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Methodology to determine the optimal replacement age of mobile mining machines

D. NUROCK and C. PORTEOUS

Sandvik Mining

Fleet management of mobile machinery in the mechanized mining environment is essential to the economic exploitation of an orebody. Due to the complex nature of the machines and the environment in which they operate, effectively managing such a fleet proves to be a challenge currently not fully understood or addressed by mining houses. With constant pressures on increasing production figures and cutting costs, in addition to the global strain on machine lead times, the management of trackless equipment has become a top priority. A study was undertaken by Sandvik, with input from Anglo Platinum, in an effort to provide a solution to their customers. The aim was to provide a tool to determine the optimal time to replace a machine based on actual data, using lifecycle cost calculations and the theory of vehicle replacement given a specific customer environment. The factors affecting this decision were determined, quantified and inputted into a model, which can calculate the optimal replacement age of a machine. The objective of such was to provide an indication of the most economical point to replace a given machine in a given environment in order to extract the most value for the mine. This can be used to plan and motivate capital expenditure as well as optimize machine operating costs.

Introduction

Background

The management and maintenance of mining machinery, especially in underground applications, is a difficult task. In addition to this, the costs associated with running and maintaining a trackless fleet are significant. The costs increases resulting from older machines are not well understood or quantified, and hence accumulate a large proportion of hidden as well as direct costs. This is due to a number of reasons, namely:

- The complex nature of the machines where numerous and various components exist, and are interrelated
- The way information is recorded and the type of information recorded
- The nature of the mining cycle does not easily allow one to determine the impact of an unreliable machine.

A range of additional costs associated with older machines is derived from unquantifiable trends and intangible benefits (to be discussed under 'replacement factors'.

In addition to this, it is understood that in a number of mining houses there is no justified or standardized approach in determining the optimal machine life, which would provide the basis for effective machine replacement programmes. This leads to an array of shortcomings, namely increased lifecycle costs, increased downtime (and hence productivity losses) and, given the current supply problems, an extremely long lead time for replacement machines. These challenges are compounded by the capital planning and budgeting process employed by many mines, where capital application is required annually, and for the next year.

In partnering with customers to develop solutions used to improve their customers business, Sandvik has responded to current market demands, in initiating an analysis of this. A study into current replacement methods used in the mining industry, similar industries and appropriate methods available was undertaken. From this, with input from Anglo Platinum and on-site maintenance personnel, a model was formulated.

Objectives

The model has more specific objectives which are to provide a simple guideline to:

- Predict machine replacements (for capital motivation, capital planning, and to facilitate machine replacement programs)
- Optimize lifecycle costs, and
- Provide a basis for benchmarking sites.

Due to the complexity and diversity of all Sandvik machines, used to mine PGM's, namely bolters, drill rigs, trucks, dozers and loaders, the aim was for a replacement approach, but the model has been specifically developed based on the fundamentals of the loaders.

Replacement environment

The machine replacement topic has initiated a wide variety of debate from many schools of thought, and without carefully scoping the replacement environment, one can render results inappropriate if not meaningless. Hence, in an attempt to create a manageable task and provide representative results, a specific environment in which the replacement would take place has been described in Figure 1.

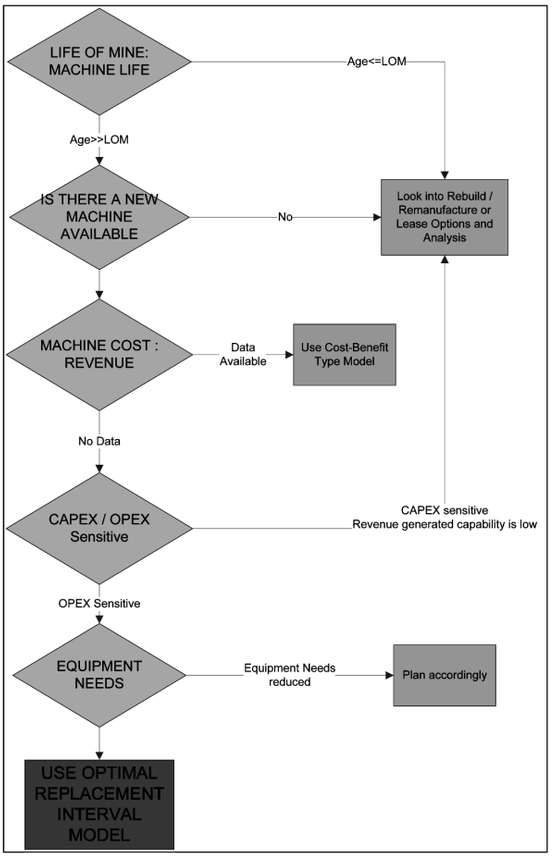

Figure 1. Environment applicable to the optimal replacement interval

It looks at the:

- *Life of mine (*LOM)—if machine life exceeds the life of mine, machine replacements are not viable (alternatively rebuild/remanufacture or rental options are preferable here or a business case should be conducted to determine the viability of running the old machines)
- *Machine availability*—where no replacement machine exists at the end of a current machine's life, clearly a replacement option is not an alternative, and the above-mentioned options should be considered
- *Machine cost: revenue*—where information exists, other analysis tools using cost benefit analysis or payback type methods could be used
- *CAPEX* (capital expenses) *or OPEX* (operating expenses) Sensitivity—if a mine wishes to optimize (or is sensitive to) CAPEX, through lower capital cost alternatives, other options need to be explored other than new machine replacements. It is important to keep in mind that this is generally at the expense of OPEX. On the other hand, a mine may aim to optimize its OPEX (at the expense of a higher CAPEX). It is premise on which this model is based
- Eq*uipment needs*—it is recommended that prior machine replacements are planned, and the production parameters are checked to determine if in fact new machines are required.

It is under these conditions in which the replacement model described in this paper is best suited.

Current methods

An investigation was carried out to determine how the mining houses currently use relevant information to determine the replacement lives of their trackless mobile machinery. It was evident that, in most cases, either simplistic assumptions or experienced estimates were used and in some instances purely reactive planning occurs.

A number of applicable methods exist, either in theory or in practice, and the challenge is to adapt these methods and format this information into a useable, valuable and applicable medium.

The most applicable methods are listed below.

- C*ost per ton trends*—this uses the total machine costs divided by the number of tons a machine produces. It is based on the principle that as a machine ages, the running costs increase and as the availability of the machine decreases, the tons are reduced, hence increasing the cost per ton. The minimum cost per ton is the optimal replacement point. In a sense this uses the similar methodology of a cost-benefit or payback analysis and is very appropriate since the purpose of the machine is to produce tons, thereby, using this measure as a financial indicator. However information about the tons produced is required and often not available
- *Equivalent annuit*y (EA)—this method looks at the cash flows associated with the machine and the times in which they are incurred. It uses the time value of money to be able to compare different timing alternatives. It then calculates the total value or cost of an alternative (a replacement age) and equates this to an annuity. Annuities of different alternatives can now be compared, on the same basis, and the lowest annuity represents the lowest cost option. This method is very powerful and is an accepted asset appraisal method, although it is commonly not easily understood and hence accepted
- *Theory of vehicle replacement*—this is a well-known theory and is based on the trade-off of decreasing capital cost and increasing running costs with the age of a vehicle. A point exists where the total cost is a minimum, which indicates the optimal replacement age.

The model developed uses a combination of all the above methods, based on the available information and with the aim of providing a simple guideline to determining the optimal replacement age.

Model development

Initially, due to the fact that the machines are physical assets, the first step is to establish the design life of the machine. However, this proves a futile exercise since:

- Machines can be repaired or rebuilt several times to prolong life
- The maintenance philosophy, methods, expertise and effectiveness affect the life and operation of many of the parts and hence the whole machine
- Different maintenance conditions, operating conditions, practices and environmental factors also affect the life of the machine.

As a result of these factors, it was decided that the economic life of the machine would be the best measure. This type of approach, although initially considered illogical, is consistent with the aim of business—to make money; hence looking at the economics of the machine

replacement decision is a business decision. However, not overlooking the nature of the problem at hand, the model needs adequately to take into account the above-mentioned factors. Following the identification of the key factors that influence the replacement decision, these need to be quantified in order to be translated into an economic decision.

A number of factors exist that need to be included in the replacement decision, some of which are relatively simple to calculate and others which prove somewhat more difficult. Some of the reasons include the fact that the parameters themselves can be difficult to quantify, over and above the lack of data, quality of these data or the format of the data available. A challenge in developing an appropriate model is to retrieve and use realistic and representative data in the absence of accurate quantitative information. The aim is to quantify the causes—factors influencing the replacement decision. This can be done by looking at the effects that are assumed to be representative of the causes, in this case the costs of running machines and the machine availability. Figure 2 expands on these pertinent factors; the importance of such a step in the model development is the justification for the primary inputs to the model, namely running costs and availability. These parameters are easily accessible due to the reporting system used by Sandvik on site, where they maintain the customer's machines.

The advantages of using these figures are borne out by the fact that these are actual figures, hence representing site specific and machine specific influencers. This yields a distinct advantage in that the information is realistic and representative, although limitations could exist where historical data are required in order for decisions to be made. This could constrain the replacement modelling life, machine type or site. Another disadvantage associated with using historical data is that only retrospective planning can be done. What this means is that one a machine has been operating and accumulated data, one can look at the trends and see when the machine was suppose to be replaced. It cannot account for changes that have occurred for example, an improvement in roadways, maintenance practices, operating practices, etc. However, this still contributes towards the aim in that it provides a general idea or guideline from which to predict machine lives and can be seen as a starting point.

A note of caution must be made when using and developing such models; as obvious as it may seem, the quality of the outputs depends completely on the quality of the input information.

Replacement factors

Operating costs

Operating costs include maintenance costs, consumables and labour. Due to the nature of the reporting system, the maintenance cost and availability data are inputted in intervals of 1 000 hours. It follows that the model uses analyses in 1 000 hour intervals. As previously discussed, the maintenance costs are the actual parts costs, excluding the cost of parts used for damages. The consumables are based on inputs and assumptions. Ground engaging tools (GET) and tyres are excluded since is it assumed that these are independent of age and hence will merely shift the curve up, but will have little effect on identifying the optimal replacement age. Labour is based on standard values used in Sandvik maintenance contracts, based on labour compliments where man:machine ratios are used. The reduction in machine availability with age, entails an increase in maintenance labour time. This has been included in the model and is based on the availability trend.

Financing costs

The capital cost of the machine has a significant role in determining the machine life since this cost is spread over the life of the machine. The model caters for a simple input of the purchase price of the machine. However, to maintain a simple useable model, the cost of capital has been excluded. The cost of capital is the cost incurred in financing the machine. By virtue of the methodology applied, the depreciation is taken into account, by spreading the capital cost of the machine over its life. When one looks at different replacement alternatives, the machine cost is divided by the number of hours for that interval, and hence is a representation of the depreciation. The tax shield is a benefit from tax where the capital cost is converted to an expense (through depreciation), this reduces the company's net income and hence reduces the tax payable. This is basically the company tax rate multiplied by the depreciation value.

The effect of tax shield on the replacement decision

Keeping in mind the aim of the model, which is to generate a simple guideline to indicate the optimal replacement period, the tax shield was assumed inconsequential. With differing alternatives of machine lives, the financial cost (through depreciation) is spread over different time periods. This results in depreciation values being incurred both at a different rate and in a different time period for each replacement alternative. Inevitably the total capital cost of the machine is depreciated and a tax benefit is gained, the timing of which plays a role. An analysis was carried out in order to determine the effect of this role on the replacement decision and hence to determine if the initial assumption was correct.

The model uses a methodology, explained under the 'Model methodology' section, to determine the costs associated with each alternate replacement interval, the most optimal point being termed the optimal replacement interval (ORI). In the tax shield analysis, the average cost per each replacement alternate interval was calculated based on no tax advantage and compared to the interval costs where the tax shield has been included. Figure 3 shows the trends and relationships of the data. This figure further shows that the average cost is lower when gaining the tax advantage and that both curves follow the same trend, as expected. Looking at the differences in the two curves, it is apparent that the discrepancy between them is

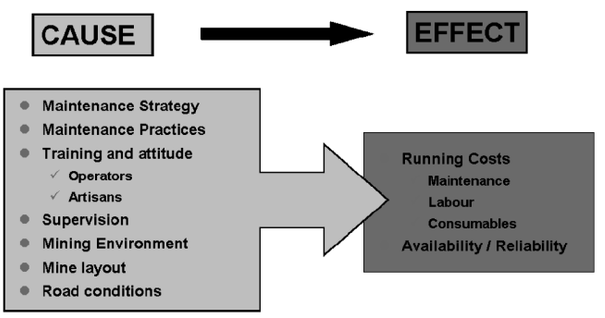

Figure 2. Cause and effect diagram

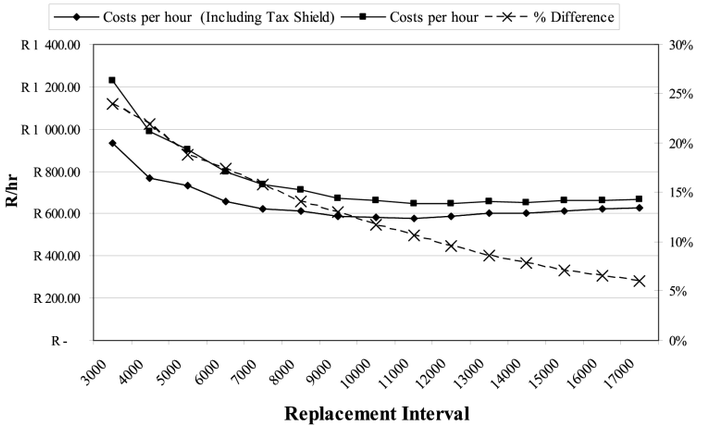

Figure 3. The effect of tax shield on ORI

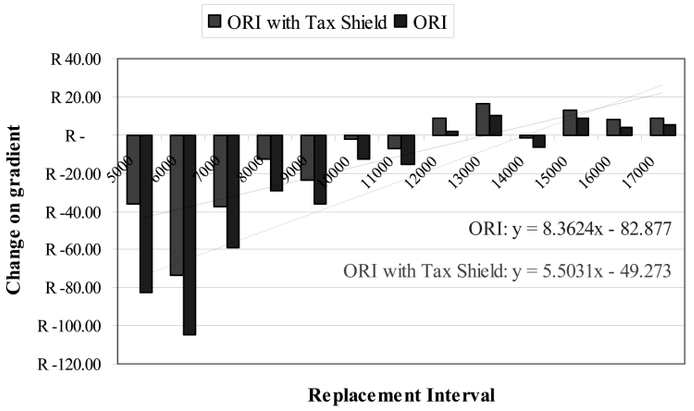

Figure 4. Trend of ORI gradient

highest for smaller replacement intervals where differences reach 28%. This is in direct correlation with the actual tax shield where the company tax rate is 29%—which is slightly discounted to account for the time the machine needs to accumulate its 1 000 hours. The difference drops to 6% and is on average 15%. However, these differences do not play a part in changing the ORI, the ORI in both instances equating to 11 000 hours based on the given inputs.

Changing differences in the curves indicates variations in the shape of the curves, which could favour earlier replacement ages if the ORI is marginal and the tax shield has been accounted for. To determine the impact of including the tax shield, on marginal cases, one can look at the change in the shape of the ORI themselves and determine how this would affect marginal cases. One approach to quantify the shape of the curve is by looking at the derivative of the curve—generally calculated from the formula of the function. However, to keep it simple, we will use the derivative analogy by looking at the gradients. The first derivative of a curve indicates the direction of the curve. If the gradient is positive this indicates an upward sloping curve where an increase in the dependant variable results in an increase in the independent variable. This is shown in Figure 4. As expected, the gradients are negative since the average cost per hour decreases as the replacement interval increases, driven by the financial cost of the machine. After the curve reaches the minimum point (here at 11 000 hours) it becomes positive as the average costs per hour start increasing. However, this tells us little about the steepness of the curve, which is the aspect that influences the marginal ORI. The steepness of the curve is measured by the second derivative, which is the gradient of the gradient of the initial curve. There is no clear trend to these points so to get an estimate of the nature of the relationship, a linear trend line has been fitted. A larger gradient implies that a change in the independent variable (the replacement interval) results in a larger change in the dependant variable (R/h) and hence results in a less marginal outcome. In a situation like this, marginal results are not preferable since the outcome of one scenario is only slightly better or worse than its next best alternative, which increases the risk of allowing marginal (and assumed insignificant) factors playing a larger role on the decision. Looking at the equations of the trend lines shown in Figure 5, it can be seen that the gradient of the ORI not including the tax shield (≈ 8) is greater than the gradient of the ORI with tax shield (≈ 5) meaning that the ORI (not including the tax shield) is less marginal and hence a better option. These results are not notably different but allow one to justify the exclusion of the tax shield in the model.

Availability costs

The production loss associated with an unreliable or unavailable machine is by no means insignificant. However, this is a tricky aspect to deal with since (a) it is

difficult to equate the effect on production of one machine being down and (b) the production loss is not lost forever, it is merely transferred later in time. Even though this definitely has a cost associated with it and will affect the project's NPV. In absence of a more applicable approach, this production loss, termed availability cost, will be included based on a number of factors. These are: the machine's production rate, the machine's average utilization percentage, the machine's effectiveness, the basket price of the commodity being extracted, the dilution and recovery, and most importantly, for purposes of the model, the machine's availability.

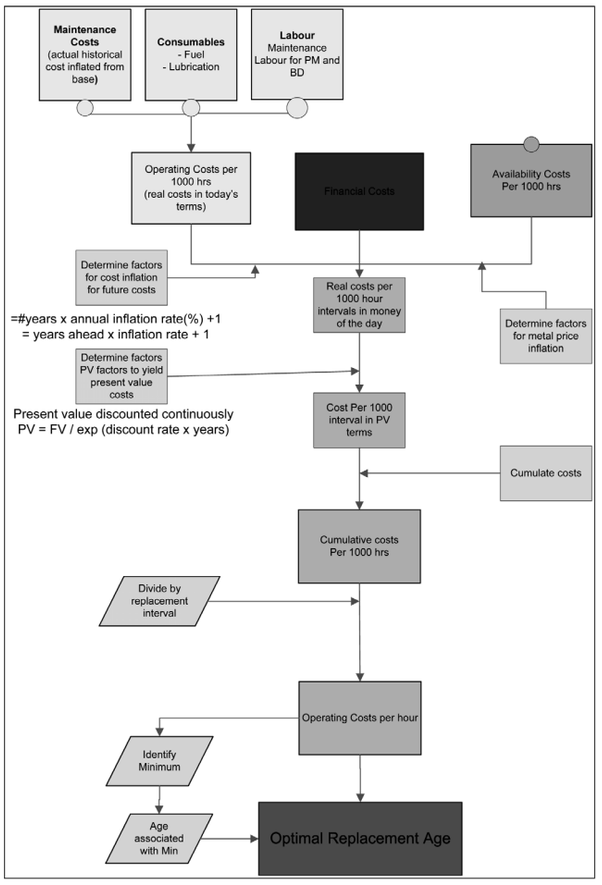

Figure 5. The optimal replacement interval methodology

Other factors

A number of intangible and non quantifiable factors exist, which have not been included in the model, due to their nature. These include factors such as:

- Decrease in utilization of older machines
- Increase in damages on older machines
- Benefit due to technological advantages in machine performance, maintainability, consumption and operator comfort.

Assumptions

In order to achieve the aim of the model, a number of assumptions have been made, some of which are based on history and experience whereas others simplify the model to a manageable proportion. The list is fairly detailed and is not conducive to the aim of this paper and has hence been omitted. The nature of the assumptions deal with the trends of machine availability, utilization, inflation, metal price forecasting, consumable costs, intangible benefits, etc.

Model methodology

The methodology used in the model uses the cost per hour to determine the optimal replacement life. This incorporates the fundamentals from the theory of vehicle replacement in that is uses the lifecycle costs, which are driven by the capital and running cost parameters and the timing advantage of equivalent annuity by applying discounting factors to future cash flows. The resulting outcome is similar to the cost per ton analysis. It achieves this through a number of steps, which are indicated in Figure 5, a simplified and easy to follow flow diagram.

- The basic principles of this methodology are based on deriving input parameters for operating costs, availability costs and financial costs per 1 000 hour intervals (Figure 6)
- In order to account for the risk and cost of money for future cash, a discounting factor is applied based on the annual utilization. The time value of money is a concept which is widely known, and the application of this can be found in numerous sources and hence is not addressed in this paper

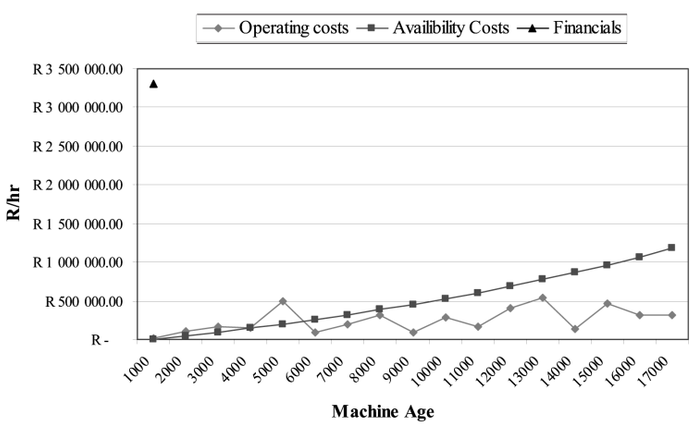

Figure 6. Cost per interval

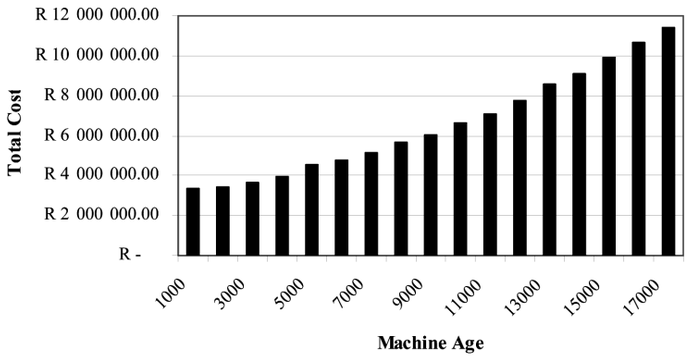

Figure 7. Cumulative costs

- Since using the data in the raw form tells us little and can be very erratic, due to expensive component change-outs for example, these costs are then cumulated (Figure 7). This cumulative cost represents the lifecycle cost of the machine up until that stage in its life
- This cumulative cost is then divided by the number of hours accumulated (its life) for different life scenarios (Figure 8)
- The results of this yield a cost per hour, which represent the average costs over the life of the machine.
- This can be compared to the alternate life options and the lowest cost per hour is the optimal replacement interval.

Figure 9 shows the drivers of cost for each replacement interval and as expected, for small replacement intervals the capital cost of the machine is predominant and for longer replacement intervals, the availability and operating costs become more prominent.

An exercise was carried out to compare the outcomes of the optimal replacement interval (ORI) methodology versus an equivalent annuity model and the results were comparable. This has been done for a number of alternatives based on real data. A simple example has been prepared to show how each methodology works and to show the comparison between the two. The details of this exercise are seen in Table I and a graph has been plotted in Figure 10. From this figure it is clear that the same relationship between the ORI and EA exists. In this instance, the EA life was 4 000 hours and the ORI life is 5 000 hours. This acts as a confirmation of the applicability of the ORI.

Outcomes of the model

Based on a test case, the figures have been generated and act as an example of what the model outputs. It gives an indication of the relative cost per hour values for each replacement alternative from which the minimum can be found. Further investigation will determine the difference in value lost by prolonging the life of the machine and its impact on NPV. In this instance the ORI was 11 000 hours. This model can easily be run for a number of machines on a site to determine the average, economically optimal life expected from machines on that site. In addition to this, the model can be used to compare machines on different sites by running the model for a number of machines.

Sensitivity analysis

To reduce the risk associated with inaccurate or sensitive inputs, a sensitivity analysis was conducted. Considering the nature and environment of the inputs, and their inclusion in the model in terms of the calculations, a number aspects were identified as being the risk factors and hence the reason for sensitivity analysis. These are

- Commodity price (which affects the cost of availability)
- Capital cost of the machine
- Discount rate
- Annual utilization (since this affects the timing of cash flows).

The sensitivity analysis was done using the optimal replacement interval as the dependent variable. In addition to this, sensitivity analysis was also carried out looking at the changes on the cost per hour. There are a number of reasons for including the cost per hour:

- the replacement age is discrete, i.e occurring only in 1 000 hour interval, and if an input is changed the corresponding output may not change, whereas the cost per hour is more sensitive and will show the difference i.e it reflects the marginal cost
- additionally since this output is more sensitive, it can be used to verify mechanisms in the model and in the sensitivity analysis.

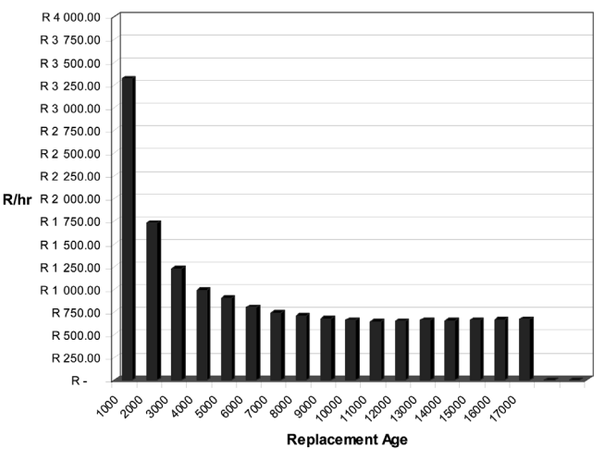

Figure 8. Optimal replacement interval

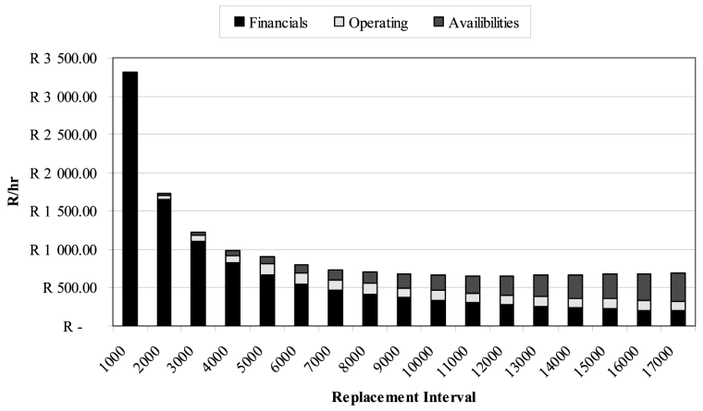

Figure 9. Breakdown of costs

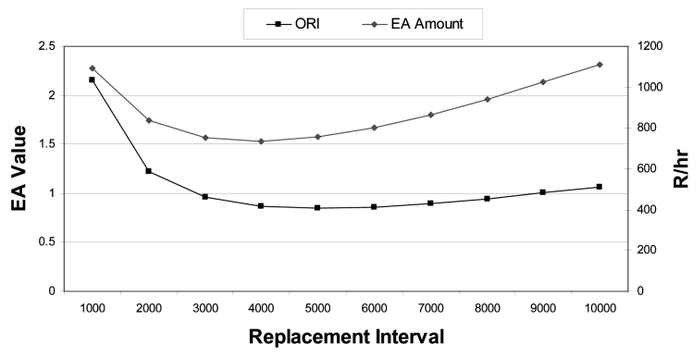

Figure 10. ORI vs EA

Table I
ORI vs. EA calculations

Year	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Age	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
Capital cost	R2,000	R-	R-	R-	R-	R-	R-	R-	R-	R-	R-
Maintenance cost	R-	R50	R75	R100	R125	R150	R175	R200	R225	R250	R275
Availibility cost	R-	R100	R200	R300	R400	R500	R600	R700	R800	R900	R900
Total costs per period	2000	150	275	400	525	650	775	900	1025	1150	1175
PV factor	1	0.9712859	0.9433962	0.9163074	0.8899964	0.864441	0.8396193	0.8155103	0.7920937	0.7693494	0.7472582
NPV for the period	2000	154.43445	291.5	436.53472	589.89	751.93105	923.0374	1103.6034	1294.0389	1494.7695	1572.4151
Total NPC	2000	2154.4345	2445.9345	2882.4692	3472.3592	4224.2902	5147.3276	6250.931	7544.9699	9039.7394	10612.155
EA factor	1	1.9712859	2.9146821	3.8309895	4.7209859	5.5854269	6.4250462	7.2405565	8.0326502	8.8019996	9.5492577
EA amount	2000	1092.9082	839.1771	752.40853	735.51568	756.3057	801.13473	863.3219	939.28775	1027.0098	1111.3067
ORI	200000	2.1544345	1.2229672	0.9608231	0.8680898	0.844858	0.8578879	0.8929901	0.9431212	1.0044155	1.0612155

As expected one can see the discrete nature of the replacement ages in Figure 11, which shows no clear measure of relative sensitivity. The graph shows an increase in replacement life with a decrease in capital cost — since a higher capital cost would warrant a longer life in order to justify this. The same trend is seen for the discount rate. With a higher discount rate, future values are discounted more heavily and so their impact is reduced, indicating higher running and availability costs in the future are less significant. Replacement age remains fairly stable with a change in annual utilization. However with a very high utilization, it appears the life is extended, assumed to be as a result of the lower effect of discounting, since with a high utilization the time periods are much smaller. Additionally, as expected, the higher the availability cost, the lower the machine life, due to a large cost associated with machine downtime, which increases with age and hence does not justify longer lifetimes.

Figure 12 shows sensitivity relative to cost per hour. As can be seen, this is less discrete than the replacement life sensitivity figure. It is clear from this graph that the capital cost and availability are the most sensitive parameters. With an increase in availability and capital costs, the whole cost per hour curve increases, hence the cost per hour at the optimal replacement age is higher. It can further be seen that as discount rate increases cost decreases since costs are

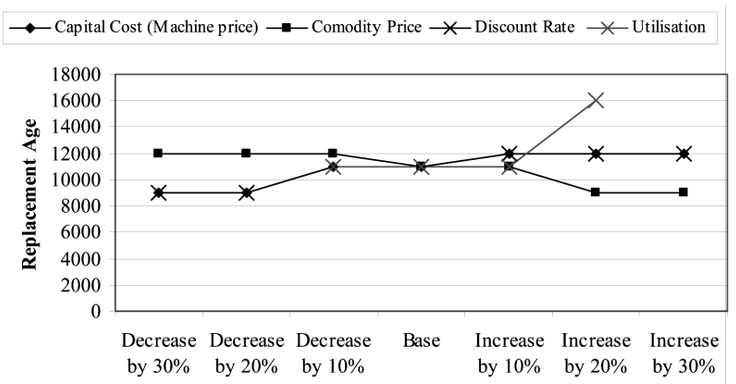

Figure 11. Sensitivity analysis (replacement age)

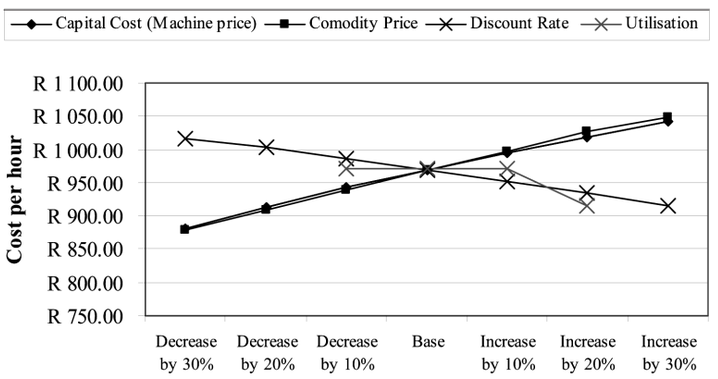

Figure 12. Sensitivity analysis (cost per hour Age)

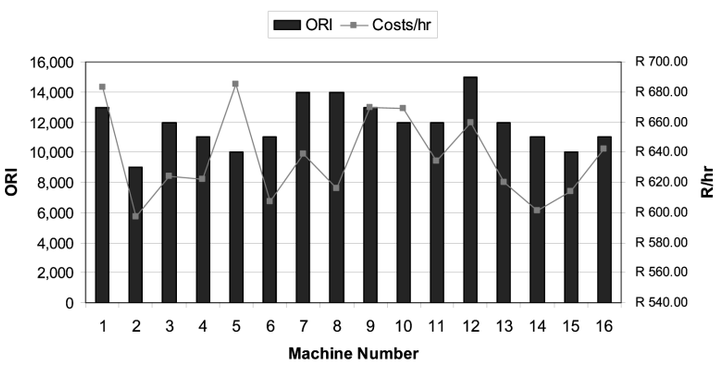

Figure 13. ORI and cost per hour for a fleet

now discounted by a larger amount: the higher the discount rate, the smaller the present value (PV) factor and hence the smaller the cost of the day.

Application of the model

The model has been run on for number of load-haul-dump LHDs) on one particular site. Figure 13 shows the optimal replacement aes for each machine and their corresponding cost per hour. Based on the inputs, the estimated ORIs are in the range of 9000–15000 , with an average of 12 000 hours. These numbers are thought to be very representative of these machines in their specific environment. This type of analysis can be used to determine the average machine life and hence put together a planned replacement schedule for a site. Other uses for this type of analysis can be to compare the same machine type on different sites and to compare the ORIs to the current machine ages, as can be seen in Figure 14. In this case, it is clear that all the machines are over their ORI and essentially are destroying value for the mine. However, from an analysis like this it is difficult to calculate exactly how much money is being wasted, in present value terms. This is a topic for future work.

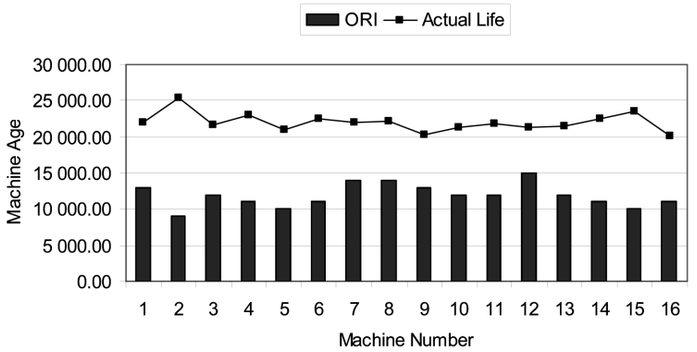

Figure 14. ORI vs Current machine lives

Conclusion

This model provides a simple tool to determine the economically optimal replacement ages of machines on different sites in any given environment. Although the approach used is applicable to a range of machine types, the model was based on low profile loaders. The machine ages outputted from the model range from 9 000–15 000 hours. This is based on a fleet of low profile 5 ton LHDs mining a platinum orebody. From observations and discussions with personnel, these figures are considered very reasonable and representative. The outcomes of the model are retrospective in that this was the optimal replacement life of the machines in the given the environment, which can provide a basis for future forecasts. Due to the nature and set-up of the model, machine analyses on a variety of machine models and on a range of sites is possible, but constrained to the historical data available.

Acknowledgements

Ideas and observations have been taken from and discussions have been underway with a number of people relevant to this topic, they include:

- Seppo Tolonen, [Wa Technologies Oy. Finnish Maintenance Management Consultant]
- Economic Life Model, Leon Kruger, De Beers
- Optimal Replacement Model, Wain Chaplain, – Sandvik.

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