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Optimised asset replacement strategy in the presence of lead time uncertainty

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ABSTRACT

This paper develops an optimal replacement strategy for capital intensive equipment with long delivery lead time. The strategy is based on an extended version of the real options approach to repeated replacement decisions, in which the goal is to determine the operating cost and delivery lead-time conditions upon which a replacement should be ordered.

The real options approach to capital replacement problems is superior to traditional net present value (NPV) approaches, as it values of the option to adapt decisions based on current (rather than predicted) system conditions. However, previous applications of the real options approach to repeated replacement have not considered the impact of long and uncertain lead times, and have therefore focused on when to replace rather than when to order. Delivery lead times are an important consideration in an expanding mining sector in which demand for heavy mobile equipment (HME) exceeds the capacity of suppliers to provide the equipment in a timely manner.

The inclusion of a lead time element results in a decision with an "option" period and an "optionless" period. Simulations are used to demonstrate the improved outcome of real options based replacement strategies compared with those derived using a traditional NPV approach, both with and without lead times. Further the performance of the order placement strategy with different boundary conditions, bounded and reflecting, is explored. No appreciable difference in performance of these strategies was identified. The optimal order placement strategy incorporating delivery lead times is displayed on a simple chart which is accessible to fleet management personnel.

1. Introduction

Mining companies commit significant funds annually to purchase Heavy Mobile Equipment (HME) including dump trucks, wheel loaders, water trucks, graders and wheel dozers. In some cases this annual figure can be in the order of hundreds of millions of dollars. Given the huge expenditure involved in procuring, operating and maintaining HME, it is vital that companies optimise their replacement and procurement strategies.

Over time, mining companies incur operation and maintenance costs on their HME to maintain a specified level of performance. These costs tend to rise as the total operating hours of the equipment increases. Instead of continuing to incur rising operation and maintenance costs, there comes a point at which it is no longer economical to continue using the existing equipment, and it should be scraped and replaced with new equipment. An important consideration for any procurement department is to determine some criteria by which to recognise this point, or more specifically, the point at which such a replacement is expected to yield minimal life cycle cost (LCC).

Traditional methods for analysing equipment replacement decisions involve an estimation of the net present value (NPV) of all LCCs associated with a possibly infinite sequence of equipment life cycles. Given these cost estimates it is then possible to investigate how the timing of replacement decisions will affect the NPV. Examples of such replacement analysis include Galisky et al. (2008), Navon and Maor (1995), Yatsenko and Hritonenko (2011) and Chien (2010).

In the simplest case the costs associated with operating and maintaining equipment are assumed to be deterministic, however, in reality there are significant uncertainties associated with LCCs, including changes in technology, varied utilisation and operating conditions, economic factors, and changes in maintenance practices. This is considered a major limitation in using a deterministic model, and has lead to significant interest in models which incorporate uncertainty. There are two main classes of models which have been utilised to examine the impact of uncertainty on capital replacement decisions; Monte Carlo simulation, and dynamic programming.

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The key role of uncertainty in a replacement decision derives from the fact that as time passes, new information comes to hand which may influence the decision. Any approach which fails to represent the value/impact of new information on present decisions, necessarily fails to represent the role of uncertainty in the replacement decision (Adkins, 2005; Brealey and Myers, 1984), and neglects the value of the option to adapt the timing of the replacement decision. In the case of Monte Carlo simulation, if replacement decisions are simulated to occur at a particular machine age, or after a particular number of machine operating hours (Lugtigheid, 2008), then aside from providing some additional insight into how the NPV of a piece of equipment can vary with different parameter realisations, the incorporation of probability density functions into an NPV formulation cannot be expected to offer significant improvement relative to the decision obtained using expected values for the key variables.

Dynamic programming approaches to optimisation are based on the dynamic programming principle, which declares that the optimality of future decisions given a particular system state is independent of the past decisions which lead to the present state (Bellman, 1955). Numerous models based on a dynamic programming formulation have been proposed in connection with the economic replacement problem, incorporating various degrees and sources of uncertainty. For example, Brown (1993), Fleischer (1985), Hearnes (1995), and Lohmann (1986) combined the dynamic programming approach with other methods such as Monte Carlo simulation, probabilistic cash flows and fuzzy set theory, to study the impact of uncertainty in payoffs/cash flows over time, while treating the state of the assets as deterministically dependent on its age (not utilisation). Other authors have focused on the role of asset state uncertainty on replacement decisions, either directly by modelling state transitions as Markov Processes (Derman, 1963), or indirectly using uncertainty in asset utilisation (Hartman, 2001). Dynamic programming methods have also been used as a basis to study the interaction of deterioration and technological change in influencing optimal replacement decisions (Bean et al., 1994; Hartman and Rogers, 2006; Hopp and Nair, 1991; Nair and Hopp, 1992).

An issue associated with the use of a dynamic programming approach is in the use of a finite time horizon. More specifically, it is unclear how to choose an appropriate termination time when the termination time is unknown. A number of papers have considered the impact of using a finite time horizon (when the true termination time is unknown) as opposed to an infinite time horizon. According to De Sousa and Guimaraes (1997) and Scarf and Hashem (2002) the choice of horizon can have a significant impact on the optimal replacement strategy identified in a finite time formulation.

In this paper the asset replacement decision will be formulated over an infinite time horizon using a real options framework. The real options framework involves a dynamic programming formulation, however, in the case of an infinite time horizon the approach to optimising decisions is not based on a backward moving iterative algorithm. Under certain choices of stochastic dynamics which govern the uncertain cash flows, the optimal replacement problem over an infinite time horizon can be formulated as an ordinary differential equation in terms of the expected net present value of future associated cash flows (Dixit and Pindyck, 1994).

The repeated replacement problem has been considered in a number of previous papers. The basic formulation, derivation and solution of the second order ordinary differential equation associated with replacing an asset whose cost evolves via arithmetic Brownian motion (ABM) is considered in Ye (1990), however, it is not done from an options perspective. ABM is the linear combination of a linear function component and a continuous time stochastic process with stationary independent increments (i.e. standard Brownian motion). This work is extended in Mauer and Ott (1995) via the introduction of tax uncertainty, technological uncertainty, and the use of a contingent claims approach in deriving the differential equation. The focus is on how changes to the various problem parameters such as cost volatility, purchase price, corporate tax rate and salvage values impact the timing of replacement decisions. For example, decisions tend to be delayed with increased volatility in the underlying cost, increases to the purchase price of a new asset and increases to the corporate tax rate, while decisions tend to be brought forward with increases systematic cost increases, increases in salvage value and increases in investment tax credits. As opposed to Ye (1990), Mauer and Ott (1995) models cost via geometric Brownian motion (GBM) rather than ABM. GBM is the exponential of ABM.

The issue of repeated real options in an environment of rapidly, and stochastically evolving technology is considered in Malchow-Moller and Thorsen (2005). These results clearly demonstrate the inadequacy of a single option type approach in situations involving repeated options/replacements. They also observe that parameter sensitivity is less of an issue when options are repeated rather than one-off. Examples of a single option analysis in the context of the mining industry include the valuation of mining tenements, patents, oil tracts, and other expansion/contraction/abandon type decisions (c.f. for example Damodaran, 2005; Koller et al., 2005).

Other papers considering the repeated real options formulation for asset replacement are Dobbs (2004) and Adkins (2005). The former obtains an estimate for the expected machine life under an optimal replacement strategy, since the replacement time is a random variable. It also considers the sensitivity of the optimal replacement point to changes in the basic model parameters (similar to Mauer and Ott, 1995). The latter recaps the superiority of the real options approach over the standard Net Present Value approach, and also contrasts the dynamic programming formulation (relying on an exogenously defined discount rate), to the contingent claims formulation in which the discount rate is defined via a twinning portfolio of assets.

One of the main limitation of the replacement policies described above is that new equipment is assumed to instantaneously arrive exactly when a replacement is required. That is, no lead-time for equipment is considered. This is an unrealistic assumption in the context of the mining industry where lead-times are typically large and uncertain, and therefore present a significant burden to industry. In this paper we extend these considerations by focusing on a criteria by which to place an order for new equipment given the potentially significant lead times associated with obtaining new equipment.

A key point to note in this situation is that unlike the replacement models discussed above, the incorporation of lead time introduces an "option-less" interval into the replacement cycle. That is, once you commit to ordering a replacement asset you give up your option to utilise new information that comes to hand up until the new asset arrives and the cycle starts again. The objective in this context will be to place the order so that the actual condition of the equipment is expected to match the condition of the equipment at the optimal replacement point. However, due to the stochastic nature of the costs associated with operating and maintaining equipment, this condition cannot be guaranteed. We propose and compare two possible formulations which could be used to identify the optimal order placement condition.

The optimal procurement point is a function of the prevailing lead-time, leading to a procurement frontier. In the case considered here the procurement frontier is displayed in two dimensions,