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Case Study: Model for Economic Lifetime of Drilling Machines in the Swedish Mining Industry

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The purpose of this article is to develop a practical economic replacement decision model to identify the economic lifetime of a mining drilling machine. A data-driven optimization model was developed for operating and maintenance costs, purchase price, and machine resale value. Equivalent present value of these costs by using discount rate was considered. The proposed model shows that the absolute optimal replacement time (ORT) of a drilling machine used in one underground mine in Sweden is 115 months. Sensitivity and regression analysis show that the maintenance cost has the largest impact on the ORT of this machine. The proposed decision-making model is applicable and useful and can be implemented within the mining industry.

Introduction

Economic globalization increases competition among mining companies, pushing them to achieve higher production rates by increasing automation and mechanization and using new and more effective equipment. This forces companies to use more reliable capital equipment with higher performance capabilities; naturally, these are more expensive. The equipment used in underground mining industries is subject to degradation throughout its operating life. This increases the operating and maintenance costs and reduces production rates, causing a negative economic effect. In addition, the equipment used in underground mining is subject to a harsh working environment, and this accelerates degradation. Given all of these factors, key questions for the mining industry include the following. When should the company replace the equipment to minimize cost? How can the maintenance manager

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convince finance and production managers to replace capital equipment at a specified time in its life cycle? To answer these questions, life cycle cost analysis should be done in advance of an equipment replacement decision.

The optimum replacement age of equipment is defined as the time at which the total cost is at its minimum value (Jardine and Tsang 2006). In the mining industry, the costs associated with owning equipment can be grouped into categories: initial purchase, installation, direct downtime, maintenance and operating, financing, and cost recovery on disposal. The sum of these costs represents the total cost required to own the mining equipment (Hall 2007). Life cycle cost analysis helps decision makers justify equipment replacement on the basis of the total costs over the equipment's useful life. It allows the maintenance manager to specify the optimal replacement time at the time of the equipment's purchase.

Cost function models can be allocated to the various categories to allow easy estimation of the total cost. Such models can be generally classified as detailed models, analogous models, and parametric models. A detailed model uses estimates of material quantities and prices, labor time, and rates to estimate the direct costs of equipment. Analogous models identify similar equipment and adjust costs to account for differences between it and the target equipment. Cost estimation with a parametric model is based on predicting the equipment's total cost by using regression analysis based on technical information and historical cost (Asiedu 1998). Life cycle cost (LCC) analysis should not be seen as a method for defining the total cost of the equipment but as a help in decision making; thus, LCC analysis should be restricted to costs that can be controlled. In general, LCC is determined by summing up all of the potential costs associated with equipment over its lifetime. It is well known that the value of expenditure today costs more than the same value of expenditure next year because of the "time value of money." A discount rate is used to take into consideration the time value of money. To compare costs incurred at different times we must shift expenditure to a reference point in time. Thus, in this article, we are interested in estimating the equivalent present value of earlier or future costs.

Literature Survey

Standard models for economic replacement time decision contain an estimation of the discounted costs by minimizing the LCC of the equipment. The assumption of these models is that equipment will be replaced at the end of its economic lifetime by a continuous sequence of identical equipment (Hartman and Tan 2014). Recently, a number of researchers have studied the economic lifetime of capital equipment. Some consider the optimal lifetime of capital equipment using economic theories and vintage capital models, represented mathematically by nonlinear Volterra integral equations with unknown limits of integration (Boucekkine et al. 1997; Cooley et al. 1997; Hritonenko 2005; Hritonenko and Yatsenko 2003; Yatsenko 2005). Others use the theory of dynamic programming considering technological changes under finite and infinite horizons (Bellman 1955; Bethuyne 1998; Elton and Gruber 1976; Hartman 2005; Hritonenko and Yatsenko 2008; Mardin and Arai 2012). Yatsenko and Hritonenko (2005) studied the lifetime optimization of capital equipment using integral models. The study designs a general investigation framework for optimal control of the models. Hritonenko and Yatsenko (2007) studied optimal equipment replacement without paradoxes. Using an integral model to calculate the economic lifetime of equipment and considering technological changes (TCs), they showed that the economic lifetime of equipment is shorter when the embodied TC is more intense. Hartman and Murphy (2006) offered a dynamic programming approach to the finite-horizon equipment replacement problem with stationary cost. Their model studies the relationship between the infinite-horizon solution (continuous replacement of equipment at the end of its economic lifetime) and the finite-horizon solution. Hritonenko and Yatsenko (2009) constructed a computational algorithm to solve a nonlinear integral equation. The solution is important for finding the optimal policy of equipment replacement under technological advances. Kärri (2007) considered the optimal replacement time of an old machine, using an optimization model that minimizes the machine cost. The model is built to handle capacity expansion and replacement situations. Using real costs without inflation, Kärri (2007) modeled the costs of the old machine with simple linear functions. He also used an optimization model that maximizes profit. Scarf and Bouamra (1999) addressed the capital replacement problem using a discounted cost criterion over a finite time horizon. They presented a robust approach to solving the fleet replacement problem in which the fleet size is allowed to vary at replacement. A survey of multiple and single asset solution techniques under a variety of settings, including tax, variable utilization, various uncertainties, and technological change, was addressed by Hartman and Tan (2014). They also illustrated a number of open problems that are worthy of future research. Generally speaking, these studies focus on estimating the economic lifetime of equipment, considering technological changes and using integral models, theories of dynamic programming, vintage capital models, and algorithms to solve nonlinear integral equations.

Despite the available information, it can be difficult for users to implement complex models to calculate the optimal replacement time of equipment. Moreover, these models sometimes require specific types of data that, as in our case study, are not available. These can include data on production output, technological labor/output coefficient, revenue, profit, etc. Thus, the aim of this study is to identify the replacement age of a mining drilling machine from an economic point of view, using available data from a mining company, specifically, the operating and maintenance costs, purchase price, and machine resale value. In this study, equivalent present value of these costs was considered by using a discount rate.

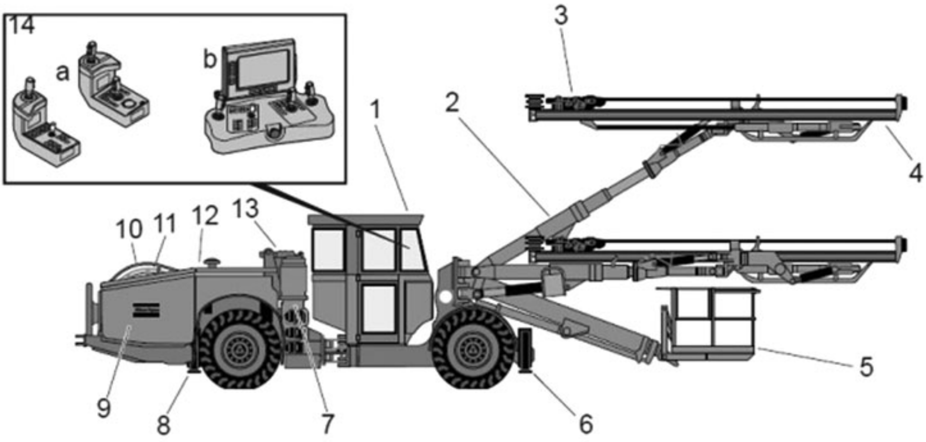
Description of Drilling Machine

The drilling machines typically used in mines are manufactured by different companies and have different technical characteristics; for example, capacity and power. An example of a drilling machine and its components is presented in Figure 1.

The drilling machine is divided into several subsystems connected in series configuration (see Atlas Copco Rock Drills AB 2010). If any subsystem fails, the operator will stop the machine to fix it. Thus, all machine subsystems work simultaneously to achieve the desired function.

Data Collection

The cost data used in this study were collected over 4 years in the Maximo computerized maintenance management system (CMMS). The cost data contain corrective maintenance costs, preventive maintenance costs, and repair time. The corrective and preventive maintenance costs contain spare parts and labor (repair person) costs. In CMMS, the cost data are recorded based on calendar time. Because drilling is not a continuous process, the operating cost is estimated by considering the utilization of the machines. It is important here to mention that all cost data used in this study are real costs without inflation. Due to the company regulations, all cost data are encoded and expressed as currency unit (cu) for this study. Samples of cost data can be seen in Table 1.



1	Cabin	8	Rear Jack
2	Boom	9	Electric cabinet
3	Rock drill	10	Hose reeling unit
4	Feeder	11	Cable reeling unit
5	Service platform	12	Diesel engine
6	Front jacks	13	Hydraulic oil reservoir
7	Hydraulic pump	14a	Operator panel, designed for seated operator
		14b	Operator panel, designed for standing operator

Figure 1. Drilling machine. Source: Andreas Nordbrandt, Vice President Service Operations, Atlas Copco Rock Drills AB (2010).

Methodology and Model Development

In this study the following assumptions are made for the optimization model:

- The cost of capital is given by the mining company involved in this study.
- Acquisition cost of the machine remains constant at each replacement.
- There is no installation cost for the machine.
- The optimization model is used for a finite time horizon.
- Production losses due to lead time during machine replacement are not considered.
- The machine will be used as a redundant machine after it reaches to its scrap value.

The taxes are included in the purchase price and operating and maintenance costs; for that reason, taxes are not included as an independent parameter in the optimization model.

The study develops a practical optimization model based on the total cost. Associated operating and maintenance costs, as well as purchase price and machine resale value, are considered. The maintenance costs (MC) for each month of operation consist of corrective maintenance (CM) and preventive maintenance (PM) costs:

$$MC = CM + PM. \tag{1}$$

The corrective and preventive maintenance costs are given by

$$CM = SP_c + LC_c \tag{2}$$

$$PM = SP_p + LC_p. \tag{3}$$

Table 1
Sample of cost data

Work description	Actual working time (h)	Actual materials cost (cu)	Total real cost (cu)	Actual labor (cu)	Actual service cost (cu)	Actual start date	Inventory description	Work type
Extension Extender 2 bolts of V-feeder	1	28.148	28.598	0.45	0	20xx-03-15 13:23	Feeder	PM
FU1 Atlas L2C/2	5	9.836	14.018	0	4.182	20xx-03-15 13:24		PM
Mount the sensor cables	6	0	2.7	2.7	0	20xx-03-15 22:41	Steering system	CM
Atlas Copco L2C	16	0	7.2	7.2	0	20xx-03-16 13:17	Electrical system	CM
Replacing the hose feeding shift	0.5	0	0.225	0.225	0	20xx-03-19 07:30	Hoses	CM

Because drilling is not a continuous process in the collaborating mine, operating cost (energy cost and steel rod cost) is calculated for each month based on the utilization of the drilling machine. The company plans to use the machine for 120 months. Therefore, extrapolation for the operating and maintenance cost data was done. Figures 2 and 3 illustrate the maintenance and operating costs determined by the data extrapolation.

In Figures 2 and 3, the dots represent the real historical data for maintenance and operating costs. Curve fitting was done using Table Curve 2D (Alfasoft AB, Göteborg, Sweden) software to show the behavior of these costs before and after the time when data were collected. Note that the fitting would be better if more data were available for a time period of more than 4 years. This software uses the least squares method to find a robust (maximum likelihood) optimization for nonlinear fitting. It is worth mentioning that the drilling machine in this case study has no multilevel preventive maintenance programme. In addition, it was new at the start of utilization. This is the main reason why the maintenance cost is quite low in earlier months. The history shows that when the maintenance costs started growing, the user company began to keep track of cost data by using CMMS.

The Lorentzian cumulative equation of extrapolation for expected maintenance cost obtained by the software is expressed as

$$Y = \frac{a}{\pi}\left[\arctan\left(\frac{x-b}{c}\right) + \frac{\pi}{2}\right], \tag{4}$$

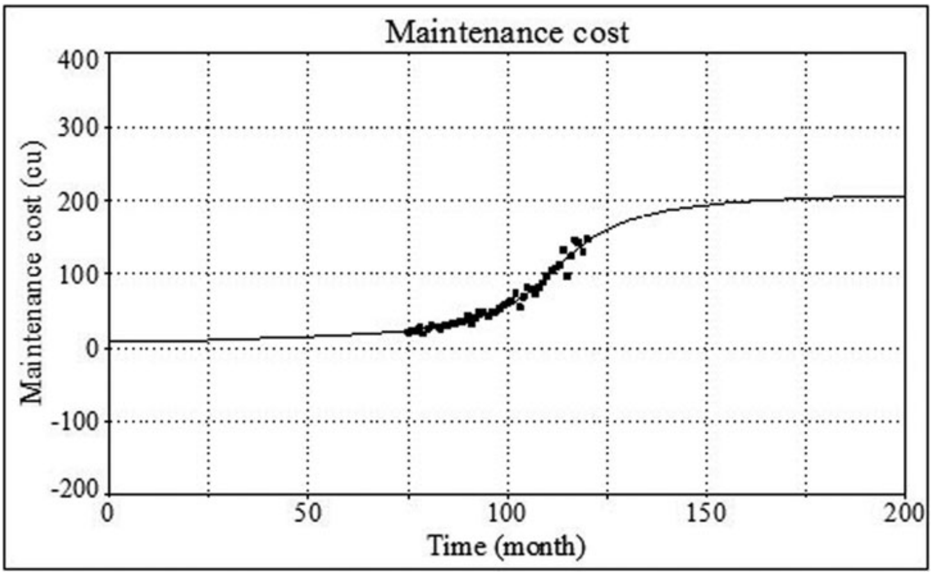


Figure 2. Maintenance cost.

where Y represents the expected maintenance cost, $a = 217.42$, $b = 112.37$, $c = 13.63$, r^2 (adj.) $= 0.97$, and X represents the time (1, 2, 3, 4, ... , n months). Similarly, the Lorentzian cumulative equation of extrapolation for expected operating cost is expressed as

$$Y = \frac{a}{\pi}\left[\arctan\left(\frac{x-b}{c}\right) + \frac{\pi}{2}\right], \tag{5}$$

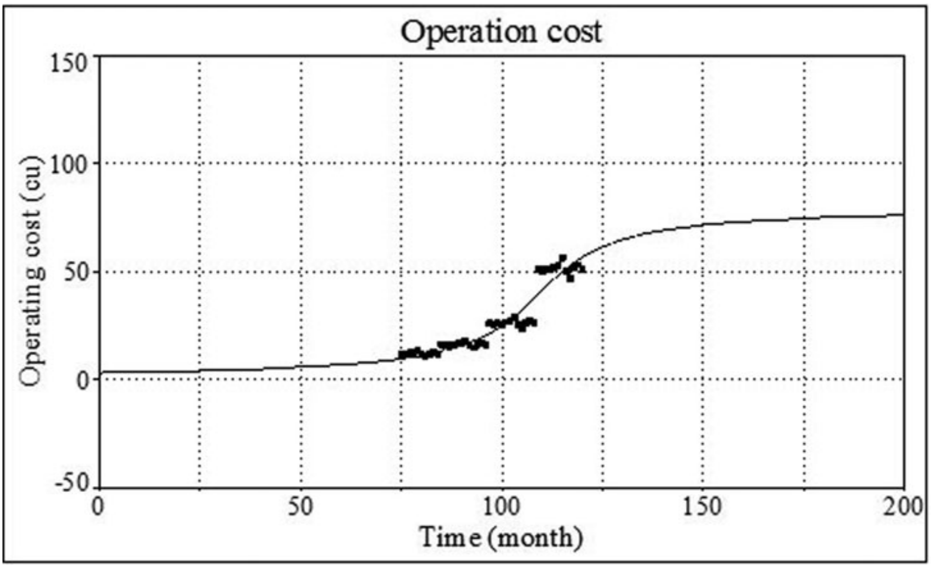


Figure 3. Operating cost.

where Y represents the expected operating cost, $a = 79.89$, $b = 109.2$, $c = 13.85$, r^2 (adj.) $= 0.91$, and X represents the time (1, 2, 3, 4, ... , n months).

As the figures show, the operating and maintenance costs increase over time. In fact, the number of failures increases with time and/or the machine consumes more energy due to machine degradation.

A declining balance depreciation model is used to estimate the resale value of the machine after each month of operation. The machine's resale value is its value if the company wants to sell it at any time during its planned lifetime. The resale value of the machine, denoted $S(i)$, is assumed to be given by the following formula (Eschenbach 2010; Luderer et al. 2010):

$$S\,(i) = BV_1 \times (1 - Dr)^i\,, \tag{6}$$

where i represents time (month), $i = 1, 2, 3, \ldots, 120$, and BV_1 is the machine's value at the first day of operation. In addition,

$$BV_1 = PP \times a, \tag{7}$$

where a represents the percentage that multiplied by the machine purchase price to represent the machine value at the first day of use. During discussions with us, company experts agreed that the machine's purchase price decreases by 10% on the first day of use (i.e., $a = 0.9$). In this study, the machine purchase price is 6,000 cu. Hence, the machine's value on the first day of use is 5,400 cu.

The depreciation rate that allows for full depreciation by the end of the planned lifetime of the machine is modeled by the following formula (Luderer et al. 2010):

$$Dr = 1 - \left(\frac{SV}{BV_1}\right)^{\frac{1}{T}}, \tag{8}$$

where T represents the planned lifetime of the machine, 120 months in the case study. The machine was assumed to reach scrap value after 10 years. The machine's resale value is given by

$$S\,(i) = (PP \times a) \times (1 - Dr)^i\,. \tag{9}$$

The declining balance depreciation model is suitable in this case because it assumes that more depreciation occurs at the beginning of the equipment's planned lifetime and less at the end. It also considers that the equipment is more productive when it is new and its productivity declines continuously due to equipment degradation. Therefore, in the early years of its planned lifetime, a machine will generate more revenue than in later years. In accountancy, depreciation refers to two aspects of the same concept. The first is the decrease in the equipment's value. The second is the allocation of the cost of the equipment to periods in which it is used. The scrap value is an estimate of the value of the equipment at the time it is disposed of. In this case study, 50 cu is assumed to be the scrap value of the machine at end of its planned lifetime, a figure given to us by experts at the company. Figure 4 shows the drilling machine's resale values using the declining balance depreciation model.

It is clear from Figure 4 that the machine's resale values decrease with time until it reaches scrap value at the end of its planned lifetime.

The next step in the calculations is to calculate the total ownership cost over each operating month. In this study, the economic lifetime of the drilling machine is defined as

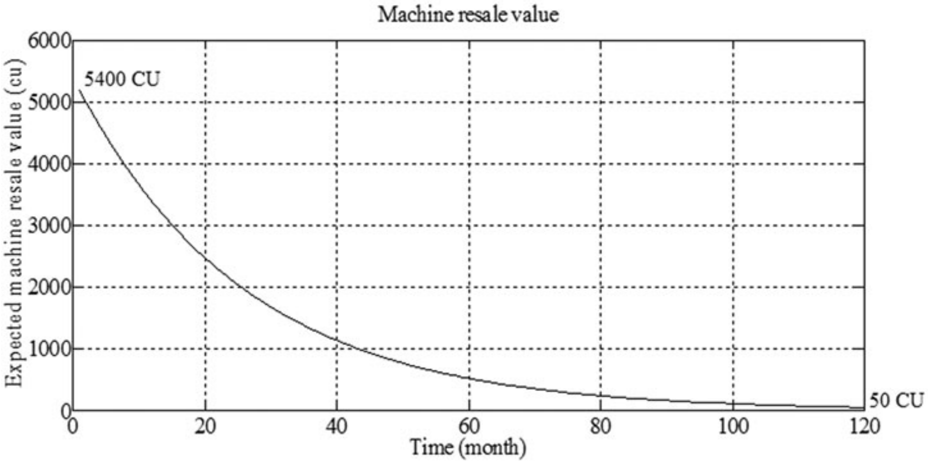


Figure 4. Machine resale value.

the machine age that minimizes the machine total ownership cost. The total ownership cost over period i is denoted by TOC_i, $i = 1, 2, 3, \ldots, n$, where n is the number of operating months. By definition,

$$TOC_i = PP + \left[\sum_{i=1}^{RT} (MC_i + OC_i)\right] - S(i), \tag{10}$$

where MC_i and OC_i is the maintenance and operating costs for the ith month.

The reason for using total ownership cost is that the machine's PP, OC, and MC represent costs, whereas the resale value represents income for the company when it is willing to sell the machine.

The objective is to determine the optimal replacement time that minimizes the total ownership cost over the machine's planned horizon. We assume that the replacement machines (i.e., the new machines) have the same performance and cost as the existing machine (i.e., identical machines). The number of replacement cycles during the planned horizon is modeled as

$$M = \left[\frac{\text{Planned lifetime}}{\text{Replacement time}}\right] = \left[\frac{T}{RT}\right]. \tag{11}$$

Figure 5 illustrates the expected total ownership cost of the machine over the planned horizon.

As Figure 5 shows, the total ownership cost increases with time for two reasons: first, operating and maintenance costs increase over time; second, the machine's resale value decreases over time until reaches its scrap value.

The optimal replacement time is the value of RT that minimizes the total ownership cost value, as shown in Eq. (12). A discount rate of 10% was used to consider the time value of money as mentioned by the collaborating mining company.

$$TOC_{value} = \left[\left\{\left(PP + \left[\sum_{i=1}^{RT} MC_i + OC_i\right] - S(i)\right) \times \frac{1}{(1+r)^{\frac{i}{12}}}\right\} \times M\right]. \tag{12}$$

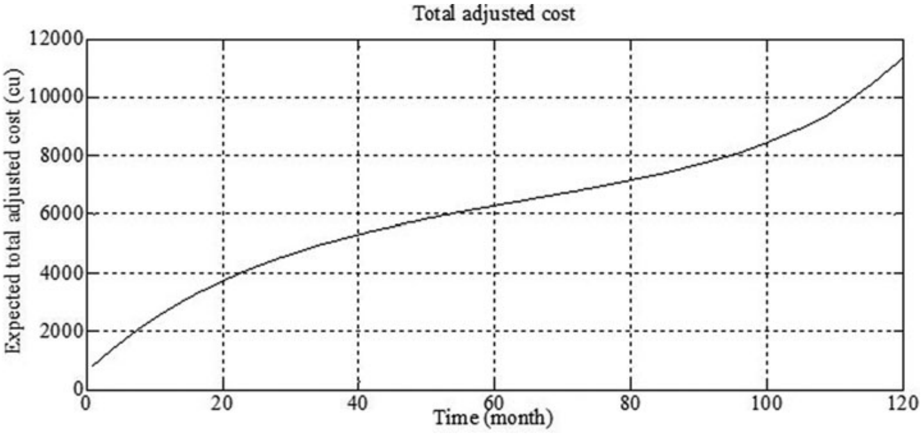


Figure 5. Expected total ownership cost.

Results and Discussion

Figure 6 shows the results when MATLAB (MathWorks, Natick, MA) software is used to enable a variation of the parameter RT of Eq. (12) for a planned horizon of 120 months. This is done to identify the optimal replacement time (ORT) of a drilling machine that minimizes $\mathrm{TOC}_{\mathrm{value}}$. The figure shows the $\mathrm{TOC}_{\mathrm{value}}$ versus a different replacement time RT.

To show the behavior of the optimization curve for a period more than the planned horizon, we assume that the optimization is used for a new finite time horizon of 240 months; see Figure 7. The total ownership cost for each operating month of the new planned horizon (i.e., $i = 1, 2, 3, \ldots, 240$) is computed by using the total ownership cost

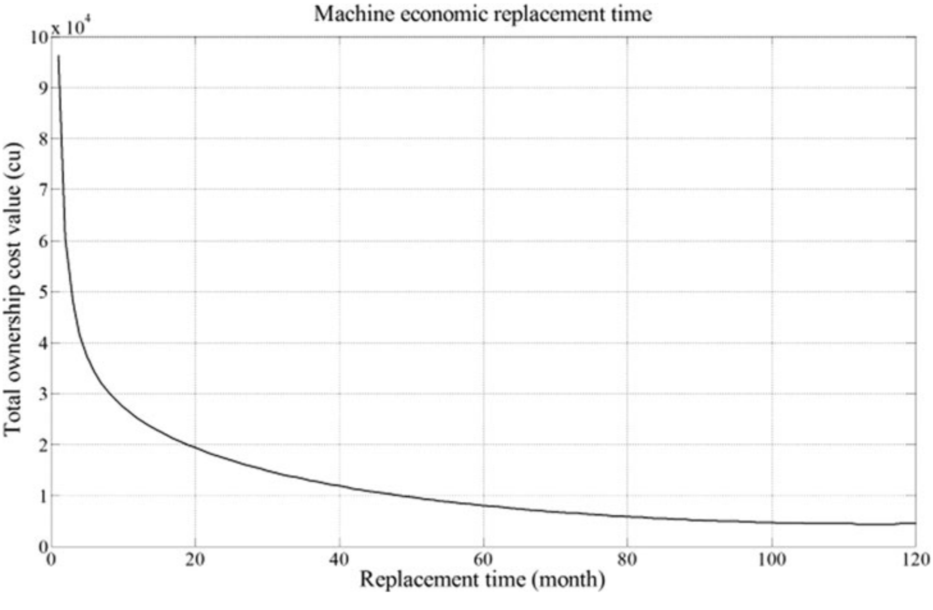


Figure 6. Total ownership cost versus replacement time of existing drilling machine.

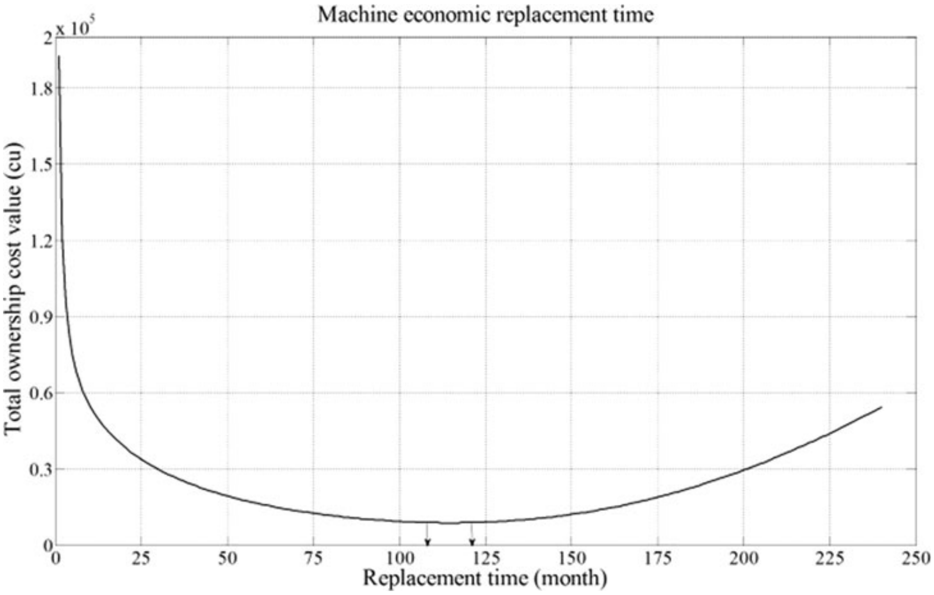


Figure 7. Optimal replacement time of existing drilling machine.

function obtained from Figure 5. This function is the fit of the calculated total ownership cost over the machine's old planned horizon (i.e., 120 months).

As is evident, the absolute lowest possible TOC_{value} can be achieved by replacing the machine with an identical new one every 115 months. However, it must be noted that RT = 115 months generates the absolute minimum cost. As Figures 6 and 7 also show, within that, there is a range (e.g., 110–122 months) when the minimum TOC_{value} can still be achieved in practice. In this study, we call it the optimum replacement range. Finding the optimum replacement range is an important result of our study because it can help users in their planning. A decision to replace equipment before or after this optimum replacement range incurs greater cost for the company. The use of a lower replacement age (i.e., less than 110 months) incurs higher costs due to the high investment cost. Meanwhile, if the lifetime of the machine exceeds the upper limit of this range (i.e., more than 122 months), losses will increase for two reasons:

1. The cost of operation and maintenance increases when the operating time increases due to machine degradation.
2. The machine's resale value will decrease each month of operation until it reaches its scrap value at the end of its planned lifetime.

Sensitivity Analysis

We next perform a sensitivity analysis to identify the effect of purchase price and operating and maintenance costs on the ORT of the drilling machine. However, because most of the factors may be interrelated, we use a multisensitivity analysis to identify the effect of multiple changes of cost factors.

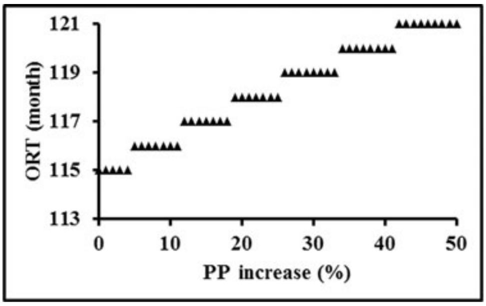


Figure 8. Effect of increasing purchase price.

Single-Variable Sensitivity Analysis

A single-variable sensitivity analysis varies one factor and keeps the others constant. The factors considered in our sensitivity analysis include machine purchase price, as well as operating and maintenance costs. Figure 8 illustrates the effect of an increasing purchase price on the ORT of the drilling machine.

Figure 8 shows that the ORT is an increasing step function of PP (based on the percentage of purchase price); the ORT remains constant for a specific range of PP increments and then increases stepwise. As an example, if the purchase price increases from 1 to 4%, the ORT is constant. This means that the ORT increases stepwise at specific PP percentage increments; that is, 5, 12, 19, 26, 34, and 42%.

Figure 9 illustrates the effect of decreasing machine operating cost (based on the percentage of operating cost) on the ORT. It is obvious that when the machine's operating cost decreases, the ORT will increase stepwise, although it remains constant within a specific range of decreasing OC. This means that the ORT is not sensitive to a specific range of operating cost reductions and will increase stepwise at a specific OC rate of reduction; that is, 15 and 34%.

Figure 10 illustrates the effect of decreasing machine maintenance costs on the ORT of the drilling machine. When the maintenance cost decreases, the ORT will increase as a step function of MC reduction. In addition, note that the ORT increases at reduction steps of MC—that is, 7, 15, 23, 30, 36, 42, and 48%—and remains constant within these steps.

Figures 8, 9, and 10 show that with increasing purchase price and decreasing operating and maintenance costs, the ORT of a new model of this machine will increase stepwise at a

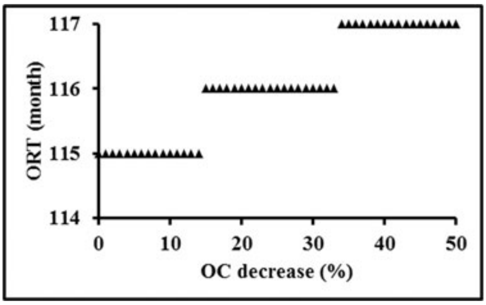


Figure 9. Effect of decreasing operating cost.

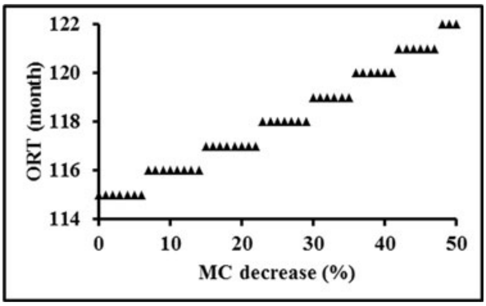


Figure 10. Effect of decreasing maintenance cost.

specific percentage of these factors. This may occur because there is a significant effect of these factors on the total ownership cost at these specific percentages of increasing factor of purchase price (IFPP), reduction factor of operating cost (RFOC), and reduction factor of maintenance cost (RFMC).

Multivariable Sensitivity Analysis

To increase our understanding of the correlation of input and output variables in the optimization model, a multisensitivity analysis was performed considering three different cases. MATLAB software was used to enable a variation of the three factors, IFPP, RFMC and RFOC, to show their effects on the ORT of the drilling machine. In all three cases, the purchase price increases while the operating and maintenance costs decrease. Case 1 represents the effect of decreasing machine maintenance costs while increasing purchase price and decreasing operating costs at different percentages at the same time. Figure 11 shows the correlation between decreasing machine maintenance cost and increasing purchase price for a given 15% reduction in the cost of operation. As the figure shows, decreasing maintenance cost while increasing purchase price has a positive effect on increasing the machine's optimal replacement time.

Case 2 studies the effect of increasing machine purchase price while simultaneously decreasing the maintenance cost at a given percentage of operating cost reduction. Case 3 considers the effect of decreasing the machine's operating cost while decreasing maintenance cost at a given percentage of increasing purchase price.

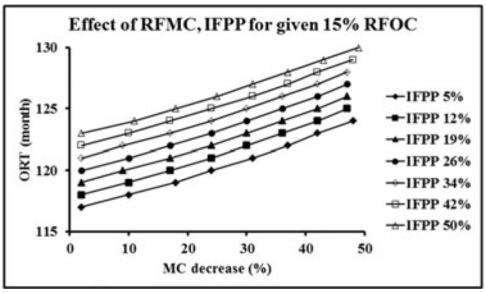


Figure 11. Effect of RFMC and IFPP for a given 15% RFOC.

From the results of the three cases (Figure 11), it is clear that the ORT of a new model of this machine will increase as a result of increasing its purchase price, decreasing the maintenance cost, and decreasing the cost of operation at different percentages. The explanation is that a new model of this machine is assumed to be more reliable than the old ones. This will lead to a decreased failure rate in a new model of this machine, which, in turn, reduces the maintenance cost. In addition, a new model of this machine is more productive than an old one; thus, it will finish the same job in less time. This will decrease the energy consumption of a new model of this machine, which leads to a reduction in the operating cost of it.

Regression Analysis

Our regression analysis of the ORT results obtained from the previous three cases uses Minitab (Minitlab Inc., State College, PA) software and the least squares method. The ORT of a new model of drilling machine is modeled as a linear function of IFPP, RFOC, and RFMC. IFPP is defined as the percentage increment on the machine's purchase price. RFOC is the percentage reduction in the machine's operating cost, and RFMC is the percentage reduction in the machine's maintenance cost. The regression analysis results in the following mathematical model:

$$ORT = 114 + 0.133 \times IFPP + 0.0682 \times RFOC + 0.164 \times RFMC, \tag{13}$$

where IFPP $= 5\%$, RFOC $= 6\%$, and RFMC $= 12\%$. The ORT resulting from the regression model is calculated as follows:

$$ORT = 114 + 0.133 \times 5 + 0.0682 \times 6 + 0.164 \times 12 = 117\ (month).$$

The ORT obtained from the regression model is compatible with the values shown in Figure 11. The other values of IFPP, RFOC, and RFMC can be calculated and checked as well.

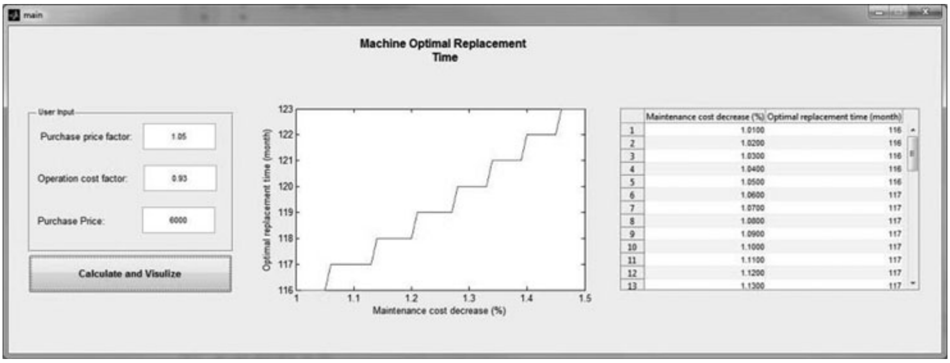
The high R^2 adjusted value obtained from regression analysis, R^2 (adj.) $= 98.6\%$, indicates that the ORT of a new model of this machine depends linearly on the IFPP, RFOC, and RFMC. Following the results of the sensitivity and regression analyses, the rank of the factors affecting the ORT of a new vintage model of a drilling machine is as follows:

1. The reduction in maintenance cost.
2. The increase in purchase price.
3. The reduction in operating cost.

Many studies have considered reliability, maintainability, and optimum replacement decisions; readers are referred to, for example, Ahmadi and Kumar (2011), Wijaya et al. (2012) and Dandotiya and Lundberg (2012) for further studies in the recent literature.

Graphical User Interface

During the study, we noticed that the user company is not always able to go through the process introduced here. Therefore, to facilitate the decision-making process and to enhance the company's ability to make the right decision at the right time, we developed a graphical user interface (GUI) to compute the ORT. The proposed GUI is designed to enable checking of the effect of changing any of the factors; that is, IFPP, RFOC, or RFMC. Figure 12 represents the GUI for case 1.



Purchase price factor: 1.05

Operation cost factor: 0.93

Purchase Price: 6000

	Maintenance cost decrease (%)	Optimal replacement time (month)
1	1.0100	116
2	1.0200	116
3	1.0300	116
4	1.0400	116
5	1.0500	116
6	1.0600	117
7	1.0700	117
8	1.0800	117
9	1.0900	117
10	1.1000	117
11	1.1100	117
12	1.1200	117
13	1.1300	117

Figure 12. Graphical user interface.

The selected input factors appear on the left side of Figure 12; the program calculates the ORT of the machine according to the selected input. The generated fields shown on the right of the figure represent the ORT values, calculated after applying the proposed optimization model. A plot representing the ORT trend appears in the figure's central column. From this, decision makers can determine the best time economically to buy a new machine. They can choose one of three factors: purchase price, operating cost, or maintenance cost. They can determine its effect on the ORT by observing the plot on the interface. This method also provides decision makers with useful information if they are negotiating with manufacturers over the purchase price of a new model of this machine.

Concluding Remarks

This article presents a comprehensive and practical approach that can be used to provide the optimal replacement time of an underground mining drilling machine. The following conclusions can be derived from this study:

1. Although many other models require reliability and failure data to identify the optimum replacement age, the approach presented herein is based on financial data on the purchase price, operating and maintenance costs, and the machine's resale value. This makes it very practical for industries.
2. According to the results obtained from the optimization curve, the absolute ORT of the drilling machine at the case study's mine is 115 months of operation. However, the ORT has a practical range of 110 to 122 months, during which the total ownership cost remains almost constant. This means that the company has the flexibility to make replacements within the optimum replacement age range; that is, 12 months. Therefore, there is no fixed date or age at which the TOC_{value} is minimum. In general, a range of months provides the minimum TOC_{value}.
3. The results of the sensitivity analysis indicate that increasing the purchase price and decreasing the operating and maintenance costs have a positive effect on increasing the ORT.
4. The results of the regression analysis show that the ORT of the new machine depends linearly on its IFPP, RFOC, and RFMC. These results confirm the computation and the results of the sensitivity analysis.
5. The results of regression analysis show that the reduction in maintenance cost has the largest impact on the ORT, followed by the increase of purchase price and

reduction of operating cost. Hence, the manufacturer must make a greater effort to improve the reliability and maintainability of the drilling machine to reduce the costs associated with maintenance and to increase the ORT. However, a detailed RAMS analysis is required to identify the weakest points of the machine from reliability, maintainability and supportability points of views.

6. Economists at the user company can easily use the GUI to estimate the ORT of a new machine and see the behavior of its ORT at IFPP, RFOC, and RFMC. These factors will provide a clear view of the ORT of the new machine. Knowing this will help the user company determine when to buy a new machine and assist them in any negotiations with the manufacturer over the purchase price.

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Nomenclature

a	Purchase price percentage at first day of operation (%)
BV_1	Machine's value at first day of operation (cu)
LC_c	Labor cost for corrective maintenance (cu)
LC_p	Labor cost for preventive maintenance (cu)
M	Number of replacement cycles
$S(i)$	Resale value (cu)
SP_c	Spare part cost for corrective maintenance (cu)
SP_p	Spear part cost for preventive maintenance (cu)
T	Planned lifetime (month)
$\mathrm{TOC}_{\mathrm{value}}$	Total ownership cost multiplied by number of replacement cycles (cu)

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