Economic lifetime of a drilling machine:

A case study on mining industry

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Abstract

Underground mines use many different types of machinery during the drift mining processes of drilling, charging, blasting, loading, scaling and bolting. Drilling machines play a critical role in the mineral extraction process and thus are important economically. However, as the machines age, their efficiency and effectiveness decrease, negatively affecting productivity and profitability and increasing total cost. Hence, the economic replacement lifetime of the machine is a key performance indicator. This paper introduces an optimisation model that gives the optimal lifetime for a drilling machine. A case study has been done at an underground Swedish mine to identify the economic replacement time of a drilling machine. It considers the purchase price, maintenance and operation costs, and the machine's second-hand value. Findings show that the economic replacement lifetime of a drilling machine in this mine is 96 months. The proposed model can be used for other underground mining machines.

Key words: Drilling machine, Optimal equipment lifetime, Optimization model.

1 Introduction

Mines are a source of energy resources and minerals. Thus mines play a key role in the economic growth of industrialised countries. Many different machines are essential in the

mineral extracting process; one example is the drilling machine. Economic competition and customer demand have pushed companies to achieve higher production rates through greater mechanisation and automation. This has lead to high investments in equipment (Duffuaa et al., 1998). The trend towards larger and more expensive equipment in underground mining to achieve cost effectiveness raises the question of replacement. When should a company replace the existing equipment to maximise production and minimise cost? Because drilling machines are a key element of production, they are important economically. A significant cost issue is the machine's maintenance cost. At long-term profitability, the Maintenance can play a key role for a firm, where it can have major impact on cost (Baglee and Knowles, 2010). Up to 40% of the total production cost of the heavy industries represents by maintenance cost (Lee and Wang, 1999). A study by the Swedish mining industry shows that the cost of maintenance in a highly mechanized mine can be 40-60 % of the operating cost (Danielson, 1987). Thus, the important factors behind these costs needs to be measured for their performance, like; measuring value created by the maintenance, justifying investment and revising resource allocations (Parida and Kumar, 2006). These factors are related to the cost of mining equipment and its economic lifetime.

The growing interest in modelling the economic lifetime of capital equipment has dramatically increased during recent decades. The optimal economic replacement of productive machines is a fundamental question faced by researchers, economic engineers and management engineers. Researchers concerned with cost optimisation are especially interested in the optimum replacement time of production equipment.

Many researchers have studied optimal procedures for replacing old equipment with new. Some have used the theory of dynamic programing considering technological changes under infinite and finite horizon (Bellman, 1955; Bethuyne, 1998; Elton and Gruber, 1976; Hritonenko and Yatsenko, 2008). Another study optimised the lifetime of capital equipment using integral models (Yatsenko and Hritonenko, 2005); the study designed a general investigation framework for optimal control of the integral models. Many researchers have studied the optimal lifetime of capital equipment through economic theory by using vintage capital models, represented mathematically by non-linear Volterra integral equations with unknown limits of integration, (Boucekkine et al., 1997; Cooley et al., 1997; Hritonenko and Yatsenko, 2003; Hritonenko, 2005). (Hartman and Murphy, 2006) presented a dynamic programming approach to the finite-horizon equipment replacement problem with stationary cost. Their model was introduced to study the relationship between the infinite-horizon solution (continuously replace equipment at the end of its economic lifetime) and the finite-horizon solution. (Kärri, 2007) studied the optimal replacement time of old machine. He used an optimization model which minimizes the machine cost; the model has been built for capacity expansion and replacement situation. The costs of old machine were modelled with simple linear functions and all costs that he used in his study are real costs without inflation. He also used another optimization model which maximizes profit. (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. Other researchers such as (Galar et al., 2012) used different cost models to define the efficiency of the operation of an industrial installation in a finite time horizon. They develop a methodology for the calculation of operation costs in industrial facilities.

The optimum replacement age of equipment is defined as that time at which the total cost is at its minimum value (Jardine and Tsang, 2006). In this case study the economic lifetime of drilling machine is defined as the optimal age which minimises the total adjusted cost value.
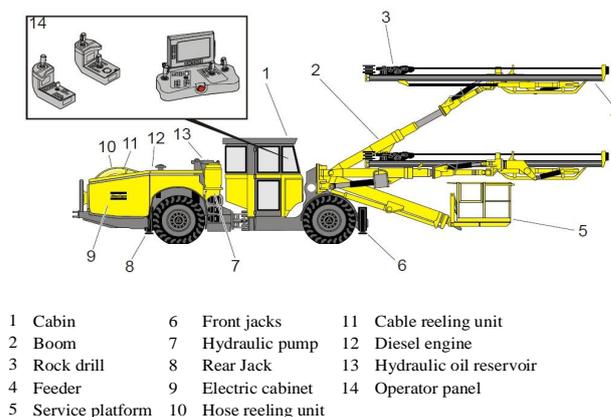
The term "total adjusted cost value" is defined as the summation of the machine purchase price, operation cost, maintenance cost and machine second-hand value. The machine second-hand value is the value of the machine in case the company wants to sell the machine at any time during the machine's planned lifetime. In this study, the most influential factors in the drilling machine's economic lifetime have been considered; cost data were collected for four years.

A previous literature review found that researchers have focused on estimating the optimal lifetime of equipment considering technological changes by using integral models, theories of dynamic programing, vintage capital models and algorithms to solve a nonlinear integral equations; it is sometimes hard for users to implement these models. Moreover, these models sometimes require specific types of data that, as in our case study, are simply not available. Thus, the aim of this study is to present a practical optimisation model to more easily estimate the economic lifetime of drilling machine, using available data from the mining company.

The rest of the study is as follows. Section 2 describes the drilling machine, while Section 3 discusses data collection. Methodology and model development are presented in Section 4; results and a discussion appear in Section 5; Section 6 offers conclusions and Section 7 offers future work.

2 The Drilling Machine

All drilling machines for mining applications are composed of similar operational design units: cabin, boom, rock drill, feeder, service platform, front jacks, hydraulic pump, rear jack, electric cabinet, hose reeling unit, cable reeling unit, diesel engine, hydraulic oil reservoir, operator panel and water tank. A typical drilling machine is shown in Figure1 (Atlas, 2010).

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

Figure 1. Drilling machine (Source: Atlas Copco Rock Drills AB)

Drilling machines manufactured by different companies have different technical characteristics, e.g. capacity and power. Based on the operation manuals, field observations and maintenance reports from the collaborating mine, in this study the drilling machine is considered a system divided into several major subsystems connected in a series configuration. If any subsystem fails, the operator will stop the machine to maintain it. Thus,

all machine subsystems work simultaneously to achieve the desired function. Figure 2 is a block diagram of drilling machine subsystems.
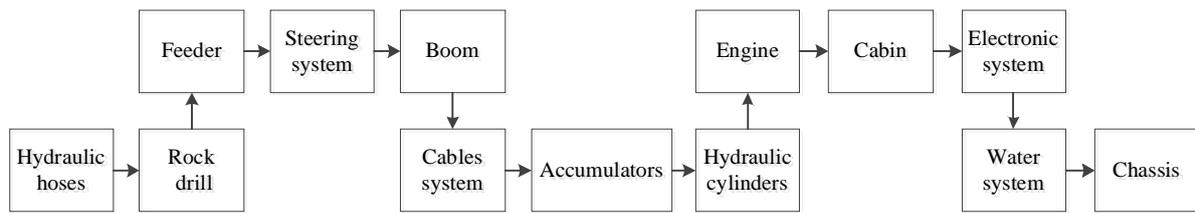

Figure 2. Block diagram of drilling machine subsystems

3 Data collection

The cost data used in this study were collected over four years in the Maximo computerised maintenance management system (CMMS). The cost data contain corrective and preventive maintenance costs and time to repair. The corrective and preventive maintenance cost contains spare part and labour (repair man) cost. In CMMS, the cost data are recorded based on calendar time. Since drilling is not a continuous process, the operation cost is estimated by considering the utilisation of the machine. All costs data that used in this study are real costs without inflation.

4 Methodology and model development

In this study, the notation for maintenance and operation costs as well as the machine purchase price with other quantities used in the optimisation problem is given in Table 1.

Table 1. Definition of model variables

Variable	Definition
cu	Currency unit
pp	Purchase price (cu)
rT	Replacement time (month)
MC	Maintenance cost (cu)
CMC	Corrective maintenance cost (cu)
PMC	Preventive maintenance cost (cu)
SPC	Spear part cost (cu)
LC	Labour cost (cu)
OC	Operation cost (cu)
$SHV(t)$	Second-hand value (cu)
Dr	Depreciation rate
BV_1	Booking value at first day of operation (cu)
SV	Scrap value (cu)
TAC_i	Total adjusted cost (cu)

The maintenance costs (corrective and preventive) for each operation month were calculated as follows:

$$MC = CMC + PMC \qquad (1)$$

$$CMC = SPC + LC \qquad (2)$$

$$PMC = SPC + LC \qquad (3)$$

Determination of the utilisation of the drilling machine was based on the estimation of the operation cost because drilling is not a continuous process in the collaborating mine.

The company planned to use the machine for ten years. For that reason, extrapolation has been done for maintenance and operation cost data. Figures 3 and 4 illustrate the expected maintenance and operation costs data extrapolation.
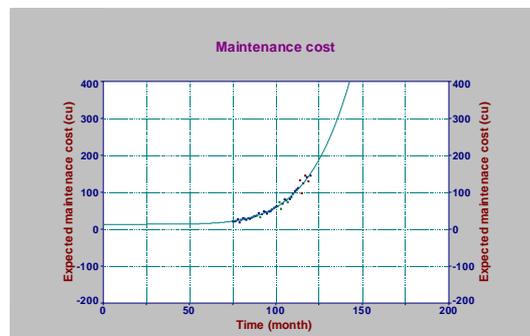
Figure 3. Expected maintenance cost

Figure 4. Expected operation cost

In Figures 3 and 4, dots represent the real data for maintenance and operation costs. Curve fitting is done by using Table curve 2D software to show the behaviour of the machine in term of these costs before and after the time of collected data. The figures show that the maintenance and operation costs increase over time. Possibly, the number of failures increases with time and/or the machine consumes more energy due to machine degradation.

A declining balance depreciation model was used to model the second-hand value of the machine after each month of operation. The second-hand value of the machine was estimated from the following formula (Luderer et al., 2010):

$$SHV(t) = BV_1 \times (1 - Dr)^t \tag{4}$$

where (t) represents time (month), $t=1, 2, 3... 120$.

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

$$Dr = 1 - \left[\left\{ \frac{SV}{BV_1} \right\}^{\frac{1}{L}} \right] \tag{5}$$

where (L) represents the planned lifetime of the machine (in this case 120 months). The machine's second-hand value was modelled by the following formula:

$$SHV(t) = (pp - a) \times (1 - Dr)^t \tag{6}$$

Where a represents the machine's depreciation in value on the first day of use. It is assumed that the machine's total lost value will be 10% on the first day of use. Hence, the machine's second-hand value at the end of the first day of operation is $(pp\text{-}a) = 0.9 \times pp$.

We have chosen the declining balance depreciation model because it is suitable for representing the depreciation of industry equipment, especially repairable systems. The declining balance depreciation model assumes that more depreciation occurs at the beginning of the equipment's planned lifetime, less at the end. 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, it 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 sold or disposed of; in this study, 50 cu was assumed as the scrap value. Due to the secrecy policy of the company, all cost data were encoded and expressed as currency unit cu.

Figure 5 shows the drilling machine's second-hand value using the declining balance depreciation model.
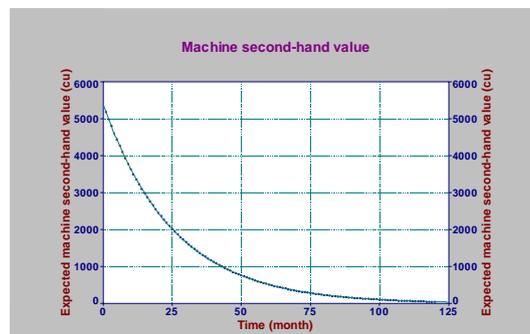
Figure 5. Expected machine second-hand value

Figure 5 shows that the machine's second-hand value decreased with time until it reached scrap value at the end of its planned lifetime.

The next step in the calculations is to compute the total adjusted cost TAC_i during a period i of operation using the following formula:

$$TAC_i = pp + \left[\sum_{k=1}^{rT} (MC_k + OC_k) \right] - SHV(rT) \tag{7}$$

where $i = 1, 2, 3, ..., N+1$. $N+1$ represents the number of operation periods.

For example, TAC_1 represents the total adjusted cost of the first period of operation and TAC_2 represents the total adjusted cost of the second period of operation.

The optimisation model assumes that the replacement machines have the same performance and cost as the old machines. The number of replacements during the optimisation time horizon is determined by the following formula:

$$N = \frac{\text{Optimization time horizon}}{\text{Machine replacement time}} = \frac{T}{rT} \tag{8}$$

Figure 6 illustrates the expected total adjusted cost of the machine over the machine's planned lifetime.

Figure 6. Expected total adjusted cost

Figure 6 shows that the total adjusted cost increased with time for two reasons: first, maintenance and operation costs increased over time; second, the machine's second-hand value decreased over time.

To show the behaviour of the optimisation curve after the optimal replacement time, we assumed that the machine would survive for a finite horizon of 360 months; see Figure 7. The total adjusted cost for each operation period of the optimisation time horizon was computed by using the total adjusted cost function. This function is the fit of the calculated total adjusted cost over the machine's planned lifetime (120 months). Table Curve 2D software was used to find the total adjusted cost function which can be used for any time horizon. Equation 8 expresses the total adjusted cost function used here:

$$TAC(t) = a + b \times \ln(t) + c \times [\ln(t)]^2 + d \times [\ln(t)]^3 + e \times [\ln(t)]^4 + f \times [\ln(t)]^5$$
$$+ g \times [\ln(t)]^6 + h \times [\ln(t)]^7 + i \times [\ln(t)]^8 + j \times [\ln(t)]^9 \tag{9}$$

where *a= 814.0, b= 13834.3, c= -56718.9, d= 95747.0, e= -86169.8, f= 45829.6, g= -14863.2, h = 2890.3, i= -309.9, and j= 14.1.*

The optimal replacement time (*rT*) which minimises the total adjusted cost value can be calculated by the following formula:

$$Min\left(TAC_{value\ rT}\right) = Min\left[\left\{pp + \left[\sum_{k=1}^{rT}\left(MC_k + OC_k\right)\right] - SHV\left(rT\right)\right\} \times N\right] \qquad (10)$$

5 Result and discussion

Microsoft Excel™ software was used to enable variation of the *rT* of Eq. (10) for a period of 360 months, to identify the optimum replacement lifetime of a drilling machine that minimises *TAC_{value rT}*. Fig.7 shows *TAC_{value rT}* versus different replacement time *rT*. As is evident, the lowest possible *TAC_{value rT}* can be achieved by replacing the machine every 96 months (8 years). Hence, a decision to replace before or after 96 months incurs greater cost for the company.
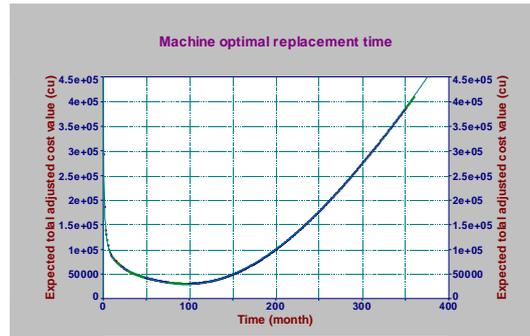

Figure 7. Optimal replacement time

The losses will increase if the lifetime of the machine exceeds 96 operating months for two reasons:

1. The maintenance and operation cost increase when the operation time increases due to machine degradation;

2. The machine's second-hand value will decrease until it reaches scrap value at the end of its planned lifetime which is 120 months.

6 Conclusions

We derive the following conclusions from the present study:

1. This study gives a basic approach to determining the optimum economic lifetime of a drilling machine, which facilitates the management in making investment decision making.

2. When using the purchase price, operation and maintenance costs, and second-hand value, the optimum lifetime of the drilling machine is the minimum sum of the associated total adjusted cost value.

3. We recommend replacing the machine between 90-102 months if the company only considers the cost.

4. This model helps engineers and decision-makers decide when it is best economically to replace an old machine with a new one. Thus, it can be extended to more general applications in mining industry.

7 Future works

Further research is needed to extend the developed model by performing a sensitivity analysis to identify the effect of purchase price, operation and maintenance costs on the optimal replacement time of the drilling machine on mining industry.

Acknowledgments

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