Mining Earth Moving Equipment Major Component Change-Out Approach: A Broader Perspective

Dr. Dyson Galatia, PhD

Zambia
dysongalatia[at]gmail.com

Abstract: ***The dynamic production budgets and the volatile metal prices in the current mining industry have stimulated and strengthened a continuous search for operating efficiency in all areas of the production process, with reliability of the earth moving equipment being one of the core aspects. Unpredicted breakdown of earth moving machine major components usually cause serious consequences such as loss of production, extra cost and deviation from mine plans. From a financial perspective, these components are one of the key cost drivers among the top Mine cost centers and success in managing them (achieving expected life cycle and operational cost) is essential in meeting maintenance and production cost (cost/ton) of the equipment. Whereas relatively small and frequent repairs largely affect availability, operational cost is directly affected by major component failure. In trying to maximize the operating efficiency of earth moving equipment, various maintenance strategies and methodologies have been tried, tested and initiated. However, the challenge in most, if not all operations, has been to find an accurate method to determine the exact expected replacement point of major components. This phenomenon has been challenging, though a number of operations engage in a time-based replaced strategy as recommended by most equipment manufacturers, replacement schedules are rarely executed as panned. The norm however, has been to draw up a calendar of parts to be replaced each year during budgeting time and scheduled intervals of replacement are set following the Original Equipment Manufacturers' (OEM) recommendation. Nevertheless, these schedules have not conclusively determined the point at which the replacement is economically justified. This study therefore, highlights the challenges of the traditional time-based component replacement strategy and recommends an approachbased on condition assessment.The data used in this study are obtained from different Mines as well as the experience of the researcher(ethnological study in the industry). The study concludes that, to realize optimum utility from a component, a component management strategy must start right from equipment selection and purchase decisions. Thus, criticalcomponents, which require preventive replacement, need to be identified and monitored through condition monitoring. Condition inspections must bescheduled in such a way that they do not adversely affect the availability of the equipment.***

Keywords: Major Component, Reliability, Life Cycle, Condition Monitoring, Maintenance

1. Introduction

In trying to optimize the operating efficiency of earth moving equipment in the mining industry, various maintenance strategies and methodologies have been tried, tested and initiated.Several mining operations have established maintenance processes, with appropriate resources, which are executed by skilled and competent personnel; however, determining the most economical point or replacing a major component remains a challenge. A number of mining organizations have initiated component replacement programs, referred to as Planned Component Replacement (PCR), which they have incorporated into the overall organizational maintenance and repair processes and routines. Nevertheless, despite these programs being in place, major component replacement schedule timetables are rarely achieved.The component replacement strategy within the industry has emerged as an essential approach when itcomes to the management of equipment components. The aim of this process is to ensure optimum usefulness of componentswhile at the same time maintaining high machine availability andminimizing downtime.The standard in the industry has been to draw up a calendar at the beginning of each financial year indicating the parts to be replaced and the time of replacement designed to the Original Equipment Manufacturers' recommendations. Tables 1 and 2 are extracts of such schedules fromtwo different Mines used as examples.

Table 1: Component Change-out Plan (Mine 1)

					Component life>20,000 hrs in red							
No	Plant No	Model	Machine Hours	Cost	Engine & Fitment kit	Final Drive Group-LH	Final Drive Group-RH	Hydraulic Pump	Radiator (Service Kit)	Rear Diff	Torque Converter	Transmission
1	DT35	CAT 775F	13,256		13,197	13,197	13,197	13,197	13,197	13,197	13,197	13,197
2	DT03	CAT 775F	39,011		14,403	14,403	17,023	14,403	14,403	14,403	14,403	6,663
3	DT33	CAT 775G	16,214		16,106	16,106	16,106	16,106	16,106	16,106	16,106	16,106
4	DT31	CAT 775G	17,470		17,376	1,725	17,376	17,376	17,376	17,376	17,376	2,390
5	DT32	CAT 775G	17,214		0	17,111	17,111	17,111	17,111	17,111	0	17,111
6	DT13	CAT 775G	32,769	59,328	109	7,942	7,942	3,972	32,769	7,942	32,769	7,942
7	DT30	CAT 775F	14,988		3,746	14,882	14,882	3,746	14,882	961	14,882	14,882
8	DT04	CAT 775F	44,077	34,645	18,525	18,525	18,525	18,525	43,973	43,973	690	18,525
9	DT23	CAT 775F	25,373	120,249	6,272	25,373	25,373	6,272	6,272	2,072	6,272	423
10	DT16	CAT 775G	30,511	150,176	8,928	30,449	15,677	8,928	30,449	30,449	8,928	5,876
11	DT12	CAT 775G	30,933	449,773	30,913	30,913	27,903	1,477	30,913	30,913	14,996	5,101
12	DT14	CAT 775G	35,856	247,951	29,640	11,291	11,291	6,738	35,853	35,853	14,280	14,280
13	DT15	CAT 775G	29,621	348,862	26,514	3,142	26,514	1,137	29,621	29,621	17,325	17,325
14	DT11	CAT 775G	34,723	312,442	11,724	27,164	2,360	34,453	34,453	34,453	34,453	36,270
15	DT21	CAT 775F	25,355	179,913	1,962	25,252	25,252	5,981	25,252	25,252	25,252	2,509
16	DT10	CAT 775F	36,184	164,957	5,496	36,073	36,073	5,496	36,073	1,721	36,073	17,796
17	DT25	CAT 775F	25,096	334,745	25,009	25,009	25,009	25,009	25,009	25,009	25,009	688
18	DT24	CAT 775F	24,711	329,637	24,707	2,266	2,119	4,653	24,707	24,707	4,653	24,707
19	DT22	CAT 775F	26,436	183,466	15,456	26,340	26,340	26,340	26,340	26,340	26,340	13,716
20	DT34	CAT 775F	20,213		20,104	20,104	20,104	20,104	20,104	20,104	20,104	20,104
21	DT29	CAT 775F	25,236	316,235	25,134	25,134	25,134	8,816	25,134	6,002	25,134	12,135
22	DT28	CAT 775F	25,861	358,209	25,861	10,903	10,903	25,861	25,861	25,861	25,861	25,861
23	DT19	CAT 775F	27,042	458,770	27,042	27,042	27,042	27,042	2,202	27,042	27,042	27,042
24	DT27	CAT 775F	28,258	334,745	28,250	28,250	28,250	28,250	28,250	28,250	28,250	6,467
25	DT20	CAT 775F	26,547	334,745	26,442	26,442	26,442	26,442	26,442	26,442	26,442	3,588
26	DT17	CAT 775G	33,000	496,173	32,909	32,909	13,479	32,909	32,909	4,911	32,909	22,738

Table 1 is a planned component replacement schedule with components in red indicating components that are overdue (passed the planned replacement period) and require immediate replacement. The target replacement point of these components as indicated by the Planning Department at the Mine is 20,000 hours.However, as seen from Table 1, most of the components have not been replaced as planned. Thus, the budgeting and component replacement scheduling ends up as a wasted effort. Table 2 is another change out plan from a different operation.

Table 2: Component Change-out Plan (Mine 2)

		Jun-16	Jul-16	Aug-16	Sep-16	Oct-16	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17
Loaders	Engine	$ 60,000	$ 60,000	$ -	$ -	$60,000	$ -	$ -	$120,000	$ -	$ -	$ -	$ -	$ -
	Torque Converter	$ 23,274	$ 23,274	$ 23,274	$ -	$ -	$ 23,274	$ -	$ 23,274	$ -	$ 23,274	$ -	$ -	$ 23,274
	Transmission	$ 58,262	$ 58,262	$ 58,262	$ -	$ -	$ 58,262	$ -	$ 58,262	$ -	$ -	$ -	$ -	$ -
	Front Axle	$ -	$248,542	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 82,847	$ 82,847
	Rear Axle	$173,979	$ 57,993	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 57,993	$ 57,993
	Tilt Cylinder	$ 16,932	$ 33,863	$ 33,863	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Lift Cylinder-RH	$ 5,079	$ 5,079	$ 5,079	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 5,079	$ -
	Lift Cylinder-LH	$ 3,555	$ 3,555	$ 3,555	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 7,110	$ -
	Steering Cylinder -RH	$ -	$ 7,047	$ 7,047	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Steering Cylinder -LH	$ -	$ 7,047	$ 3,524	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Radiator Assembly	$ 90,365	$ 30,122	$ -	$ -	$ -	$ -	$ -	$ 30,122	$ -	$ -	$ -	$ 30,122	$ 30,122
		$431,445	$534,784	$134,604	$ -	$60,000	$ 81,536	$ -	$231,657	$ -	$ 23,274	$ -	$183,151	$194,235
Dump Tuck	Engine-Detroit	$ 69,114	$ 69,114	$ 69,114	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 69,114
	Engine-Volvo	$ -	$ -	$ -	$ -	$ -	$ -	$ 75,000	$ -	$ -	$ -	$ -	$ -	$ -
	Torque Converter	$ -	$ 37,751	$ 37,751	$ -	$ -	$ 75,502	$ 75,502	$ -	$ -	$ -	$ -	$ 37,751	$ -
	Transmission	$ 88,147	$176,294	$ 88,147	$ 88,147	$ -	$ 88,147	$264,441	$ -	$ -	$ -	$ -	$ 88,147	$ -
	Front Axle-Dana	$ 56,715	$ 56,715	$113,429	$ -	$ -	$ -	$ -	$ -	$ -	$ 56,715	$ -	$ -	$ -
	Rear Axle-Dana	$ 81,021	$ 81,021	$ 81,021	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$162,042	$ -	$ -
	Front Axle-Kessler	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 92,847	$185,695
	Rear Axle-Kessler	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 64,993	$129,986
	Lift Cylinder-RH	$ 13,789	$ 27,578	$ 13,789	$ 13,789	$ -	$ -	$ -	$ -	$ -	$ 13,789	$ -	$ -	$ -
	Lift Cylinder-LH	$ 9,652	$ 19,305	$ 9,652	$ 9,652	$ -	$ -	$ -	$ -	$ -	$ 9,652	$ -	$ -	$ -
	Steering Cylinder -RH	$ 6,011	$ 18,034	$ 6,011	$ -	$ -	$ 6,011	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Steering Cylinder -LH	$ 6,011	$ 12,023	$ 12,023	$ -	$ -	$ 6,011	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Radiator	$ 59,958	$ 89,936	$ 29,979	$ -	$ -	$ 29,979	$ -	$ 29,979	$ -	$ -	$ -	$ 29,979	$ -
	Intercooler	$ -	$ -	$ 28,897	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 57,794
	Retarder Brake assembly	$ -	$ -	$ -	$ -	$ -	$ 31,372	$ -	$ -	$ -	$ -	$ -	$ 31,372	$ 62,743
		$390,418	$587,771	$489,814	$111,588	$ -	$237,022	$414,943	$ 29,979	$ -	$ 80,156	$162,042	$345,089	$505,332

Table 2 equally shows the component replacement schedule with associated component cost. The crowding of components from June 2016 to August 2016 shows that, a number of components were not replaced as planned in the previous year. Mine 2 financial year starts in June.

In both cases, it is observed that, though a component replacement program exists, the actual replacement of component does not work according to schedule. This is evident from the data obtained from the two Mines. Note that, may more Mines were reviewed and the results were similar.

This study, therefore, highlightsthe demerits of the traditional time-based component replacement approachand recommends the use of a condition assessment strategy. Through a condition assessment plan, critical equipment components, which require preventive replacement, must be identifiedand their reliability monitored through condition inspections (condition monitoring). Condition assessment result will guarantee the continuous use, replacement or repair of a component.

2. Objective of Major Component Replacement

The main objective of planned major component replacement is to maximize the use of a component and avoid stochastic or unplanned failure.Thus, mining operations view planned component replacement as maintenance carried out for the sake of reliability, instead of maintenance for the sake of liability.However, though this thought process may stand true, it is difficult to justify the most economical point at which a component should be replaced.This is because the time at which a component fails is assumed to be deterministic or indiscriminate where failure may follow a certain probabilistic distribution. Bentley (1999) indicates that, the state of interest in component replacement is to optimize some functionsuch as minimizing cost or maximizing utilization. But a question may still arise, what is the exact optimal replacement point at which this optimization can be achieved? It is therefore, important to understand several factors which affect component effective life cycle and to find ways of monitoring the deterioration rate of a component other than merely replacing a component based on its age.

Other advantages advanced towards an effective component replacement strategy include among others:

1) Low component repair cost: The cost of repairable components tends to be low when the wear to the component is not excessive.
2) Efficient use of time: When component replacement is planned, the replacement time is equally planned with less interruption to Mine production schedules. Further, other resources such as labor are organized in time before the machine stoppage and this avoids unplanned labor utilization, which usually results in untimely pullingout of manpower from other demanding tasks.
3) Collateral failure is minimized: In certain situations, catastrophic failure of one component may cause collateral failure of other parts. This condition results in other machine parts failing or having to flash systems such as hydraulic circuits. This is not only time wasting, but also costly as huge volumes of oil may be discarded.
4) Prevents extended equipment downtime: The lead time of major components is usually long and this can be managed through a planned replacement schedule where replacement parts are projected and procured in time. Machine component run-out leads to extended machine downtime resulting in missed miningoperation deadlines.
5) Avoids lamping huge expenses in a single month: Since the spending is known in advance, provisioning is made easy. The recording of the liability (spending) is matched with an appropriate expense account with the correct period when the component is used.

Though within the industry, there is a deterministic performance deterioration concept believing that, as the machine age increases, the operating cost also increases due to maintenance cost. The contrary has been observed, many components have been seen to operate way beyond their expected life cycle with minimum maintenance. Additionally, other components have demanded more maintenance in the early stage of their life cycle and evening out as they age. Such conditions have made component replacement a complex phenomenon in the mining industry;as such, some organizations have opted for a run to failure norm.

3. Factors Affecting Component Life

Mining is a complex operation and various factors are bound to affect the performance of equipment components. Thus, it must be bone in mind that, the component life is not only affected by cycle time, but starts from needs analysis through to machine configuration and application. Some of the major factors affecting equipment component life include:

3.1 Equipment Selection/Design Decision

Mining equipment comes in different form and each mining application requires a specific design to meet the intended duty. However, appropriate selection of equipment to effectively meet production needs of a Mine as well as operating within acceptable cost of production is one of the real challenges in Mining. Some organizations are driven by the cost of equipment and override the critical element of the machine duty. It is therefore, important for a mining organization through Mine Planning and Maintenance Department to commence purchase decisions by developing a site-specific machine specification document before purchase of equipment. This document should include:

3.1.1 Needs Analysis

A needs analysis is a systematic process for determining and addressing needs, or "gaps" between current conditions and desired conditions or "wants". The discrepancy between the current condition and wanted condition must be measured to appropriately identify the need. The need can be a desire to improve current performance or to correct a deficiency. Needs analysis is carried out by the department intending to purchase the equipment, for primary mining earth moving equipment; this is carried out by the Mining Department. The requesting Department will give a rough account ofthe type of machine, capacity, operational parameters and the timeframe within which the machine would be required. This forms part of the Mine Plan.

The need is identified as early as possible in the mining production cycle and a Statement of Need (SON)/ Specification of Requirement (SOR) is prepared, highlighting:

1) The benefits expected from the equipment
2) Expected time of the machine
3) Whether other equipment will be replaced or will be an addition to the existing units
4) How the acquisition would promote productivity or services
5) Payback criteria/payback period
6) Any other suggested alternative means

3.1.2 Specifications

Before commencing any purchasing process, the Engineering Department in consultation with the Mine Planning Department, reviews the machine duty and determine the specifications required. This process becomes the most effective way to reduce the overall risk exposure in purchasing mining mobile equipment. The approach may be referred to as “Front-end elimination” of risk, or at least, front-end minimization of risk. Eliminating or minimizing risk during the purchase phase limits the overall risk exposure that a piece of equipment may carry after purchase and during the entire life cycle of the equipment. This is certainly much more effective than attempting to manage in-built risks later during the equipment operating phase. Risk reduction during the operating phase may be restricted to implementing procedures and training, which have limited effectiveness, or retro-fitting of engineering solutions which may be costly to the company and counterproductive.

3.1.2.1 Site Build Specifications

The Engineering Department has to developsite build specifications which are provided to the supplier of equipment before a purchase order is issued.The site build specifications give a detailed analysis of the mine environmental conditions and some special features as well as features that may be required on a machine. This is also meant to assist the equipment supplier quote for a correct machine and avoid rework.

3.1.3 Risk Management

In this context, Risk Management is termed as the process of identifying, assessing and controlling threats to an organization's capital and earnings. These threats, or risks, could stem from a wide variety of sources, including financial uncertainty, legal liabilities, strategic management errors, accidents and natural disasters.

3.1.3.1 Operational Risk Assessment

An Operational Risk Assessment is a proven process for identifying and evaluating risks to operational readiness for the expected equipment.Upon receiving the quotation and equipment specifications, the Mining Department needs to conduct an Operational Risk Assessment to ensure that, all the functionality of the machine are within acceptable limits and would not pose any danger to the operator or other personnel including the equipment itself.At this time, all the legal requirements of the machine are determined. In certain countries, if the machine is new to the local mining industry, the Mine Safety Department is notified before the machine is purchased.Where possible, training of operators commences before the machine is delivered to site. With special arrangements, the OEM may conduct the training if the equipment is new to the mine.

3.1.3.2 Maintenance Risk Assessment

The maintenance personnel equally carry out a Machine Risk Assessment to counter check the supplier's specifications against the mine set standards. The Risk Assessment ensures that, the features and functionality of the machine to be procured comply with the mine standards and all legal provisions. This may include such aspects as determination of:

1) Machine capacity
2) Model
3) Parts configuration/Design
4) Type and model of major components
5) Availability of both service parts and insurance parts
6) Maintenance skills availability on the mine site
7) Fuel quality
8) Lubricant type
9) Safety features such as brake type, cabin type, equipment physical size and other safety mechanisms.

3.1.3.3 Determination of Critical Spare Parts

Critical spares should be identified and a good stock must be ordered together or before the machine arrives. Certain maintenance parts such as filters, if not replaced in good time, may affect the performance and life of major equipment; therefore, their availability on site is significant.

3.1.4 Maintenance Strategy

In this context, maintenance strategy is considered as the replacement or repairs of components and assemblies (before or after failure), so that the equipment or component concerned can perform its designated function over its projected life. Therefore, after confirming and certifying the equipment specifications, a maintenance strategy should be developed if not already in place. The strategy should take into consideration;

1) Planned maintenance schedules
2) Determination of maintenance frequency
3) Condition monitoring system
4) Labour requirements
5) Component life cycle analysis
6) Determination of minimum and maximum level of spare parts (min/max)

This should be clearly defined by the Maintenance Planning team in agreement with the shop floor personnel.

It should however, be noted that, selecting an effective maintenance strategy requires appropriate knowledge of maintenance management principles and practices as well as knowledge of specific equipment performance. Nevertheless, there is no one correct formula for maintenance strategy selection and, more often than not, the selection process encompasses a mix of diverse maintenance strategies to suit the specific equipment performance and operating conditions.

3.1.5 Original Equipment Manufacturer (OEM) Support

In an event of new equipment on site, the equipment manufacturer or agent is expected to provide the following services:

1) Maintenance Training: Training should take into account both theoretical and practical aspect to ensure the Technicians and Engineers get to the level of technology specified by the machine manufacturer.
2) Operator Training: Training to the mine equipment operators, which may include simulator training. This is required to minimize operator error, which may lead to component abuse.
3) The OEM must take sufficient time monitoring the performance of the machine before leaving it entirely in the custody of the purchaser. This allows the OEM to note any abnormal settling-in problems on the machine and take immediate correction where required.

3.1.6 Pre-Delivery Inspection (PDI)

Pre-delivery inspection should be conducted before final delivery of the equipment to the Mine site. The inspectionshould include various checks of the equipment to ensure that the machine complies with the customers' requirement and the OEM standards before it is presented to the purchaser. Representation of the purchaser is encouraged where possible during PDI.

3.1.7 Commissioning

This is the where the machine is tested to verify whether it is of the stated design and usually takes place at the purchaser's premises. All these stages are followed to ensure that, the equipment purchased is fit for purpose and that both the operating and maintenance Department fully understand the technology of the machine. Purchasing a piece of equipment without fully understanding its design and functionality could result into serious consequences, such as wrong operation which may compromise the reliability of the machine.

3.2 Environmental Conditions

When purchasing equipment, environmental conditions must be seriously considered. Hong, Zhou and Ye (2014) state that, components in engineered systems are subjected to stochastic deterioration due to the operating environmental conditions, and the uncertainty in material properties. These conditions may be dynamic, changing from season to season or place to place and this could have a negative impact on machine components and systems. Some of the environmental factors to be considered include:

1) Temperature: On electrical components, high temperature can cause thermo-ageing such as insulation failure. On the other hand, physical expansion can be responsible for structural failure through differential expansion of different materials. Polymer materials for example could be affected the most. High temperature can affect viscosity of oils, thus causing loss of lubrication properties which could result in failure of such component as bearings and friction plates. Additionally, extreme ambient temperature may affect the efficiency of heat exchangers and consequently, parts that require constant cooling such as engines. A number of mining operations located in extremely hot geographical areas are prone to loosing equipment cylinder heads due to inefficient cooling systems.
2) Tropical conditions/moisture: The presences of moisture can cause rust (Corrosion) in certain equipment components and accelerate failure of such parts. Additionally, moisture can cause distortion in certain materials. An increase in absorbed moisture leads to swelling of certain components, more especially electrical parts where lowering of surface and volume resistance could occur. In terms of metal part metal parts,Anodic and cathodic reaction introduces pitting, a condition that could permanently distort the part or reduce the component life as seen from the formula;

   $\text{Anode: Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$

   $\text{Cathode: O}_2 + 4\text{e}^- + 2\text{H}_2\text{O} \rightarrow 4\text{OH}^-$

   $\text{Formulation of Rust} = \text{Fe}^{2+} + 2\text{OH}^- \rightarrow \text{Fe(OH)}_2$

   When exposed to moisture ferrous metal tend to react with moisture thereby, creating rust, which forms permanent damage to the parts.
3) Rough operating conditions (uneven ground): Uneven ground has a negative impact on mobile equipment parts such as the machine drive train where components such as torque convectors, transmissions, differentials, final drives and suspension components form part. Though equipment tyres are usually "silent" when discussing machine components, they form part of the equipment major componentsspectrum and have a life cycle. Therefore, poor road and worksite conditions will cause tyres to fail prematurely, hence increasing the equipment downtime as wellas operating cost.
4) Steep ground conditions (mine design): An incline that is out of machine specifications may have serious consequences on machine components. In trying to negotiate the incline, the machine will have to work harder and usually out of specification. This condition can accelerate wear in most of the rotating parts. Heat and torque, become the most contributors to failure of components in this case.

3.3 Maintenance Practices

Maintenance is a set of actions necessary for retaining or restoring a piece of equipment, machine, or system to the specified operable condition to achieve its optimal useful life. In other word, maintenance is a task that is carried out on a piece of equipment or system to ensure that it continues performing its indented purpose according to set standards. Maintenance is carried out to ensure the desired reliability of a piece of equipment is achieved and maintained. However, the inherent reliability level of most mining equipment components is dependent on scheduled maintenance activities. Scheduled tasks generally involve, lubrication, replacement of filters, oil analysis (condition monitoring), adjustments, analytical inspection etc. Performing the maintenance task, though, does not absolutely eliminate the failure from occurring; it does delay it and may minimize the severity when it does occur.Therefore, the contribution or effectiveness of maintenancemust be examined to determine the level of influence on the life cycle of a component.

Therefore, selecting a successful maintenance strategy that will support component life requires a good knowledge of maintenance management principles and practices as well as knowledge of specific equipment performance. As such, management of equipment components needs to be managed by a skilled and competent team of maintenance personnel.From the study conducted by Motsoeneng, Benzuidenhout and Schulz (2013) on the performance of mining equipment, it is concluded that, relevant skills and development are a necessity for maintenance personnel to carry out their tasks effectively. If not well managed, maintenance can have a serious negative impact on the life of components.

3.4 Fuel and Lubricants

Fuel and lubricants play a significant role in the life of a machine. Fuel does not only affect the environment through pollution. A bad fuel may create incomplete combustion which can result into low power output of the engine and generate excess heat.Excessive heat in an engine causes metal to expand, thus, putting pressure on gaskets and seals. Additionally, continuous heating of the engine causes the coolant to boil and due to this phenomenon, a number of events may take place, all of which might mean the end of the engine or accelerated deterioration of the engine. This action may also have a collateral effect on other parts of the machine such as the heat exchanger (radiator). Excessive heating of the system could lead to the radiator failing prematurely from thermal and pressure effect.

The primary function of a lubricant in a machine is to minimize friction by creating a boundary layer between mating surfaces. Additionally, a lubricant dissipates heat from surfaces, enhancing the performance and efficiency of the equipment. It is therefore, important to choose a correct lubricant for each application. Parts such as machine links for example, require adequate lubrication to minimize wear of parts. However, not every lubricant will be suitable for any application, as such, maintenance personnel ought to determine the right lubricant for a specific application. Lithium grease for instance, has shown to impart the advantages of high adherence, non-corrosiveness, and moisture resistance making it compatible with several applications. A wrong lubricant will accelerate wear and cause components and parts to fail prematurely.

3.5 Operator Practices

Equipment operators have a significant impact on the overall operation of mining equipment and its associated major components. Operators generally receive comprehensive training on appropriate operating procedures, basic troubleshooting, and best practices for safe equipment use relevant to the equipment they operate. However, certain operator practices and behaviorslead to equipment failure or component life deterioration. This usually occurs for instance, when an operator is not adequately trained to operate certain equipment and at times, mere behavioral issues.

Negative transfer, thus, switching of operators between machines has been observed as one of the contributing factors to equipment failure. Inconsistent design of controls across these machines facilitates negative transfer resulting into control errors (such as the use of the retarder) and consequently affecting equipment component life. Operator attitude and fatigue are other factors that lead to equipment breakdown. New operators, if not well trained to manipulate machine controls can cause serious damage to machine components.

3.6 Number of Equipment Available

In some cases, production requirements outweigh the number of equipment available. Therefore, in order to meet the production budget, equipment tends to be overused and at times maintenance overlooked. Every piece of equipment has its inherent reliability; therefore, trying to push a machine beyond this level does not provide any extra benefit, but merely compromises the life of a machine components.Inherent reliability is the level of reliability that is established by the design and manufacturing process of the equipment. In other words, it is a measure of the overall "toughness" of a system or piece of equipment and it provides an upper limit to the reliability and availability that can be achieved. It is therefore, important to match production requirements with the number of equipment available. A safety margin is always advised.

3.7 Wrong Application of Equipment

Due to shortage of equipment as a result of factors such as breakdowns, certain equipment may be used for work it’s not designed to do. For example, when there is a shortage of Dozers in the pit, Frond End Loaders may be used to push ground. This action has the potential to damage the machine components or reduce the life span of certain machine parts. Such activities make it very difficult to accurately project the life cycle of a machine component as failure and deteriorations becomes absolutely stochastic even under a well-defined condition monitoring program. Wrong sizing of equipment is another aspect that has a big effect on equipment, this usually results into overloading of the machine, hence, putting more stress on the machine components, thereby, reducing machine life.

4. Overview of Component Replacement Strategy

As earlier stated, management of equipment components is a critical activity in running earth moving equipment. Replacement of these parts call for substantial amount of funds, thus, with a reason to replace major components, each piece of component needs to be evaluated to determine whether the replacement decision is economically viable. Though OEMs may specify the life of components, the life cycle and performance of a component is determined by a combination of various controllable and uncontrollable factors. Therefore, an effective component management strategy should take into consideration certain critical activities as well as high level of skills and knowledge of the operation of the parent machine and should include the following:

4.1 Defining Component Life Goal

The Mine through the maintenance Department should clearly define the need for a component change out plan and this should be communicated to the maintenance personnel. Essentially, the main goal of a component replacement strategy is to maintain the capability of the equipment in order to optimize capital equipment life, thereby minimizing machine downtime and maximizing machine productivity. Additionally, the component replacement plan must be incorporated into the overall mine maintenance and repair processes while at the same time maintaining high machine availability and minimizing downtime for the replacement.

4.2 Defining Component Strategy

Every machine component has a life cycle. Therefore, to ensure effective management of these components, the maintenance Department must have a well defined strategy to this effect.An effetive startegy must take the following into consideration:

1) Replacement of componenst based on performance indicators. This is what is referred to as condition monitoring.
2) Maintenance cost of a component.
3) Obsolescence
4) Change in operating conditions
5) Technological advancement

The traditional method of component replacement strategy puts emphasis only on time and pays little attention on other aspects which influence the reliability of a comonent. It is therefore, important to look beyond time in developing an equipment replacement startegy to ensure optimum use of the component.

Condition monitoring

Condition monitoring is where selected physical parameters associated with equipment operations are observed in order to determine the integrity of a component or system. Once component base lines are set, continued use, maintenance type and repair or replacement decisions will be based on the set baselines.

Fluid analysis is the most common method of condition monitoring used on earth moving equipment and the components monitored through this process include; engines, transmissions, gearboxes, differentials, final derives and heat exchangers.Fluid analysis shows the rate of deterioration of a component as well as providing the level and type of contamination in these units.

It is therefore, important to set specific intervals for carrying out checks on each component, however, certain unusual component behaviours may prompt fluid analysis before the planned time.Fluid analysis provides the very earliest warning of failure. As such, used properly as part of a maintenance strategy, fluid analysis will offer an inexpensive way to reduce the inherent failure rate of components.Thinkness test is another form of condition monitoring carried out on items such as wear pads to determine the wear rate.

From commissioning, componenet must be monitored in order to determine the rate of wear of parts and if this data is accurately trended and recorded, it will be used as a tool to indicate the most appropriate and economical time to replace a component. On the other hand, When an abnormal condition or parameter is identified through fluid analysis at any point of a component life, immediate action may be taken to correct the root cause or to mitigate a developing failure.

Maintenance cost of components

Though a component life may be predicted to a certain extent, the cost of maintaining it also has a great influence on the replacement decision. At whatever stage in the life cycle of a component, if the maintenance cost is unpropotionally high, a decision must be made to prematurely replace the component.Contineous failure and repair of a component calls for incresed maintenance and labour cost, downtime cost as well as hiden costs associated with the uplanned stoppage.

Obsolescence

In recent years, the technology of mining equipment hasbeen evolvingat a faster rate making the older and fairly new equipmentmodels obsolete.The need to efficiently move huge volumes of material hasmotivated and reinforced a continuous search for new technology in the mining industry.With this technological advancement, most equipment components have been rendered obsolete even before completing their full life cycle. When components become obsolete, maintenance cost may rise or OEM support may not be readily available, making it difficult to manage such components.In such cases, it becames a wise business case to replace the component to align with the trending technology.

Change in operating conditions

Mining earth moving equipment is made to suite a certain level of harshness in environmental conditions, however, these conditions may change to extreme and have a major impact on the performance of the machine components and systems. Roadway gradient for example,increase in gradient implies more engine power, if the engine is not designed to operate at such an incline, modification to the machine may be required and this could dictate the replacement of components such as engines in order to respond to the power requirements.

Other factors such as the need for more loading capacity, speed and ground coditions have generated the need for changing or upgrading equipment.

Technological advancement

Rapid advances in technological innovation, including through automation, digitization, and electrification, have presented a fundamental impact on the mining sector. Mining organizations are responding to these technological shifts by abandoning or modifying the old equipment where possible in order to increase efficiencies and productivity.

In order to catch up with the new technology, certain machine parts may require replaccing. Though this may not be a very common phenomenon in the industry, being aware and preparing for such change is inevitable.

4.3Determining Component Inventory

Though through condition monitoring of equipment components, an economic analysis can be developed exclusively to determine the point at which the replacement of a componet is justified, it is important to have a certain level of protective stock of components at all times as sudden failure is still expected in the face of a good condition monitoring plan.

Therefore, instead of drawing up a time based component replacement plan and hold inventory for each machine, it is a wise decision to hold a predetermined minimum number of protective stock per specific fleet type.This minizes holding of excess cash in inventory.

4.4 Establish Performance Baseline

Guidelines should be set as to which conditions should effect the replacement of a component; these should be based on the contents of the earlier sections. The identification of significant changes from the baseline state should be the central purpose of baseline identification. These should be clearly stipulated and all maintenance personnel informed.

In machine components, condition monitoring does not only give the deterioration rate of a component, but also the condition of fluids. If a flue degrades beyond a certain point or if the presence of a particular chemical or gas is above acceptable limits, the fluid should be replaced.

4.5 Implementing an Effective Component Tracking System

Having established the baselines and in order to ensure compliance, the Reliability Section in conjuction with the Planning Section should formulate a tracking system for component life. Component life (hours) and performance should be accurately recorded for reference. Thus, all activitivities associated with the component life must be documentd and tracked on a regular basis and should form the basis for component replacement decisions.

4.6 Defining Planned Maintenance Activities

The life of most major components is influenced by the performance of other components and systems linked to them. Therfore, extending the life of a component does not only depend on how well the component is maintained, but also, the way other parts of the machine are managed. For example, if the efficiency of a brake hydraulic pump is low, brake binding will be experienced and if this is not managed in time, the machine brake assemblies will be damaged.

A well designed maintenance pan should, therefore, be developed with the frequency and nature of maintenance determined through risk assessment, taking into account:

1) The type of machine
2) The manufacturer's recommendations
3) The application of the machine
4) Operating environment (e.g. temperature, corrosion, weathering, terrain)
5) Operator knowledge and experience
6) Machine age
7) Daily machine work hours

Though it is important to follow the manufacturers' maintenance plan, onsite conditions usually warranty change in the maintenance strategy. Certain critical parts of the machine may need a higher and more frequent level of attention than other components. However, a risk assessment should always be conducted by qualified and competent maintenance personnel before deviating from the manufacturers' recommended maintenance plan. Another aspect to always be considered is, having the right skills, Maintenance work should only be undertaken by competent personnel, who have been provided with sufficient information, instruction and training.

4.7 Initiate Condition Monitoring

Condition monitoring is a proactive approach to collecting and analyzing data crucial to the health of the equipment.In other words, condition monitoring can be viewed as an evolution of predictive maintenance or proactive maintenanceand is one of the most innovative solutions for anticipating failures in machine components. The most common form of monitorig on earth moving equipment is fluid analysis, where oil, fuel and coolant samples are cut from critical machine components and analysed to deternine the wear rate of components. It also highlights the presence or development of certain elements that may affect the performance and/or life of a component.

Therefore, the maintenance personnel need to formulate an accurate time table for collecting and analysing these samples with prompt results.Certainmodern equipment is fitted with condition sensors. This may be in form of transducers such as accelerometers, acoustic emission sensors, tachometers, thermocouples, etc., which are subsequently segmented into discrete and coherent analysis intervals to extract feature vectors that are fed into pattern-recognition algorithms and post processing including diagnosis, prognosis, sensor-failure detection, and reporting.

Critical replacement decision points must be set for each component to ensure that, the conponent does not run beyond a safe point, otherwise catastrophic failure of the component may ocuur. All results from the analysis must be properly documented by the Planning personnel and reference made on stated intervals.

4.8 Planning and Scheduling

This is a acritical function in component life cycle management.The Planning Section provides a proactive maintenance support system in which the condition and application of equipment is monitored regularly. As such, all maintenance actions are efficiently and effectively managed and executed, supporting the goal of equipment reliability and avoiding unplanned equipment downtime. This is done by identifying potential problems before failure, and by so doing, the Planning Section assists in avoiding unscheduled downtime, productivity loss and potentially more costly repairs.

In managing major component life, the Planning Section should have a detailed register of all equipment with associated life cycle activities of each component. A fluid analysis result register should be introduced and it is easy to display these results in graphical form (trends) and set critical points whers a component should not go beyong. When this critical point is reached, the component must be removed. However, certain items of low value and low risk may be run to failure.

Further, the Planning Section should set up a component replacement plan and schedule in such a way that it should take into account the initial component life predictions through condition monitoring, site maintenance practices, and the application in which the machine is used. The health of the components should be tracked, trended, monitored and factored into the general maintenance plan. Thus, component history, actual performance, and failures associated with the component as well as repairs must be accurately recorded.

To avoid stock run out of components, the Planning Section must keep a minimum level of each component per fleet. It must be noted that, component availability and acquisition time are key factors to be considered in the component management process. Stocking too many components as a safety stock is a major cost to the organization and stocking too low may result in stock run out of parts and leading into extended equipment downtime.

The Planning Section should not only look at the component itself, but should also consider and include the availability of manpower, facilities, tooling, installation parts kits and other activities associated with component replacement. During the time of replacing the component, opportunity maintenance should be carried out to clear backlog work.

Figure 1(created by: Dr. Galatia, 2021) is an illustration of how a component can be managed to maximize its use.

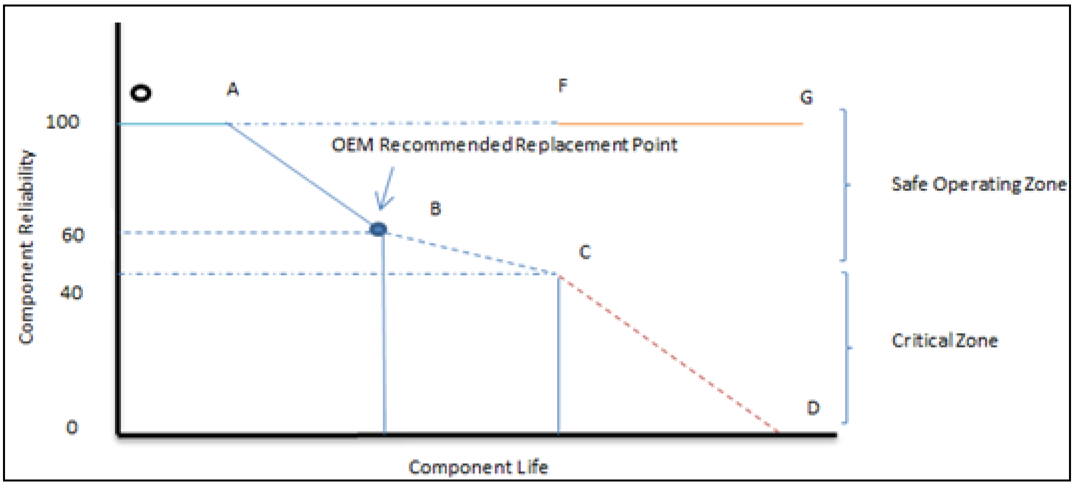

Figure 1: Component Life Cycle Concept

Operationalisation of the Component Life Cycle Concept

When a new or refurbished component is installed on a machine, its reliability is assumed to be at 100% and starts deteriorating with time and usage.

Reliability in the context of this study is defined as the probability that a component will continue performing its intended function in a specified period of time under stated conditions. Walter and Samuel (2013) define reliability as the probability that the item will perform its intended function throughout a specified time period when operated in a normal (or stated) environment. From the two definitions, reliability can therefore, be calculated as an exponentially decaying probability function, which depends on the failure rate [$\boldsymbol{R}(\boldsymbol{T}) = \boldsymbol{e}^{-\lambda T}$]. As such, since failure rate may not remain constant over the operational lifecycle of a component, the average time-based quantities such as MTBF can also be used to calculate Reliability of earth moving equipment.

From Figure 1, the reliability of a component starts to decline at Point A until point B where the OEM recommends to replace the component.

However, the OEM recommended point (usually in hours) may not always be the most optimal point to replace a component. It is always important to determine the life of a component through condition monitoring techniques such as fluid analysis and when a set critical level, say Point C is reached, the component may be replaced. The decision to replace the component will be based on the fluid analysis results. Point B is determined by the amount of wear detected from the analysis results (trends analysis). Using a component from Point C becomes a risk as the component may fail at any time. However, low risk components may be allowed to work beyond Point C, thus working to failure, Point D.

Though it has always been assumed that a component, from installation to removal stage, takes a declining trend in reliability, the contrary may be true. If a component such as an engine, transmission, differential, final drive etc., does not breakdown and all the performance parameters are within specification to its removal point, then, going by the definition of reliability, it is correct to state that, a component operated at 100% throughout its life. In reference to Figure 1, it is correct to indicate that, the component performed along line OG to its removal stage.

5. Summary

It is important for a component management strategy to follow a Reliability Centered Maintenance (RCM) approach since components are affected by different factors and no single maintenance process fits all. Reliability Centered Maintenance is a corporate level maintenance strategy that is implemented to optimize the maintenance of equipment or facilities. The main objective of RCM is to identify failure modes that can affect the equipment or system function, prioritizing the failure modes and selecting applicable and effective tasks to control the failure modes. This concept, therefore, is appropriate in managing components as it looks at a machine or system in its operating context and recommends maintenance in line with a machine or system performance characteristics. It takes away rigidity in maintenance such as the replacement of components based on time. Component life cycle hours may however, be used as an indicator to signal the point at which monitoring of a component may require extra attention.

Therefore, a well formulated component replacement program should be based on condition assessment of components as opposed to replacement based on time. By managing equipment components effectively, unscheduled failures which lead to extended downtime, productivity loss, and potentially more costly repairs can be avoided.

Condition monitoring can either be through trend monitoring or condition checking. Trend monitoring is the continuous measurement and interpretation of data collected during the component life cycle, to show variations in the condition of the component. This involves the selection of suitable and measurable indication of the component deterioration and the study of the trend in this measurement with running time to indicate when deterioration approaches the critical range. Whereas, condition checking is where a check measurement is taken with the machine running, using some suitable indicator and this indicator is then used as a measure of the component condition at that time. To be effective the measurement must be accurate and quantifiable, and there must be known limiting values which must not be exceeded for more than a certain number of permitted further running hours.

Nevertheless, it is worth noting that, each time a machine is stopped for condition monitoring,there is a cost associated with downtime, as such, the frequency of stoppages must be schedule in such a way that downtime is minimized.Roy and Naika (2013) give caution by stating that, too close maintenance intervals could lead to frequent operational stoppages. Thus, production losses could occur due to excessive downtime which may outweigh the economic benefits of maintenance. As such, during these stoppages, other backlog work and inspections must be carried out to avoid further machine downtime. On the other hand, if time intervals between maintenance are increased, frequent failures of components during operation is likely to occur due to overworking of certain parts which may have a collateral influence on major components. For example, overusing engine filters can have a serious impact on the performance and life of an engine.

Though condition monitoring is a good tool for observing the condition of components, caution is required in dealing with some components, as doing certain maintenance routines too often can eventually shorten their useful life.

The purpose of conducting condition assessment is to ensure that the components operate within safe operating parameters and reduce the likelihood of failure. In an event where a potential failure cause is noticed through condition monitoring, the component can be fixed in advance to prevent unforeseen failures or lower the risk of failing. However, where the problem is beyond certain critical limits, the components may be replaced immediately or major repairs carried out. Thus, the primary goal of condition monitoring is that of making a component or system more reliable through inspection.

An effective component replacement strategy must identify criticalcomponents with significant value which would require preventive replacement as opposed tocomponents that could run until failure, this assessment is critical. Therefore, a major component register must be drawn up to indicate such components as well as the kind of maintenance required. This should show the frequency of monitoring such as oil sampling dates.

If monitoring of components is adequately planned and executed, the utility from the use of the components ismaximized and satisfy the condition; ‘the rationale behind the idea of a component replacement plan is to minimize cost by optimizing the use of the component as well as maximizing equipment utilization by avoiding stochastic catastrophic failure of machine major components which can lead to lengthy equipment downtime.’

Jardine and Tsang (2006), take a similar approach, stating that, the objective of a planned component replacement plan is to minimize the operating cost so that there is a balance achieved between the replacement cost and increased operating cost and further justify the basis of the concept througha mathematical computation:

c (t) = The operating cost per unit time at time t after replacement
C_r = Replacement Cost
t_r = Time between replacement
T_r = Replacement time
C (t_r) = The objective function to be minimized

$$= \frac{\text{The operating cost in interval } (0, t_r)}{\text{Length of interval}}$$

$$\text{total operating cost in interval } (0, t_r) = \int_0^{t_r} c(t)dt + C_r$$

$$\text{length of interval} = t_r + T_r$$

$$C(t_r) = \frac{\int_0^{t_r} c(t)dt + C_r}{t_r + T_r}$$

However, in the real mining environment, the time between replacementst_r is highly stochastic due to various uncontrollable factors. This is what makes projecting the component replacement point based on time (component hours) difficult.

The other important aspect in component management is having the right skills.For condition monitoring to be effective, personnel managing the system must be knowledgeable to understand the nature and characteristics of factors which affect component performance. One inhibiting factor to this is the lack of reliability Engineers to manage the process.

6. Conclusion

Earth moving equipment components are one of the key cost drivers in a mining operations and their performance relies mainly on the type and quality of maintenance, design as well as operating conditions. Thus, major components must be effectively and efficiently managed to optimize productivity of the equipment.

Therefore, to realize optimum utility from a component, a component management strategy must start right from equipment selection and purchase decisions. Additionally, when the equipment is in operation, a component replacement strategy mustbe based on condition assessment and not merely on component age. As such, components that require preventive replacement must be identified and condition monitoring scheduled at specified intervals throughout the life of the component.These intervals must be efficiently spaced to avoid extended equipment downtime and caution must be taken in dealing with certain components where carrying out maintenance too often can eventually shorten their useful life.

References

[1] Bentley, J., Introduction to Reliability and Quality Engineering, 2nd edition, Pearson Education, 1999
[2] Hong,P.H., Zhou,W., and Ye, W. Z. (2014), Optimal Condition Based Maintenance Decisions for Systems

with Dependent Scholastic Degradation of Components, 121, pp 276 – 288. Imagination.

[3] Jardine, K.S. A and Tsang, H.C. A, (2006) Maintenance, Replacement, and Reliability, 1st Edition, Taylor & Francis Group

[4] Motsoeneng, Benzuidenhout, A, and Schulz, C. (2013), Electronic mail: Skills needed by Engineers in the Platinum mining Industry in South Africa: Proceeding of PICMET'13: 2013 conference of Technology Management for Emerging Technologies held at San Jose, United of America.

[5] Roy,S.K,. Bhattacharyga, M.M and Naika, V.N. (2013), 'Maintainability and Reliability Analysis of a Fleet of Shovels, Journal of Mining and Technology, 110 (3), pp163 – 171.

[6] Siddiqui, S. (2009). Reliability cantered Maintenance. Available from:https://www.researchgate.net/publication/28225333 8Reliability Cantered Maintenance (accessed, 4th Jun 2018).

[7] Waeyenbergh, G., and Pintelon, P. (2004), "*Maintenance concept development: a case study*", International Journal of Production Economics, Vol. 89, pp. 395-405.