methodology

An algorithm was used to determine the viability of the replacement technology. The notation i was used to index the facility areas and the notation a was used to index the subdivisions per area. For each area or subdivision, alternatives to reduce energy use were considered, as well as any qualifying constraints. The predetermined measurements in this research were the following:

- The kilowatts per hour (kWh) consumed by all equipment were measured;
- The hours that the equipment operates per day were reported;
- The cost of kilowatts per hour was known;
- The cost of purchasing and installing systems for energy saving was calculated;
- Power factor correction was implemented; and
- The time the company requires to recover the investment was determined.

4.3. Smart Meter

A smart meter that records active power, apparent power and reactive power, was used to electronically record the electric energy usage at hourly or smaller intervals. The information was then sent to the utility for monitoring and billing daily. It made provision for tariffs as prescribed by NERSA. Tariffs vary according to the time of day and the meter measured the kWh that was consumed.

4.4. Identifying the High Energy Consuming Elements

The 5 highest energy consuming elements were identified based on the literature by Sebu (2016). The viability of replacement was established by individual algorithms. Energy consumption values from each element were obtained from the specifications to determine the baseline consumption. These values were used as inputs to the algorithm explained for every high energy consuming element. Positive result of the algorithm on any element replaced by more efficient technology, implies energy saving on consumption according to the operational costs calculated in the specific area or sub division, making the replacement viable. The most common recovery period set in literature is 2 years. The algorithms, based on the payback method, for the evaluation of the feasibility of the alternative system are represented in Table 1.

4.5. Technology Replacement

The core focus of the energy saving framework in this study is technology replacement. Measuring the power consumption of the

Table 1: Algorithms for feasibility of replacement

Element	Algorithm	Payback method
Air conditioning	$(ACC_{ia}-ACS_{ia})*HR*KC=SAC_{ia}$	SAC_{ia}*amount operational days to recover >cost of replacement
Lighting	$(KIA_{ia}-KIR_{ia})*HR*KC=SI_{ia}$	SI_{ia}*amount operational days to recover >cost of replacement
Compressed air	$(CAC_{ia}-CAS_{ia})*HR*KC=SCA_{ia}$	SCA_{ia}*amount operational days to recover >cost of replacement
Production machines	$(PMC_{ia}-PMS_{ia})*HR*KC=SPM_{ia}$	SPM_{ia}*amount operational days to recover >cost of replacement
Workstations	$(WSC_{ia}-WSS_{ia})*HR*KC=SWS_{ia}$	SWS_{ia}*amount operational days to recover > cost of replacement

elements before the energy saving framework was implemented and after the technology replacement has been completed, determined the total energy saving of the framework in the plants. The replacement technology tested in the study included the air conditioning systems, lighting, air compressors, soldering irons and the production machines.

4.5.1. Air conditioning system

The LG advanced inverter technology was tested. It operates 44% faster and reduces noise level to as low as 6 db. It also includes fresh air percolation, providing clean air.

4.5.2. Lighting

Light emitting diodes (LEDs) are highly energy-efficient, using only 2-10 watts of electricity, and does not generate the same heat as incandescent lamps. The T8 Equivalent LED Tube with power consumption of 16 W and COS θ = 0.87 was used as replacement element.

4.5.3. Air compressor

The more efficient element the Compare 3000, was tested. It aims to prevent the loss of energy, through better heat recovery, of up to 12%. It features a closed loop water-cooling system that takes heat from all major components. It is also designed to prevent any warm air from leaking into the compressor room by processing and cooling the warm air within the unit, where it is re-circulated around the compressor via the base frame.

4.5.4. Soldering iron

The Smart Heat Turnigy 908 Soldering Iron with temperature control, was tested. The power supply is 230 V and the power consumption equals 65 W, with a temperature range between 50°C and 450°C and COS θ = 0.72.

4.5.5. Production machines

Pick-and-place robots are used in many ways, depending on the product being handled and the manufacturer's need for automation. The improved pick-and-place platform can produce 90,000 components per hour, with 10% higher throughput and 25% better accuracy.

4.6. Data Analysis

The statistical software SPSS version 16.0, was used to analyse the data. Frequency tables were used to present the percentages and counts for all categorical variables. The Cramer's V was employed for further analysis of the data.

4.6.1. SPSS statistical software

The SPSS package was applied for this research because of its statistical capabilities and reputation in managerial sciences research (Bryman and Bell, 2007). The data had to be coded using statistical software to ensure accessibility in the future and for use in alternative studies.

4.6.2. Pearson's Chi-square

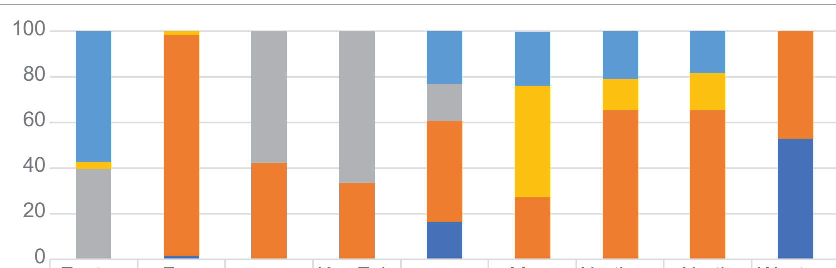
With the Chi-Square test, the p-value was determined as an indication of the level of confidence. The level of confidence higher than 95% was accepted as applicable, thus meaning that any value smaller than 0.05 will be regarded as acceptance of the hypothesis. The research hypotheses were stated in favour of the energy reduction framework as well as the increase in production after implementation. The Pearson's Chi Square at 0.05 level of confidence was used to test the hypotheses.

5. RESULTS AND ANALYSIS

5.1. Highest Energy Consuming Elements Replaced Per Plant

Figure 4 depicts the total view of elements replaced per plant as a percentage. It should be noted that there is only 1 plant per province. Every plant has its own flow of manufacturing due to the fact that different products are manufactured in the different regions. It can be seen that the Western Cape plant had the highest air conditioning replacement at 52.8% followed by Limpopo with 16.4% and the Free State with 1.7%. The highest lighting replacements took place in the Free State with 96.7%, the Northern Cape and North West with 65.5% each and followed by Western Cape with 47.2%. The highest number of production machines were replaced at KwaZulu Natal with 66.7% while 58% were replaced in Gauteng. The highest compressed air element

Figure 4: Percentages of elements replaced per plant



	Eastern Cape	Free State	Gauteng	KwaZulu Natal	Limpopo	Mpu-malanga	Northern Cape	North West	Western Cape
Work stations	57.1	0	0	0	23	23.7	20.7	18.2	0
Compressed air	2.9	1.7	0	0	0	49.2	13.8	16.4	0
Production	40	0	58	66.7	16.4	0	0	0	0
Lighting	0	96.7	42	33.3	44.3	27.1	65.5	65.5	47.2
Air conditioning	0	1.7	0	0	16.4	0	0	0	52.8

replacement was in Mpumalanga with 49.2%, the North West with 16.4% and the Northern Cape with 13.8%. The highest number of workstation percentage was in Eastern Cape at 57.1% followed by Mpumalanga with 23.7% and Limpopo with 23%.

5.1.1. Percentage of elements replaced

The areas in every plant was further divided into subdivisions. The replacement of the highest energy consuming elements was recorded and is detailed in Figure 5. It is evident that the element that needed the most replacement was lighting at 47.6%. The production machines were the second highest consuming element and 22.4% replaced. Third in line were the workstation with a 13.1% replacement. The workstations make use of soldering irons and are also responsible for quality control. In total 9% of the air compressors were replaces and 8% of the air conditioning systems.

The following sections present the statistical analysis of the collected data and set out to accept or reject the hypotheses of the study. The hypotheses in this study state that an energy reduction framework reduced energy consumption while increasing the production at a South African manufacturing plant. The null-hypotheses thus state that the energy reduction framework does not reduce energy consumption and does not increase production at a South African manufacturing plant.

5.2. Chi-square Tests Results of Production Increase

The Chi-Square test shows in Table 2 a value of 0.000 which is <0.05. With the hypotheses being the empirical proof that the framework can improve the production of the manufacturing plant. After the implementation of the framework a definite increase in production was noted and 81.1% of the plants produced more than 500 units/month.

5.3. Chi-square Tests Result Analysis of the Production Increase per Plant

The overall Chi-square test shows a value of 0.000 which is <0.05. This implies that the null-hypotheses can be rejected and that the framework had an increase in production. The results indicated that 81.1% of the plants produced more than 500 units/month. Interesting to note is that no increase was recorded in the Eastern Cape with a P-value of 0.220 as well as well as KwaZulu Natal with P = 0.520.

5.4. Chi-square Test Results of Energy Reduction on All High Consuming Elements After the Framework Implementation

The Pearson's Chi-square test was applied to the measurements from the high energy consuming elements. The p-value for each of the replaced elements were 0.000 which is <0.05. This implies that the null-hypotheses can be rejected and that the framework had a definite reduction in energy consumption after implementation. The detailed results for each of the elements can be seen in Table 3. The North West and Western Cape plants also did not record any results on this test as noted with the Cramer's V.

The total replacement and energy consumption reduction for each of the elements over the complete manufacturing company were as follows:

Figure 5: Total percentage element replacement

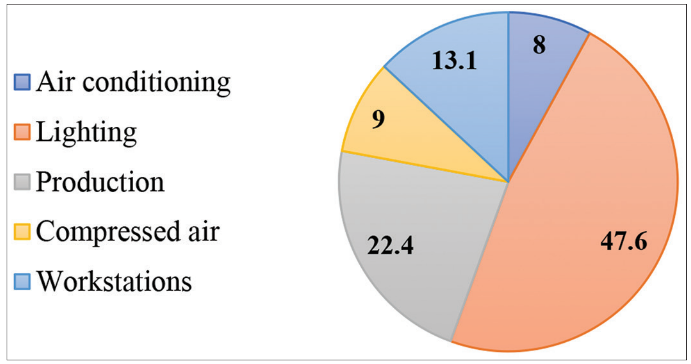


Table 2: P-value for production of the framework

	Value	df	Asymptotic significance (P-value)
Pearson Chi-square	617.631[a]	16	0.000
Likelihood ratio	324.267	16	0.000
Linear-by-linear association	206.534	1	0.000
N of valid cases	489		

Table 3: Chi-square test for all the high consuming elements

	Value	df	Asymptotic significance (P-value)
Air conditioning systems			
Pearson Chi-square	272.421	6	0.000
Likelihood ratio	324.647	6	0.000
Linear-by-linear association	178.710	1	0.000
N of valid cases	489		
Lighting			
Pearson Chi-square	595.923[a]	12	0.000
Likelihood ratio	493.708	12	0.000
Linear-by-linear association	254.509	1	0.000
N of valid cases	489		
Production machines			
Pearson Chi-square	433.950	12	0.000
Likelihood ratio	364.842	12	0.000
Linear-by-linear association	121.552	1	0.000
N of valid cases	489		
Compressed air			
Pearson Chi-square	570.430	12	0.000
Likelihood ratio	288.869	12	0.000
Linear-by-linear association	101.591	1	0.000
N of valid cases	489		
Work stations			
Pearson Chi-square	582.241	9	0.000
Likelihood ratio	521.896	9	0.000
Linear-by-linear association	286.452	1	0.000
N of valid cases	489		

- Air conditioner systems: The air conditioning systems were the third highest energy consuming element with 13.1% of total highest energy consuming elements replaced. Of the air conditioning systems 98.8% reduced its energy consumption with more than 40%.
- Lighting: The lighting element was the element that consumed the most energy and therefore also the element that was mostly replaced. Lighting elements replaced measured 47.6%. Of the lighting systems 98.8% reduced its energy consumption with more than 40%.

- Production machines: The production machines were the second highest energy consuming element with a total of 22.4% replaced. Of the production machines 97.3% reduced its energy consumption with more than 40%.
- Compressed air: The compressed air systems indicated the fourth highest energy consuming element with 9% from the total of elements replaced. Of the compressed air systems 98.2% reduced its energy consumption with more than 40%.
- Workstations: The workstations were the lowest energy consuming element with 8% from the total of elements replaced. Of the workstations 94.7% reduced its energy consumption with more than 40%.

5.5. Total Production Impact of the Framework

Table 4 indicates that production significantly increased after the framework was implemented. It shows that 83.1% machines produced more than 500 units/month. This correlates with the research question to determine the impact the framework would have on production.

When statistically analysing the results, it was noted that two manufacturing plants, North West and the Northern Cape, showed no increase in production, despite the improvement on the efficiency of the environmental factors and manufacturing machinery. This is not in line with the findings of the other seven manufacturing plants.

The production managers of these two sites were interviewed and the possible causes for this anomaly were identified as inefficient processes, insufficient skills and a poor quality in products causing the rework of products, which is counterproductive and costly.

Table 4: Total production impact of the framework

		Frequency	Percent	Valid percent	Cumulative percent
Valid	101–200 units	2	.4	.4	.4
	201–300 units	31	6.5	6.5	6.9
	301–400 units	48	9.8	9.8	16.7
	>500 units	407	83.1	83.1	99.8
	6	1	.2	.2	100.0
	Total	489	100.0	100.0	

5.6. The Payback Period

The implementation of the energy saving framework over the entire spectrum of the manufacturing plant, resulted in a potential saving of 876,157.00 ZAR/month. This will bring about a yearly saving of 10,512,806.00 ZAR. The total investment for the implementation calculated to 16,618,222 ZAR, therefore the payback period will be 1.8 years.

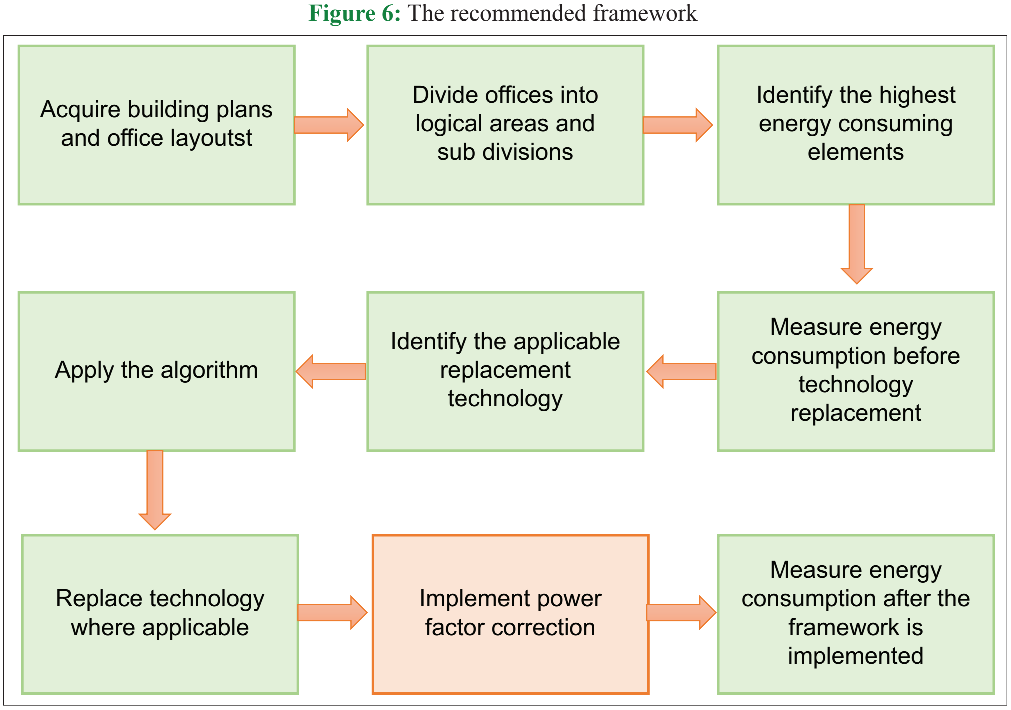
5.7. The Final Recommended Framework

The framework in this study was successfully tested and implemented. It can therefore be regarded as a model. The final recommended framework presented in Figure 6, consists of the same flow of activities as the implemented framework in the study. A power factor correction element has been added to enable further savings. One of the biggest challenges for energy reduction in the industry, identified by Javied et al. (2015), is to pinpoint the applications and systems which require huge amounts of energy. The framework of this study identified the exact systems which require the most energy and commercial benefits. It is therefore recommended that this model, inclusive of power factor correction is implemented at other industries to shorten the payback period to <1.8 years.

6. CONTRIBUTION OF THE STUDY

This study significantly contributes to the existing body of knowledge regarding energy reduction frameworks. Since the

Figure 6: The recommended framework



implementation of it led to an energy saving of up to 57%, it can assist many manufacturing plants to not only become more energy efficient but to also cut down on overhead expenses. The simplicity of the framework addresses some of the issues identified in the industry. The framework further closed the gap in research that existed due the disregard of unifying two different tools. The most unique contribution is in the fact that no other framework has been identified with the ability to reduce energy consumption while increasing production.

7. CONCLUSION

It is concluded that the framework reduced the power consumption of a manufacturing plant with an average of 57% and that the sample size is inferent to the manufacturing industry. These results were compared, validated and proven as correct. One should take into consideration that the manufacturing processes and disciplines are not the same in all manufacturing businesses, but it is possible that this framework can be successfully implemented in any manufacturing plant that make use of any electric drive, heat generating element or inductance of any kind. It should be noted that the areas and sub division identified in the plants needed to be separated to determine the accurate consumption of every functional business The consumption of the energy must be measured and billed in KWh units for it to be quantifiable and reflected in a percentage saving to enable the reader to associated himself/herself with the true impact of the study.

The results from this study underline its efficacy. While the energy reduction framework has been confirmed in a well-ordered location, further energy consumption reduction is still possible. The analysis shows that the most energy consumption by the electric drives and heat generating elements in the industry can be allocated to a few applications in manufacturing. The dominant applications are, compressed air systems and air conditioning systems, manufacturing robots, and lighting elements.

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