Quantifying the life cycle cost of a high pressure grinding roll in a mineral processing plant

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by

Mr. Njabulo S.E. Buthelezi

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Supervisor: Dr. A Marnewick

Co-supervisor: Dr. H Nel

DECLARATION

I, Njabulo S.E. Buthelezi, currently enrolled at the University of Johannesburg hereby declare that the minor dissertation “Quantifying the life cycle cost of high pressure grinding rolls in a mineral processing plant” submitted in fulfilment of the degree of magister philosophiae in Engineering Management at the Faculty of Engineering and the Built Environment at the University of Johannesburg, is my work, thoughts and interpretation. This work has never been submitted to any institution or university for any degree.

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Firstly, I extend my thankfulness to the Lord for providing me the vision and strength to complete this research. *"The Lord is my strength and my song; He has given me victory"* – Exodus 15:2

My appreciation goes to my Supervisor, Dr. Marnewick, for the continued encouragement and motivation throughout this 3 year journey. Thank you for your valuable contribution on this work.

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ABSTRACT

The accelerated advancement of technology and the global economic crisis has prompted the need to improve equipment efficiency, reduce unpredicted equipment failures and operating costs in order to improve production and profitability.

An emerging research trend around 2008 showed growing concerns on stringent availability performance constraints, specifically system reliability. Increasingly, further attention is directed to Life Cycle Cost (LCC) of equipment with an objective of identifying key factors affecting both system availability and LCC. Furthermore, the trend extended to focus more on understanding the equipment's operational and maintenance costs which are driven by the system and component specific maintainability as well as required replacement time. This also include the understanding of the LCC concept, available LCC models, implementation of LCC analysis within an organization and the benefits thereof, as well as ways of quantifying LCC through the use of existing calculation formulae. It also echoed the importance of the data availability and quality which provides a solid foundation to the success of the LCC analysis.

Hence, the aim of this research is to quantify the LCC as well as to determine the major cost drivers of the High Pressure Grinding Roll (HPGR) during its operating and maintenance life cycle for a period of four (4) years using existing LCC models. The research is presented in the form of a case study which is selected as an appropriate method of investigating empirical research for a real life problem or situation. The case study is based on the HPGR which has been in operation since 2007. The HPGR is currently installed and operating within a mineral processing circuit for one of the largest platinum group subsidiaries in the world.

In order to address the above research objectives, an in-depth investigation on the operating and maintenance cost, intervals, break-down occurrences, spare parts supply, overhauls, archive documents and consumables was necessary. These values were then used an inputs into the derived model for processing and yielding outputs. From the results, the LCC was quantified for a period of four (4) years. The results indicate that the LCC during operation and maintenance phase was significantly higher than the acquisition cost. Furthermore, the result also indicate that the LCC which considered time value of money portrayed a linear increase and is lower than the LCC calculated based on the actual costs. This is possible due to a number of reasons: the unexpected number of equipment failures, maintenance strategies and the fact that LCC based time value of money does not consider imperfect maintenance conditions.

It is evident that maintainability and reliability management must be regarded as a vital part of a corporate strategy. Successful implementation of this strategy is reliant on the "buy-in" of senior management which in turn will ensure organizational market share and competitive advantage is maintained.

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ABBREVIATIONS

ABC	–	Activity Based Cost/Costing
CBM	–	Condition Based Maintenance
CBS	–	Cost Break-down Structure
CM	–	Corrective Maintenance
EDF	–	Exponential Distribution Function
EPC	–	Engineering, Procurement and Construction
ERDM	–	Enterprise Reliability Data Management
ERP	–	Enterprise Resource Planning
HPGR	–	High Pressure Grinding Roll
LCC	–	Life Cycle Cost
LCA	–	Life Cycle Assessment
MTBF	–	Mean Time before Failure
MTTF	–	Mean Time to Failure
MTTR	–	Mean Time to Repair
NPV	–	Net Present Value
PM	–	Preventative Maintenance
PMRP	–	Parallel Machine Replacement Problem
RAMS	–	Reliability, Availability, Maintenance and Supportability
RCM	–	Reliability Centered Maintenance
RIO	–	Reliability Investment Optimization
SAP	–	Systems, Applications and Products
TPM	–	Total Productive Maintenance
WDF	–	Weibull Distribution Function

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1 CHAPTER 1 – INTRODUCTION

This chapter outlines the main objectives of the research. It commences with the background relating to an industry problem identified by the researcher which required investigation. The aim of the investigation is to introduce findings which can contribute to the existing body of knowledge useful to researchers and organizations.

The development of new technology in terms of improved material grades, the degree of digitization and automation of equipment is increasing enormously, and it inclines to sophistication and more stringent precision (Chen et al., 2011). Waghmode and Patil (2016) stated that complex product development due to complex manufacturing process is increasing global competition, particularly in the areas of mining, defence and space technology. As a result the cost of equipment ownership is increasing exorbitantly and has become the barrier restricting development and global growth. Chen et al. (2011) supported this statement and added that not only are the acquisition costs escalating but that the maintenance costs are escalating sharply at the same time. Hence, the need exist to precisely analyse the cost drivers, particularly Life Cycle Cost (LCC) of engineering systems, in order to derive improved methods to minimize ownership costs throughout the life cycle of the equipment (Safaei et al., 2012).

In analysing the Life Cycle Cost (LCC), various methods have been presented and compared by numerous researchers (Lanen et al., 2010; Seif and Rabbani, 2014 and Goralczyk and Kulczycka, 2005). However, many of these methods tend to focus primarily on the initial acquisition costs or, solely, on individual LCC components (such as operating and maintenance or environmental or disposal costs) with minimal consideration given to the entire life cycle of the equipment (Suresh and Sudhakar, 2013). Contrary to this, the life cycle cost from the end-user's point of view should be inclusive of procurement cost, spares cost, operation and maintenance costs as well as disposal cost (Seif and Rabbani, 2014). In support of this statement, Goralczyk and Kulczycka (2005) stated that focus has diverted from the production process to analysing the complete life cycle of the equipment. Hence, Life Cycle Cost continues to be a point of relevance for sustainability and market dominance for many organizations.

1.1 Life Cycle Cost and Reliability Background

The term life cycle costing (LCC) has been researched and used in various literatures since the mid 1960s (Sinisuka and Nugraha, 2013). According to Dhillon (2012), it refers to a method of estimating the cost summation of the equipment incurred by the consumer from acquisition to disposal of such equipment; in short it is the total cost of ownership. The cost of ownership can fluctuate from 20 to 200 times the original purchase cost (Seif and Rabbani, 2014). As a result consumers continue to seek means of controlling, or even better, minimizing these costs. Schwabe et al. (2015) emphasized that one of the LCC key focus areas for controlling these costs is related to decisions in the replacement of aging equipment.

From research history, a model presented by Al-Chalabi et al. (2014) indicated that a substantial portion of the LCC was mainly contributed by the operating and maintenance costs. In contrast to this, Fabrycky and Blanchard (1991) concluded that a substantial portion of the LCC for a system emanated from consequences of decisions made during initial planning stages where the age of equipment is not considered. Kleyner et al. (2004) also emphasized that the popular life cycle accounting models presented in literature primarily considered the design cycle cost, but very often neglected components of product validation cost throughout its entire life cycle. Moreover, the life cycle of equipment is analysed purely on the condition and its impact to the environment where associated costs are not considered. This fragmented approach is noticeable on the life cycle assessment (LCA) models presented by various researchers.

Traditionally, LCA models assisted consumers with environmental impact decision making capabilities but lacked the incorporation of associated costs. During 1994, a new LCA assessment method was introduced, which presented an optimally rated life with an objective of formulating a technique which incorporated costs into the life cycle assessment (LCA). Hence, this integrated model commonly known as life cycle cost assessment (LCCA) was derived by Warren and Weitz (1994). This model offered an integration of economic costs into environmental costs which provided decision makers with an upfront assessment of the life cycle costs.

Moreover, emerging research around 2008 showed growing concerns on stringent availability performance constraints, specifically system reliability (Dersin et al., 2008). Increasingly, further attention was directed to LCC with an objective of identifying key factors affecting both system availability and LCC. The aim was to provide valuable information to equipment maintainers and designers with guidelines on how to achieve forecasted availability targets at considerably low operational costs.

The trend extended to focus more on the equipment's operational costs which were driven by the system and component-specific maintainability as well as required replacement time (Hinow and Mevissen, 2011). In the avionic and mining industry, reliability of equipment influences the LCC extensively, and the level of reliability achieved relies on the consideration of viable reliability programs during the design cycle (Al-Chalabi et al., 2014). Hence, in 1983 the Reliability Investment Optimization (RIO) was developed to identify the levels of reliability investment that would reduce the LCC (Al-Chalabi et al., 2014). This model utilises the growth pattern on reliability levels to calculate LCC as function of mean time between failures (MTBF) (Seger, 1983).

The evolution of the LCC in the research field continued to grow with more improvements to existing models. In 2007, Rodriguez and Emblemsvag (2007) made improvements to the traditional Activity Based Cost (ABC) with an illustration of a new approach for long-term planning. The ABC concept gained ground on conventional models over two decades ago (Pintilie et al., 2012). With this concept, the LCC is analysed based on the activity which is undertaken on specific equipment. Some of the other improvements included component based life cycle costing which incorporated the effect of aging of equipment to the parallel machine replacement problem (PMRP) (Seif and Rabbani, 2014).

Continually, life cycle cost improvement has become a focal point of infrastructure and system engineering economic study. This is due to exorbitant maintenance costs of engineering products which has become a barrier for the affordable supply of products (Thaduri et al., 2013). It is evident that the consumers' decision is not only dependent on the maturity of the product but predominantly on the LCC (Wang et al., 2009). Thaduri et al. (2013) further emphasized that the crucial consideration for consumers to purchase a particular product depends on the availability, maintainability and reliability costs for its entire life cycle.

1.2 Definition of the Problem Statement

According to Waghmode and Patil (2016) hard economic times and increased competition has led to increasing attention to customer satisfaction and retention. As a result equipment LCC and reliability has become a topic of interest to many researchers and organizations. Balaba and Ibrahim (2011) further emphasized that cost effective operation and maintenance strategies are compulsory in order to reduce operational costs and to achieve availability and production targets. However, more concerns are apparent in literature from various researchers in this field of study which can be summarized as follows:

- Life cycle impact is often abandoned and the initial acquisition cost is regarded as crucial benchmark when making buying decisions (Ahmed, 1995);
- Over half of organizations do not have adequate decision support tools for precise planning and investment forecasting (Collan and Langstrom, 2002);
- Many organizations tend to overlook comparisons of actual and forecasted costs and as a result loose the opportunity to understand the equipment's cost behaviour as well as an opportunity to predict more realistic cost estimations (Lindholm and Suomala, 2007); and
- Due to improper record keeping and lack of awareness of cost incurred by consumers in many instances, it is often cumbersome to obtain realistic view of the overall costs without a methodical life cycle analysis (Lindholm and Suomala, 2007).

In conjunction with the financial information, analysing of the operational data is crucial in categorizing significant cost drivers (Wouters et al., 2005). Costs can be controlled and managed by enhancing operating and maintenance strategies, providing training to operators or by deriving more cost efficient ways of operating equipment through process and design improvements.

From the research findings presented above, it is evident that an opportunity exists for further research in this field of study. Hence, the problem statement of the research is:

Determine the importance of quantifying the LCC of a high pressure grinding roll (HPGR) during the operating and maintenance life cycle in order to determine whether low reliability yields high LCC and vice versa.

1.3 Research Questions

In order to have some degree of guidance and direction as well as to explore whether LCC during operating and maintenance is influenced by reliability, this research focuses on answering the following questions from the data that was collected and analysed:

- What is the LCC of a high pressure grinding roll (HPGR) during its operating and maintenance cycle for a period of four (4) years?
- What are the key cost drivers impacting the LCC of an HPGR?

It is vital that these questions are answered in a precise and unambiguous manner to ensure key factors are addressed and well understood by the intended readers. To achieve this outcome thorough research must be conducted through a well-defined research process.

1.4 Research Objectives

The purpose of the research is to quantify the LCC of a High Pressure Grinding Roll (HPGR) during its operating and maintenance life cycle using existing LCC models. The precise objectives of this research will:

- Quantify the LCC of an HPGR using existing models
- Identify key cost drivers which affect the LCC of HPGRs and how to control them
- Derive conclusions and recommendations that will contribute to the existing body of knowledge

In achieving these objectives, the outcome of the research is presented to outline key factors which must be considered during an evaluation of the LCC as well as provide information which can contribute to the existing body of knowledge useful to researchers and organizations.

1.5 Research Contribution to the Industry

Research conducted over 25 years ago indicates the lack of available tools that have a capability of addressing the full spectrum LCC due to the availability of poor quality data in the development phase of LCC models (Al-Chalabi et al., 2014). Olorunniwo (1992) further iterated that models for LCC analysis must not only address concerns relating to acquisition costs but also those concerns relating to operating, maintenance and disposal costs of products.

It is evident from research that LCC models are fully optimized to cater for the needs of consumers. However, the benefits of LCC analysis of these models are not optimally capitalized due to the lack of knowledge by equipment designers and manufacturers as well as the lack of quality operational data. Hence, the research within this field of study aims to contribute the following:-

- Knowledge on how to quantify LCC and the benefits thereof;
- A systematic method of implementing LCC models within an organization;
- An approach on how to determine cost drivers/factors affecting LCC and how to manage these through improved processes/ strategies from the operational and maintenance point of view; and lastly;
- An introduction to an LCC model to quantify LCC for the product's entire life cycle.

In recent research, Hayek et al. (2005) noted that the accelerated advancement of technology and the global economic crisis has prompted the need to improve equipment efficiency, reduce unpredicted equipment failures and operating costs in order to improve production and profitability. As a result, equipment designers and manufacturers continue to invest into research and development with the sole purpose of deriving ways of designing and manufacturing equipment with improved maintainability and reliability as well as low operating costs (Waghmode and Patil, 2016). To achieve this objective, Sinisuka and Nugraha (2013) alluded that thorough understanding and quantification of the equipment LCC based on the maintenance practises carried out by end-users is as vital as the inclusion of acquisition; operating and maintenance and discarding costs.

As noticed, a gap within the research field exists to provide more knowledge on LCC and its benefits to the research fraternity and organizations. For a streamlined and beneficial research outcome certain questions must be answered to ensure that the research objectives are achieved.

1.6 Research Process

The research process adopted follows an approach which is categorized into three stages: invention stage; data collection stage; and drafting and revision stage (Sreejesh et al., 2014).

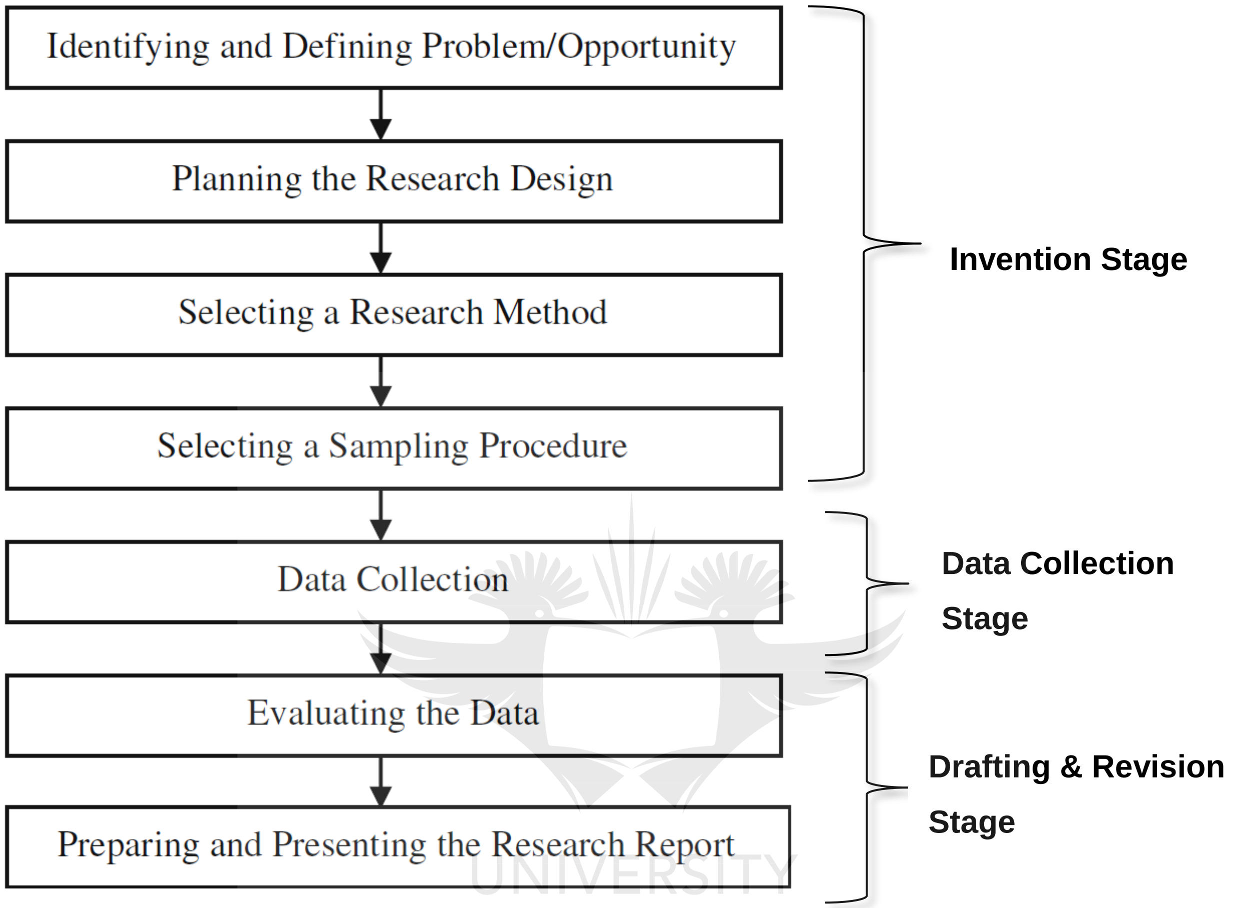


Figure 1-1: The research process (Sreejesh et al., 2014)

1.6.1 Identification of the Problem

The initial step in the research process is to identify a problem within an organization or industry. Therefore, it is imperative to define the problem in a well-thought-out and precise manner. A properly defined problem enables the researcher to map out the direction for conducting a thorough investigation (Sreejesh et al., 2014).

The continuous dissatisfaction of equipment end-users on the exorbitant operating and maintenance costs of the HPGR prompted the researcher to conduct an investigation into this problem. After conducting research to better analyse and understand the problem, an investigation on the LCC of the HPGR was chosen by the researcher as the topic of research to be conducted. In this way the researcher’s employer will be able to establish the underlying concerns pertaining to the exorbitant operating and maintenance costs. This will enable the researcher’s employer to derive strategies on improving equipment reliability as well as implementing measures to reduce operating and maintenance costs.

1.6.2 Planning the Research Design

Upon completion of the problem identification, the process of research design should commence (Sreejesh et al., 2014). A research design is regarded as the definite framework for research that expands on precise details of the process which is followed in conducting the research.

The research is formulated as per the objectives defined during the research initial stages through literature review and consultations with field experts, researchers and colleagues. The researcher then puts forward a proposal outlining the research objectives, problem statement, research limitations, research questions and contribution to the research community. Furthermore, the proposal outlines the time schedule to be followed in order to ensure on-time completion of the research.

1.6.3 Selection of the Research Method

A proper research plan is derived from the selection of an appropriate research method which consists of four fundamental methods for conducting a research study, including surveys, experiments, secondary data studies and observations (Sreejesh et al., 2014).

The appropriate research design method is selected based on the objectives of the research, estimated costs of the research, the availability and quality of the data, and lastly the significance and urgency of the decision to be made based on the research findings (Sreejesh et al., 2014). The conclusion of the research will be depicted by the sample procedure selected.

1.6.4 Selection of Sampling Procedure

Generally, sampling is considered to be part of the research design but is often separated in the research process. By definition, sampling is a process that considers a minimum number of components within a system to draw conclusions regarding the entire system (Sreejesh et al., 2014).

All the steps performed in the research process from the identification of a problem to selecting the appropriate sampling procedure constitute the planning phase. However, the research process execution phase initiates with data collection which is the next step after the sampling procedure.

1.6.5 Data Collection

Data collection can be executed in two stages, namely the feasibility/pre-testing stage followed by the main research. Pre-testing comprises of data collection from a minor sub-sample to assess the suitability of data collection plan for the research (Sreejesh et al., 2014). This assists the researcher to mitigate any probable inaccuracies that may creep up during the research. The results obtained from the pre-test may be useful in deciding on a method to tabulate and structure the collected data.

As soon as the researcher is satisfied with the data collected, the research process continues to the next stage, which is data evaluation and analysis.

1.6.6 Data Evaluation and Analysis

The most crucial phase of data evaluation is to translate the data collected into a format which can assist in effective decision-making by fellow researchers and organizations. The main reason for analysing the data is to attain results, to formulate a research report and draw useful conclusions and recommendations (Sreejesh et al., 2014).

Several statistical tools can be utilized for data analysis to obtain results appropriate for effective decision-making. The data statistical analysis may vary from simple frequency distribution tables to complex analysis with several possible variations.

1.6.7 Preparation and Presentation of the Research Report

After completion of all the preceding stages, the research report is produced and the research findings presented in the most logical manner. The research report structure is presented in section 1.8.

1.7 Research Limitations

In order to simplify the scope of this research, focus is directed mainly to the operating and maintenance life cycle phase of the HPGR within the comminution circuit in a mineral processing plant. By definition comminution is a process of reducing large solid ore material to a smaller particle size by means cutting, grinding and crushing (Pinto and Delboni, 2016). The research also focuses on only two different sizes of HPGRs which are installed at different plants which processes different ores. This is done for comparison of results obtained from data analysis in order to validate the LCC model used in the research. This is covered in a number of sections within the research structure.

1.8 Research Structure

In order to structure the research in a systematic and easy-readable manner, it will be divided into chapters which will cover the key topics and sub-headings pertaining to the research work.

Chapter 2 is a literature review which outlines investigation of existing research in the field of study researched. The objective of the literature review was to collect, analyse and select relevant information to this research. The focal point was on the LCC models researched and implemented in various industries in order to identify and incorporate proven theories to evaluate LCC of a HPGR. Moreover, key factors affecting the LCC were investigated as well as how reliability influences the overall LCC.

Chapter 3 elaborates on various research methods which are evaluated in order to assess and select the most appropriate research method for this research. Furthermore, the research design is demonstrated to outline the approach followed to collect and identity relevant data appropriate to answer the questions of this research.

Chapter 4 includes extensive data collection from the company's project archives as well as actual recorded operational data from the plant which comprises historical maintenance data, actual running hours and both operational and maintenance costs incurred. Furthermore, this chapter will demonstrate an approach on how the collected data is systematically analysed. The results obtained will validate whether the LCC model presented can be applicable to other industries.

Chapter 5 concludes with findings and recommendations drawn from the research and lessons learned during the execution of the research. Emphasis is placed on the importance of LLC analysis to facilitate informed decisions and continuous improvement to organizational strategies for continued growth and sustainability. Furthermore, possible future improvements to, and expansion on, the research are identified and shared with the research community.

1.9 Conclusion

From the initial research evaluation of LCC methodology presented above, it is evident that much work has been carried out to develop LCC models and tools in an attempt to aid organizations in making informed decisions to manage costs associated with a product more effectively. However, the practical implementation of these LCC models and analysis within organizations is still noted as a challenge by researchers and as a result consumers, designers and manufacturers cannot confidently identify cost drivers for their equipment.

Successful implementation of a LCC analysis should be viewed as a long term process to allow sufficient time to collect and analyse data in order to transform poor cost awareness into cost understanding of future costs. This will also assist organizations in understanding key factors which impact LCC and thereby deriving or revising current strategies to efficiently manage and control these factors.

Chapter 2 presents literature by various researchers and the aim of this chapter is to understand the LCC concept; available LCC models and key factors which affect the LCC. It will also investigate the role that reliability plays in a LCC analysis and to what extend it can impact the LCC.

2 CHAPTER 2 – LITERATURE REVIEW

The aim of this chapter is to outline all the relevant information available from the literature. This is done to better understand this field of study and to derive answers to research questions. Hence, the focal point of this chapter will be specifically to address the following:

- Definition and concept of LCC
- The benefits of implementing a LCC analysis within an organization
- Available LCC models and their limits of application
- Calculation of LCC using existing methods and formulae
- Key factors which impact LCC and how they can be managed, and
- Influence of reliability on the overall LCC and the management thereof.

2.1 Definition – What is Life Cycle Cost?

Before understanding the benefit of LCC and its application, it is vital to first understand the definition of LCC. There are many definitions of the life cycle cost, commonly referred to as LCC by many researchers. The precise definition by various researchers and institutions may vary, however similarity is noticed in the definitions. Amongst many definitions available in the literature – the most known are (Goralczyk and Kulczycka, 2005):

- *"LCC is the overall cost of acquisition and ownership of a product or system during its life cycle. It includes development, acquisition, operation and maintenance, conservation and final disposal costs"* (Centre for Systems Management Glossary of Project Management Terms)*;*
- *"LCC is defined as the overall cost of a system during its entire life cycle. It includes development, acquisition, operation and maintenance, conservation and final disposal costs"; "LCC is the summation of all incurred costs during the life cycle of a system, product or building. It includes project, development, acquisition, operation and maintenance, conservation and salvage costs" (US Federal Acquisition Institution Glossary of Acquisition Terms).*
- *LCC accounts for all system costs which are broken down into several categories to include development and design cost; construction and/ or manufacturing cost; operating and maintenance cost; and retirement and material disposal cost (Blanchard, 2004).*

For this research, the definition by Blanchard (2004) is adopted. This definition clearly stipulates the various components and related cost of a product/ equipment LCC in a manner which the researcher finds self-explanatory and can be easily understood by intended readers.

Given that the definition of the LCC has been stipulated, it is worthwhile in understanding the concept of LCC as well as the inter-relation of each life cycle phase with one another.

2.2 Life Cycle Cost Concept

Traditionally, the total LCC of equipment incorporates the summation of costs for acquisition, operating, maintenance and discarding of the equipment at the end of its life cycle (Olorunniwo, 1992). Understanding the life cycle a product undergoes from its inception to disposal life cycle involves knowledge of the product's history cost and its current cost behaviour as well as forecasting its future costs (Kulmala et al., 2002). The estimation of future costs should be carried out in conjunction with cost monitoring during the life cycle of a product in order to derive more accurate estimations (Woodward, 1997).

In fact, as the product progresses towards its disposal life cycle, the importance of LCC alters from cost estimation to cost monitoring. The cost estimation should be based on the analysis of previous costs through proper collection of cost data, thereby deriving at a LCC analysis which demonstrates the overall influence of the product on the performance of an organization (Lindholm and Suomala, 2007). Hence, the availability and quality of input data are imperative for an accurate LCC analysis in order to sharpen the cost overview to more realistic figures. This evolution of the LCC from a product's acquisition to disposal is illustrated in Figure 2-1.

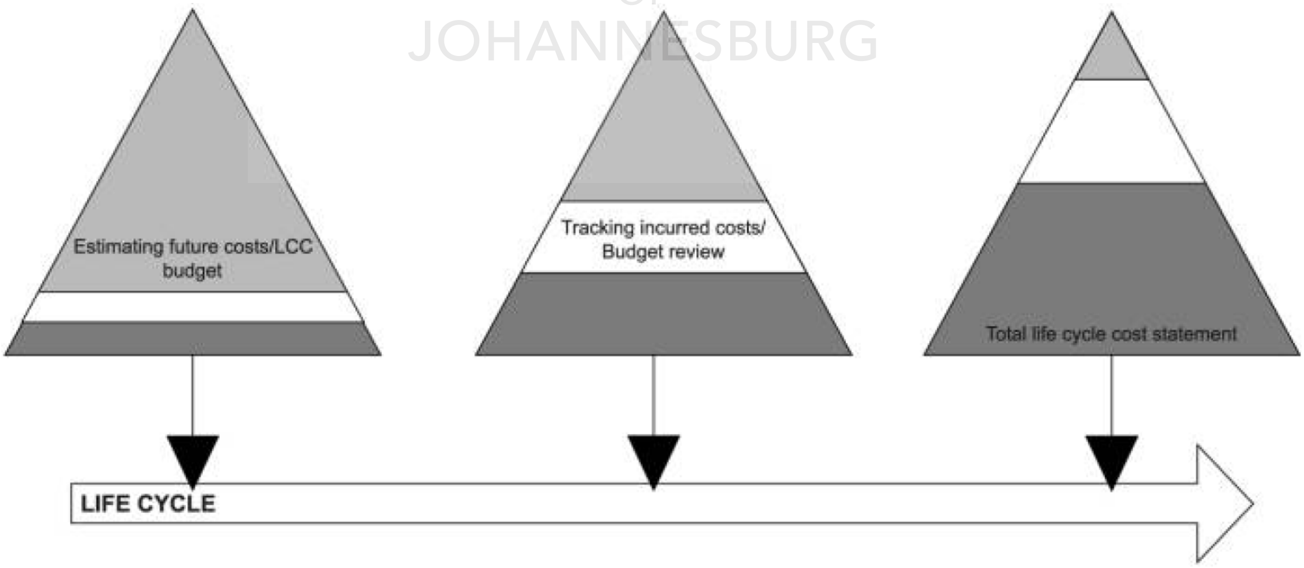


Figure 2-1: LCC during a product's life cycle (Lindholm and Suomala, 2007)

Traditionally, during the product's acquisition, several organizations estimate revenues and future costs as well as costs linked with the investment through capital budgeting which entails the net present value, internal rate of return and payback (Lindholm and Suomala, 2007). When these estimations are conducted thoroughly and efficiently, the core foundation and benchmark for LCC can be derived. However, it is vital to consider capital budgeting as a vital input for continuous management of LCC rather than as the anticipated output which can be overlooked throughout the product's life cycle.

Previously, it has been claimed by Kulmala et al. (2002), Raffish (1991), Asiedu and GU (1998), and Lindholm and Suomala (2007) that approximately 80-90 percent of the product cost that will ultimately be incurred by end-users is pre-determined during the product development phase. As a result, emphasis in profitability management is likely to be stronger on product development and design. Contrary to this, Cooper and Slagmulder (2004) argued that significant savings can be achieved during the product's operational life cycle for both products with long or short life cycles. Cooper and Slagmulder (2004) further emphasized that stringent cost management usually focused on product design as well as profitability management should be considered throughout the entire life cycle of a product.

To illustrate the percentage distribution of costs for the entire life cycle, Jing et al. (2012) used a Pareto curve (Figure 2-2). The horizontal axis denotes the various life cycle phases and the vertical axis denotes cost accumulation in percentage. From the solid line curve, this is based on estimates derived at during the acquisition phase where that 70% of the equipment's life cost is confirmed at the exploration phase. Prior to the development phase (validation) approximately 85% of the equipment's life cost is confirmed; thereafter 95% is confirmed as the development phase.

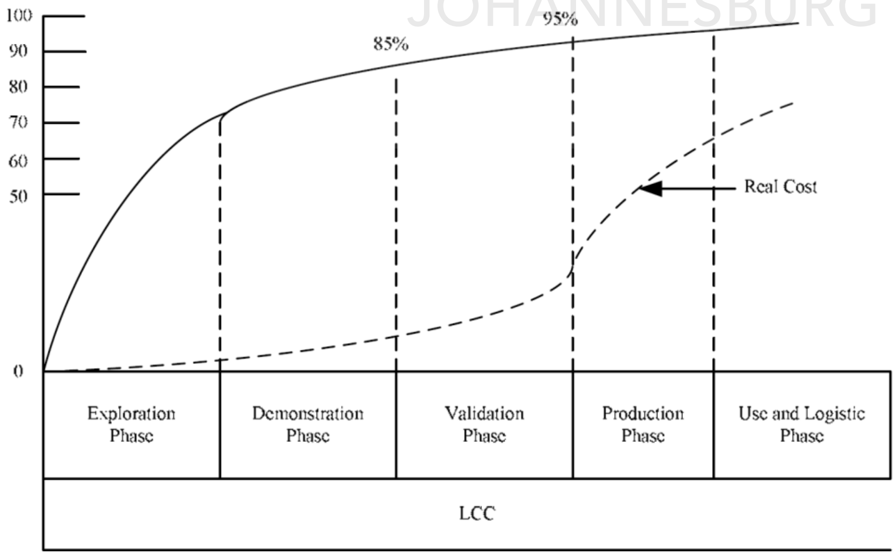


Figure 2-2: Pareto Curve of LCC (Jing et al., 2012)

Contrary to this, from the real cost curve (dashed line on Figure 2-2) it is noted that the majority of the LCC which equates to approximately 70% of the product's life cycle is confirmed during the operating and maintenance phase (Jing et al., 2012).

In support to this estimation, Wang et al. (2009) suggested that approximately 50 – 60% of the LCC is accounted for in the operating and maintenance phase. However, LCC should be considered throughout the entire life cycle. It is clearly evident that all the product's life cycle phases are crucial as they contribute a percentage to the total LCC. This is illustrated in Figure 2-3.

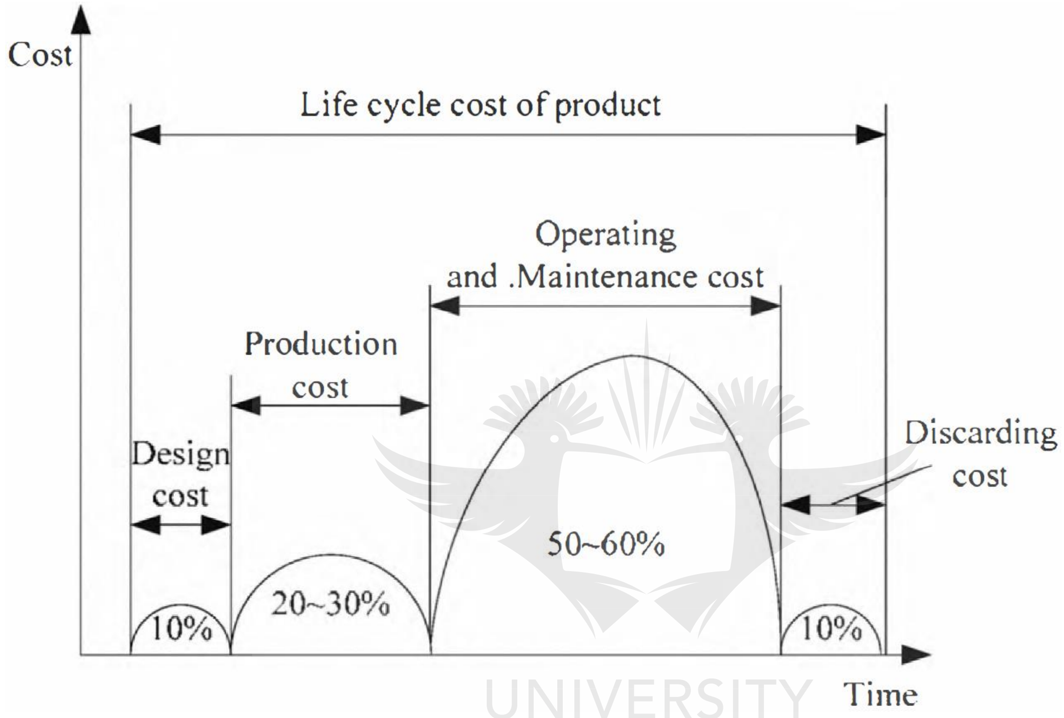


Figure 2-3: Life cycle phase cost proportion (Wang et al., 2009)

As noted from the figures above, LCC analysis is a method within the management accounting field which focuses primarily on the total costs incurred during a product's life cycle (Ahmed, 1995).

Hence, knowing the LCC of a product is one of the pre-requisites when considering acquisition and/ or outsourcing of maintenance work to external contractors (Lindholm and Suomala, 2007). Notwithstanding that, the implementation of an all-inclusive interpretation of LCC can be a laborious exercise. However, as a starting point, it is possible to implement a LCC model in an individual organization.

2.3 Life Cycle Cost Implementation

According to Blanchard (2004), the LCC analysis process initiates in the design conceptual phase. The aim of introducing the LCC analysis as a vital consideration in the design phase enables cost targets to be identified as design-to-cost factor. Furthermore, in the preliminary and detail design phases, LCC analyses are utilized in the assessment of alternative design options at the sub-system level and below. Later, LCC analyses are conducted during the construction, manufacturing, operating and maintenance phase to assess the product's performance as well as the environmental impact at the disposal phase (Blanchard, 2004). This is crucial in identifying major cost drivers in order to implement a continuous improvement approach and cost management strategies to reduce costs.

To conclude, it is imperative to emphasize the importance of conducting LCC analysis during all the various phases in order influence the product design, manufacturing, operating and disposal strategies from an economic perspective. The basic steps for implementing a LCC analysis within an organisation include (Blanchard, 2004):

- **Define the system requirement**
    - Define the operational requirements of a system such as the technical performance measures and maintenance concept.
- **Describe the system life cycle & identification of phase activities**
    - Establish a baseline for forecasting annual costs for the anticipated system's life cycle.
- **Develop a cost break-down structure (CBS**
    - Provide a top-down, as well as a bottom-up, structure to include all associated costs for the purpose of initial cost allocation as well as collection and simplification of costs.
- **Identify data input requirements**
    - The type and the amount of data required will be dependent on the extent of the analysis and the phase of the system's life cycle.
- **Establish cost for each CBS category**
    - Derive a cost-estimating relationship and forecast the yearly costs for each component of the CBS.
- **Select a suitable cost model for analysis and evaluation purposes**
    - Select an appropriate computer based model to enable the LCC analysis process to be initiated. The model must be able to cater for the system to be evaluated.
- **Develop a cost profile and summary**

- Develop a cost profile indicating the distribution of costs over the entire life cycle of a product as well as the percentage of each distribution.

- **Identify major cost drivers and establish cause-and-effect relationships**
  - Indicate the components within the system which necessitate investigation for probable design modification or improvements in order to reduce costs.
- **Conduct sensitivity analysis**
  - Thoroughly evaluate the model and the result of the analysis to ensure the analysis approach is valid as well as suitable for the system analysed.
- **Construct a Pareto diagram and identify priorities for proposed problem solutions**
  - Identify the level of importance for problem resolution.
- **Identify practical alternatives for design evaluation**
  - Based on the LCC analysis outcome, several design alternatives can be explored.
- **Evaluate the most practical alternatives and implement the preferred approach**
  - Establish a cost profile for the individual design alternatives, compare the costs for each alternative, derive a break-even analysis and select the most feasible design alternative.

2.3.1 Benefits of Implementing LCC Analysis

LCC analysis can be viewed as new approach to the management of cost and not purely as a costing tool as it emphasize the product's performance from a long-term perspective by utilizing various management accounting methods (Waghmode and Patil, 2016).

Hence, the key benefits for implementing a LCCA within an organization can be summarized as follows (Sacks et. al, 2012):

- It is an unique tool for decision making where several options exist to assist in selecting the best option;
- All costs associated with the components/ system are clearly visible throughout the entire life cycle;
- Major costs drivers can be easily identified and control measures can be derived to reduce and/or control the impact from these drivers;

- The correlation between various business functions can be identified (for example, low acquisition cost which may potentially lead to exorbitant maintenance costs); and
- It allows for proper and more accurate budgeting as actual costs can be reflected in each phase throughout the entire life cycle.

From the research presented, it is evident that implementing a LCC analysis can assist an organization with better decision making and proper cost control measures. However, successful implementation is not only dependant on an organization's requirements to implement a LCC analysis but extensively on the availability and quality of input data to be used on suitable LCC model. According to Asiedu and Gu (1998) the ability of an organization to compete is dependent on the quality as well as the cost of its product. Hence, it is crucial to understand the available models as well as its suitability based on an organization's requirements in order to improve both product quality and cost.

2.4 Life Cycle Costing Models

There are a number of LCC analysis models presented by researchers such as Seif and Rabbani (2014); Lanen et al. (2010); H'midaa et al. (2006); Goralczyk and Kulczycka (2005); Nacthmann and Needy (2003); Rodriguez Rivero and Emblemsvag (2007); Goralczyk (2003); McClurg and Chand (2002); and Asiedu and Gu (1998). A significant number of these models are structured according to the three following classifications (Gupta, 1983 and Kolarik, 1980):

- **Conceptual models** – these models generally consist of assumed relationships mainly used in qualitative frameworks and at macro levels of a given system or equipment. Hence, these models can handle limited information and lacks the ability to quantify the cost characteristics of a system.
- **Analytical models** – these models are derived on mathematical relationships which are systematically intended to define a certain condition of a system/ equipment based on pre-defined assumptions. The shortcoming of these models is the restriction due to the assumptions defined upfront; as a result the actual system's performance is not highlighted.
- **Heuristic models –** these models are derived through computer simulations and are based on the fundamentals of analytical models. However, these models are more complex than the analytical models as they employ a modified approach which yields more realistic and effective solutions.

Based on these classifications, various models were presented by numerous researchers and these models are presented below. However, this research does not attempt to categorise these models according to the above classifications but merely present the various available models.

2.4.1 Activity Based Costing (ABC)

Recently, activity based costing (ABC) is being regarded as the common trending tool associated with the analytical cost relation methods (Haroun, 2015). It advocates that services consume activities which in return deplete cost generating resources. Hence, ABC evaluates cost drivers and quantifies costs incurred on performing an activity or service. This ensures that costs are accurate and distributed in proportion to the activities performed since cost estimates are derived from actual performed activity.

Developing an ABC system consists of four steps (Lanen et al., 2010):

- **First step –** identification of resource consuming activities and assignment of associated costs
- **Second step –** identification of cost drivers associated with individual activity
- **Third step –** computation of cost rate per cost driver; and finally
- **Fourth step –** allocation of the activity cost to product by quantifying the product of volume of cost driver units consumed by the product and the cost driver rate.

Traditionally, costing methods have proven defective and not providing accurate costs as the overheads are constantly distributed over activities with varying scope and complexities (H'midaa et al., 2006). Hence, ABC accounts precisely for the total costs associated with specific activity thus eliminating the probability of over-estimating or under-estimating an activity. However, comparable to other costing models, ABC falls short, more especially when the quality of input data is questionable (Asiedu and Gu, 1998; Durairaj et. al, 2002).

In 2003, Nacthmann and Needy (2003) used the Monte Carlo simulation as a probability tool to handle uncertainty in activity based costing (ABC). The Monte Carlo method is used to evaluate the degree of unclear input variables on the anticipated outcome. The main objective is to account for uncertainty in the LCC analysis input variables by utilising probability distributions to mathematically quantify the impact this uncertainty has on the output variables (Rodriguez Rivero and Emblemsvag, 2007).

Generally, these distributions are established on assumptions and estimates which are not derived from historical data and hence their degree of accuracy remains questionable. However, incorporation of the Monte Carlo simulation methods makes it possible to precisely trace and manage risk, uncertainty and cost effectiveness in a realistic approach of fairly complicated models

(Rodriguez and Emblemsvag, 2007). Figure 2 below illustrates the layers of a new activity based LCC approach and how LCC analysis is achieved for a specific activity.

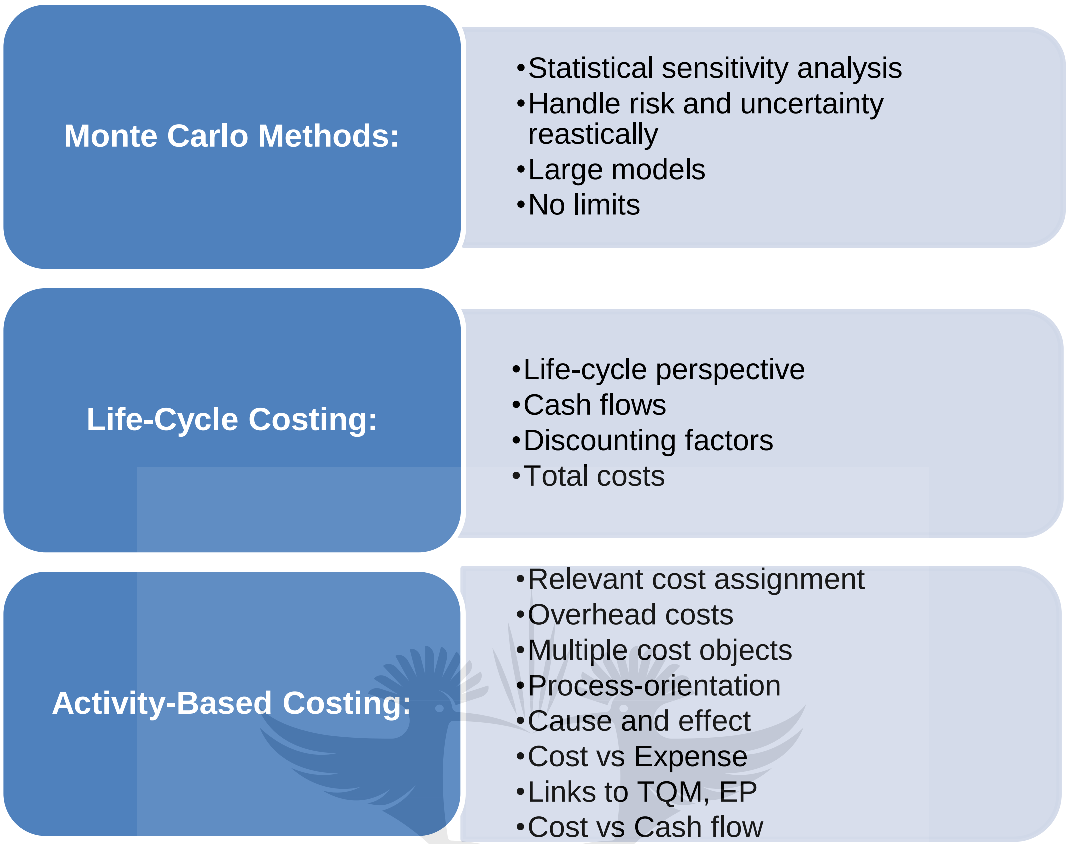


Figure 2-4: The three layers of activity based LCC (Rodríguez Rivero and Emblemsvag, 2007)

In implementing an activity based LCC analysis, practical challenges associated with the collection of accurate data and committing to long term cost management are anticipated (Lindholm and Suomala, 2007). However, irrespective of the quality of data, LCC analysis always consists of uncertainty as some of the input data has to be derived at on the basis of assumptions and estimations. In order to overcome this, probability methods are utilized to handle uncertainty in cost models (Asiedu et al., 2000).

2.4.2 Parallel Machine Replacement Problem (PMRP)

Based on the failure rates of machine components, the LCC is assessed, modelled mathematically and incorporated into the parallel machine replacement problem (PMRP) with the consideration of capacity expansion. The problem is then modelled, as mixed integer programming (MIP), with an objective to reduce the overall costs during the planning phase of various periods for the operating machines of similar type and varying age (McClurg and Chand, 2002). The decision outputs are the number of machines to be acquired/ salvaged during each period (Seif and Rabbani, 2014).

Several mathematical models have been developed over the years and the overall LCC is considered within the input parameters for individual periods within the planning horizon. These include a model by McClurg and Chand (2002) which considered the finite planning horizon where a deterministic number of machines were continuously operating. The model assumes that the older the machine the higher the operating costs; hence the replacement decision would be a function of the excessive operating costs. Furthermore to this development, Seif and Rabbani (2014) incorporated the effect of aging equipment to the traditional PMRP model. Generally, equipment has various components with varying failure distribution functions. Hence, these distributions allow for the calculation of failure rates thus ensuring better repair cost estimation in each period of the planning horizon. The components are classified into three classes based on their failure characteristics, as follows (Seif and Rabbani, 2014):

- Normal Distribution Functions (NDF):- these are the functions that follow normal distribution failures due to wear and tear as a result of normal use e.g. bearings, wear liners.
- Exponential Distribution Functions (EDF): - these are the functions that describe the probability to fail at any given time and failure is independent of the equipment age e.g. electrical components. Therefore the mean time to failure (MTTF) for each component must be calculated individually.
- Weibull Distribution Functions (WDF):- these are mainly mechanical components, such as bearings, with a probability to fail unexpectedly. Hence, the EDF is a specific case of Weibull distribution.

The classification of the components based on their failure mode enables precise quantification of the probabilistic number of failures of the equipment based on its components failure rate (Seif and Rabbani, 2014). Thus, better and more accurate cost estimations are achieved and unforeseen failure costs are minimized.

Traditionally, in conventional LCC models presented in literature, the overall corrective maintenance (CM) costs of equipment is considered as a summation cost which does not specifically calculate the CM costs of individual components based on their failure rate (Seif and Rabbani, 2014). Hence, by quantifying individual component CM costs, the LCC can be more accurately estimated in a precise and realistic manner.

2.4.3 Cost Break-Down Structure

For this model, Fabrycky and Blanchard (1991) presented a complex model which accounts for in-depth analysis of overall costs associated with the product’s entire life cycle. It’s dominance with the research fraternity is given by its in-depth cost break-down structure and can be grouped into four (4) distinct categories which caters for the total life cost. These include:

- Conceptual design or research and development costs;
- Manufacturing and erection (construction) costs;
- Operation and maintenance costs; and
- Disposal and retirement costs.

Utilizing the cost break-down structure (CBS) is one of the crucial steps in LCC analysis. The CBS assists in establishing the framework for outlining the categories of LCC and offers a valuable platform for cost analysis and reporting as well as for cost control. Therefore, it is crucial to understand the extent and quality of the information required when developing a CBS in order to ensure that the assessment is valid, major cost drivers are identified and cause-and-effect relationships between components/ systems and life cycle phases are established (Durairaj et. al, 2002).

Cost emphasis is resonated throughout this LCC analysis model; as a result major cost drivers can be identified (Durairaj et. al, 2002). Furthermore, the model is flexible and adaptable to various applications, for example, from a cost break-down structure the environmental concerns and costs may be incorporated into the model.

The model is governed by the methodology illustrated in the figure below (Sinisuka and Nugraha, 2013). From this figure, it is evident that the LCC analysis is a continuous and iterative process which can be adapted to any system/equipment or problem. This allows for a pre-defined and formal process to be followed in an event where realistic alternative solutions are available for a specific problem and a decision is to be made on the more feasible solution. Hence, the analyst would be in a position to clearly define the requirement for analysis, derive an analysis approach, select a model for the evaluation process, produce the adequate information for each solution, evaluate each solution, and provide recommendation of the most feasible solution that will address the problem.

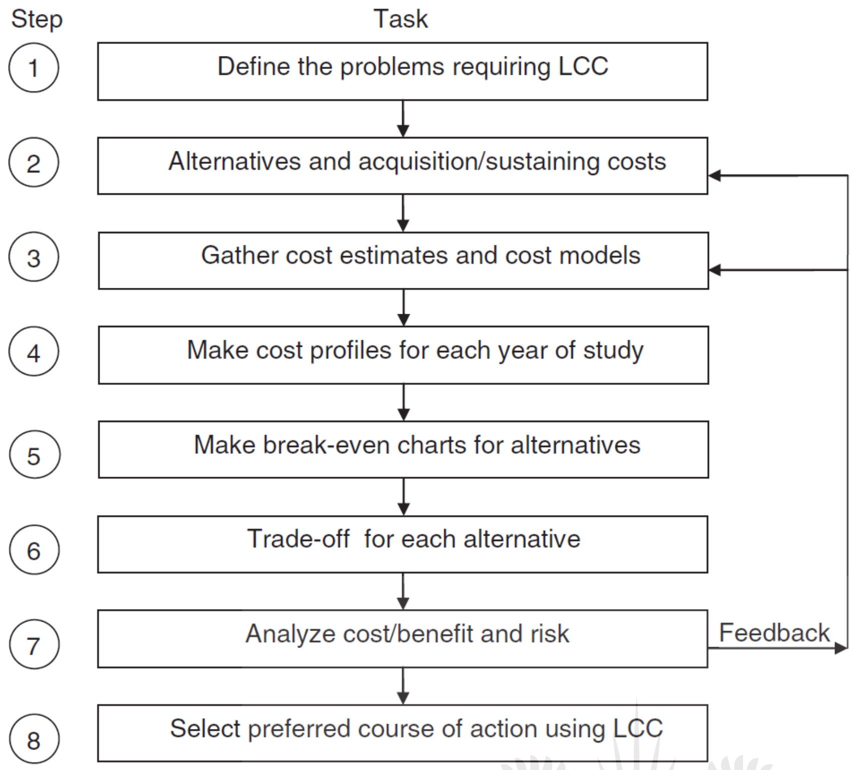


Figure 2-5: LCC process diagram (Sinisuka and Nugraha, 2013)

2.4.4 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is one of the environmental management tools used to evaluate and identify the environmental impact caused by a product or equipment during its entire life cycle (Goralczyk and Kulczycka, 2005). Traditionally, LCA does not incorporate economic aspects of the environmental impact. As a result hereof the LCC is not conclusive and accurate in portraying the actual cost incurred for the entire period of the product's life cycle.

However, Goralczyk and Kulczycka (2005) amongst other researchers developed an integrated model from the conventional LCA to incorporate environmental impact costs in order to derive LCC analysis for effective cost management, now referred to as life cycle cost assessment (LCCA). These environmental costs include contaminant disposal, carbon emissions and environmental inspection costs. Apart from the objective of understanding and quantifying environmental costs, the need for an integrated model is partially driven by the requirement and penalties imposed by the International Standard Organization (ISO) 14001 standards pertaining to environmental compliance for a hazard-free and friendly environment (Goralczyk, 2003).

The aim of the integrated LCCA is to assist product designers, manufacturers and end-users in better decision making regarding environmental preservation, not only based on the impact caused by their products but also with the consideration of costs associated with such impact (Steen, 2005). In order to identify, manage and reduce all associated LCC, namely internal and external costs, thorough analysis must be conducted for each functional unit (Goralczyk and Kulczycka, 2005). By solely utilizing the conventional LCC method for each functional unit, only the direct costs (i.e. water consumption, fuel and personnel) are considered. Meanwhile, the indirect costs include environmental fines, penalties and fees. Therefore, combining the costs of all functional units and further including the indirect costs provides more accurate and useful total internal costs incurred for a given system. This is illustrated in Figure 2-6 where the provisional external costs budget should be provided by the polluter (product end-user) and government.

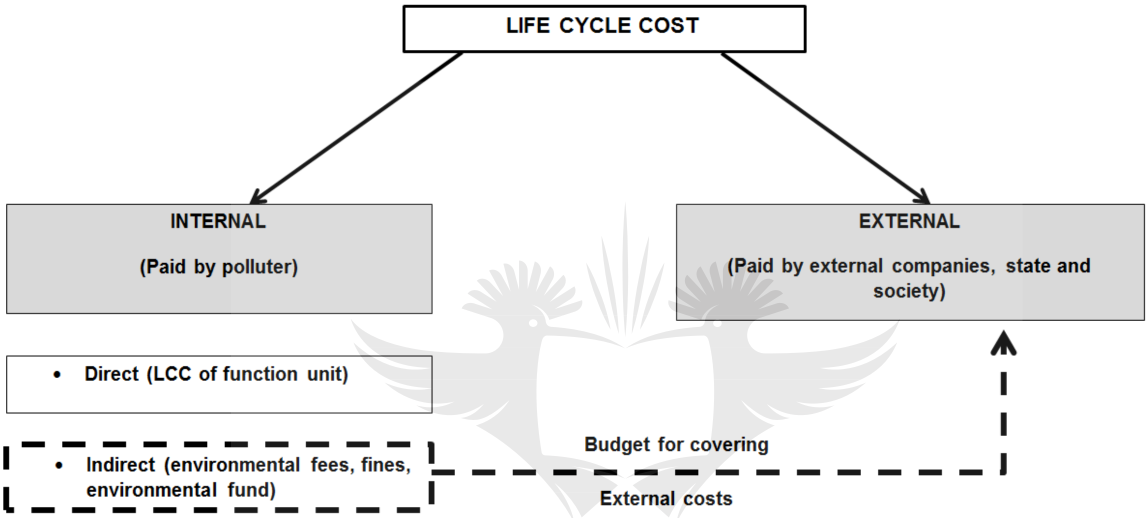


Figure 2-6: LCC definition (Goralczyk and Kulczycka, 2005)

According to Warren and Weitz (1994), the life cycle stages considered in LCA include raw materials acquisition (inception phase), manufacturing (production phase), operating and maintenance (operational phase) and recycling (disposal phase). LCA identifies variable inputs and outputs through the assessment of probable impacts of such inputs and outputs on the environment and human health, thereby identifying opportunities for improvements. The LCA approach is categorized into four (4) inter-related components as illustrated in Figure 2-7.

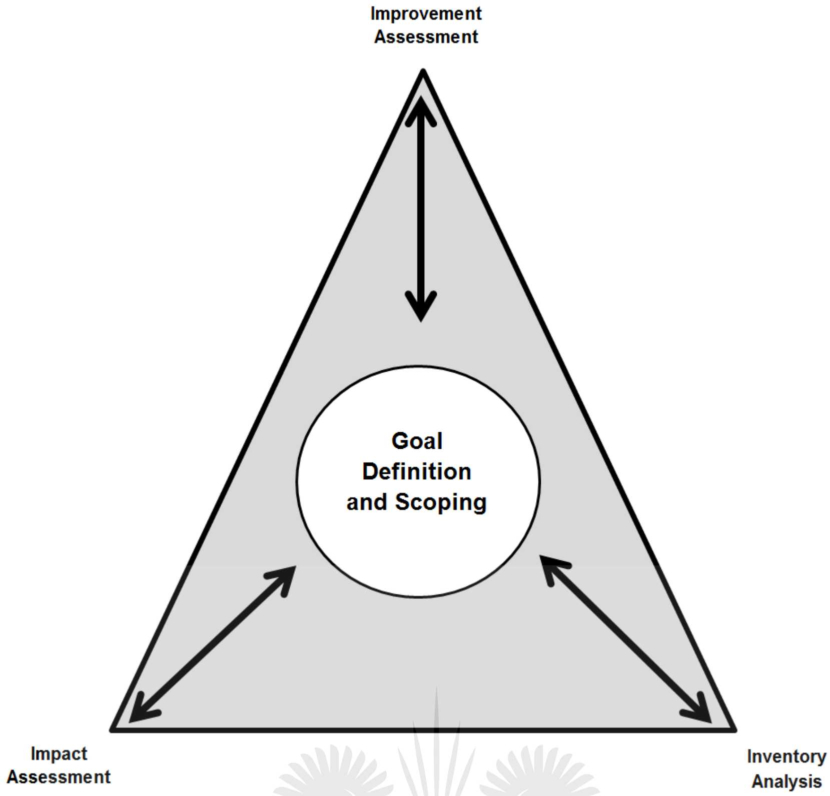


Figure 2-7: LCA framework (Warren and Weitz, 1994)

The structure formulated by a LCA analysis provides a precise estimation and perception of the environmental impact induced by a product, equipment or system (Goralczyk and Kulczycka, 2005). It creates a foundation for a thorough assessment of impact and provides an indication of which product, equipment or system yields the largest environmental cost.

2.4.5 Investment Decision Making

The establishment of the model was driven by the crucial planning and assets monitoring for the entire life cycle. This model is aimed at improving the value for money by accounting for all the costs factors pertaining to the equipment. Hence, with this model the investment options can be evaluated effectively as the impact of total life cycle cost is considered as opposed to only the acquisition costs (Woodward, 1997).

In this way, the investors are made aware of the potential ownership costs before making the decision to buy. However, the success of this model is extensively dependant on the quality and the availability of the information.

The implementation of this model encompasses the appropriate selection of a methodology to be adapted. This implementation includes eight (8) steps (Woodward, 1997):

- **Operation profiles establishment**: - this is the operation cycle in which the equipment will, or will not be utilized.
- **Utilization factors establishment**: - these factors specify the manner in which the equipment will operate within every operational profile mode.
- **Identification of all cost components**: - this involves the identification of all inclusive costs from equipment acquisition to the disposal phase.
- **Identification of major cost drivers**: - these are the factors that contribute to the highest percentage of costs throughout the life cycle of the equipment.
- **Cost calculations based on present price**: - this includes the calculation of all costs by considering the present cost price.
- **Cost escalations based on assumed inflation rate**: - this involves the quantification of all costs by considering inflation and the rate of exchange as well as import/export rates.
- **Discounting all costs based on time period**: - cash flows at varying time periods are discounted back to the same period for comparability purpose.
- **Establish net present worth (NPV)**: - the calculated discounted costs are summed in order to quantify the NPV.

2.4.6 LCC Model Comparison

Table 1 provides a comparison of the models discussed above. The comparison is adopted from the research conducted by Durairaj et al. (2002) where the application and the limits of the models are highlighted. Durairaj et al. (2002) made the following assumptions in order to simplify the comparison:

- Only key features relating to the selected LCC analysis models are compared.
- Only a relative and relevant comparison has been made based on the suitability for this research.
- Great emphasis has mainly focused on the features that accounted for the total life cycle cost.

The selection of these fundamental features is derived on their significance in the development of an all-inclusive LCC analysis model (Durairaj et al. 2002). Each feature in the comparison is assigned a grade. These include Grade ‘‘A’’ (Available) or ‘‘NA’’ (Not Available) which represents the availability of a specific feature and Grade ‘‘E’’ (Excellent) or ‘‘G’’ (Good) which represents the quality and usage of a specific feature. The grades chosen in each comparison is well-defined and based on the description and effectiveness of each feature in a specific model as well as the virtual comparison with the same feature of other LCC models represented above.

Table 2-1 – Comparison of existing LCC models (Durairaj et. al, 2002)

No	**Features**	**Models**				
		ABC	**PMRP**	**CBS**	**LCA**	**Investment Decision Making**
		Rodríguez Rivero and Emblemsvag (2007)	McClurg and Chand (2002)	Fabrycky and Blanchard (1991)	Goralczyk and Kulczycka (2005)	Woodward (1997)
1	Objective	Cost Reduction.	LCC of Replacement	Cost Alternates	Eco-design	LCC of assets
2	Identification of alternatives	A	A	A	A	A
3	Development of CBS & CBRs	E	E	E	E	E
4	Identification of suitable cost model	E	G	E	E	G
5	Generation of cost estimate	E	E	E	G	E
6	Availability of cost profiles	A	A	G	G	A
7	Break Even Analysis	A	A	A	A	A
8	Determination of High Cost contribution	A	NA	A	A	NA
9	Total Cost Determination	A	A	A	A	A

No	Features	Models				
10	Incorporation of ECO-cost	NA	NA	NA	G	NA
11	Correlation with Design changes	A	NA	NA	A	NA
12	Implementation of a Design solution	A	NA	NA	A	NA
13	Quality Aspects	NA	NA	NA	NA	NA
14	Inclusion of Supplier Relationships	NA	NA	NA	A	NA
15	Trade – offs	A	NA	NA	A	E
16	Employment cycles	NA	E	NA	NA	NA
17	Sensitivity Analysis	A	A	A	A	A
18	Risk Analysis	A	A	A	A	A
19	De-manufacture concept	A	NA	NA	A	NA

A – Available; NA – Not Available; E – Excellent; G – Good.

The most significant objective of this comparison is to assist decision makers with an easy reference to understand the numerous available LCC analysis methodologies as well as to select the most appropriate and suitable method for their organizations based on the fundamental features available. After selection of the most suitable method, the LCC analysis can commence using calculation formulae utilized in these methods.

2.5 Life Cycle Cost Calculation

The LCC structure of a product can be divided into two phases: production cost and consumption cost as illustrated in Figure 2-8 (Wang et al., 2009). These phases can be classified into: purchase/ acquisition cost; and operating and maintenance cost, respectively. The purchase cost is a once-off cost incurred in a relatively short time period and includes design, manufacturing, transportation and construction costs. Whereas, the operating and maintenance costs are incurred for the duration of the product while in use and include operating, maintenance and disposal costs (Jing et al., 2012).

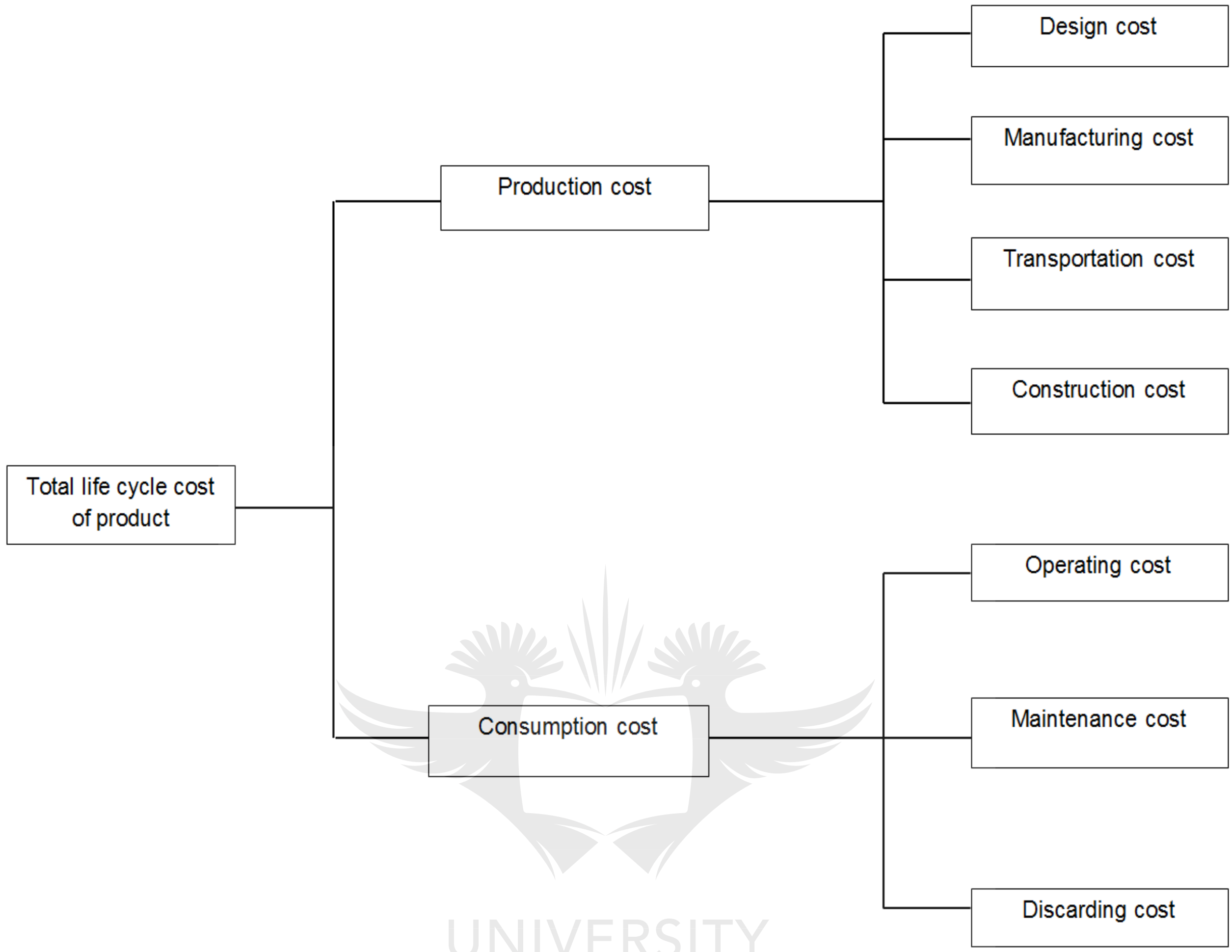


Figure 2-8: Constitution of life cycle phase cost (Wang et al., 2009)

2.5.1 Life Cycle Cost Calculation Formulae

As stipulated above the LCC consist of a series of costs incurred throughout the equipment/ product's life cycle. In order to quantify these costs various formulae are presented by numerous researchers (Jing et al., 2012; Thaduri et al., 2013; Waghmode and Patil, 2016; Kim et al., 2009; Goralczyk and Kulczycka, 2005).

2.5.1.1 LCC calculation using simulation based acquisition (SBA)

The simulation based acquisition approach is based on system engineering as it caters for all costs throughout the equipment/ product's entire life cycle. Jing et al. (2012) shows the LCC is given by the equation below:

$$LCC = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \quad (1)$$

Where:

C_1 – Design cost

C_2 – Manufacturing & transport cost

C_3 – Construction cost

C_4 – Operating cost

C_5 – Maintenance cost

C_6 – Discarding/ disposal cost

2.5.1.2 LCC calculation using time value for money and failure rate

This approach considers the time value for money by taking into account interest for a specified period of time. This period could be the estimated life of the equipment/ product or a period for evaluation which can be determined by the organization/ decision maker. Furthermore, the approach considers the equipment/ product failure rate throughout the specified period for evaluation. The reason for this is to account for maintenance cost as well as for the reliability of the equipment/ product. Waghmode and Patil (2016) show the LCC is given by the equation below:

$$LCC = Acquisition\ costs + Operational\ costs + Failure\ costs + Support\ costs - Net\ Salvage\ Value \quad (2)$$

Where:

$$Net\ Salvage\ Value = Salvage\ Value - Disposal\ cost \quad (3)$$

From an empirical representation:

$$LCC = C_U + [F_O + P_A(i, t_d)C_O] + [P_A(i, t_d)C_f \frac{t_0}{MTTF} + [F_S + P_A(i, t_d)C_S] - [P_F(i, t_d)S] \quad (4)$$

Where:

C_0 – Annual operating cost

C_f – Cost per failure

C_S – Annual supporting cost

C_U – Acquisition cost = Design + Manufacturing + Transport + Construction costs

F_0 – Fixed operating cost

F_S – Fixed supporting cost

i – Annual interest

P_A – Annual value

P_F – Future value at end design life

S – Salvage value

t_0 – Operating hours/ year

t_d – Design life in number of years

$\frac{t_0}{MTTF}$ – Expected number of failures/ year (failure rate)

$P_A(i, t_d)$ – Annuity factor

$P_F(i, t_d)$ – Single present value

Time value for money is expressed as follows:

$$P_{F/A} = \frac{C}{(1+i)^{t_d}} \quad (5)$$

2.5.1.3 LCC calculation using failure rate and maintenance labour rate

This approach considers the reliability of the equipment/ product by taking into account the failure rate as well as related costs in maintaining such equipment/ product. Kim et al. (2009) shows the LCC is derived at by using the equation below:

$$LCC = AC + CMC + PMC + HC \quad (6)$$

Where:

AC – Acquisition cost = Design + Manufacturing + Transport + Construction costs

CMC – Corrective Maintenance Cost

$$CMC = \frac{TOT}{MTBF}.(MMH_{CM}.LC_{CM} + MC_{CM}) \quad (7)$$

Where:

TOT – Total operating hours

MMH_{CH} – Mean Man Hour for corrective maintenance

LC_{CM} – Labour cost for corrective maintenance

MC_{CM} – Material cost for corrective maintenance

MTBF – Mean Time between Failures

$$PMC = \sum_{i=1}^{NoPM} \frac{TOT}{MTBM}.(MMH^i{}_{CM}.LC^i{}_{CM} + MC^i{}_{CM}) \quad (8)$$

Where:

PMC – Preventive maintenance

NoPM – Number of types of PM

MMH^{i}_{CM} – Mean Man Hour for preventive maintenance

LC^{i}_{CM} – Labour cost for preventive maintenance

MC^{i}_{CM} – Material cost for preventive maintenance

MTBM – Mean Time between Maintenance

HC – Hazard cost

$$HC = HCSA + HCSE \tag{9}$$

Where:

HCSA – HC Safety Failures = (TOT/MTBF) x PC_{SA} (10)

HCSE – HC Service Failures = (TOT/MTBF) x PC_{SE} (11)

PC_{SA} – Penalty cost per safety failure

PC_{SE} – Penalty cost per service failure

The LCC calculations contain variables which are assumed on instances where the quality of the information is questionable. One of the useful tools generally used to compensate for these probabilities is the effectiveness equation (Sinisuka and Nugraha, 2013). According to Blanchard et al. (1995), the effectiveness equations described as having numerous elements of probability with the similar objective to quantify the system effectiveness. This makes provision for lowest long-term cost of ownership and quantification is achieved by using the following equations (Blanchard, 2004):

$$Effectiveness = Availabilty \times reliability \times maintainability \times capability \tag{12}$$

$$System\ effectiveness = Effectiveness/LCC \tag{13}$$

Therefore, it is crucial to define the objectives to be achieved as well as to assess the availability of quality information to derive accurate results and to minimize the number of assumptions. This can be achieved by using the comparison of the formulae as described in the following section.

2.5.2 Life Cycle Cost Formulae Comparison

The LCC models and formulae presented in the sections above cater for numerous requirements depending on an organization’s objective. The table below provides a comparison of the formulae discussed above. The objective is to depict similarities and differences between formulae which can be used as reference for selection of the formula which best suit the organization’s objective.

On one hand choosing the most suitable formula to use for LCC analysis is important. However, equally important in the success of LCC calculations to portray a realistic cost image of the equipment/ product, is the dependency on the availability and quality of data.. The data must include the actual costs incurred by organizations, as well as operational data containing all maintenance activities performed (both planned and unplanned), running costs and operational parameters. Hence it is imperative that the quality and accuracy of the data is also considered throughout the assessment of the LCC as poor data can depict a cost image which does not reflect the true cost.

Table 2-2 – Comparison of LCC formulae (derived by researcher)

		Formulae		
		Simulation Based Acquisition	**Time value for money & failure rate**	**Failure rate & maintenance labour rate**
		Jing et al. (2012)	Waghmode and Patil (2016)	Kim et al. (2009)
Formulae reference number		(1)	(2)	(6)
Similarities and Differences	Acquisition cost	A	A	A
	Maintenance cost	A	NA	A
	Operating cost	A	A	NA
	Disposal cost	A	A	NA
	Time value for money	NA	A	NA
	Failure rate	NA	A	A
	Labour rate	NA	NA	A

A – Available; NA – Not Available

As noted in Table 2-2, there is an existence of a gap within the LCC models and formulae presented above. Each model/ equation is more applicable to specific cases and only caters for some components of the LCC phases/ stages and lacks the combination of features from one another. Hence, an integration of these models and formulae can allow decision makers to incorporate more features, resulting in a precise and accurate LCC analysis being achieved. This integration is proposed by the researcher in the following section. This approach, as well as the motivation therefore, is explained.

2.6 Proposed Integrated LCC Framework

It is evident that for a more realistic LCC analysis, the entire life cycle as well as cost contributing factors must be considered. As stated above existing models and formulae cater separately for phases of a product's life cycle.. Hence, the researcher proposes an integrated LCC framework which allows for a combination of all the components within LCC analysis.

As illustrated in Figure 2-9, the proposed integrate LCC framework initiates with a vital stage which is used to select and implement the most appropriate LCC Model(s) which will suit the organisation's requirements. As stated by Lindholm and Suomala (2007) the decision as to which model(s) to use is also dependant on the availability of data and the quality thereof.

These models are explained in detail in section 2.4. The benefits of combining these models include the ability to clearly define the objectives, outline the expected outcomes from the LCC analysis and ensure that all cost associated with the LCC analysis are considered.

For this framework the activity based costing (ABC) and cost breakdown approaches are combined. Firstly, the reason for choosing the ABC approach is to ensure that each activity performed on the HPGR can be accounted for and all associated costs are included. Secondly, the reason for the cost breakdown approach is that the HPGR is broken down into various components and life cycle phases (i.e. planned major overhauls/ mid-life refurbishments). Hence, each life cycle phase can be analysed and major cost drivers can be easily identified.

As the model(s) have now been identified, a well-structured implementation plan is now possible and all relevant data can be identified and collected. The data, with variables, will then be input into a computerized excel spreadsheet which will calculate the expected LCC based on the LCC formulae.

The next stage of the proposed framework will be the LCC quantification/ calculation. From Table 2-2, the simulation based acquisition (Jing et al., 2012) as well as the time value for money and failure rate formulae will be used. The reason for this approach being to ensure all LCC phases are considered while ensuring that aspects like time value for money, the cost of maintenance activities and maintenance strategies utilized are considered.

Thus the initial acquisition, manufacturing, transport, construction and commission costs in the LCC analysis are accounted and compounded annually based on inflation/ interest. As a result this will be applicable to systems where certain components need to be replaced after a certain period (hours or years) of operation. This is the case with HPGR as well as for most engineering systems.

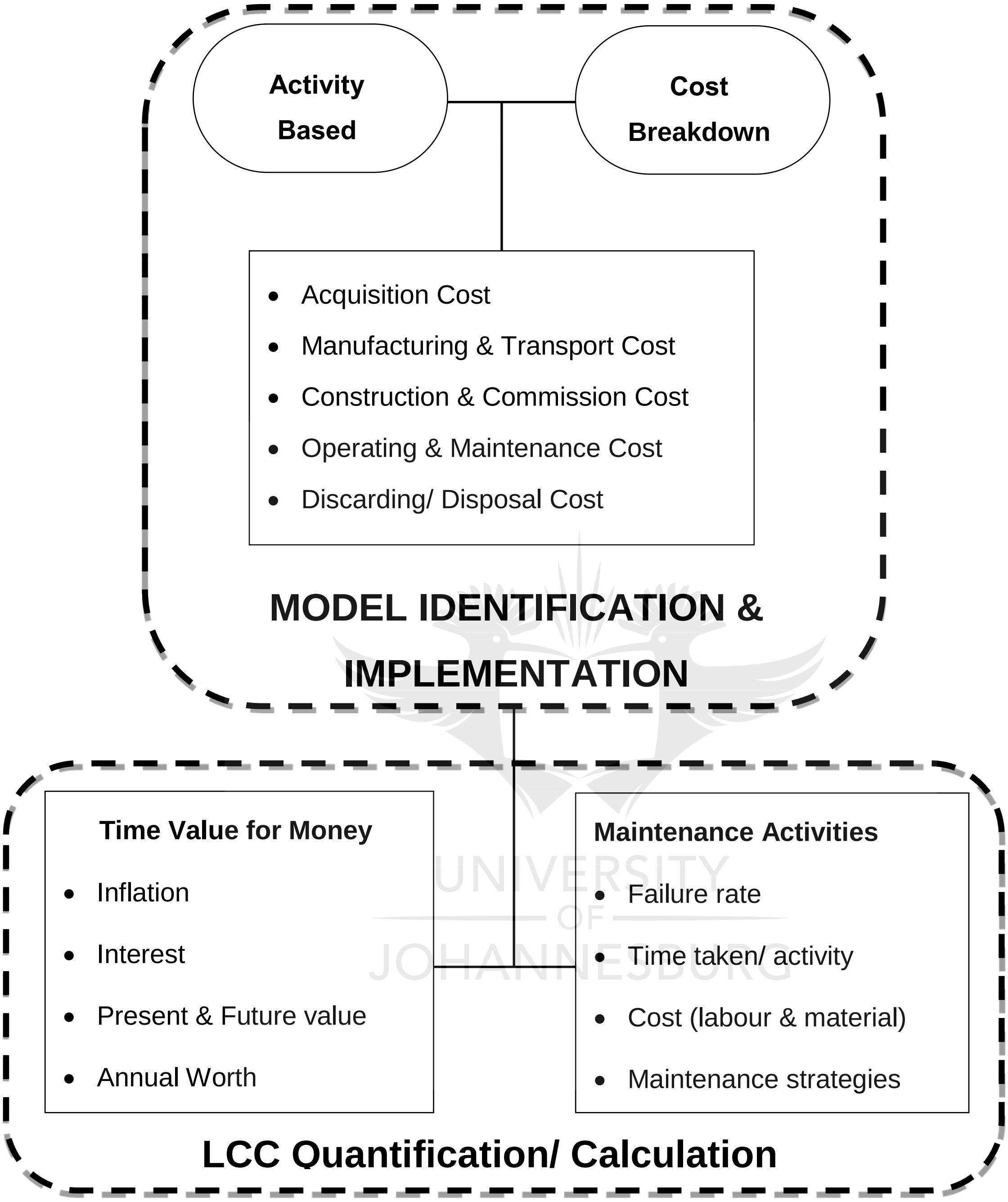


Figure 2-9: Proposed Integrated LCC Framework

Furthermore, the formulae allow for accurate cost capture of all the operational and maintenance costs during the HPGR operational and maintenance life cycle which will present a more accurate cost image. Thus, the perceived benefits for the integrated proposed framework will allow the identification of the following:

- Resources consuming activities and associated costs;
- Cost drivers associated per activity;
- Quantification of cost rate per cost driver; and most importantly
- Achieve the correct allocation of the activity cost drivers against the appropriate product lifecycle phase. This is achieved by quantifying the cost driver units at each product lifecycle by considering the volume of product produced against the costs consumed by the product. This will dictate the highest lifecycle cost drivers and the correct cost rate(s) that can be applied at a specific lifecycle phase.

Therefore, as much as the availability and quality of data is of the uttermost importance for the LCC analysis, equally important are the factors which influence the LCC analysis. These must be considered and strategies implemented to control or mitigate these specific factors.

2.7 Factors affecting LCC

The combination factors such as cost growth (both acquisition and operational costs), rising inflation, budget restrictions, reduction in capital expenditure and growing competition have prompted an awareness of the total cost of products, equipment and systems (Fabrycky and Blanchard, 1991). It is also noted that not only are the acquisition costs increasing exponentially, but that the operating and maintenance costs are also increasing drastically. This is due predominantly to a combination of cost growth and inflation factors as a result of the following (Chen et al., 2011; Fabrycky and Blanchard, 1991:

1. Continuous design changes during the design and development phase
2. Changing of suppliers (designers/ manufacturers) in the purchasing of system components
3. Inferior quality of products, equipment and systems in use
4. Inferior maintenance strategies – reduced system efficiency
5. Inaccuracies in LCC estimating and forecasting
6. Unforeseen occurrences and issues

The current challenges faced by the industry are further amplified by additional problems pertaining to the quantification of the total LCC for the product’s entire life cycle (Chen et al., 2011):

- Budgeting strategies employed by organizations are often inflexible regarding the re-allocation of funds to aid with cost improvements during the operating and maintenance phase.

- Individual costs factors are often incorrectly allocated although these costs are identified - direct costs are allocated as indirect costs (and vice versa).
- Current accounting management policies and models do not always allow for a timely and more realistic assessment of total LCC. Furthermore, it is often challenging (if not virtually impossible) to determine any costs incurred during the product's life on a functional basis.
- Total system cost is often not visible at the acquisition phase, particularly the costs associated with the operating and maintenance as well as disposal of the product/ equipment. This is illustrated in Figure 2-10 which depicts the LCC visibility problem as associated with an "iceberg" effect.

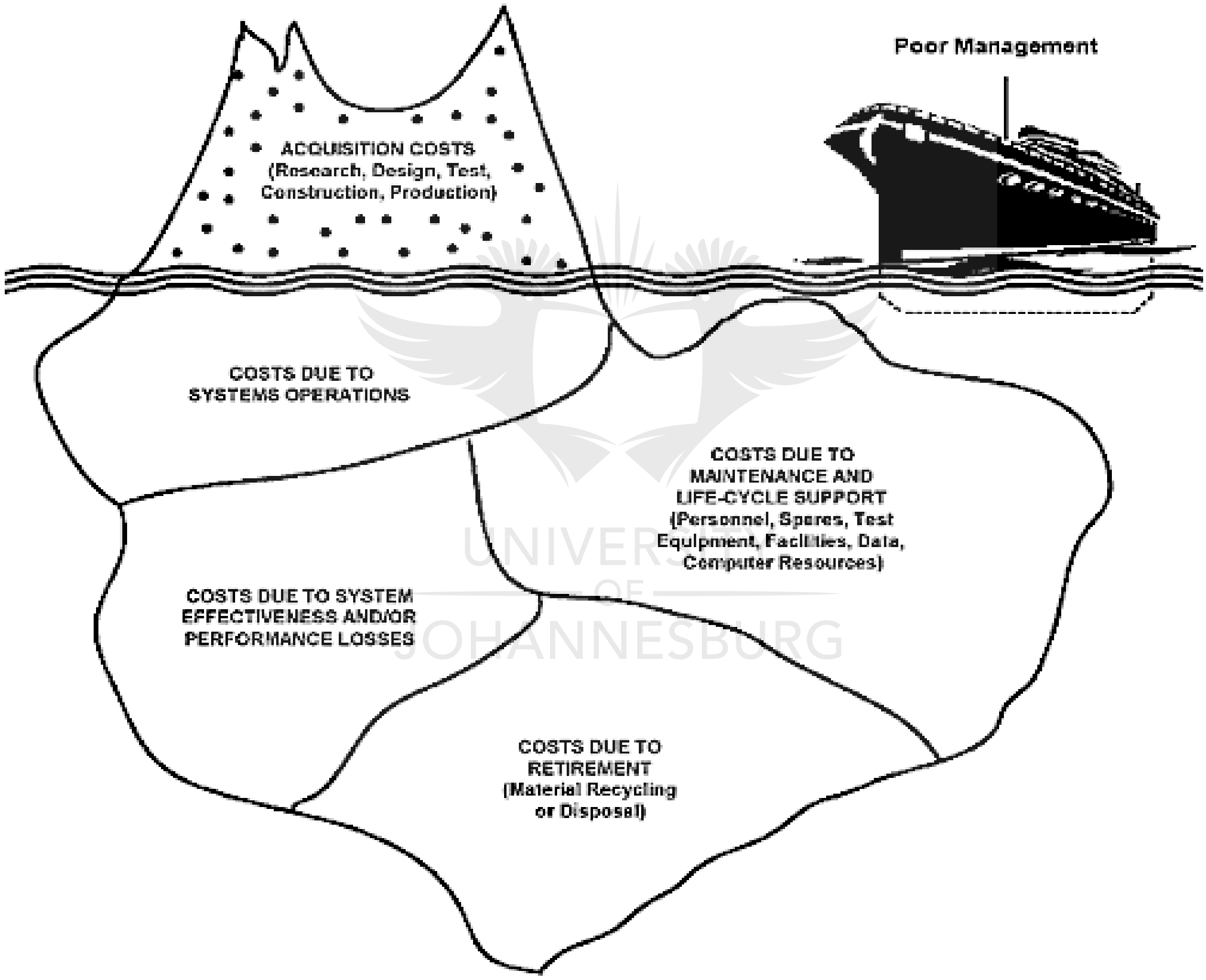


Figure 2-10: Life cycle cost visibility (Woodward, 1997)

The current trends show a continued increase in cost of ownership of equipment. This is anticipated to worsen unless an improved level of cost consciousness and control thereof is assumed by equipment suppliers and designers. Economic feasibility studies must not only include a portion of the costs incurred by a product or a certain phase of the product's life cycle but must address all the costs and phases of the product's entire life cycle (Jing et al., 2012).

Kleyner et al. (2004) further noted that the reliability of the product/equipment/ system has a major influence in the total LCC – higher reliability yields lower LCC but adversely increase the acquisition cost of such a product/equipment/ system. Therefore, a probable solution would be to quantify an ideal reliability target which is satisfactory to the organization's requirement (both operational and economical) and in return corresponds to lower or much expected total LCC (Wu et. al, 2006). It is without any dispute that understanding the influence of reliability on the total LCC will facilitate better control of the total LCC.

2.8 Reliability - Factor Influencing LCC

As noted by Al-Chalabi et al. (2014), the reliability of equipment, systems or product extensively influences the total LCC; hence the level of reliability achieved is a function of investment made into a reliability program at the inception life cycle. From research, it appears that more investment made into reliability improvement early in design is claimed to improve efficiency and availability of equipment and system during the operational phase.

Understanding the concept of reliability as defined by O'Connor and Kleyner (2011):

"The probability that an item/system will perform a required function without failure under specified conditions for a specified period of time".

According to Blanchard (2004), Reliability can be defined as:

"The probability that a product or system will perform in a satisfactory manner for a specified period of time when operated under specified operating conditions".

Reliability can also be expressed as the number of failures over a period of time.

Generally, when low reliability levels are observed after delivery of the system, the costs to improve reliability are exorbitantly greater than during the development phase. This is attributed to various factors such as: tight delivery schedules, budget constraints and unforeseen technology problems (Al-Chalabi et al., 2014). Moreover, catastrophic consequences of high maintenance cost and low availability of systems have led to the requirement by end-users for high availability, reliability and maintainability, as well as high mean time to failures and in-between failures (Saraswat and Yadava, 2008).

As noted previously, equipment and systems are not always able to fulfil these requirements as well as their design intent due to inferior design and the lack of product support. However with appropriate attention to reliability, availability, maintainability and supportability (commonly referred to as

RAMS) in the design, manufacturing, operation and installation phase, the number of failures and their consequences could be minimized extensively (O'Connor and Kleyner, 2011).

Numerous design methods and theories are available in literature (as detailed in numerous references, handbooks and standards) which is interrelated to design for RAMS. The relationship and interdependencies of RAMS is illustrated in the Figure 2-11: . Although these methods and theories are applied with noticeably more or less success in some industry sectors, in general, industry makes minimal use (if any at all) of these known reliability improvement techniques.

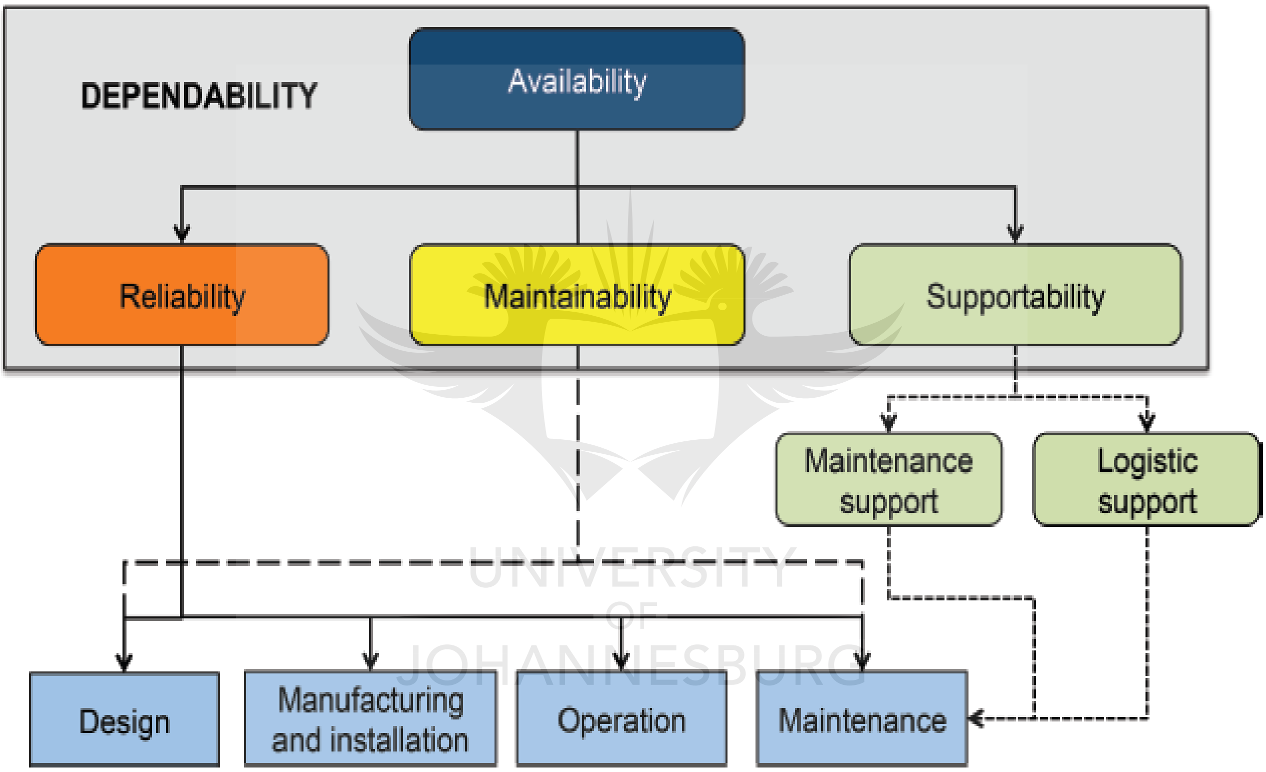


Figure 2-11: Main attributes of dependability and the lifecycle (https://reliabilityweb.com/)

2.8.1 Reliability Analysis Approach

Reliability is a vital factor in the planning, design, and operation of any engineering equipment or systems (Dhillon, 2012). The concept of importance measure is vital for any reliability analysis as it can be used to establish the criticality of each component within a given system (Andrews and Beeson, 2003). This enables precise identification of contribution to low reliability, thereby, facilitating sound decisions in necessary modifications that will improve overall system reliability (Wu et. al, 2006).

The simplified relationship between LCC and reliability is depicted in Figure 2-12. From the figure, it is clear that low LCC is a function of deriving equilibrium between acquisition, operating and maintenance costs. This rationale forms the core basis of the hypothesis that the researcher aims to validate, as well as to quantify the percentage cost distribution of each life cycle phase towards the overall LCC.

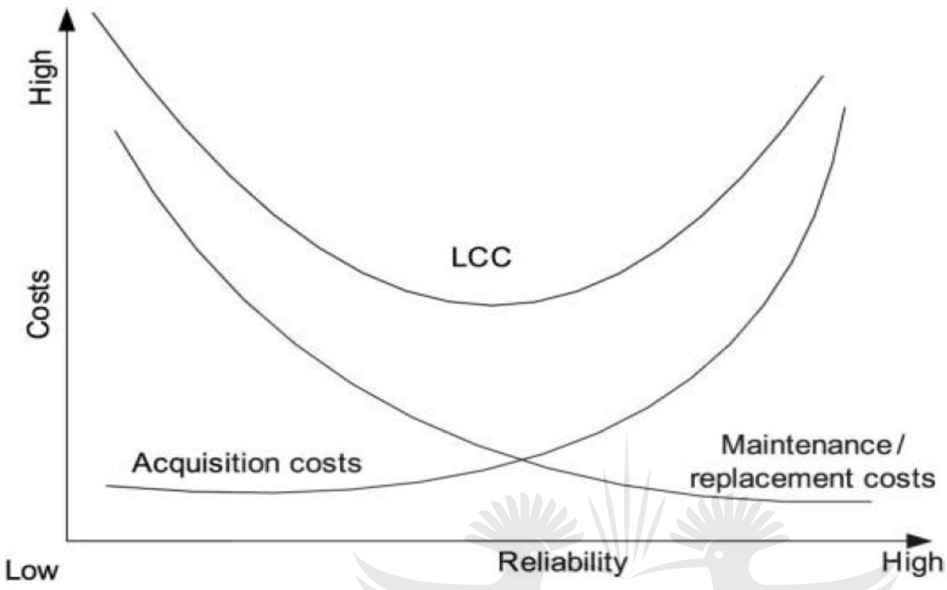


Figure 2-12: Relationship between reliability and LCC (Wu et. al, 2006)

Therefore, in order to improve the overall reliability focus should be directed at component(s) which have the greatest impact on reliability while yielding low lifecycle costs. From this an appropriate reliability management strategies can be derived and implemented in order to ensure high reliability at low LCC.

2.8.2 Reliability and Maintainability Management

Reliability and maintainability management is increasingly becoming a vital part of their asset lifecycle management strategy for various industries, including mining and manufacturing, with numerous research efforts on this subject globally over the past decades. Great emphases have been drawn to the lack of effective maintenance management which has led to substantial financial loss by numerous organisations as a result of substantially low reliability levels (Madu, 2005).

Furthermore, the research by Sinha (2015) outlined the importance of having maintenance strategies and models which can be implemented with an objective of improving the overall efficiency and availability of the plant. However, these strategies are exclusively reliant on the plant personnel's experience and skills for effective execution. Without a proper and methodical approach, maintenance functions cannot be executed satisfactorily (Sinha, 2015).

Indeed, maintenance management requires a wide range of technical knowledge, skills and on-site exposure in order to analyse and fulfil maintenance requirements through efficient management and effective implementation of the organisation's maintenance strategies (Lam et al., 2010). Efficient management of scheduled/planned maintenance as well as proper implementation and execution of preventative maintenance can greatly contribute to uninterrupted plant production due to improved reliability and availability of equipment (Sacks et. al, 2012).

Therefore, the availability of equipment is dependent on reliability, proper maintenance planning (as shown in Figure 2-11) and efficient execution of maintenance activities. Successful execution of these activities is dependent on a number of factors which include allocated resources skills and experience, sequencing of tasks, and economic factors.

To achieve effectiveness and efficiency, a logical approach which can be implemented in stages, is necessary. These stages are generally referred to as actionable program for maintenance illustrated in the figure below. These stages are executed from the outer to inner circle. The outer circle represents the preparation, planning and devising of maintenance strategies and how these can be implemented. The middle circle represents the implementation of these strategies where regular inspections and preventative maintenance are performed. Finally, the inner circle represents more planned maintenance which must be performed in order to achieve the anticipated life expectancy of the equipment.

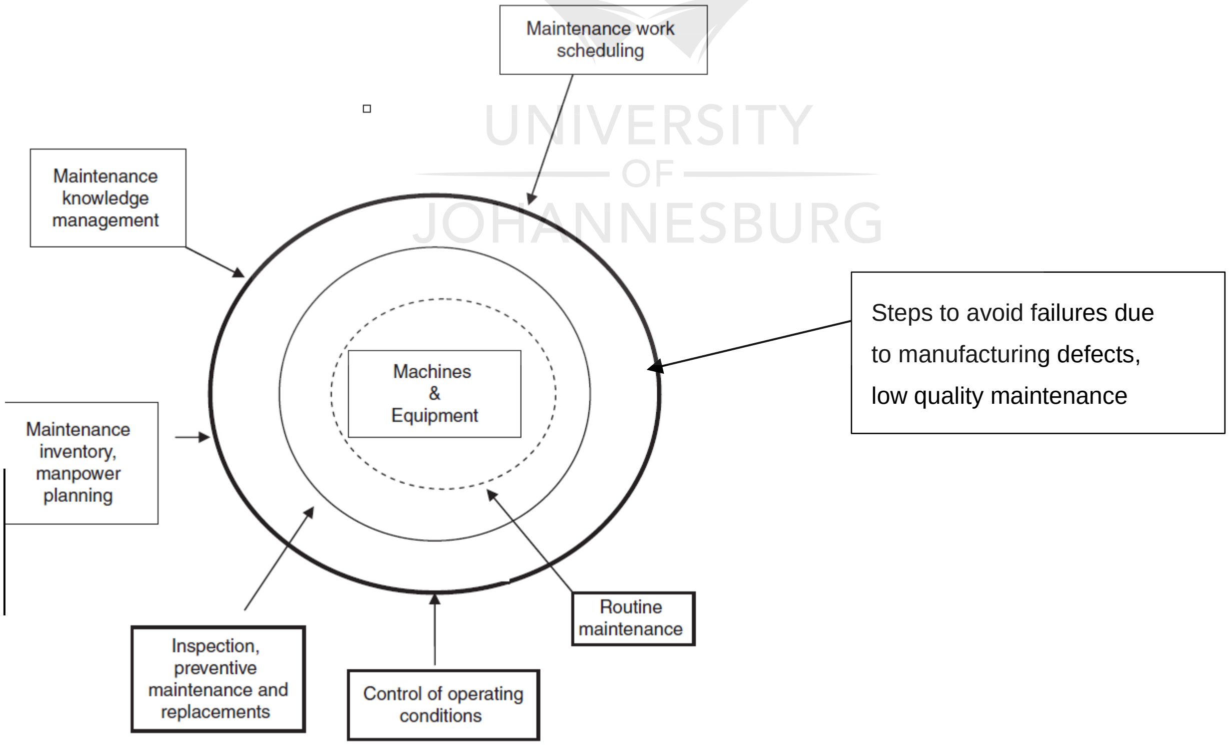


Figure 2-13: Actionable program for maintenance (Sinha, 2015)

2.8.3 Reliability Information System – Data Quality

Information management is crucial to sound and efficient maintainability and reliability management. Information is required to categorize crucial components within a system, to analyse the modes of failure and the causes of such failures (Madu, 2005). Therefore, the more accurate the information, the better the analysis of reliability of the LCC with the result that the largest cost driving component(s) is identified. However, regardless of the quality of available data, the life-cycle cost analysis incorporates elements of uncertainty as part of the input data and is classified on the basis of varying assumptions and estimations, pertaining to the development of costs and revenues in an extended period (Obiajunwa, 2013).

There are a number of stages in a product development phase which are undertaken by many participants in the supply chain. Therefore it is imperative to a have a central system that interconnects all relevant participants. As a result, Madu (2005) proposed an integrated enterprise resource planning (ERP) system to formulate enterprise reliability data management (ERDM). The aim is to have a single view of information thereby ensuring that all participants have access to the latest and most accurate information. Furthermore, this approach eradicates the duplication of information and maximizes the benefits through knowledge sharing. The system is illustrated in Figure 2-14.

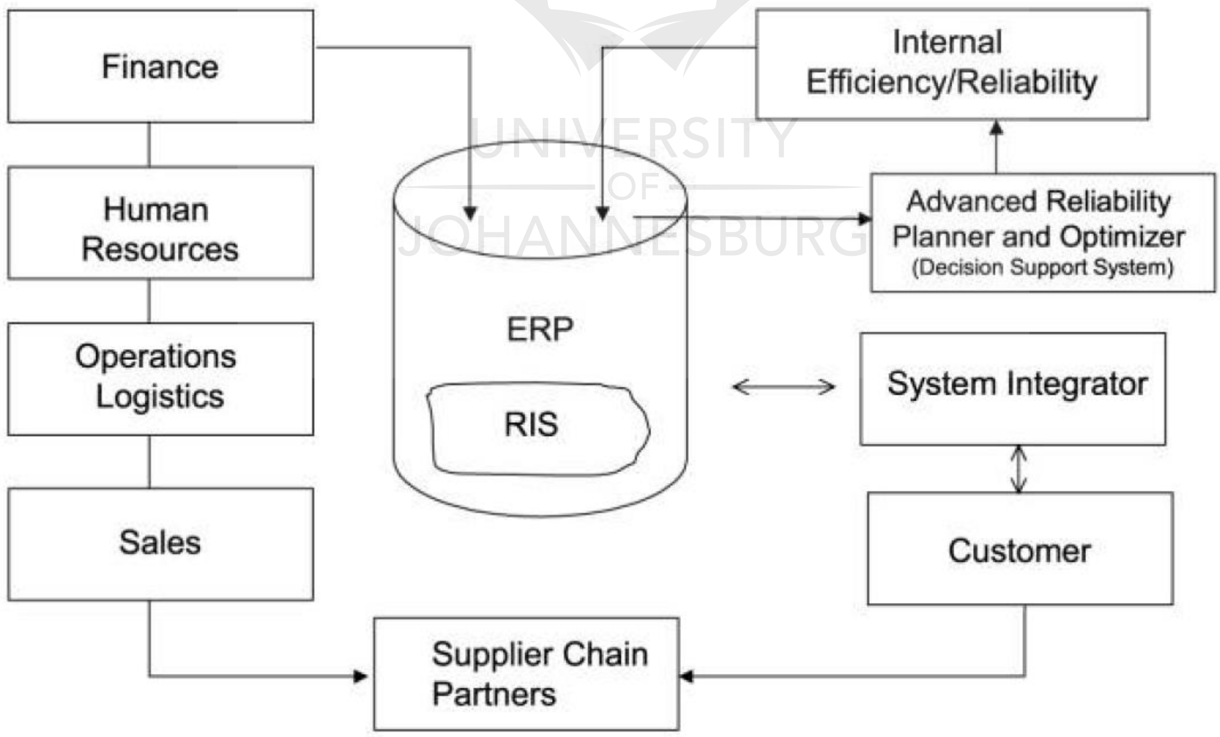


Figure 2-14: ERDM – Reliability information system integrated into ERP system (Madu, 2005)

From Figure 2-14 it is evident that information on reliability management emanates not only from the customers but also from within the organisation and its external suppliers. The use of an ERP ensures that reliability information is updated on a more frequent basis and is accessible to all timeously thus assisting in better decision making.

2.8.4 Maintenance Strategies – Reliability Improvement

Maintenance plays a crucial support role for the plant process in ensuring that production targets and the annual profit as anticipated by shareholders, are met (Obiajunwa, 2013). It also contributes greatly to the business success and continued market growth in this highly competitive business environment. Hence, organisations implement various maintenance strategies to ensure the optimum achievement of production and efficient performance of equipment. These strategies include routine preventative maintenance (PM), corrective maintenance, total productive maintenance (TPM), condition based maintenance and reliability centred maintenance (RCM) (Tabucanon and Dahanayaka, 1989).

According to Hipkin and De Cock (2000) certain barriers exists which hinder satisfactory maintenance management. These include: lack of top management support and commitment; lack of time to complete the maintenance analysis; lack of historical data; lack of plant and process knowledge; and fear of production disruptions, interference in production/operations.

Furthermore, Marquez and Gupta (2006) emphasized the importance of maintenance management and derived a framework to establish efficient maintenance management in an organization governed by three essential support pillars: the maintenance engineering methods pillar; the information technology pillar; and the organizational pillar (emphasizing the importance of human aspects). Furthermore, they identify the need to control scheduling of maintenance activities, control of inventory of maintenance materials and the quality of maintenance actions for effective maintenance management.

2.8.4.1 Preventative Maintenance

Preventative maintenance (PM) consists of maintenance activities that are conducted on a system or component after a specified period of time in operation (Herbaty, 1990). This type of maintenance is dependent on the projected probability that the system or component will break down or experience a decline in efficiency in the specified period. The preventive activities undertaken may include parts replacement, refurbishment, equipment cleaning, re-torqueing, lubrication, and adjustment.

2.8.4.2 Corrective Maintenance

In corrective maintenance, the concept to prevent system or component failures is further expanded for the improvement of equipment in order to eliminate equipment failure through improving the reliability (Ahuja and Khamba, 2008). The prime difference between preventive and corrective maintenance is that a failure or deterioration in efficiency must occur before corrective actions are taken. The prime purpose of corrective maintenance is to improve equipment design weaknesses, maintainability, reliability, and safety in order to reduce deterioration and failures with an objective of maintenance-free equipment of maintenance-free equipment. Figure 2-15 below illustrates the time indication for completion of one corrective maintenance cycle.

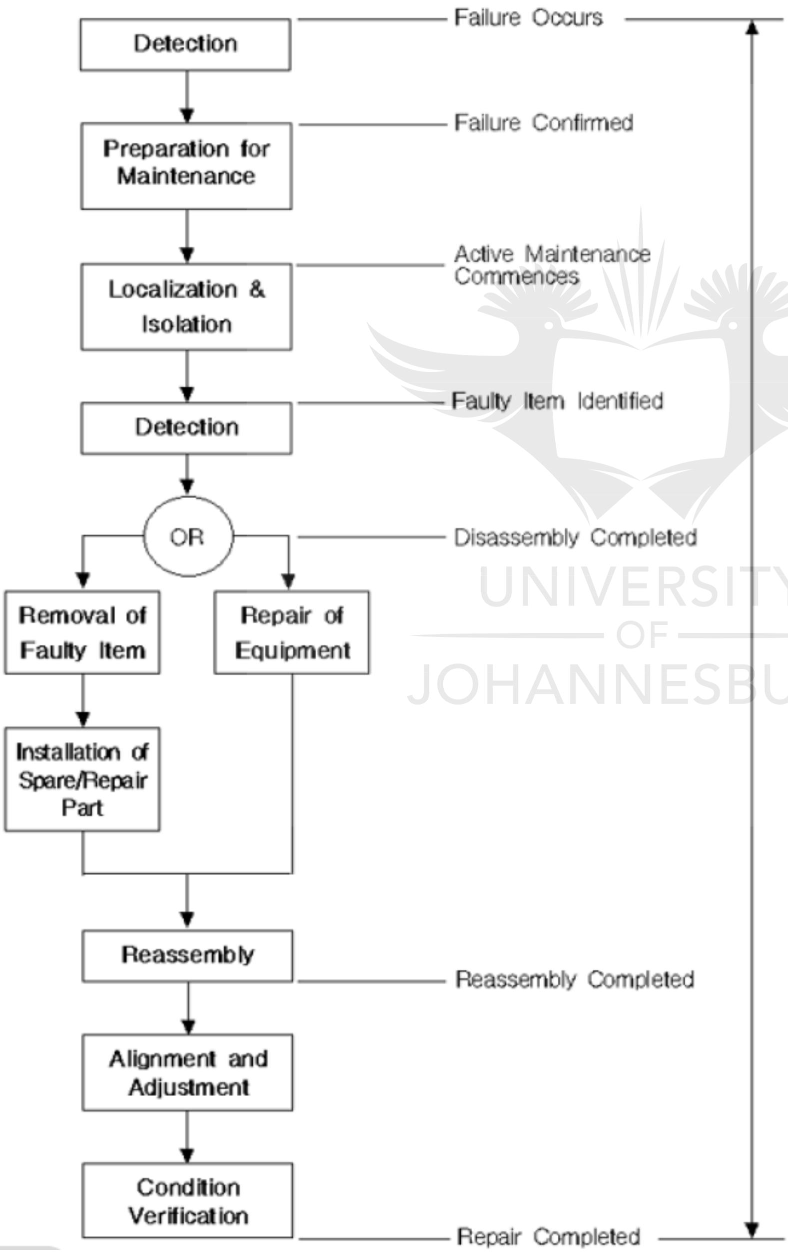


Figure 2-15: Corrective maintenance cycle (Blanchard, 2004)

2.8.4.3 Total Productive Maintenance

TPM provides an all-inclusive life cycle analysis approach to equipment management that reduces production defects, equipment failures, and accidents (Ahuja and Khamba, 2008). It involves all individuals in the organization, from senior management to production staff, as well as production support groups and external suppliers. The objectives of TPM are to continuously improve the availability of systems as per design intent and to prevent the aging of equipment in order to achieve maximum effectiveness (Ravishankar et al., 1992). Hence, these objectives are reliant on support from management as well as continuous utilization and training of work groups, as well as performing minimum quantity of activities to achieve progressive improvements. The implementation plan is illustrated in the figure below.

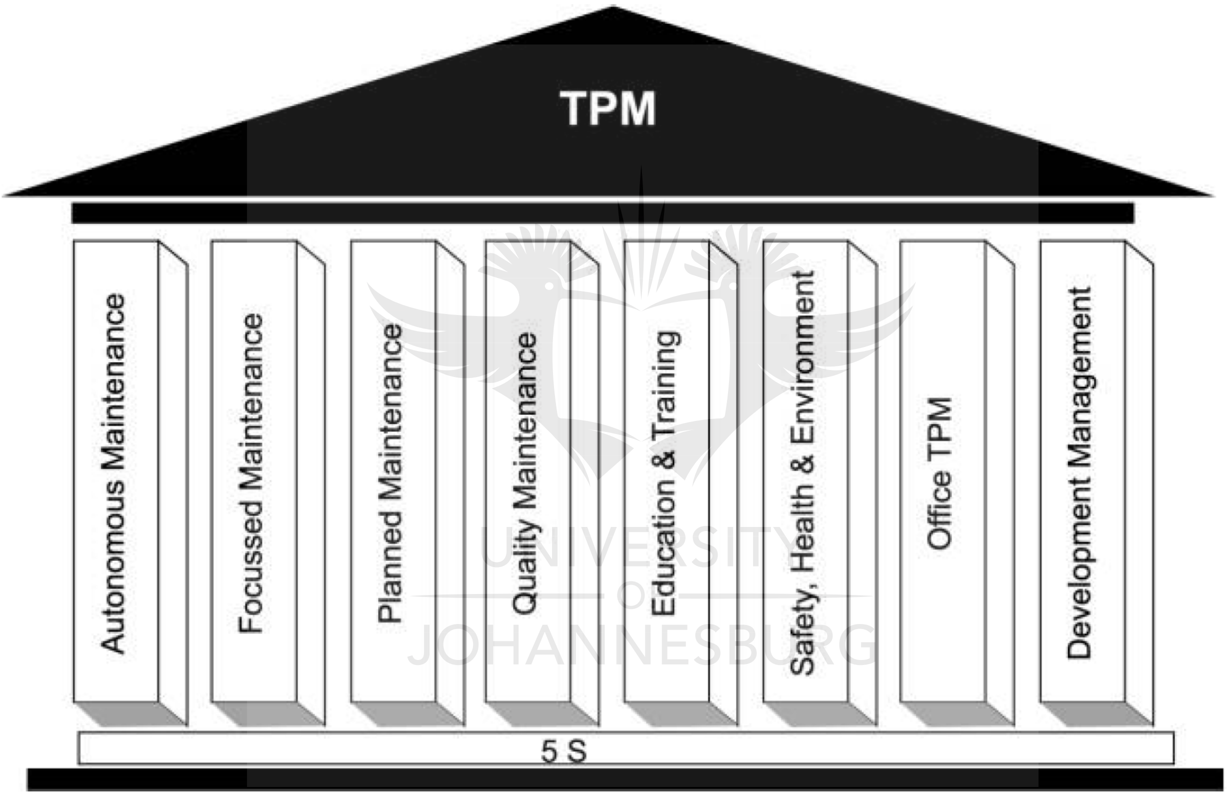


Figure 2-16: TPM implementation – eight pillar approach (Ahuja and Khamba, 2008)

2.8.4.4 Condition Based Maintenance

Condition-based maintenance (CBM), also known as predictive maintenance, entails monitoring the conditions of the system or component and making maintenance decisions dependent on its condition. It is regarded as an alternative method of preventive maintenance as it is not based on the component's time in operation (Barbera et al., 1999). Monitoring of the component's conditions may be performed continuously through using instruments, or, periodically through visual inspections.

Some researchers such as Kumar and Chaturvedi (2011) have used artificial intelligence models such as fuzzy logics and neural networks for maintenance modeling and decision making. Implementations of such models may require high human resources inputs; however these models have proven to be successful in certain instances.

2.8.4.5 Reliability Centred Maintenance

Reliability centred maintenance (RCM) is a systematic approach to maintenance planning and it takes into consideration the reliability aspect of each component by analysing the function of such component, the causes of failures and the consequences of the failures (O'Connor and Kleyner, 2011). A number of computer-based software is available to assist in formulating appropriate maintenance policies for crucial systems and components through statistical lifetime distributions in a more structured manner. The processing function of the RCM software is based on the logic illustrated by Figure 2-17.

RCM comprises of a seven (7) step philosophy to meet maintenance challenges (Samantha et al., 2001). These steps comprise of selecting plant areas that are crucial to production, establishing their key performance and functions criterions, determining possible failure modes and their consequences, determining potential function failures, selecting reliable and feasible maintenance strategies, scheduling and implementing selected strategies, and optimizing strategies based on outcomes (Moubray, 1997).

The various tools employed for affecting maintenance improvement include Fault Tree Analysis (FTA), Failure mode effect and criticality analysis (FMECA), Physical Hazard Analysis (PHA), Failure mode and effect analysis (FMEA), Optimizing Maintenance Function (OMF) and Hazard and Operability (HAZOP) Analysis.

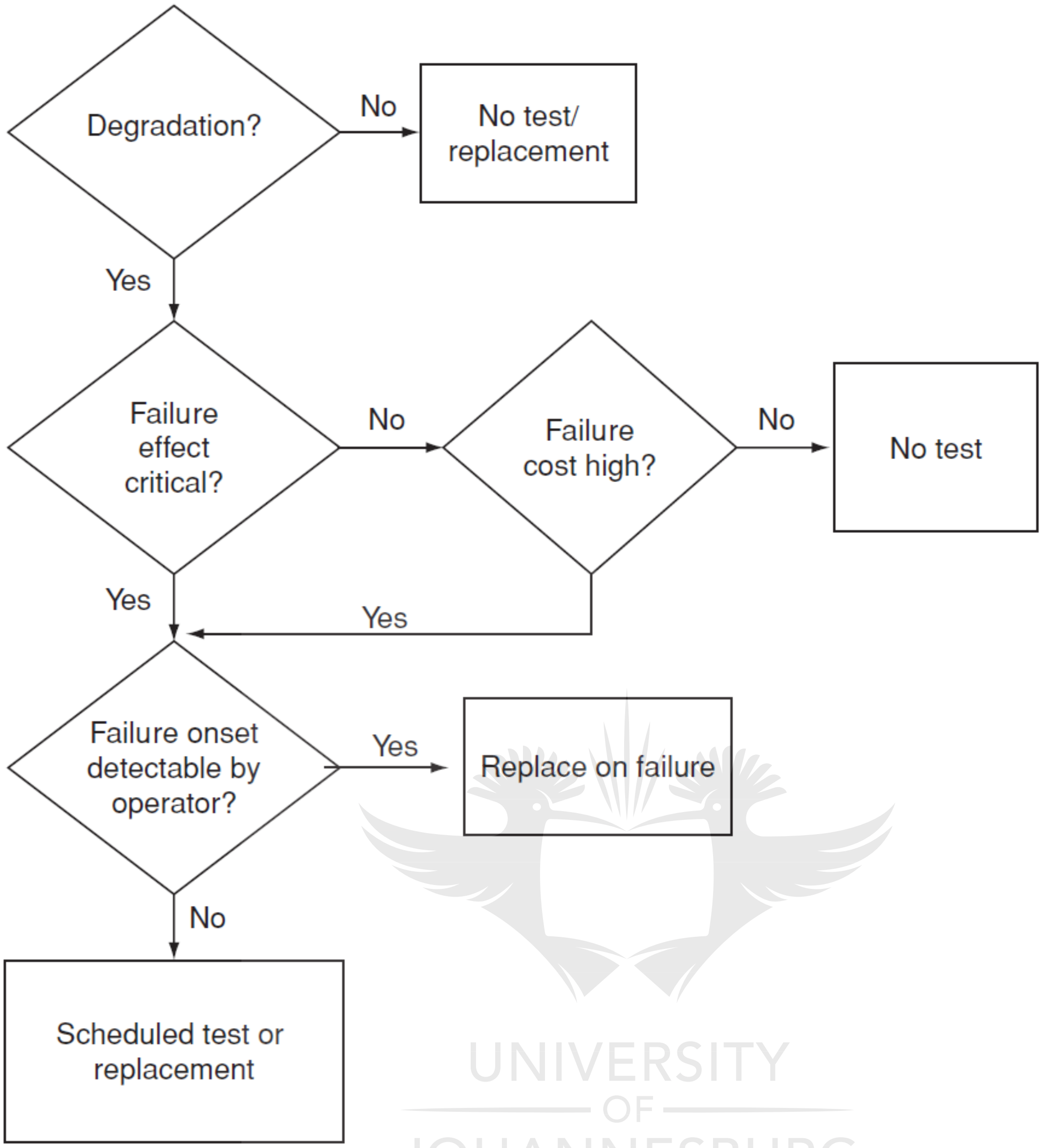


Figure 2-17: RCM logic (O'Connor and Kleyner, 2011)

Satisfactory maintenance of equipment and machines relies extensively on the knowledge of how the equipment/ machines are designed and operated as well as how these may fail and how such failures can be resolved (Sinha, 2015). Hence, it is worth noting that equipment failing unexpectedly results in severe production interruptions. These failures may be caused by one, or a combination of the following: manufacturing defects; fatigue; wear; material deterioration; corrosion; abnormal operating conditions; temperature effect; vibration and shock; and sub-standard quality of maintenance repairs (O'Connor and Kleyner, 2011).

To improve plant reliability and to avoid unplanned breakdowns, sound maintenance and reliability strategies must be established on facts obtained through analysis of quality measurable operating data (Balaba. and Ibrahim, 2011).

2.9 Conclusion

The chapter provided an in-depth insight of life cycle costing aspects. This included the understanding of the LCC concept, available LCC models, implementation of LCC analysis within an organization and the benefits thereof, as well as ways of quantifying LCC through the use of existing calculation formulae. It also echoed the importance of data availability and quality which plays a vital role in the success of the LCC analysis.

The chapter further analysed factors which influence LCC as well as the impact of reliability on the overall life cycle cost. It emphasized the importance of sound and efficient maintenance strategies which must be implemented and practised regularly in order to control, manage and minimize life cycle cost.

From the literature review it is evident that maintainability and reliability management should be regarded as a vital part of a corporate strategy. It should no longer be a subject left at the strategic level for consideration but one that receives the attention it requires, and must be seen as a critical business enabler for corporate performance and economic survival. Once senior management admits that maintainability and reliability management plays a pivotal role in contributing to organizational market share and competitiveness, a need will be evident to develop and implement support frameworks and action plans to support this drive for efficient reliability and maintenance management within the organization.

In order to achieve this, a change in mind-set of the organisation is necessary regarding its perception of, and attitude towards a sustainable and efficient reliability and maintenance management to be in place. Hence, implementation of appropriate lifecycle costing tools for equipment in operation is necessary in order to quantify the actual life cycle cost and outline the major cost drivers as well as to derive maintenance management strategies to control the total LCC.

The following chapter will outline the research method to be used to further analyse the research problem.

3 CHAPTER 3 – RESEARCH METHOD AND DESIGN

In order to quantify the total cost of ownership of the HPGR, an in-depth knowledge and understanding of the LCC analysis is required. Hence, a structured approach is necessary to facilitate this process and this can be achieved through the utilization of a sound research methodology.

This research study will analyse the research objectives and present the research investigation in a case study format. According to Gomm et al. (2000), a case study is an appropriate method of investigating empirical research for a real life problem or situation. In context of a case study definition, this research study will investigate the LCC of HPGR (installed in a Platinum mine in South Africa) during its operating and maintenance life cycle. Hence, a case study is adequate in presenting the operation, functionality and maintenance of the HPGR as well as all the relevant operating data, maintenance practices and operational costs.

Most importantly, the aim of this chapter is to compare available types of research methods and to select the most suitable research method for the case study. For this research, motivation is outlined for selecting the quantitative approach as the most appropriated research method for addressing the research objectives as well as to provide answers to the research questions.

3.1 Quantitative Research Approach Definition

According to Worthington (2006), quantitative research is a process which investigates descriptive analysis of a relationship between variables with an aim of confirming, measuring, explaining or validating phenomena. Tallent-Runnels et al. (2006) explains a variable as a quantitative expression which can alter as a result and is expressed as a value.

Typically, quantitative research concludes with an outline of the verification process which either qualifies, or disqualifies, the hypothesis tested through a deductive approach (Worthington, 2006). Greener (2008) defines a deductive approach as a systematic process which commences firstly by evaluating a theory, secondly establishes a hypothesis from the theory which relates to the research objective(s), thirdly continues to test and lastly validates the theory.

Furthermore, Bryman and Bell (2015) defines quantitative research as a process that pertains to the generation of quantitative data which can be subjected to extensive quantitative analysis in a formalized and stringent manner. Traditionally, quantitative research can be categorized into five approaches, namely: experimental, non-experimental, simulation, inferential and correlation (Bryman and Bell, 2015; Johnson and Christensen, 2008; Trochim et. al, 2008; Sukamolson, 2010).

These are described as:

Experimental approach: - with this approach certain variables can be altered to identify their influence on the other variables – cause and effect relationship. Hence, the researcher has ultimate control over the research environment as well as the derived results.

Non-experimental approach: - this approach is an inverse of the experimental approach. With this approach variables cannot be altered to identify their influence on the other variables. What this implies is that a relationship between variables can be noted but the researcher cannot assume a cause and effect relationship. Hence, the researcher has no control over the research environment or the results.

Simulation approach: - this approach entails a formation of a synthetic environment where pertinent data and information can be generated. The environment is formulated under controlled conditions in order to realise the dynamic behaviour of equipment and overall systems. This approach can also be useful in constructing models for understanding future conditions of equipment and overall systems.

Inferential approach: - this approach enables a formation of a database from which to deduce characteristics or relationships of population. Generally, this is conducted as a survey where a defined portion of the population is studied to determine its characteristics, and it is then concluded that the entire population has similar characteristics.

Correlational approach: - this approach examines variances of characteristics or variables of two or more units. A correlation is observed when one variable decreases or increases similarly with the other variable. Typically, data is gathered on the two or more variables in a particular group. This data are numbers that reflect the measurement of the characteristics of research hypothesis.

The above definitions from the various researchers depict commonality amongst the definitions, which is to understand the relationship between variables in order to prove the accuracy of a hypothesis.

3.1.1 Quantitative Research Strengths and Weaknesses

Sukamolson (2010) and Ramona (2011) summarized the strengths of quantitative research as follows:

- Objective method – it provides precision since it is standardized and definitive.
- Allows for statistical assessment between various groups.
- Indicates the comprehensiveness of attitudes held by people.

- Measures the level of trends, actions and occurrence.
- Provides results which can be summarized as statistics.
- Iterative process which yields accurate and meaningful results - data accuracy increases as the business gains experience.
- Can answer such questions as “How much?”, "How often?" and "How many?"

As with any other research approach, quantitative research has weaknesses. Sukamolson (2010) and Ramona (2011) summarized the weaknesses of quantitative research as follows:

- The methods of calculation quantification are complex and cumbersome.
- The results, particularly for this type of research, are usually presented only in monetary values and are often not easily understood by persons without experience.
- This approach has no universally accepted standards and information for implementation.
- Difficult to implement without an automatic processing tool.

It is evident that practical knowledge plays a vital role in understating how LCC is obtained in practice. The strengths of quantitative research support the objectives of this research which can lead to an in-depth understanding on how LCC of a HPGR can be analysed and its relationship to reliability can be established or confirmed.

Hence, it is pivotal that a systematic and structured approach is followed to yield a robust research design. The following section provides a comparison of various quantitative research methods and an explanation of why this research approach was selected.

3.2 Research Method Comparison

Generally, there are two distinct research methods commonly used in the research field, namely: quantitative (which is already explained in section 0) and qualitative research method.

Qualitative research method utilizes in-depth interviews in order to discover underlying desires and motives by the research population (Johnson and Christensen, 2008). According to Greener (2008), this is an inductive approach which commences by outlining the focus of research (such as economic issues or a business problem within an organization, social problems facing a specific community, etc.) and concludes by generating a theory from the research through intense investigation by utilizing various research methods.

In comparison, the qualitative research method involves an understanding of a relationship between variables through validation of a theory. There are a number of research types and as a result it is not simple to quantify the exact number of research types available as researchers may employ different criteria to classify research types. A summary is provided in the figure below to assess the best suitable research method based on a situation (Sukamolson, 2010). Generally, research can be classified into 3 main sections based on (Sukamolson, 2010; Kumar, 2005):

- The application of the research study;
- The objectives in undertaking the research; and
- How the information is collected and sought.

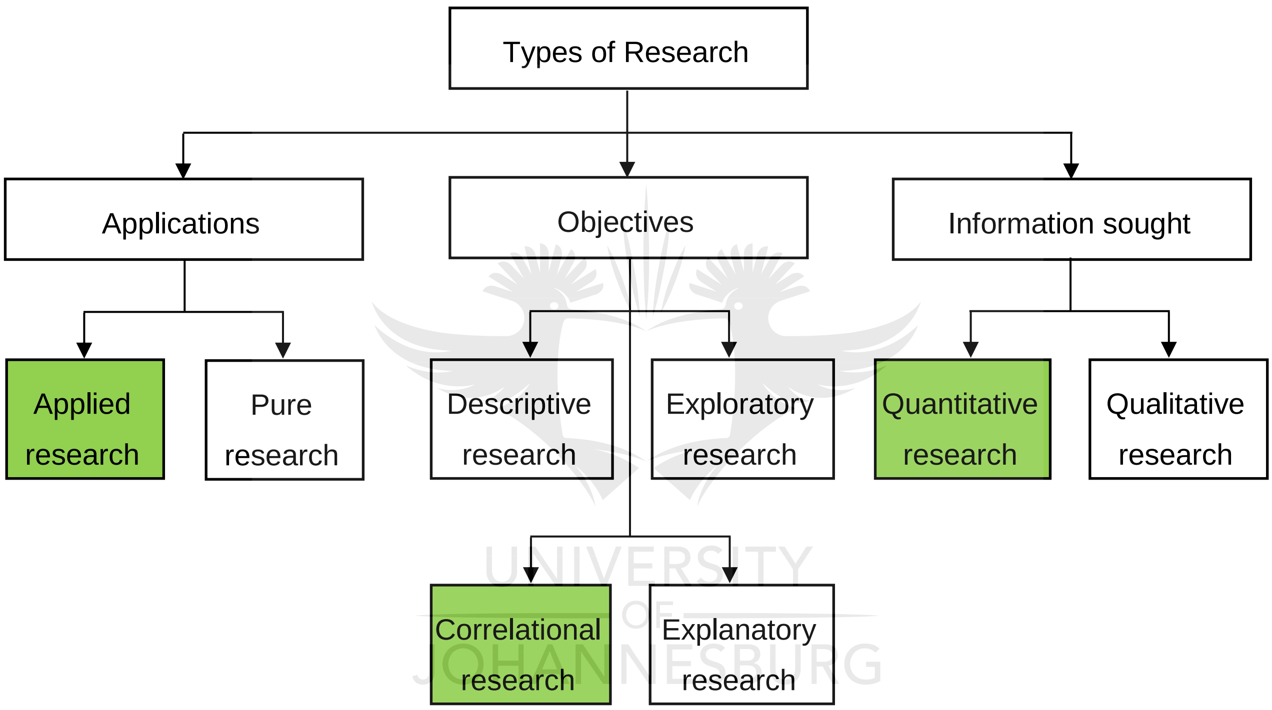


Figure 3-1: Types of research (Sukamolson, 2010)

As stated previously, selecting a research method is governed by the objectives to be achieved by the research study. The main objectives of this research were to address the following research questions:

- What is the LCC of a high pressure grinding roll (HPGR) during its operating and maintenance cycle?
- What are the key cost drivers impacting LCC of an HPGR?

From the figure above, the selected research approach is highlighted in green and the reasons for the selection are explained. Firstly, the research questions based on the "Information sought" best favour the quantitative research approach. The reason for this is that to quantify the LCC of a HPGR during its operating and maintenance cycle as well as to identify key cost drivers actual costs have to be collected and calculated using empirical formulae.

Secondly, the research questions based on the "Objectives" best favour the correlation research approach. The reason for this is that in order to reduce the LCC and improve reliability, the relationship between the LCC and reliability must be proven. As a result an influence of one variable over the other must be observed.

Finally, the research questions based on "Application" best favour the applied research approach. The reason being that applied research investigates and solves research problems by employing universally known and proven principles and theories. According to Rajasekar et al. (2006), applied research is concerned with real life problems such as increasing machine efficiency, gaining factor of production and reducing operational costs.

From the selected research approach a robust research method and design process can be derived and discussed in-depth in the section that follows.

3.3 Research Method and Design Process

According to Johnson and Onwuegbuzie (2004) more researchers are showing interest in the "mixed methods research" approach where a researcher conglomerates quantitative and qualitative research approaches or methods into a single study. The key benefit with this approach is that it forces the conglomerated methods to share the same research questions, to collect matching data, and to conduct complementing analyses. A more realistic and accurate array of evidence is collected than by using any single method (Yin, 2013).

Hence, for this research, the quantitative and case study approach will complement each other in addressing the research questions and objectives. This is supported by various inputs, such as the quality and type of available data to be collected for analysis as well as the degree of control the researcher has on the research environment.

In this situation, the case study will be dependent on more holistic data collection strategies for investigating the main case but then will require a more quantitative technique to collect data pertaining to the unit of analysis, in this case the LCC of a HPGR.

The figure below illustrates the research design steps followed in structuring the case study. The sections which follow provide a more detailed explanation of each step as well as its connection to this research.

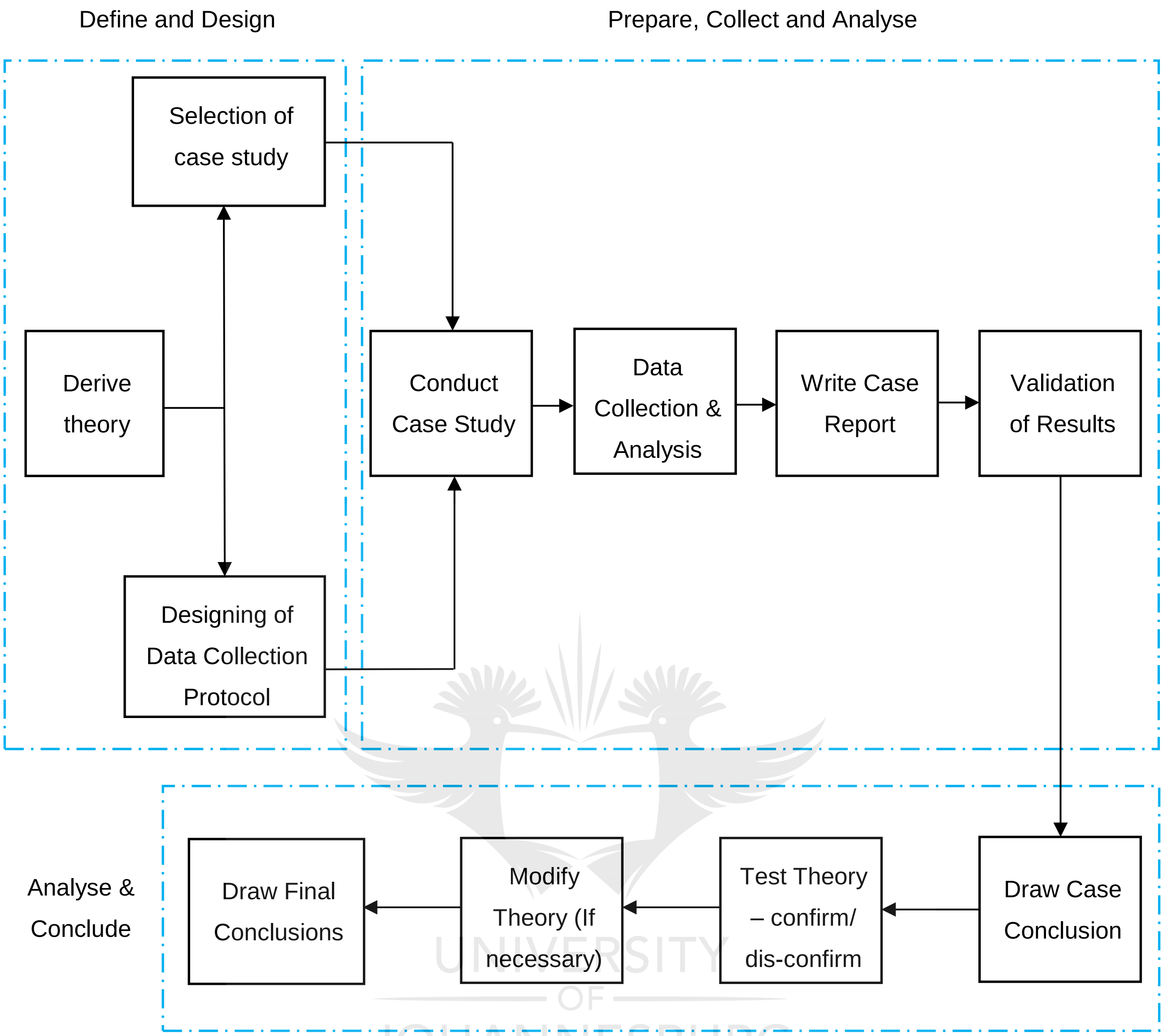


Figure 3-2: Case study method (adopted from Yin (2013))

3.3.1 Research Method Definition and Design

The research process comprises of a number of steps necessary to execute the research and to precisely outline the ideal order or sequencing of each step. These steps collectively form three phases which are illustrated with the dashed border lines. It commences with Phase 1 which comprises the following steps:

- Deriving the theory
- Case selection, and
- Designing data collection protocol.

3.3.1.1 Deriving of Theory

The deriving of the research theory was described in depth in Chapter 2 which summarized the literature review in this field of study from various researchers. From the literature review (particularly under section 2.8), reliability is highlighted as a factor which extensively influences the LCC analysis of the equipment or system during its operating and maintenance life cycle. Hence, a case study will investigate whether there is indeed a relationship between LCC and reliability of the HPGR during its' operating and maintenance life cycle. Therefore, the proposition of this research is to collect valuable data to substantiate the relationship derived from literature as well as to present the actual LCC of the HPGR during its operating and maintenance life cycle.

Further to the proposition, more data is necessary to answer the research questions as stipulated in Chapter 1, section 1.3. Hence, from the research questions a theory or hypothesis was then derived which states:

Determine the importance of correctly quantifying the LCC of a high pressure grinding roll (HPGR) during the operating and maintenance life cycle in order to determine whether low reliability yields high LCC and vice versa.

With the theory, proposition and research questions clearly defined, the condition of relevant data to the research which can be collected is also defined. The next section outlines the case selection process to ensure appropriate data is collected.

3.3.1.2 Selection of Case Study

According to Rajasekar et.al (2006); Johnson and Onwuegbuzie (2004); Yin (2013) and Gomm et al. (2000) when selecting a case study two crucial factors must be considered, these include:

- The availability and quality of data for collection – select a case where data is accessible and accurate; and
- The probability of deriving answers to the research questions from collected data – select a case where the available data can address all the research questions.

Based on these factors, a unit of analysis was identified in order to classify the case to be studied. Since the objective of this research was to obtain the cost of ownership during the operating and maintenance life cycle, therefore the unit of analysis revolves around the LCC of a HPGR and factors which influence it. Furthermore, the research investigates the relationship between the LCC and reliability of a HPGR. Hence, the following data would be pertinent to provide in-depth understanding and conclusive answer to prove this inter-relationship:

- Quantification of the LCC of an HPGR using modified existing models

- Identification of key cost drivers which affect the LCC of HPGRs and how to control them
- Evaluation of current reliability of HPGRs and its impact to the overall LCC

From the above data to be evaluated, criteria were used to ensure the case has appropriate data for collection. These criteria included the following:

- The HPGR must at least been in operation for a minimum of 5 years and all relevant operating and maintenance cost be available in order to quantify the LCC.
- Proper maintenance activities had to be recorded during each incident to ensure that components which fail frequently can be easily identified.
- Operating times and availability of the HPRG had to be recorded in order to quantify overall reliability and compare it to the LCC.

The criteria stipulated above provided a focused path in the selection of the case. A HPGR currently in operation for more than ten (10) years at a Platinum Mine in South Africa was chosen for the purpose of this research. The researcher is currently employed by the company which supplied, installed and commissioned the selected HPGR for analysis. Furthermore, the company also provide after-sale services; hence information pertaining to the acquisition, installation, refurbishment, operating and maintenance costs is readily accessible.

Currently, the employer of the researcher, as well as customer where the machine is installed, does not have a clear cost image of the HPGR LCC. The researcher's employer is currently utilizing a simplified LCC analysis tool which only caters for the known spares which have thus far been supplied to the customer. Therefore, partaking in this research will benefit both the employer and customer to better understand the LCC of the HPGR from design, installation, commissioning, operating and maintenance phase. Furthermore, the findings of this study will enable the employer of the researcher and the customer to implement means of controlling and/or reducing the overall LCC to economical acceptable costs.

From the above, clear guidelines as to what data must be collected to address the research questions are being identified; hence the data collection protocol is described in-depth in the following section.

3.3.1.3 Data Collection Protocol Design

According to Kumar (2005) data collection methods for quantitative case studies relies extensively on structured data collection instruments which is appropriate for diverse practises into pre-set response categories. In support of this statement, Gordon Rugg (2006) elaborates that certainty in the research analysis and results is governed by the ability of the researcher to collect from various sources using ranging formats that draw similar conclusions.

In order to ensure that the results are valid and reliable the researcher will collect secondary data and employ various data collection formats to triangulate the results. The reason for this approach is mainly because the data is readily available and can be easily collected. Hence, the following sources of data collection were used for this research and the reasons are also stated as to why these sources were selected:

- **Documentation** – this approach was chosen as the documents are available to the researcher from the employer. These included:
    - **Original contract** – this document contains commercial aspects for the scope of supply and design parameters. From this document, the acquisition costs (design, manufacturing, installation and commissioning) for the HPGR can be obtained.
    - **Operating and maintenance manuals** – these documents contain design drawings, component breakdown, operating and maintenance procedure as well as recommended spares. These will assist in compiling a cost breakdown structure based on the components making up the HPGR.
- **Archival records** – this approach was chosen to quantify ownership costs by reviewing historic data during the operating and maintenance life cycle phase of the HPGR. The records will contain both data from the researcher's employer and the client where the HPGR is installed. These will be broken down as follows:
    - **After-sales spares and services records** – these records are obtained from the researcher's employer and contain all the spare parts sold to the client as well as the associated costs covering the period of evaluation by the researcher's employer. Furthermore, the records include all service work performed on the client's site, i.e. schedule machine inspections, routine maintenance and breakdowns.
    - **Refurbishment records** – these records are obtained from the researcher's employer and contain all the major refurbishments done over the period of evaluation.
    - **Operating and maintenance records** – these records are obtained from the client and include the operating costs (consumables, power consumption and labour), maintenance activities (both planned and unplanned) and maintenance costs. Furthermore, these records contain operating parameters such as throughput,

power drawn, running hours and duration of maintenance activities. These parameters are used to quantify the availability and reliability of the HPGR.

- **Chain of evidence** – this was used to provide evidence of the data collected and the source from which the data was retrieved. This was to ensure traceability and authenticity of the data.

The combination of the aforementioned sources of data collection will ensure the accuracy of the results as well as to address the research objectives. Yin (2013) further emphasized that no single source of data collection method is more superior than the other, but a combination of these methods facilitate more reliable and valid results. The prime focus of this research is on reliable and valid quantitative results; hence the following section describes in depth the process of preparing for data collection, analysing and validation of collected data.

3.3.2 Prepare, Collect and Analyse

The method of data preparation, collection and analyses plays a crucial role in the reliability and validity of the results; hence the design thereof according to the availability of each source of data collection. The first section below describes the data preparation process used for this research.

3.3.2.1 Data Collection Preparation

According to Yin (2013), deciding what data to collect is an integral part of data collection. Moreover, to improve data completeness and accuracy, the initial approaches utilized during the actual fieldwork need to be reviewed and refined on a more frequent basis.

In order to ensure that the required data for collection and analysis was available, permission was granted by the General Manager of the researcher's employer to conduct this research and to have access to all relevant information. Furthermore, the researcher requested assistance from the Spares and Sales Department to obtain all information relating to spares and services offered to the customer.

The Operating and Maintenance Department (also referred to as "Asset Management") where the researcher is employed also offered to assist as this research will also assist the Department with a LCC analysis tool which can also be offered to customers.

The client was also contacted to assist with all operational and maintenance data. This included the operating parameters (availability, number of running hours, tonnage throughput, power drawn and operational costs) and maintenance records (maintenance costs, failure incidences, duration of each failure, number of planned and unplanned maintenance activities).

The following rules were agreed upon between the researcher, employer and client:

- The employer (referred to as "supplier" in this research), employees and customer names (referred to as "customer" in this research) would be kept anonymous;
- The location of the mine would be kept anonymous;
- All data collected from the employer and customer would be kept confidential but conclusions and recommendations can be made available in the public report;
- Detailed calculation of all the LCC will be kept confidential but overall costs will be indicated in the data analysis chapter; and
- The researcher would be provided with all the necessary information required for the completion of this research.

3.3.2.2 Data Collection

The data obtained from the research's employer was retrieved in three ways. Firstly, the data pertaining to the original acquisition, manufacturing, installation and commission costs was retrieved directly from the contract folder in the relevant network drives. Secondly, the data reflecting all the spares, services (inspections, on-site repairs and installations) and refurbishments was retrieved from SAP™ and the after-sale folder in the network drives. Thirdly, the data containing all operating and maintenance costs and activities performed as well as operational data was requested via e-mail from the customers.

3.3.2.3 Data Analysis

The data analysis process for this research was divided into three analytical phases. The first phase involved the compilation of data collected into a methodological and structured database. This included structuring of the data into years, maintenance activities performed, costs incurred and parts which were replaced. During the second phase, the compiled data was disassembled. The third phase involved reassembling data based on an emerging pattern. This was done to ensure that the analysis constitutes a comprehensive or good interpretation as recommended by Yin (2013).

Hence, this meant striving towards the following suggested attributes to ensure a comprehensive interpretation of the data being analysed (Yin, 2013):

- Completeness – data interpretation must have a beginning, middle and end

- Fairness – provision of an interpretive perspective that other researchers with a similar perspective would also arrive at
- Empirical accuracy – the interpretation must fairly represent data collected and analysed
- Value-added – the interpretation must add value, be new or an improvement on existing interpretation(s); and
- Credibility – independent of its creativity, the interpretation can be accepted or critiqued by peer researchers in a similar field of study.

In order to achieve meaningful and representative results, the collected data was analysed in the following manner:

1. The HPGR was broken down into various components to formulate a cost breakdown structure. This was done to ensure that LCC costs are accounted for and all cost drivers are identified.

2. The data collected was analysed through the derived formulae in Chapter 2 section 2.5 (formulae (1) and (2)) to calculate the LCC using a Microsoft Excel spreadsheet. These calculations included the following:

- **Acquisition costs** – design, manufacturing, installation and commissioning;
- **Operating costs** – consumables (wear parts, oil and grease), power and labour; and
- **Maintenance costs** – spare parts, after-sales service, major refurbishments, scheduled maintenance, breakdowns and labour.

3. To analyse reliability which includes frequency of failures, Time To Repair (TTR), total running hours, total breakdown hours, Time Between Failures (TBF), total maintenance hours; the TTR and TBF data for all the components of the HPGR was arranged in chronological order for the use of statistical analysis. This was to establish the trend of failures.

3.3.3 Analyse and Conclude

As previously stated, reliability and validity of a research investigation is based on the accuracy of quantitative reliability of the collected data. Moreover, the most vital function of a researcher is the suitable interpretation of different types of statistical data with the assistance of available tools (Bryman and Bell, 2015). These researchers further emphasized that technical interpretation of data has to be combined with a high degree of statistical experience, sound judgement, skill and accuracy. For this research, data processing was carried out in a structured manner which comprised of editing, coding classification and tabulation of the collected data.

Firstly, despite the careful collection of data, the possibility for errors and omission of vital information is possible. It is for this reason that the process of editing was necessary for this research. This process involved analysing the collected data for the life cycle period of the HPGR and removing data which was not required for this research whilst ensuring that vital data is maintained.

Secondly, the procedure of coding was used to classify the data into meaningful and useful class categories, i.e. acquisition cost, operating cost, maintenance and disposal as well as salvage costs. This procedure was selected as it would be beneficial in analysing data with a number of characteristics. Furthermore, a large volume of data can be processed timeously and accurately. According to Bryman and Bell (2015), manual data processing and analysis of lesser volumes can be carried out by using measures of dispersion, correlation regression, central tendency and other statistical methods.

Thirdly, computer processing was used for tabulation and presentation of data. For this research necessary statistical packages such as Microsoft Excel was used. According to Bryman and Bell (2015), the use of computer technology has proven to be beneficial when fairly large volumes of complex data is to be processed accurately and speedily.

According to Yin (2013), good research studies do not end with the pure analysis of the collected data or presentation of empirical findings but continues with two further steps. These steps include interpretation of the research findings and finally drawing holistic conclusion(s).

3.4 Research Validation and Quality

According to Yin (2013), research design presents a logical set of statements; therefore the quality of any research design can be confirmed through sets of logical tests. This ensures that the research and the results thereof are credible, trustworthy and reliable. For this research, the logical tests chosen for this research included four tests recommended by Yin (2013). These are construct validity, external validity, internal validity and reliability.

Since these four tests are commonly used in the research fraternity, the tests have been summarized as follows:

- **Construct validity** – requires researcher to derive accurate measures from the theories being studied

- **External validity** – requires the researcher to examine whether or not the research findings can be generalized and to what extent
- **Internal validity** – illustrates a relationship between conditions where certain conditions can lead to other conditions which can be established through pattern matching, time-series analysis and explanation building
- **Reliability –** demonstrates accuracy and repeatability of results where research method and approach can be repeated and yield similar results

In order to align this research of the above tests, Table 3-1 below shows the different approaches used to validity and accuracy of this research. Furthermore, it also provides reference of the sections within this research where each approach is described.

Table 3-1 – Case study approaches for four logical tests (Yin, 2013)

Logical Test	**Case Study Approach**	**Reference Section**
Construct validity	- Multiple sources of evidence - Archival records - Chain of evidence	3.3.1 3.3.1 3.3.1
External validity	- Use of replication - Cross-examination	3.3.1 and 3.3.3 3.3.1 and 3.3.3
Internal validity	- Pattern matching	3.3.2
Reliability	- Develop case study base	3.3.1

3.5 Conclusion

The chapter focused on a quantitative case study as a research method and outlined a research process that the researcher followed to ensure research validity and accuracy. Furthermore, it also illustrated the strengths and weaknesses of this research method.

As stated at the beginning of this chapter, using a quantitative case study as a research method provides an in-depth knowledge when investigating empirical research for a real life problem or situation. For this research, the method was used to analyse the LCC of the HPGR as well as factors which affect it. This knowledge would allow the researcher to derive efficient methods/ approaches suitable in practise to quantify the LCC of any system/ equipment. Hence, to ascertain that this knowledge was valuable, a robust research design and process was followed to yield valid and reliable results.

4 CHAPTER 4 – DATA ANALYSIS AND RESEARCH FINDINGS

In this chapter the background to the selected case study will be presented. The chapter commences with the description of the data analysis method used to derive research findings. This approach was done in a systematic manner, as discussed in chapter 3, to ensure that valid and reliable results are yielded.

4.1 Research Objectives

The data collected and evidence presented in this chapter were derived from documentation obtained from the HPGR supplier (the researcher's employer in this case) and the HPGR owner (the customer). A period of four years, starting from the beginning of 2014 to the end of 2017, was selected for this research to evaluate the operating and maintenance life cycle of the HPGR. The selected period started after the installation and commissioning of the HPGR by the machine supplier and has been operating since 2007. The reason for the selected time period was to allow sufficient time for the HPGR to reach a steady operational level, and for latent design defects to be resolved. This ensured that a more accurate reflection of the operating and maintenance costs could be obtained.

The purpose of the research was to quantify the LCC of a High Pressure Grinding Roll (HPGR) during its operating and maintenance life cycle using existing LCC models. Therefore, answers to address the following research questions were required:

- What is the LCC of a high pressure grinding roll (HPGR) during its operating and maintenance cycle?
- What are the key cost drivers impacting LCC of an HPGR?

The intention of the researcher was to obtain research data to support the hypothesis that: *during the operating and maintenance life cycle of the HPGR low reliability yielded high LCC and vice versa.*

4.2 Case Study – High Pressure Grinding Roll (HPGR)

The case study selected for the research is based on the process plant of a mine located in the central part of Limpopo province being the largest precious metal producer in South Africa with a significant global market share. This mine forms part of a large precious metals group which consists of subsidiary mines in various provinces within South Africa and other parts of Europe. The annual production turnover of the mine is estimated at 650,000 tonnes depending on the overall achieved availability for that year. Installed in the ore processing stream, during year 2007, is a High Pressure Grinding Roll (HPGR) located in the crushing and grinding section of the plant which was supplied by a European based supplier. The supplier takes pride in its products with over 200 successful installations world-wide, covering major mineral industries which include diamonds, gold, cement, copper, iron ore and platinum.

4.2.1 Life Cycle Timeline of HPGR

An agreement was entered into between the customer and supplier for the supply and commissioning of the HPGR by 2007 on an Engineering, Procurement and Construction (EPC) basis. After the handover of the HPGR to the customer, as a European based company, the supplier could only offer limited after-sales service to the customer. This was limited to spare parts supply and could not offer major overhaul due to inhibitive costs. Hence, the research objective was to evaluate the HPGR LCC for a time period commencing from 2014 to 2017 for observation. The reasons for the selected period for observation are stipulated below. Prior to the period of observation:

- the availability of data required for analysis from both the customer and supplier was limited and there was no proper record keeping system in place;
- major overhauls on the HGPR were carried out by a third party and permission to obtain data could not be granted to the researcher;
- the service unit in South Africa was only established in 2009 and sufficient time was necessary to acquire the necessary resources and skills to offer a complete service to the customer, as well as to have a proper system (Enterprise Resource Planning – ERP) in place to capture all historic information such as Systems, Applications and Products (SAP^{TM});
- very little interest was shown by both the customer and supplier to gain a better understanding of, and to quantify the HPGR LCC;

As illustrated in the figure below, in 2007 the HPGR was commissioned and handed over to the customer. From the handover period to current (2017), a number of events occurred with cost implications for the customer. In the interest of simplicity the timeline only concentrated on the major events which were classified based on the costs incurred and downtime of the HPGR.

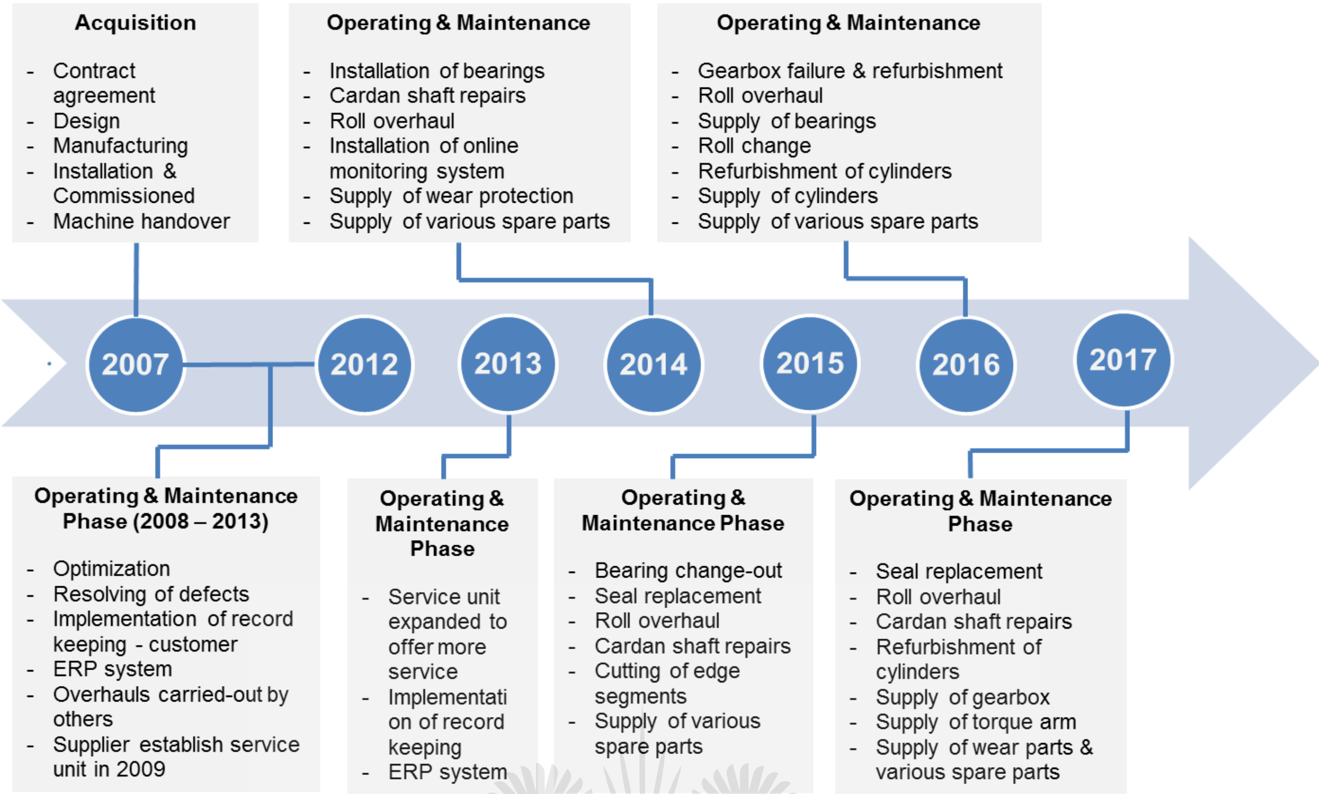


Figure 4-1: Life cycle timeline of HPGR, 2007 – 2017 (derived by researcher)

4.3 Operation Principle of the HPGR

The technical data below outlines the key design parameters for the HPGR (see Table 4-1).

Table 4-1 – Technical parameters of the HPGR (*sourced from supplier's technical specifications*).

Item	Description	Size	Units
[1]	Grinding power	2,300	kW
[2]	Throughput (design)	2,800	tph
[3]	Throughput (operating)	2,100	tph
[4]	Feed size	80 – 120	mm
[5]	Product size	8 – 10	mm
[6]	Weight of HPGR	> 250	tons
[7]	Availability per yr. (estimated @ 92%, 24hrs, 365 days)	8,059	hrs

The HPGR is used for grinding all kinds of brittle mill feed material from the field of rocks and associated products. It forms part of a comminution circuit to provide the separation between useful and waste minerals and also to produce adequate particle size distribution to other mineral processing equipment such screens, crushers and mills (Gomes and Peres, 1996).

As illustrated in Figure 4-2 below, firstly, the material is received from either storage feed bins or tippler truck into a primary crusher, then ground into the required size by a secondary crusher. On the secondary crusher the material is then ground to a required size by the HPGR and oversize material is recirculated for further crushing. The material in the HPGR is ground to size required by the ball mill and oversize material is recirculated back into the HPGR for grinding to required size. Finally, the material is ground to a final product size which can be further processed in a furnace or sold to external customers.

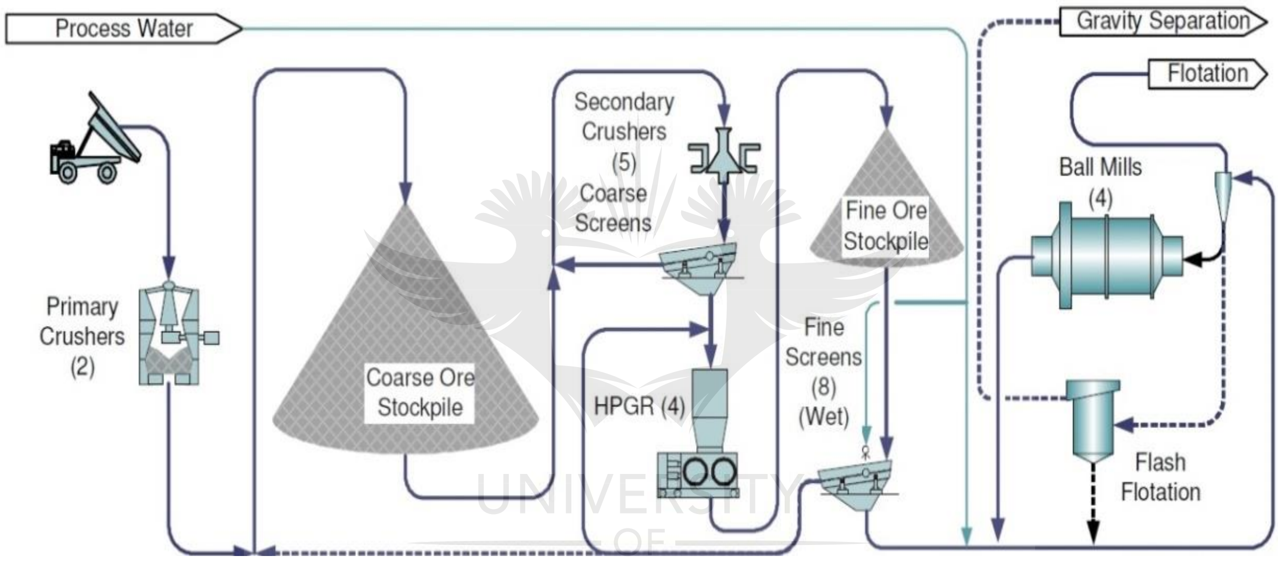


Figure 4-2: Mineral ore processing flow diagram (Boddington HPGR - Dunne et al, 2007)

All illustrated in Figure 4-3 below, the HPGR comprises of two counter-rotating rolls which are machined from a solid material and mounted onto roll shafts. These rolls are each mounted in two frictionless bearings mounted in bearing blocks. The surfaces of the rolls are usually protected by layers of hard metal welded onto the surfaces or as in most mineral applications; the roll body surfaces are protected by embedding tungsten carbide studs. This help to form an autogenous wear layer on the rolls, and improves the life expectancy of the rolls (Klymowsky et. al, 2002).

Hydraulic pressure is applied to one of the rolls (commonly referred to as the “floating roll”) by means of a hydro-pneumatic spring system, while the other roll (commonly referred to as the “fixed roll”) is held in a fixed position in the frame. The floating roll is allowed to slide on frictionless pads to regulate the pressure induced on the material being ground and the spring system.

The feed into the rolls is provided by means of a hopper mounted above the rolls. The hopper is fitted with level controlling instruments to ensure that the rolls are continuously choke-fed. The hopper receives continuous material feed from a conveyor. Normally free-flow material from the hopper as well as the rotational speed of the rolls is sufficient to induce a separating force on the rolls (Klymowsky et. al, 2002).

Each roll is driven by an electric motor (either fixed or variable speed) and connected to the roll shafts through a speed reduction gearbox. Furthermore, a torque reaction system is included to accommodate torsional forces exerted onto the gearboxes from turning and to divert any differential forces away from the roll frame.

In addition to the hydraulic system, the HPGR is also fitted with a grease lubrication system which provides grease to the frictionless bearings and slides on the floating roll to facilitate sliding. Furthermore, an oil lubrication system is also fitted to provide oil to the gearbox internals (i.e. bearings, gears and seals).

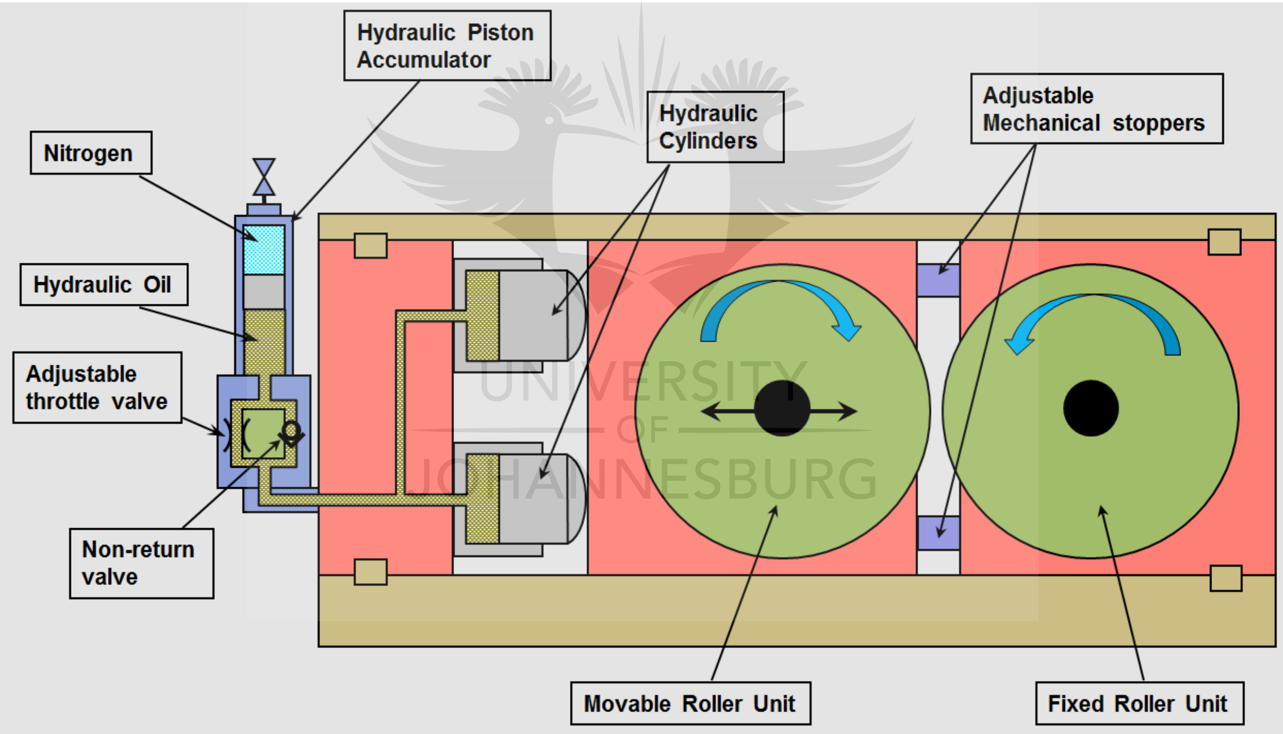


Figure 4-3: HPGR principal of operation and component overview (derived from Rule et al., 2009)

4.3.1 Components Breakdown Structure

As stated in section 2.6, it is imperative to break down the HPGR into all components to ensure that all costs associated with a specific component can be accounted for and major cost drivers can also be identified. The HPGR comprises of a number of components which include the following as illustrated in Figure 4-4 below:-

- Roll unit assembly;
    - Floating and fixed rolls – counter rotating to provide grinding action;
    - Roll shaft and frictionless bearings;
    - Roll frame and bearing blocks;
- Feed system – provides feeding of ore from secondary crusher;
- Main drive motors (2-off) and auxiliary barring motors (2-off);
- Hydraulic system – provides required grinding force;
- Grease lubrication system – provides grease to the bearings and sliding rails on floating roll; and
- Oil lubrication system – provides oil to the gearbox internals.

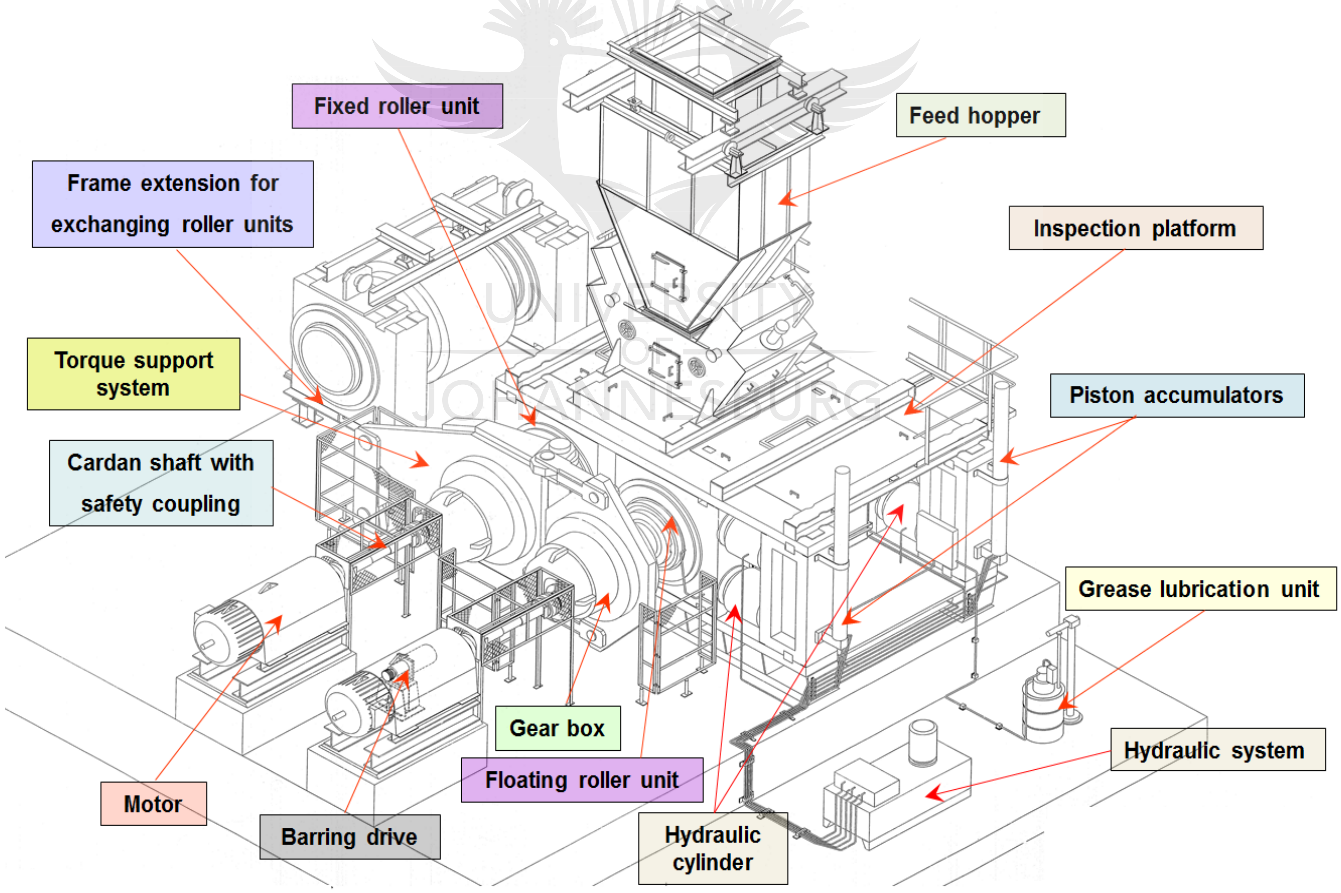


Figure 4-4: HPGR components (*sourced from supplier's technical training documents)*

Table 4-2 below contains all the major mechanical, electrical and instrumentation components as well as the total quantity which makes up the HPGR. In order to narrow the focus of this research, the components listed below exclude minor components such as cabling, piping, instruments, fasteners and consumables as well as parts which were not originally in the supplier's scope of supply. Furthermore, the components also excluded are structural parts that are less likely to fail. These are the roll frame, pressure blocks, transport frames and platforms.

Table 4-2 – Breakdown of HPGR components (internal documents from researcher's employer)

ITEM	DESCRIPTION OF PART	TOTAL INSTALLED QUANTITY
[1]	**Roll unit assembly**	
	Bearing blocks	4
	Bearing covers	4
	Shaft	2
	Roll body	2
	Hard metal stud	20706
	Self-aligning bearings	4
	Compound edge segment	32
	Guide rails	4
	V-seals	8
	Frame fasteners	
[2]	**Feed system**	
	Main feed hopper	1
	Expansion joint	1
	Wear protection – main feed hopper	2
	Material feed guide (cheek) plates	2
	Wear protection – material feed guide	2
	Material slide guide plates	2
	Actuator Auma	2
[3]	**Drive unit**	
	Main drive motor	2
	Gearbox	2
	Cardan shaft	2
	Safe-set coupling	2

ITEM	DESCRIPTION OF PART	TOTAL INSTALLED QUANTITY
	Torque support system	1
	Flange shaft - intermediate	2
	Screw bolts	40
	Auxiliary/ barring drive system	1
	Instrumentation	1 LOT
[4]	**Hydraulic system**	
	Pumps	2
	Drive motors	2
	Valve blocks	4
	Hydraulic cylinder - thrust	4
	Hydraulic cylinder – push-back	3
	Oil cooler	2
	Piston accumulator	3
	Filters	2
	Instrumentation	1 LOT
[5]	**Central grease lubrication system**	
	Pump	
	Instrumentation	1 LOT
[6]	**Oil lubrication system**	
	Pumps	2
	Drive motors	2
	Air coolers	1
	Filters	1
	Instrumentation	1 LOT

4.4 Life Cycle Cost Calculations/ Analysis

As stated is Chapter 2, it is imperative that all phases of the HPGR's life cycle are considered in order to derive at a more accurate cost image. The LCC analysis commences with the acquisition cost followed by the operating and maintenance costs. The primary focus of the LCC is on the operating and maintenance phase during the period of 2014 to 2017. The reasons for observation during this time period are stated in section 4.2.1.

4.4.1 Acquisition costs

The acquisition cost of the HPGR is the summation of the design and engineering costs, fabrication and transportation costs, installation (including cranage) and commissioning costs, maintenance tools costs, training and warranty as well as maintenance, commissioning and strategic spares costs. These costs were retrieved from the contract agreement signed by the customer and the researcher's employer. Table 4-3 below provides a summary of the total acquisition cost which was payable by the customer at different foreign exchange rates which were agreed upon contractually.

Table 4-3 – Acquisition costs of HPGR (internal documents from researcher's employer)

Item	**Description**	**SA RAND**	**Germany Euro**	**US Dollar**
			@ € 1.00=R8.00	**@ $1.00=R 6.50**
[1]	Acquisition cost	R 70 000 000	€ 560 000 000	$ 455 000 000

4.4.2 Operating costs

The operating costs of the HPGR consider the amount it costs the customer to operate the machine. These costs are categorized into three (3) groups:

- Power consumption of all electric motors
- Consumables (i.e. lubricants – oil and grease)
- Labour

In order to calculate the above parameters certain information had to be gathered which included annual running hours, availability, throughput, and inflation as well as foreign exchange rates. These are provided in Table 4-4 below where some values were calculated from empirical formulae and others were retrieved from contract documents.

Table 4-4 – Parameters for calculating operating costs

General parameters	**Value**	**Units**	**Formula/ Source**
Total number of running hours/ year	8760	hours	*24hrs x 365 days*
Assumed plant availability	92	%	*Contract document*
Tonnage throughput			

General parameters	Value	Units	Formula/ Source
Hourly	2160	tph	*Contract document*
Annually	17407872	tpa	*tph x total hours x (availability/100)*
Inflation rate - average (2014 - 2017)	6	%	*Stats SA, 2017*
Electricity annual increase	8	%	*Motiang and Nembahe (2016)*
US$/ZAR	13.16		*Nedbank, 2017*
€/ZAR	15.43		*Nedbank, 2017*

4.4.2.1 Power consumption

As indicated in Table 4-2, the HPGR consists of two (2) off main drive motors, two (2) off hydraulic pump drive motors, one (1) off grease pump motor, one (1) off Auma actuator, feed and discharge conveyor, and two (2) off oil pump drive motors as well as oil to air coolers.

From Table 4-5, the installed power rate for each drive was retrieved from technical specifications and contract documents as well as from name plates on each drive. The annual electricity cost consumed by the drives was calculated using the formula below.

$$Annual\ electricity\ cost = Power \text{ x } Annual\ Running\ Hours \text{ x } Availability \quad (14)$$

Where:

Annual electricity – ZAR

Power – kW

Availability - %

The total accumulated amount for the period of observation was in excess of R 32 million which is under 45% of the acquisition cost of R70 million. In comparison to the other drives, the main is the greatest power consumer at 37.1% of the total operating cost followed by conveyor drives at 36.2% and cooling water drives at 21.3%. The total power required to operate the HPGR was 5431.5 kW which yielded power consumption of 2.73kWh/t.

Table 4-5 – Operating costs (2014 – 2017) – Power consumption

ITEM	DESCRIPTION OF PART	Value	Unit Cost (c/kWh) or Rands	Total cost/period	% of total cost/ period
[1]	**Power consumption**			**R 31 109 264**	**100%**
	Main motor - total (kW)	4600	69.00	R 11 526 590	37.1%
	Auma actuator - total (kW)	2	69.00	R 37 587	0.1%
	Hydraulic drive motor - total (kW)	44	69.00	R 1 102 543	3.5%
	Cooling water - total (kW)	264	69.00	R 6 615 260	21.3%
	Feed and discharge conveyor - total (kW)	500	69.00	R 11 276 012	36.2%
	Auxiliary/ barring drive - total (kW)	22	69.00	R 551 272	1.8%
	Total - kW	**5431.50**			
	Total - kWh/t	**2.71**			
	Total - ZAR/t	**1.79**			

Traditionally, the power consumption is very often expressed per throughput, commonly referred to as the "specific energy". From the definition by Von Michaelis (2009), specific energy is the net power draw per unit of throughput given by using the formulae below.

$$Specific\ energy = \frac{total\ power}{throughput} \quad (15)$$

Where:

Specific energy – kWh/t

Total power – kW

Throughput - tph

For this research the cost of electricity (c/kWh) was based on the urban cost of 69c/kWh charged by Eskom to the mining and commercial industry (Department of Public Enterprise, 2014). Comparatively, this cost is significantly lower than the residential tariffs which may be due to the consumption amount by mines as well as their contribution towards the country's Gross Domestic Product. It is also noticeably lower that tariffs charged to the agricultural sector which may be as a result of the geographical location and accessibility to many farms.

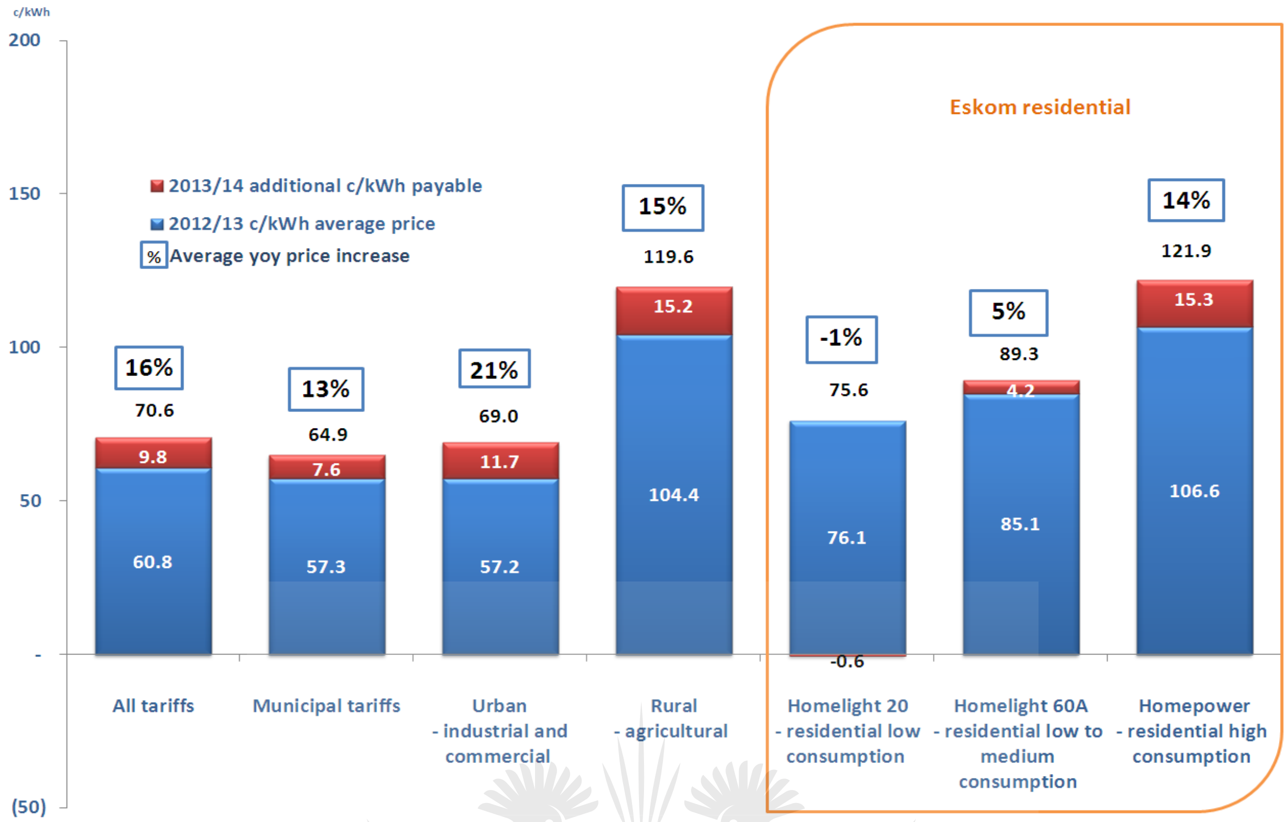


Figure 4-5: Eskom tariffs for different sectors within South Africa (Department of Public Enterprise, 2014)

According to Von Michaelis (2009) the typical specific energy values for HPGRs are in the range of 1–3.3 kWh/t. These values are significantly lower than other comminution circuits due to the fact that a given ore will absorb the required energy to a point beyond which diminutive useful work is attained. In support of this statement various researchers have conducted several test works over the years on ranging sizes of HPGRs in an attempt to prove the specific energy consumed. The results of these researchers are given in Table 4-6.

Table 4-6 – Specific energy from various researchers - Power consumption

Specific energy (kWh/t)	**Author**
0.94 – 2.35	Kumar (2014)
1.7 – 2.90	Wang (2013)
1.89 – 2.35	Rosario (2010)
2.4	Marsden (2009)
3.3	Rule et al. (2008)
2.53 – 2.73	Oestreicher and Spollen (2006)
1.7 – 2.0	Vanderbeek et al. (2006)

From Table 4-6 above, it is evident that there is no fixed value for specific energy due to varying factors which include HPGR sizes, operating parameters and process as well as plant throughput. However, it can be concluded that the calculated specific energy for this research of 2.71 kWh/t falls within the ranges from the various researchers and can be regarded as reliable and appropriate.

4.4.2.2 Consumables – lubricants

The operation of the HPGR is extensively dependant on the availability and condition of consumables. Although, these might contribute a smaller percentage of the total operating cost, the integrity and reliability of the HPGR is governed by the condition of these consumables. For this research, the consumables costs comprise of grease and oil consumption as well as the wear parts costs.

From Table 4-7, the grease and oil consumption rates were derived from technical specifications and confirmed with operating data. The associated cost per unit was obtained from archive records containing past order supplies to the customer. To calculate the total cost for grease and oil consumption the unit cost is multiplied by the consumption rate.

Meanwhile, the wear parts consumption rate is a function of the tonnage output and the HPGR mode of operation as well as maintenance. The associated costs for the wear parts were also retrieved from the archive records of operational spares supplied to the customer over the period of observation.

From the calculated costs, it is evident that the greatest cost of over 60% of the total consumable cost is attributed to wear parts followed by the grease at 26.6% and lastly the oil consumption as the lowest at 11.8%. The total accumulated amount for the consumables over the period of observation was in excess of R 5.5 million which was just over 7.8% of the acquisition cost of R70 million.

Table 4-7 – Operating costs (2014 – 2017) – Consumables cost

ITEM	DESCRIPTION OF PART	Value	Unit Cost (Rands)	Total cost/period	% of total cost/ period
[1]	**Consumables - lubricants & wear parts**			**R 5 530 966**	**100%**
	Grease - Consumption (g/h)	300	27000	R 1 470 784	26.6%
	Oil - consumption (400L/3000hrs)	400	135	R 653 682	11.8%
	Wear parts			R 3 406 500	61.6%

4.4.2.3 Labour

For continued operation and maintenance of the HPGR, human resources play a vital role to ensure that the machine is operated optimally and well-looked after. For any organization to achieve this objective, resources from with varying skill levels are required to perform various functions. Such skills are also deployed at different organisational levels. This research considers the labour cost necessary to operate and maintain the HPGR from management level to operational resources which include Engineering manager, section engineers, foremen, control room operators and field personnel.

Table 4-8 indicates that a significant percentage of the labour cost is contributed to personnel at operational level with a total of slightly below 70%. The main reason for this may be due to the fact that these are the individuals responsible for the day-to-day operation and maintenance of the HPGR. Understandably, the remaining portion of over 30% is contributed to personnel at a management/ strategic level. These individuals are less engaged in the day-to-day operation but rather focus more on the organizational goals and direction as well as to provide guidance and leadership to the operational personnel.

Table 4-8 – Operating costs (2014 – 2017) – Labour cost

ITEM	DESCRIPTION OF PART	Value	Unit Cost (Rands)	Total cost/period	% of total cost/ period
[1]	**Labour**			**R 47 521 638**	**100%**
	Engineering manager	1	1 250 000	R 5 440 744	11.4%
	Section Engineer	2	1 050 000	R 9 140 451	19.2%
	Foreman	3	856 000	R 11 177 465	23.5%
	Control room operator	5	550 000	R 11 969 638	25.2%
	Field personnel	5	450 000	R 9 793 340	20.6%

In summation of all the above costs, the total operating cost for the HPGR for the period of observation equates to an amount of just of over R 84 million, which is 20% above the acquisition cost of R 70 million. The year-on-year operating cost follows a linear increase as depicted in Figure 4-6. This trend is expected due to the price escalation of electricity cost, steel price, inflation and labour annual increase. The overall percentage increase of the total operating cost from 2014 to 2017 equates to over 21%.

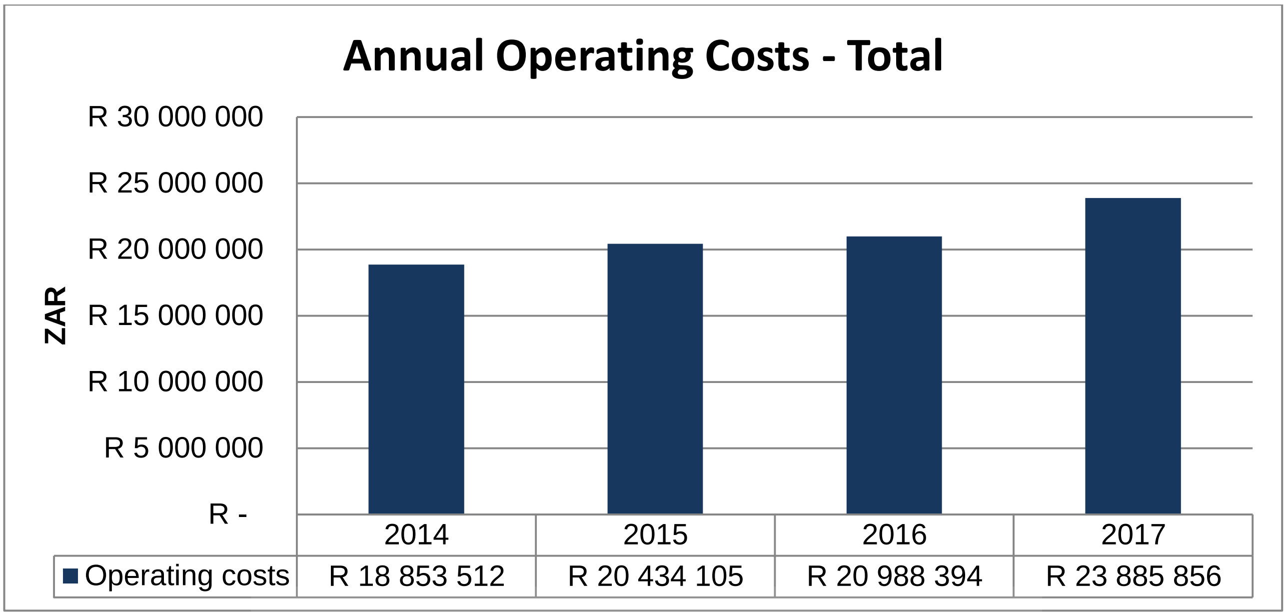


Figure 4-6: Annual operating cost

In breaking down the operating cost, it is evident that the labour cost contributes a large percentage of 56% followed by power consumption cost at 37% and lastly consumables at 7%. Figure 4-7 provides a graphical breakdown of the operating cost.

At the start of data analysis the researcher anticipated that power consumption costs would surpass labour costs. However, in the results it is evident that labour costs contribute a larger percentage. In support of these results, research by Turner (2017) also indicates that labour costs accounts as the major contributor of operating cost.

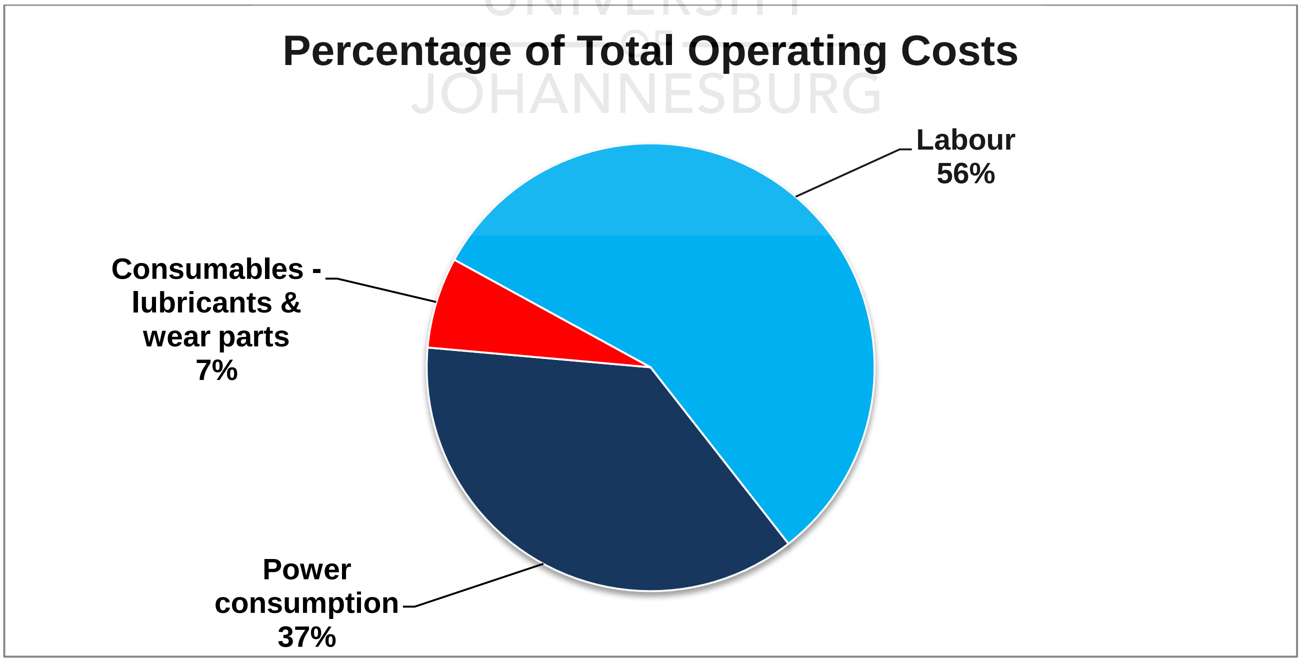


Figure 4-7: Percentage breakdown of operating cost

According to O'Donnell (2010), apart from the labour and consumable costs, operating costs within the mining industry are escalating as a result of the electricity price increases. On average the electricity costs equates approximately 11% of operating costs and this figure was forecasted in 2010 to double in three years to 20% from 2017. In support of this, Figure 4-8 presented by Turner (2017) indicated an electricity cost increase from 9% in 2007 to a 24% in 2017 of the operating cost for a gold processing mine. Further to this substantial escalation, an annual electricity tariff increase was approved by the energy regulator at an 8% annual increase for a period of five (5) years commencing from 2013 to 2018 (Motiang and Nembahe, 2016).

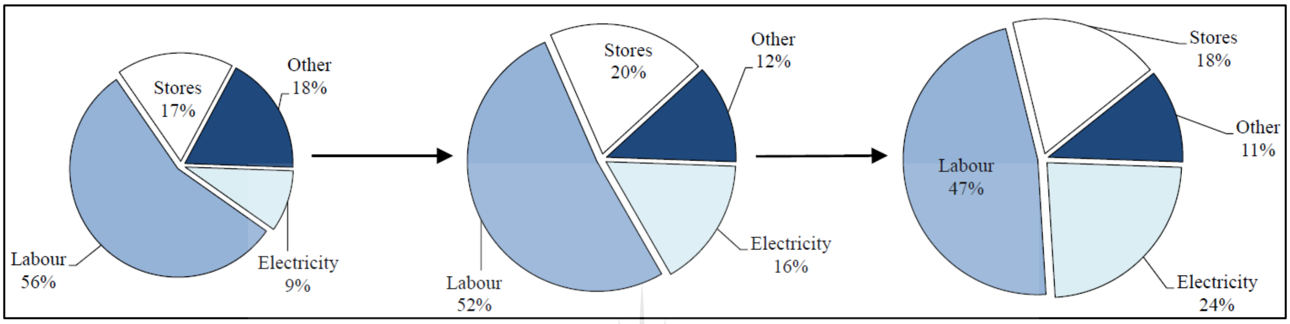


Figure 4-8: Operating cost increase from 2007 – 2017 (Turner, 2017)

In comparison with the calculated percentage of 37% for this research, the predicted 20% increase by 2017 and the actual percentage of 24% presented by Turner (2017) were most possibly due to the following reasons: lack of confirmation of actual electricity increase which were unknown in 2010, amount of actual power consumption by the plants and the variation of systems to process the minerals.

On the other hand, from the percentage breakdown of the operating costs presented by Turner (2017), the highest cost contributor is labour cost followed by spare parts (stores). Furthermore, the calculated labour cost of 56% in this research falls with a range of 47 – 56% for over a 10 year period as presented by Turner (2017).

4.4.3 Maintenance costs

According to Obiajunwa (2013) maintenance plays an essential support role for machinery and plant processes in order to ensure that production targets as well as the annual profit anticipated by shareholders are met. Obiajunwa (2013) further explains that maintenance contributes significantly to the business success and continued market growth in this highly competitive business environment. Hence it is imperative to understand maintenance requirements for a given system or machinery in order to derive adequate maintenance strategies. Moreover, Obiajunwa (2013) advises that to better understand a system's performance and reliability, it is important to breakdown the system into smaller components to better quantify associated costs for each component.

For this research, the HPGR was broken down firstly into sub-systems and then further into individual components as per Table 4-2 in section 4.3.1. The main purpose for this was to consider the actual annual maintenance cost for each component and to easily identify major drivers of the maintenance costs.

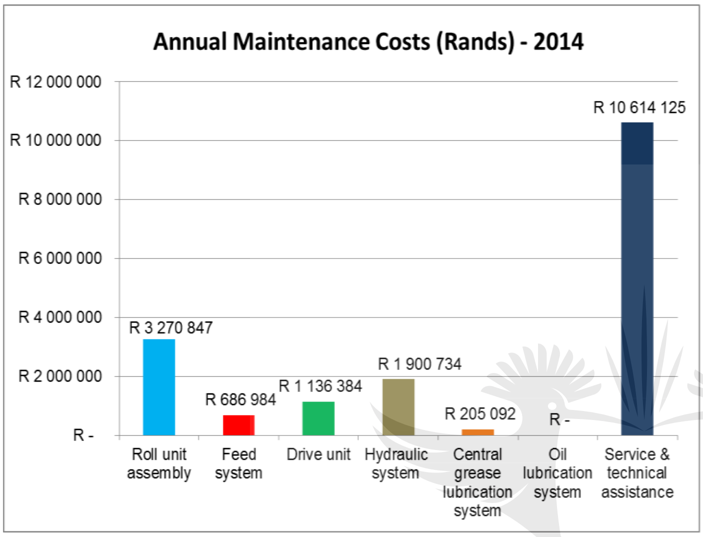
The maintenance costs were categorized into three (3) cost components: spare parts, service and technical assistance. The spare parts incorporated all spare parts purchased by the customer and supplied by the equipment supplier. These spare parts were either for strategic reasons to have stock readily available for an emergency/breakdown, or to be utilized immediately for a repair or refurbishment or during planned maintenance. Meanwhile, the service and technical assistance portions are mainly associated with labour and workshop machinery which incorporate the following costs:

- Scheduled site inspections;
- On-site repairs and failure investigations;
- On-site installation and upgrades; and
- Refurbishments and repairs at service centre.

The maintenance costs were considered annually from 2014 to 2017 in order to determine a developing trend for the major cost drivers. These costs were obtained directly from archive documents stored in an ERP system, SAP™. This information only contained a summary of the activity performed. To better understand the contributing components towards the total cost, each activity (i.e. supply of spares, breakdown assistance, refurbishment and service) was further broken down into its constituent parts in order to classify and group into the three (3) cost components (spare parts, service and technical assistance). The costs were considered as actual costs incurred annually for the period of observation. These are later converted to Net Present Value (NPV) in section 4.4.5 to cater for time value of money in order to establish the entire LCC from inception to disposal phase.

In 2014, as indicated in Figure 4-9 below, the first and obvious observation is that service and technical assistance are the highest contributor towards maintenance costs at over R10 million which equates to 57% of the overall maintenance costs for that year. The reason relates to the replacement of gearbox and torque, as well as to the refurbishment of the gearbox, bringing combined costs to slightly over R9.4 million which equates to 89% of the cost.

Furthermore from the results on Figure 4-9 below, the second noticeable observation is that the second highest contributor towards maintenance cost is the roll unit assembly at over R3.2 million, which equates to 17% of the overall maintenance costs for that year. This was due to the supply of hard metal studs, compound edge segments and guide rails with combined costs at slightly over R3 million, which equates to 92% of the roll unit cost. Lastly, drive unit, hydraulic system, feed system and central grease lubrication system respectively contributed to combined costs at slightly over R4.8 million which equates to 26% of the maintenance costs, and the oil lubrication with no associated costs towards the overall costs.



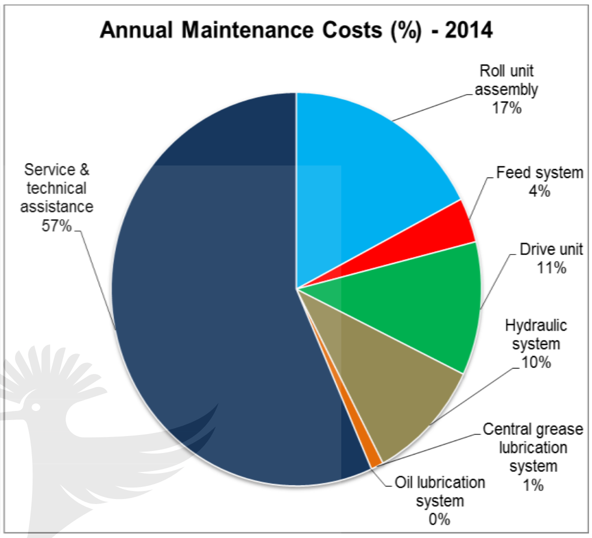


Figure 4-9: Annual maintenance costs & percentage breakdown - 2014

In 2015, seen from the results in Figure 4-10 below the first and obvious observation is the sharp increase of the roll unit cost from calculated cost in 2014. The second observation is that the roll unit is the highest contributor towards maintenance costs at over R10.3 million equating to 49% of the overall maintenance costs for that year. The reason is due to the supply of hard metal studs, compound edge segments, self-aligning bearings and v-seals for the roll unit major overhaul with combined costs at slightly over R10 million which equates to 99% of the roll unit cost.

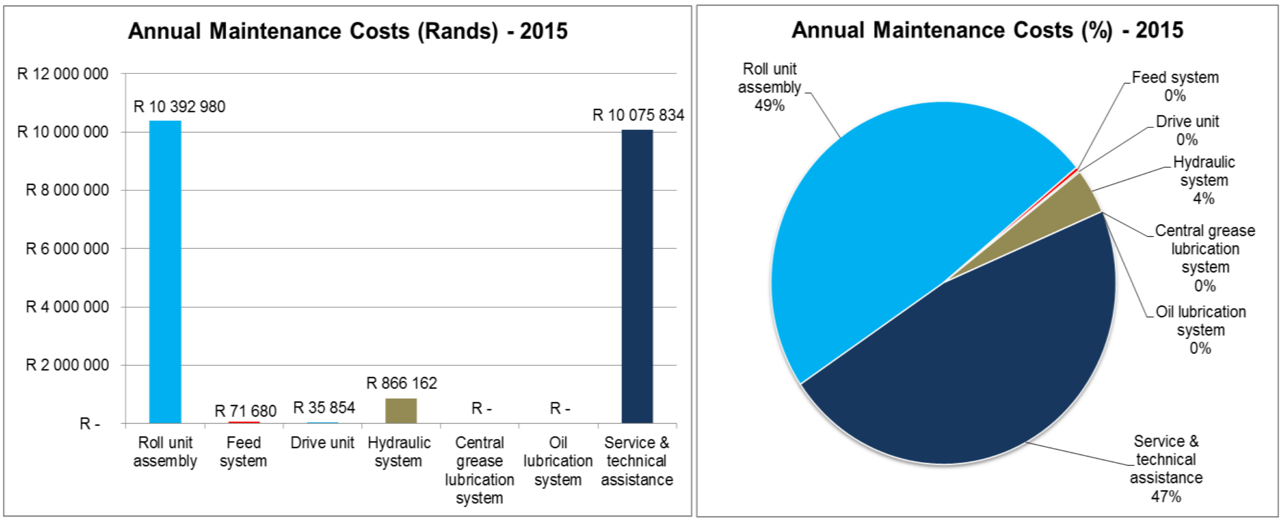


Figure 4-10: Annual maintenance costs & percentage breakdown - 2015

Further from the results in Figure 4-10 above, the second observation indicates that the second highest contributor towards maintenance cost is service and technical assistance, slightly over R10 million, which equates to 47% of the overall maintenance costs for that year. The reason being the refurbishment of the roll unit at the workshop, as well as the unplanned replacement of a self-aligning bearing on site due to catastrophic failure. The combined costs for this work were at slightly over R9.5 million which equates to 95% of the service and technical assistance cost. Lastly, this cost is followed by hydraulic system, feed system and drive unit respectively with combined costs at slightly under R1 million, which equates to 4.5% of the maintenance costs and the oil lubrication as well as the central grease lubrication system having no associated costs towards the overall maintenance costs.

In 2016, from the results shown in Figure 4-11, below the first and obvious observation is that the highest contributor towards maintenance cost is service and technical assistance at over R22 million, which equates to 58% of the overall maintenance costs for that year. The reason being another refurbishment of the roll unit at the workshop and roll unit replacement on site due to a catastrophic bearing failure in 2015, as well as another gearbox refurbishment at the workshop. The combined costs for this work came in at slightly over R22 million which equates to 98% of the service and technical assistance cost.

The second observation is a further increase of the roll unit cost from the calculated cost in 2015, making it the second highest contributor towards maintenance costs at over R12.8 million which equates to 32% of the overall maintenance costs for that year. This is due to the supply of self-aligning bearings, hard metal studs, compound edge segments and v-seals for the roll refurbishment with combined costs at slightly over R12.5 million equating to 98% of the roll unit cost.

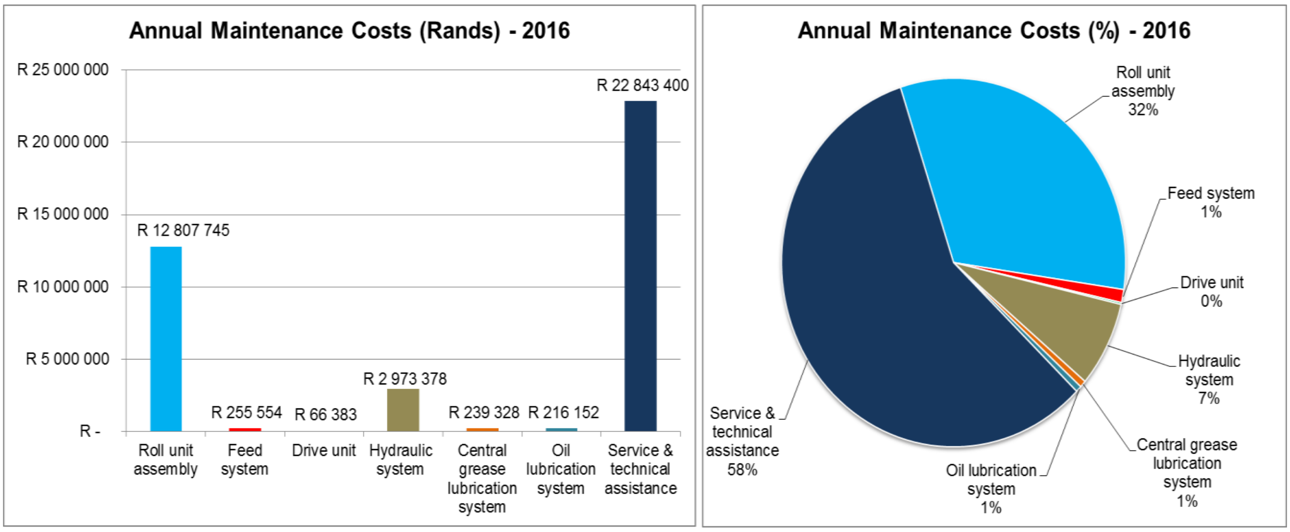


Figure 4-11: Annual maintenance costs & percentage breakdown - 2016

Further from the results on Figure 4-11 above, the third observation is that the hydraulic system is the third highest contributor towards maintenance costs at over R2.9 million which equates to 7% of the overall maintenance costs for that year. This is due to the supply of hydraulic cylinders and valve blocks with combined costs at slightly over R2.8 million, which equates to 95% of the hydraulic system cost. Lastly, this cost is followed by the central grease lubrication system, feed system, oil lubrication system and drive unit respectively with combined costs at slightly under R800 thousand, which equates to 2% of the overall maintenance costs.

In 2017, from the results on Figure 4-12 below, the first and obvious observation is that service and technical assistance cost remains the highest contributor towards maintenance cost from 2016, totalling at over R20 million which equates to 41% of the overall maintenance costs for that year. This is due to another refurbishment of the roll unit at the workshop and roll unit replacement, torque arm and gearbox replacement as well as gearbox replacement, hydraulic cylinders refurbishment and site inspections. The combined costs for this work were at slightly over R19.8 million which equates to 98% of the service and technical assistance cost.

The second observation relates to the sharp increase of the drive unit cost from the calculated cost of R 66 thousands in 2016 to over R16 million, which equates to over 240 times the value calculated in 2016. This cost surpasses the roll unit cost and totals over R16 million, which equates to 32% of the overall maintenance cost. The reason being the supply of two new gearboxes, one new torque arm and a set of associated fasteners with a combined cost at slightly over R15.9 million which equates to 99.8% of the drive unit cost.

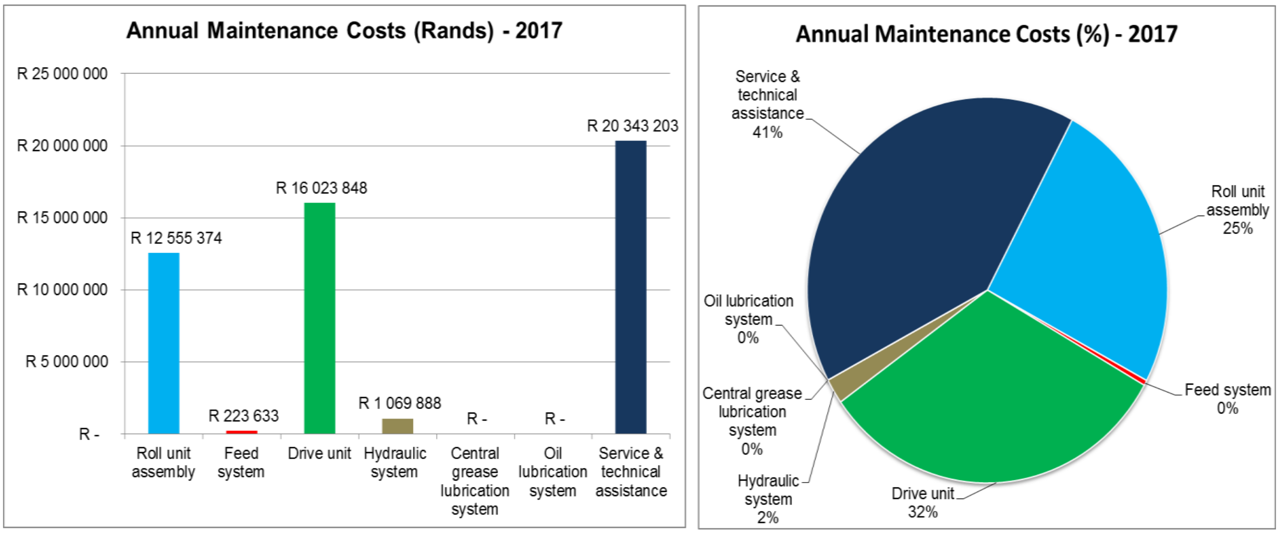


Figure 4-12: Annual maintenance costs & percentage breakdown - 2017

Further from the results on Figure 4-12 above, the third observation is that the roll unit cost remains more constant from calculated cost in 2016, making it the third highest contributor towards maintenance costs at over R12.5 million which equates to 25% of the overall maintenance costs for that year. This is as the result of the supply of two new roll bodies (which are replaced every two years depending on the wear rate), hard metal studs and compound edge segments for the roll refurbishment as well as a new shaft cooling system, which was decided upon after an investigation on the catastrophic bearing failure.

The combined costs were at slightly over R12.3 million which equates to 98% of the roll unit cost. Lastly, this cost is followed by the central grease lubrication system, feed system, oil lubrication system and drive unit respectively with combined costs at slightly under R800 thousand which equates to 2% of the overall maintenance costs.

4.4.4 Total Life Cycle Cost (LCC) of the HPGR – With No NPV

The total life cycle of the HPGR is expressed as a summation of the above costs. The above costs are calculated using Microsoft Excel through the derived empirical formulae. The summation of all the cost is based on the following formulae:

$$LCC = Acquisition\ costs + Operational\ costs + Failure\ costs + Support\ costs - Net\ Salvage\ Value \quad (2)$$

Where:

$$Net\ Salvage\ Value = Salvage\ Value - Disposal\ cost \quad (3)$$

The above equations considered actual costs which were retrieved from secondary data. These included the following:

- Annual operating and maintenance costs;
- Spare(s) supply costs;
- Power consumption costs;
- Labour and consumable costs;
- Annual throughput tonnage; and
- Availability – operating hours per year;

From the calculations, the total life cycle cost of the HPGR is tabulated in Table 4-9. The table comprises of yearly costs for operations and maintenance as well as the acquisition cost and net salvage value which remains constant for the period of observation as the original contract value. The total LCC is well over R282 million which equates to over 4 times the original acquisition cost. Furthermore the table includes the total LCC in Rand (ZAR) value which is then converted to Rands/ ton based on the calculated annual tonnage output taking into account the overall availability. This value is converted into foreign currency (i.e. USD/ton and Euro/ton) based on the average calculated exchange rate over the period of observation.

Table 4-9 – Total life cycle cost of the HPGR – With No NPV

TOTAL LIFE CYCLE COST OF HPGR (Without NPV)					
	2014	2015	2016	2017	TOTAL
Acquisition cost	R 70 000 000	R 70 000 000	R 70 000 000	R 70 000 000	R 70 000 000
Operating costs	R 18 853 512	R 20 434 105	R 20 988 394	R 23 885 856	R 84 161 867
Maintenance costs	R 18 734 166	R 21 442 509	R 39 401 939	R 50 215 946	R 129 794 561
Net salvage costs		R 845 880		R 845 880	R 1 691 760
				TOTAL	**R 282 264 668**
				ZAR/t	**R 16.21**
				US$/t	**$ 1.23**
				€/t	**R 1.05**

The above costs are presented graphically in Figure 4-13 where the acquisition cost remains constant for the period of observation. Apart from the constant acquisition cost, the first observation noticed is that operating and maintenance costs start of equally in 2014 at just over R18 million. The second observation, specifically on the maintenance cost, starts to form an inclining trend between 2015 to 2017, which resembles an exponential curve, and reaching a total of slightly over R50 million in 2017 equating to 71% of the acquisition cost. Various factors contributed to this, including repeated roll unit replacement and refurbishment; gearbox replacement and refurbishment, supply of roll unit components and drive unit as indicated under the maintenance cost section 4.4.3. These costs were associated with unplanned maintenance due to breakdowns, inadequate planned maintenance, operating the HPGR beyond design capacity and improper management of wear parts.

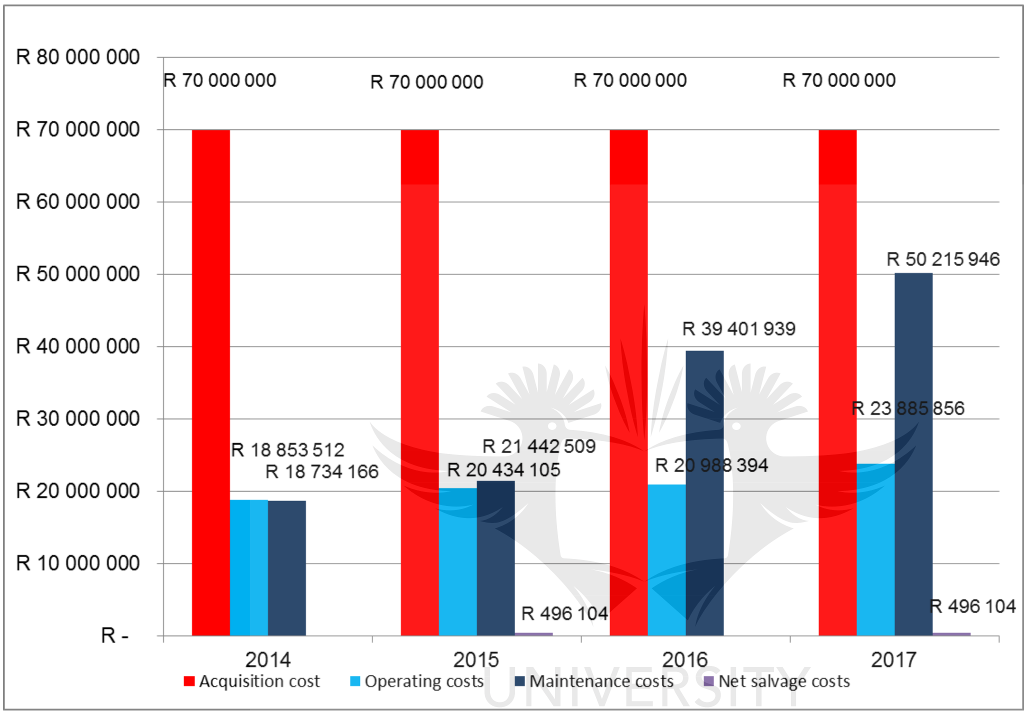


Figure 4-13: Total life cycle cost of the HPGR – 2014 to 2017

In line with this, operating costs gradually increased over the period of observation and formed a linear trend. The operating costs started at just over R18 million in 2014 and increased to over R23.8 million in 2017 which equates to 36% of the acquisition cost. The reason being the fact that components of these costs are human resources which are fairly constant throughout, as annual remuneration increases are based on individual and company performance which normally ranges between 6 – 10% for many organizations.

In breaking down the total LCC of the HPGR in Figure 4-14, it is evident that the maintenance costs contributes to a large percentage costs at 45.9%, followed by operating costs at 29.7% and lastly by acquisition costs at only 24.7%, as well as the net salvage costs at 0.4%. Figure 4-14 provides a graphical breakdown of the total LCC cost for the observation period.

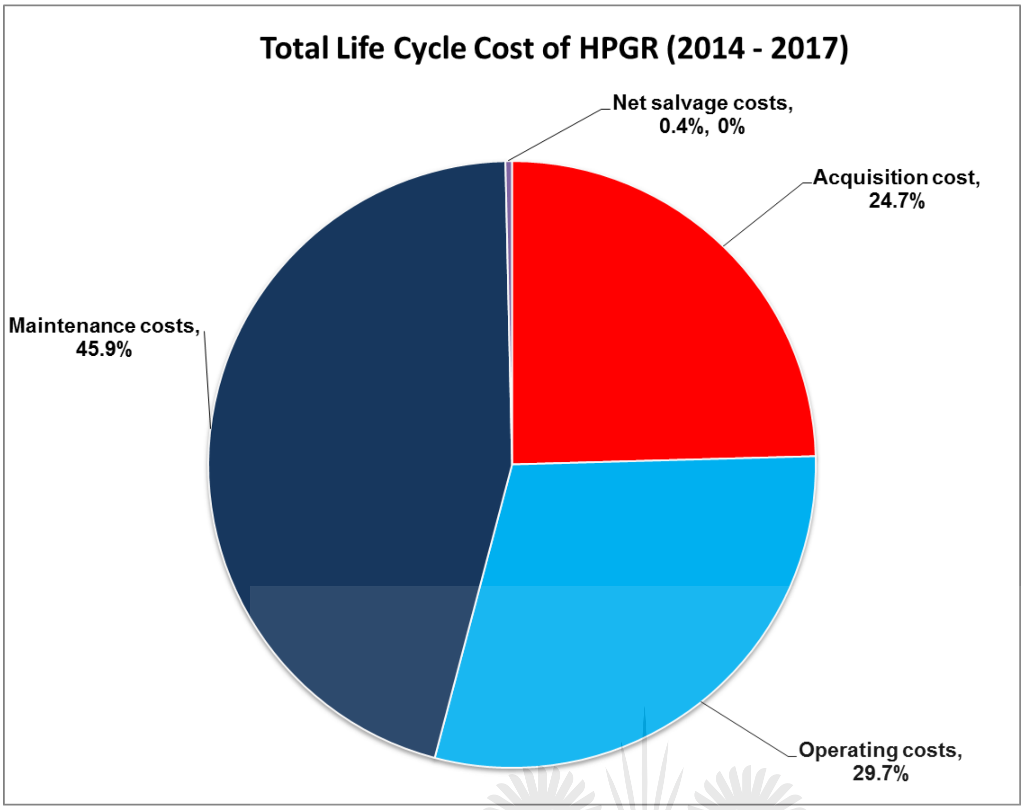


Figure 4-14: Total life cycle cost – Percentage breakdown

In summation, operating and maintenance costs yield a percentage of 75.6% of the total ownership costs. This figure is supported by research presented by Jing et al. (2012) that approximately 70% of the product's life cycle is confirmed during the operating and maintenance phase. Furthermore, in support to this estimation, Wang et al. (2009) suggested that approximately 50 – 60% of the LCC is accounted for in the operating and maintenance phase. Therefore, the percentage obtained from this research appears to be in-line with the researchers' estimations. The difference in percentages may be due to various factors which include: inflation, operating and maintenance strategies and electricity cost as well as ore processes, just to name a few.

Furthermore, the combined value of operating and maintenance costs is R214 million which equates to R12.3 per ton and subsequently translates to $0.93 per ton and €0.8 per ton for this research. From the original feasibility study conducted by the HPGR supplier the combined cost for operating and maintenance costs was estimated at €0.3 per ton. This was purely based on ideal conditions where components were assumed to be operational for their theoretical life span with roll unit replacements every two (2) years. However, the results of this research clearly yield a value which is over 2.6 times the contractual estimate. This is due to the unexpected mechanical failures which were experienced during the period of observation. Von Michaelis (2009) conducted research where a comparison from various researchers was made on the operating and maintenance costs for HPGR with ranging capacity and concluded that a range between $0.37 and

$1.45 per ton was plausible. Hence, the value of $0.93 per ton obtained in this research appears to be realistic and within the ranges presented by Von Michaelis (2009).

In analysing the operating costs, it is further noticed that the power consumption is approximately 11% of the total LCC. From research presented in Figure 4-15 by Deloitte (2012) from various mineral processing plants, i.e. gold, platinum and diversified mining groups, the percentage power consumption costs from the total cost of ownership ranged from 3 to 21%. The reasons for this vast variation as stated by Deloitte (2012) are contributed to the following:

- Within the mining sector, gold processing plants are regarded as the most electricity dependant process with electricity costs ranging from 6 to 14% of the total ownership costs, followed by platinum processing plants and lastly the wide-spread of mining groups.
- A major challenge is trying to distinguish between costs for local and off-shore activities at company level, such as imports and exports costs. As a result attempts to assess the impact and exposure to increasing costs or influence on profitability will not be vigorous.
- This challenge is further inflated in cases where a large wide-spread of mining groups are involved in a mass of activities but solely report on financial projections at a group level.
- The sharp and continued increases in electricity prices over the period from 2007 – 2017 is seen as the major driver.

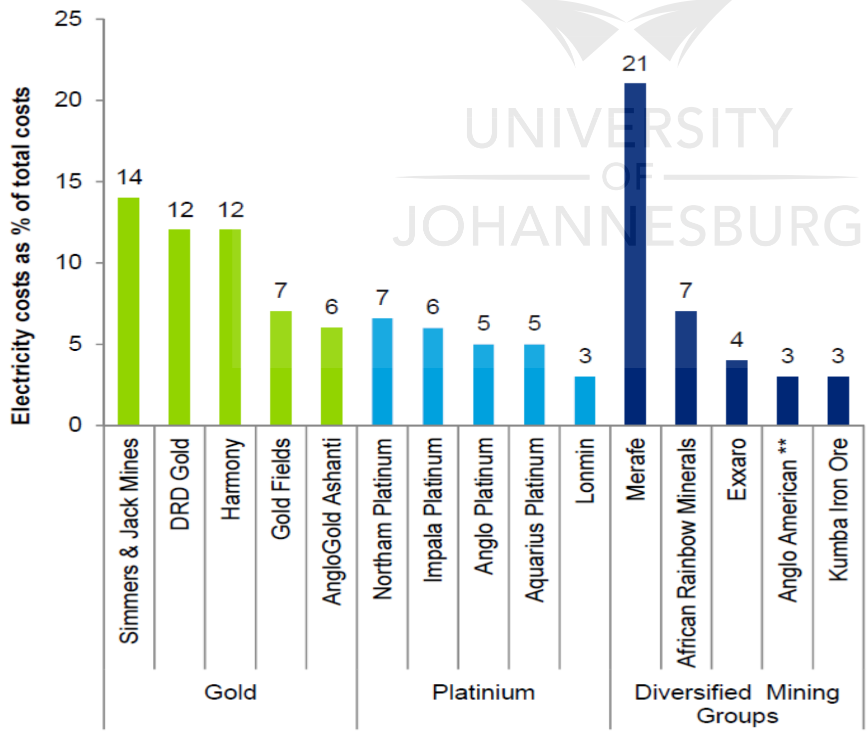


Figure 4-15: Power consumption costs as percentage of total LCC (Deloitte, 2012)

4.4.5 Total Life Cycle Cost (LCC) of the HPGR – With NPV

This section provides a holistic overview of the total LCC of the HPGR from inception phase, in 2007, to the anticipated end of 20 years design life, in 2027. In order to achieve this objective, all actual cost would be necessary to provide a more accurate cost image. However, as stated previously availability of data from 2007 to beginning of 2014 was a challenge as no proper record keeping and ERP system was instituted.

Moreover, the period from end 2017 to 2027 remains unknown. Therefore, given the above reasons, the most appropriate method to conduct an all-inclusive LCC would only be possible with Net Present Value. According to Mohamad et al. (2014) this method is most appropriate for long-term cost evaluation as it caters for time value of money.

Hence, the applicable formulae for this section are equations 2, 3 and 4 derived in section 2.5.1. The reasons for using these formulae were due to cost components considered which include the following:

- Annual operating and maintenance costs
- Cost per failure and spare(s) supply
- Labour and consumable cost
- Annual throughput tonnage
- Net salvage costs
- Availability – operating hours per year, and
- Annual inflation, interest rates and foreign exchange rates.

$$LCC = Acquisition\ costs + Operational\ costs + Failure\ costs + Support\ costs - Net\ Salvage\ Value \quad (2)$$

Where:

$$Net\ Salvage\ Value = Salvage\ Value - Disposal\ cost \quad (3)$$

From an empirical representation:

$$LCC = C_U + [F_O + P_A(i, t_d)C_O] + [P_A(i, t_d)C_f \frac{t_0}{MTTF} + [F_S + P_A(i, t_d)C_S] - [P_F(i, t_d)S] \quad (4)$$

$$Acquisition = Design + Manufacturing + Transport + Installation + Commissioning + Spares \quad (16)$$

$$Operational\ cost = [F_O + P_A(i, t_d)C_O] \quad (4.1)$$

$$Maintenance\ (Failure\ \&\ Support\ costs) = [P_A(i,t_d)C_f \frac{t_0}{MTTF} + [F_S + P_A(i,t_d)C_S] \quad (4.2)$$

$$Net\ salvage\ value = [P_F(i,t_d)S] \quad (4.3)$$

From the calculations, the total life cycle cost of the HPGR is tabulated in Table 4-10. The table comprises of yearly costs for the operating, maintenance and net salvage value as well as the acquisition cost which remains constant for the period of observation as the original contract value. The total LCC is well over R232 million which equates to over 82.4% of the amount calculated in section 4.4.4. This is possible due to a number of reasons: the unexpected number of equipment failures, maintenance strategies and the fact that LCC based time value of money does not consider imperfect maintenance conditions.

Furthermore the table includes the total LCC in Rand (ZAR) value which is then converted to Rands/ ton based on the calculated annual tonnage output take into account the overall availability. This value is converted into foreign currency (i.e. USD/ton and Euro/ton) based on the average calculated exchange rate over the period of observation.

Table 4-10 – Total life cycle cost of the HPGR – Based on NPV

TOTAL LIFE CYCLE COST OF HPGR (With NPV)					
	2014	**2015**	**2016**	**2017**	**TOTAL**
Acquisition cost	R 70 000 000	R 70 000 000	R 70 000 000	R 70 000 000	R 70 000 000
Operating costs	R 18 853 512	R 19 984 723	R 21 183 806	R 22 454 834	R 82 476 875
Maintenance costs	R 18 734 166	R 19 858 216	R 21 049 709	R 22 312 692	R 81 954 784
Net salvage costs		R 845 880		R 950 431	R 1 796 311
TOTAL					**R 232 635 349**
ZAR/t					**R 13.36**
US$/t					**R 1.02**
€/t					**R 0.87**

The above costs are presented graphically in Figure 4-16 where the acquisition cost remains constant for the period of observation. Apart from the constant acquisition cost, the first observation noticed is that operating and maintenance costs starting off in 2014 are fairly equal at just over R18 million. In the second observation, both operating and maintenance costs start to form an inclining trend between 2015 to 2017, which resembles an linear graph and reaching a total of slightly over R22 million in 2017 which equates to 31.4% of the acquisition cost. The reasons relates to the time value of money which considers the inflation and fluctuation as well as compounding interest over a period of 20 years (from 2014 to 2034).

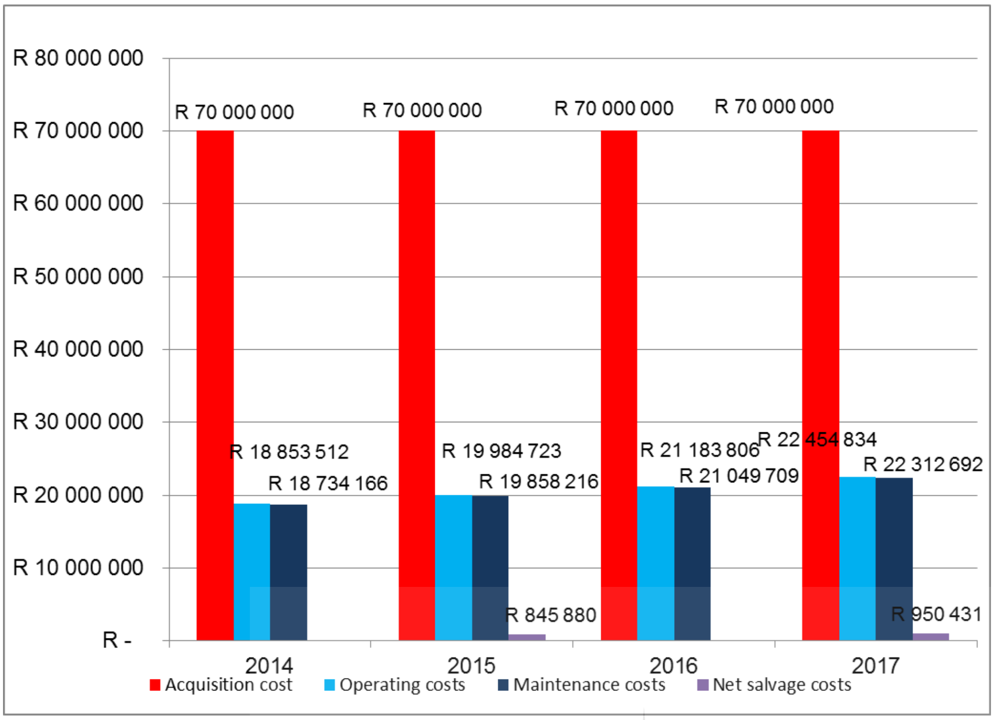


Figure 4-16: Total life cycle cost of the HPGR – 2014 to 2017 – Based on NPV

In breaking down the total LCC of the HPGR in Figure 4-17, both operating and maintenance costs both contributed large percentages of 35% each followed by acquisition cost at 29% and lastly by the net salvage costs at 1%. The reason for similar percentage for operating and maintenance costs is attributed to the similar future value of over R 18 million in 2014.

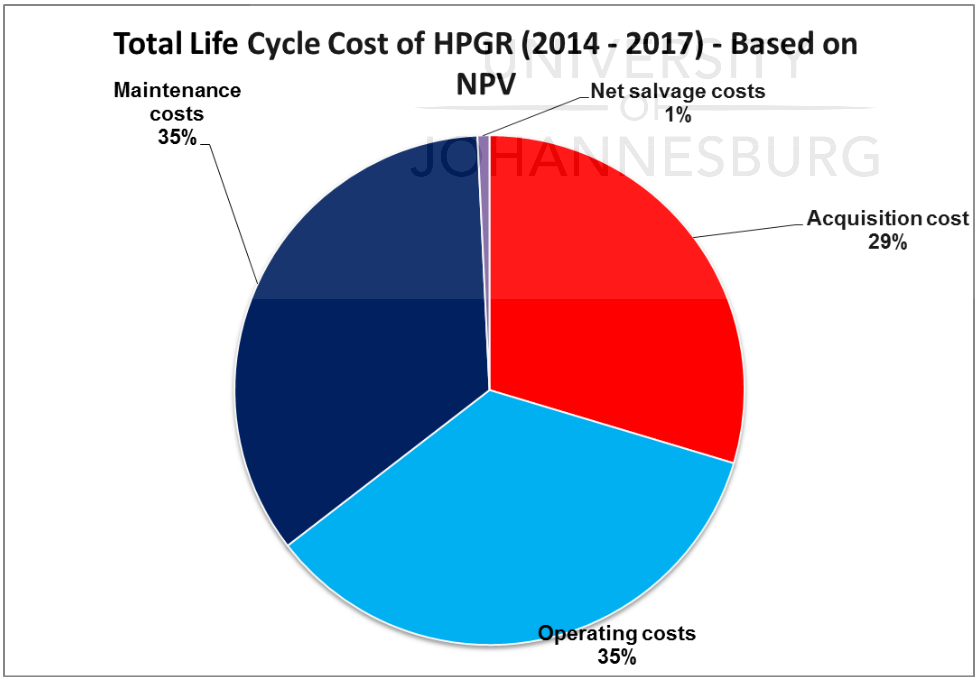


Figure 4-17: Total life cycle cost – Percentage breakdown (Based on NPV)

The entire LCC analysis for the duration of the anticipated design life is presented by Table 4-11. Tabulated in the table is the acquisition, operating, maintenance and net salvage value. Apart from the acquisition cost, these values are calculated based on the empirical formulae 3 and 4. Firstly the operating and maintenance costs in 2014 are based on the actual costs derived from archive records. These are taken as future values for a total period of 20 years. Therefore the NPV is derived for each of the years of operation. Meanwhile, the net salvage value is based on the scrap value for all the saleable components and allows for disposal costs incurred.

The rows highlighted in green indicate the period of observation for this research. The purpose for this was to generate a "snapshot" of the LCC which can be compared with values obtained in section 4.4.4. The annual interest is based on 6% and the number of period equals to 20 years.

Table 4-11 – Total life cycle cost of the HPGR – Design Period

TOTAL LIFE CYCLE COST ANALYSIS - TIME VALUE OF MONEY						
Year	**Number of years (n)**	**Acquisition cost**	**Operating Cost**	**Maintenance Cost**	**Salvage Cost**	**Total LCC (Accumaltive)**
2014	0	R 70 000 000	R 18 853 512	R 18 734 166		**R 107 587 678**
2015	1		R 19 984 723	R 19 858 216	R 845 880	**R 146 584 738**
2016	2		R 21 183 806	R 21 049 709		**R 188 818 253**
2017	3		R 22 454 834	R 22 312 692	R 950 431	**R 232 635 349**
2018	4		R 23 802 124	R 23 651 454		**R 280 088 927**
2019	5		R 25 230 252	R 25 070 541	R 1 067 904	**R 329 321 815**
2020	6		R 26 744 067	R 26 574 773		**R 382 640 655**
2021	7		R 28 348 711	R 28 169 260	R 1 199 897	**R 437 958 729**
2022	8		R 30 049 634	R 29 859 415		**R 497 867 778**
2023	9		R 31 852 612	R 31 650 980	R 1 348 204	**R 560 023 165**
2024	10		R 33 763 768	R 33 550 039		**R 627 336 973**
2025	11		R 35 789 595	R 35 563 041	R 1 514 842	**R 697 174 766**
2026	12		R 37 936 970	R 37 696 824		**R 772 808 560**
2027	13		R 40 213 188	R 39 958 633	R 1 702 077	**R 851 278 305**
2028	14		R 42 625 980	R 42 356 151		**R 936 260 436**
2029	15		R 45 183 539	R 44 897 520	R 1 912 453	**R 1 024 429 041**
2030	16		R 47 894 551	R 47 591 371		**R 1 119 914 963**
2031	17		R 50 768 224	R 50 446 854	R 2 148 833	**R 1 218 981 208**
2032	18		R 53 814 317	R 53 473 665		**R 1 326 269 190**
2033	19		R 57 043 176	R 56 682 085	R 2 414 428	**R 1 437 580 023**
2034	20		R 60 465 767	R 60 083 010		**R 1 558 128 799**

4.4.6 Total Life Cycle Cost (LCC) – Major Cost Drivers

For simplicity, only the costs above 4% of individual cost components, i.e. above 4% of total operating and maintenance costs, were considered in Table 4-12.

From the results it can be noticed that the highest major cost driver is contributed by the labour cost portion at over 22%. This value is followed by in descending order: roll refurbishment at 10%, gearbox refurbishment at 8%, hard metal studs at 7.4%, main motors at 5.4%, conveyor drives at 5.3%, gearbox supply at 5.3%, refurbishment (torque arm, gearbox and roll change) at 4.9% as well as the remainder of the components between 0.2 to 3.7%.

Table 4-12 – Major cost drivers of total LCC

Item	Description	Associated costs (Rands)	% of Total LCC
Operating Costs			
1	Labour	R 47 521 638	22.2%
2	Main motor - total (kW)	R 11 526 590	5.4%
3	Feed and discharge conveyor - total (kW)	R 11 276 012	5.3%
4	Cooling water - total (kW)	R 6 615 260	3.1%
5	Wear parts	R 3 406 500	1.6%
6	Grease - Consumption (g/h)	R 1 470 784	0.7%
7	Hydraulic drive motor - total (kW)	R 1 102 543	0.5%
8	Oil - consumption (400L/3000hrs)	R 653 682	0.3%
9	Auxiliary/ barring drive - total (kW)	R 551 272	0.3%
10	Auma actuator - total (kW)	R 37 587	0.0%
Maintenance Costs			
1	Roll refurbishment	R 21 566 506	10.1%
2	Gearbox refurbishment	R 17 131 520	8.0%
3	Hard metal stud	R 15 801 149	7.4%
4	Gearbox	R 11 293 766	5.3%
5	Roll change, refurbishment of torque arm & gearbox replacement	R 10 415 361	4.9%
6	Self-aligning bearings	R 7 681 599	3.6%

Item	Description	Associated costs (Rands)	% of Total LCC
7	Compound edge segment	R 7 624 400	3.6%
8	Roll change	R 7 022 749	3.3%
9	Roll body	R 4 638 594	2.2%
10	Torque support system	R 4 539 000	2.1%
11	Hydraulic cylinder - thrust	R 3 283 650	1.5%
12	Replacement of self-aligning bearings	R 2 836 112	1.3%
13	Gearbox replacement	R 1 820 060	0.9%
14	Valve blocks	R 1 320 026	0.6%
15	V-seals	R 1 222 908	0.6%
16	Instrumentation	R 1 144 548	0.5%
17	Flange shaft - intermediate	R 990 235	0.5%
18	Safe-set coupling	R 920 000	0.4%
19	Shaft cooling system	R 903 596	0.4%
20	Cardan shaft repair	R 765 943	0.4%
21	Frame & fasteners	R 677 427	0.3%
22	HPGR Inspections	R 575 618	0.3%
23	Hydraulic cylinder – push-back	R 561 094	0.3%
24	Wear protection – main feed hopper	R 560 256	0.3%
25	Seal replacement	R 510 591	0.2%
26	Hydraulic cylinder refurbishment	R 485 225	0.2%
27	Expansion joint	R 453 962	0.2%
28	Instrumentation	R 358 920	0.2%
29	Guide rails	R 341 472	0.2%
30	Screw bolts	R 296 127	0.1%
31	Pumps	R 270 549	0.1%
32	Filters	R 230 296	0.1%

Item	Description	Associated costs (Rands)		% of Total LCC
33	Installation edge segments	R	227 348	0.1%
34	Actuator Auma	R	223 633	0.1%
35	Pumps	R	216 152	0.1%
36	Service Level Agreement - SLA	R	214 086	0.1%
37	Hydraulic system breakdown	R	152 096	0.1%
38	Shaft	R	135 800	0.1%
39	Instrumentation	R	135 756	0.1%
40	Pump	R	85 500	0.0%
41	Vibration analysis	R	66 129	0.0%
42	Replacement of gate valve internals	R	58 734	0.0%
43	Cardan shaft inspection	R	42 414	0.0%
44	Inspection of gearbox bearings	R	41 795	0.0%
45	Edge segment repairs	R	15 943	0.0%
46	Auxiliary/ barring drive system	R	7 584	0.0%
47	Installation smart check system - online monitoring system	R	123	0.0%
48	Installation of knuckle bearing	R	-71 791	0.0%
	TOTAL	R	213 956 428	100.0%

4.4.7 Discussion of results

The overall LCC cost as presented above for the selected case study confirms that certain components have more influence on the overall LCC than the other components which contribute a rather negligible portion of below 2%. Prior to the LCC analysis, the researcher was of the opinion that labour did not have a major impact on the LCC. Power consumption was perceived to be the number one contributor. However, the results indicated otherwise where labour was shown to be the number one contributor. This further confirms the drive by many organisations within the mining fraternity to increase system automation which will require less human intervention and operation (Nettleton et al., 2016).

The results for the total LCC were presented in two parts- one giving no consideration to the time value of money and the other with consideration of the time value of money. The outcome of these two approaches indicates that there is a slight difference between the two where one cost increases exponentially and the other linearly, respectively. Another observation made by the researcher is that the approach with no NPV is more applicable where cost information is available and of good quality. While the approach with NPV also provide a better understanding on anticipated future costs which can assist in better planning and decision making on investment.

A number of researches (Rajasekar et.al 2006; Johnson and Onwuegbuzie, 2004; Yin, 2013 and Gomm et al., 2000) emphasized data availability and quality. This research also confirmed the importance of data availability and quality. The researcher encountered the following challenges:

- Information from 2007 – 2013 was not available and the period of observation had to be reduced to four (4) years;
- Information from 2014 – 2015 was available electronically where only selected information was scanned and certain original files could not be located;
- For the same period, information was not transferred to the ERP (SAP^{TM}) system; and
- Information from 2016 – 2017 was available on the ERP (SAP^{TM}) system but was grouped together with spare parts sales, technical assistance and service. This information had to be organized and grouped according to the correct cost classification.

4.5 Conclusion

The chapter focused on presenting a case study for this research and findings pertaining to the LCC of the HPGR. The case study was based on the HPGR which is currently installed and operating within a mineral processing circuit for one of the largest platinum group subsidiaries in the world.

The main objectives of the chapter was to quantify the HPGR's LCC during the operating and maintenance life cycle phase for a period of four (4) years. The LCC was quantified using empirical formulae provided in chapter 2. Furthermore, part of the objectives was to identify major cost drivers and how they influenced the overall LCC as well as the HPGR's reliability.

The use of a case study as the research method has increased the researcher's knowledge and understanding of how to quantify the LCC as well as to identify major cost drivers and what contributed to these exorbitant costs. The acquired knowledge will not only be of value to the researcher but will certainly contribute to the body of knowledge pertaining to life cycle costing analysis, and will enable key decision makers to make more informed and accurate decisions.

The next chapter presents the conclusions derived from the preceding chapters. It also provides recommendations on how to quantify LCC, as well as possible future research to improve on the body of knowledge pertaining to LCC analysis.

5 CHAPTER 5 – CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the researcher evaluates whether the research conducted accomplished the objectives set-out in the beginning. Firstly, research findings are concluded and recommendations presented. Lastly, the chapter concludes with suggestions for future research.

5.1 Introduction

The main objectives of this research were to quantify the life cycle cost of the HPGR during its operating and maintenance cycle as well as to identify major cost drivers and to provide recommendations on how these could be controlled and/ or minimised. The drive behind these objectives was fuelled by the lack of understanding of the LCC subject matter by the researcher, as well as a gap which existed within the researcher's organization where the topic had not formally taken ground.

The research explored available LCC models which could better suit the expected outcomes by the researcher. On evaluation of available models, it was concluded by the researcher that an integrated model would be appropriate for this research. A combination of an Activity Based Costing (ABC) and Cost Break-down Structure (CBS) was derived. In order to apply the integrated model, data availability was necessary and key to accomplishing the research objectives.

A case study was selected as an appropriate method of investigating this research using an empirical approach. The case study was based on the HPGR which has been in operation since 2007. The results obtained for the LCC of the HPGR was for the period of observation as well as for the major cost drivers. Furthermore, an all-inclusive LCC of the HPGR for the expected design life of years was also obtained.

5.2 Findings

Apart from the research objectives, the aim of the research was also to provide in-depth understanding of the LCC concept through addressing the research questions.

RQ 1: What is the LCC of a high pressure grinding roll (HPGR) during its operating and maintenance cycle for a period of four (4) years?

In order to address the above research question, an in-depth investigation on the operating and maintenance cost, intervals, break-down occurrences, spare parts supply, overhauls, archive documents and consumables was necessary. These values were then used as inputs into the derived model for processing and yielding outputs. From the results, the LCC was quantified for a period of four (4) years. The results indicated that the LCC during the operation and maintenance phase was significantly higher than the acquisition cost. This was possibly due to factors which could not be foreseen during the design/ acquisition phase such as unplanned events and repeated breakdowns/failures. Various research also concluded that the large portion of the overall LCC for a given system/ equipment is confirmed during the operation and maintenance phase.

Furthermore, the result also indicate a substantial difference between LCC calculated based on the actual costs and activities performed on the HPGR when compared with LCC which considered time value of money. This is due to the compounding interest imposed on current values over the period classified as the expected design life of the HPGR.

RQ 2: What are the key cost drivers impacting LCC of an HPGR?

It is evident that there are influencing factors which either drive the LCC through the roof or reduce it to acceptable levels where organizations can still realise profits. In order to derive a pattern and to identify major cost drivers, the HPGR was broken down into sub-assemblies and was further divided into component levels. From the results, it was noticed that the major cost contributor was the labour cost. However, from initial perception by the researcher this was assumed not to be the number one contributor. This value is followed in descending order from: roll refurbishment, gearbox refurbishment, hard metal studs, main motors, conveyor drives, gearbox supply and refurbishment (torque arm, gearbox and roll change).

Firstly, the roll refurbishment and hard metal were expected costs to be one of the major contributors as these costs are incurred every second year during operation due to wear life expectancy. Secondly, the drive motors were added to the list as major costs drivers due to the power consumption by these units. Lastly, supply of a new gearbox and torque arm was due to a number of reasons: contamination of gearbox oil, inadequate maintenance and improper operation of the HPGR.

5.3 Conclusions

These conclusions were drawn from various chapters within this research. It is imperative that senior management understand and accept the impact of maintainability and reliability, and the pivotal role it plays in contributing to competitiveness and market share. This acceptance will support the need to develop and implement a support framework and action plans to support this drive for efficient reliability and maintenance management within the organization is imperative.

From the research findings presented above, it is evident that much work has been carried out to develop LCC models with an attempt to aid organizations with a tool to make informed decisions and manage costs associated with a product more appropriately. From the evaluation of these tools and LCC methods, the following conclusions can be made:

- Data availability and quality plays a vital role in the success of LCC analysis.
- Proper record keeping and efficient usage of the ERP system are keys to the implementation of LCC.
- The practical implementation of these LCC models and analysis within organizations is still noted as a challenge.
- Successful implementation of a LCC analysis should be viewed as a long term process and must have “buy-in” from all stakeholders starting from top management and cascading down to operational staff.
- Sound and efficient maintenance strategies which must be implemented and practised regularly in order to control, manage and minimize life cycle cost are paramount.

5.4 Recommendations and Future Research

The LCC topic is gaining more ground as organizations seek tools and resources to better control costs which affects the bottom line. More organizations are engaging and establishing asset management divisions within their units. The main driver for this is to understand the actual cost of ownership, and not what is perceived at equipment acquisition.

The success of an asset management division is predominantly governed by an understanding of equipment/ system cost behaviour, namely the life cycle cost. This will enable decision makers to devise strategies which are more feasible and result orientated. Therefore, it is recommended that LCC should be considered at acquisition phase as maintenance strategies by both the equipment designer and the owner. This is to ensure that in-depth thinking goes into cost control from design phase to the utilization phase. From the findings of this research, maintenance played a significant role as the LCC analysis as a result continuous improvement of maintenance strategies is highly recommended.

Furthermore, at this stage proper allowance can be made as to what tools and resources are necessary for the proper management of LCC.

This research was limited to one HPGR where not all relevant information could be obtained. Sufficient knowledge has been provided in this research as to how to quantity the life cycle cost as well as to confirm major cost drivers. However, future research can also consider the following:

- Reliability of the HPGR in order to compare with the calculated life cycle cost.
- How improved reliability yields positively on cost control thus reducing overall LCC.
- What maintenance strategies should be implemented and how to implement these.

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7 APPENDICES