ON USING CURRENT INFORMATION TO VALUE HARD-ROCK MINERAL PROPERTIES

Robert D. Cairns and Graham A. Davis*

Abstract—We reformulate the “Hotelling valuation principle” to take into account the special production characteristics of hard-rock minerals. The data requirements of the revised model are still parsimonious, but the resultant valuations are some 40% below those produced by the Hotelling valuation principle. Our valuation equations are also “user-friendly,” allowing the valuer to specify price and cost expectations that need not comply with the Hotelling rule. Empirically, our model provides estimates of market value for producing mineral properties that are more accurate than those produced by the Hotelling valuation principle.

I. Introduction

MILLER AND UPTON (1985) suggest that the value of any producing mineral property can be obtained by multiplying the quantity of reserves by the current net price, or the difference between price and current marginal cost:

\[ V(S) = (p - \partial C/\partial q)S, \] (1)

where \( V \) is the current value of the property, \( p \) is the current price of the extracted mineral, \( C \) is the mine’s cost function and \( \partial C/\partial q \) is thus the short-run marginal cost of extraction, and \( S \) is the quantity of remaining reserves. They use the formula to test Hotelling’s rule for net prices and are not primarily interested in the valuation model itself. The formula does, however, perform well in their initial tests using petroleum reserve values imputed from firm market capitalizations. It is this incidental result that has drawn the profession’s interest, and the formula is currently used by mineral appraisers and others charged with valuing mineral reserves, such as national-income accountants (e.g., Bartelmus et al. (1994); Bureau of Economic Analysis (1994)).

Equation (1), known as the Hotelling valuation principle, formalizes the intuitive notion that the value of a mineral deposit is simply the quantity of reserves multiplied by some unit reserve price, in this case price less marginal extraction cost. Indeed, the related formula:

\[ V = \lambda S \] (2)

is a standard ad-hoc valuation tool among mining industry analysts, where \( \lambda \) depends on the analysts’ perception of the type and quality of reserve being valued.\(^1\) The attraction of the Hotelling valuation principle is its formalization of this valuation approach, while requiring only contemporaneous data in spite of the fact that the mineral property is exploited over time, in some cases over many years.

There are three stumbling blocks, however, to the more widespread acceptance and use of the Hotelling valuation principle. The first is that equation (1) depends on the use of Hotelling’s (1931) observation that, in equilibrium, the extraction path of a mineral is chosen by the operator such that the mineral’s net price will rise at the rate of interest. In fact, Miller and Upton motivate the principle with reference to Hotelling’s analysis, and view their empirical results as tests of whether Hotelling’s rule is valid for the petroleum industry. However, as Adelman (1990) has stressed—and indeed as is consistent with casual observation—net prices of petroleum rarely rise at the rate of interest.

The second problem is the need for an estimate of marginal cost. Usually, only average cost is available. Given this, and the complication that marginal cost need not equal average cost under nonconstant returns to scale, Miller and Upton suggest the equation:

\[ V(S) = F + (p - a)S, \] (3)

where \( a \) is average extraction cost, and \( F \) is a complex deposit-specific term of indeterminate sign and magnitude based on the effects of scale in current and cumulative production. This undoes the practicality of the equation as a valuation tool; in the absence of information about the value of \( F \), valuation practitioners assume the constant to be zero, injecting potential error into the valuation result.

The third and most damaging problem is the lack of empirical support for equation (3) when tested against actual reserve transaction data (Adelman and Watkins (1995, 1996); Watkins, (1992)). Implicitly, there is a coefficient with value one multiplying the term \((p - a)S\)^2 For oil wells, the coefficient is found to be significantly less than one, with point estimates in the range of one-third to three-quarters (Adelman (1990)). Our test of equation (3) using gold reserve transaction data, which we report in Section 3, finds that the intercept is not significant, and that the coefficient on \((p - a)S\) is again significantly less than one (approximately 0.7). These results are of concern, since the use of equation (3) in environmental-accounting exercises could overestimate the wealth of the nation, and may lead to suboptimal policy responses.

\(^1\) For example, \( \lambda \) varies between $100/oz. and $150/oz. for developed gold reserves.

\(^2\) When \((p - a)\) is measured before tax, the coefficient could be “one or somewhat less” (Miller and Upton, 1985, 13).
There is also the problem that the decline in production prescribed by Hotelling-style analyses does not accord with practice. In their decisions concerning the rate of extraction, mining engineers usually assume the following.3

- Nominal prices and instantaneous unit extraction costs either do not change through time or inflate at the same rate.
- The quality of ore is homogeneous throughout the mine.
- Before production begins, the firm invests in a level of capacity that constrains the maximal output of the firm at any time during the exploitation of the mineral deposit.
- The level of capacity is chosen to maximize the present value of the mine.
- The anticipated level of output at any time is equal to the capacity level.

Cairns (1997) characterizes this type of mining program and shows that these practices would invalidate the Hotelling valuation principle in valuing hard-rock mineral properties, even if marginal-cost data were available. He finds that, given a capacity constraint, the net price does not rise at the rate of interest. Still, the optimal control framework yields that the shadow value of a unit of reserves rises at the rate of interest. The sum of this shadow value and the shadow value of capital is equal to the instantaneous profit of the firm.

Given the predominance of the Hotelling valuation principle in applied asset valuations, this paper proposes an improved formula. Our focus is a reformulation of the Hotelling valuation principle that takes into account the special characteristics of hard-rock mining, and allows for autonomous changes in price and costs that may not reflect a Hotelling rule.4 We extend Cairns’ results to produce a hard-rock valuation formula that 1) retains the general form of equation (3) currently in use by national-income accountants. Moreover, the method prescribes the use of average cost, which is easily observed, rather than marginal cost as is suggested in reference to Hotelling’s analysis. In deriving these results we assume that “the market works,” in that the observed practices of mining engineers capture all the useful information about the orebody.

II. Valuing a Producing Mine

Let there be a known stock, $S$, of mineral that has been proved by exploration at time $t = 0$. As in Campbell (1980), we assume that a capacity choice is made by the firm before it commences production, and that no further investment in capacity is possible once production begins. Typically the deposit requires a certain mining and milling design capacity, and subsequent modifications to augment the rate of extraction are not made except where the reserve estimate is adjusted upwards substantially. Here, we take reserves as certain.

Suppose that the investment in production capacity $K$ is incurred at $t = 0$, and that its cost is equal to $\phi(K)$, where $\phi(0) = 0; \phi'(K) > 0$ for $K \geq 0$; and $\phi''(K) \leq 0$. The last assumption implies that there are nondecreasing returns to scale from investment, as revealed in practice (Camm (1991, 1994), O’Harra and Suboleski (1992)). The choice of capacity constrains the firm from making the free intertemporal trade-offs in extraction discussed by, for example, Solow (1974) in explaining Hotelling’s rule.

Capacity constraints are usually not introduced into models of equilibrium price determination, of which Hotelling’s is a prototype. In our partial-equilibrium framework, the firm is assumed to be a price taker. We have mentioned that mining engineers tend to assume a constant price of output. In a model of price determination in Hotelling’s tradition, Lozada (1993) has suggested that, under stationary conditions, price in a competitive mining industry may remain constant for certain periods because of capacity constraints. And, between 1870 and 1970, real metal prices fell on average by 0.7% per year (Myers and Barnett (1985)), implying that nominal metal prices are rising at less than the interest rate. A conclusion we would make is that the engineers’ assumption of constant prices is approximately correct, especially over periods of about two decades, the life of the mine.5

Suppose that the cost of extracting a quantity $q$ of mineral at any instant $t > 0$ is given by $C(q, K)$, and that the price of the mineral at any time in the future is anticipated to be a constant, $p$. Then the firm maximizes the value of mine,

$$\Phi(S, K) = \max \left[-\phi(K) + \int_0^T [pq - C(q, K)]e^{-rt}dt\right],$$

where $T$ is the (optimally determined) time operations cease. Cairns (1997) has shown that the anticipated level of production on an interval $[0, \theta]$, $\theta \leq T$; is $q = K$, and that on the interval $(\theta, T)$ production declines monotonically to zero. If, in addition, marginal cost is constant, so that $C(q, K) = qa(K)$, then $\theta = T$: production is expected to be at capacity until closure of the mine. One’s intuition would suggest that, as the firm is small in world markets, and as the

3 See any mining engineering text, e.g., Gentry and O’Neil (1984), or Mase Westpac, Ltd. (1990).
4 Davis and Cairns (1998) have performed a similar analysis that takes the pressure constraints of oil production into account.
5 If they were far wrong, then practice would contradict the assumption of optimizing behavior.
net price is expected to rise at less than the rate of interest for at least a portion of the mine’s life, it would prefer to extract and to sell all of its reserves at the current instant. It is constrained from doing so by its capacity, which is limited because it is costly.

In reality, output at any mine fluctuates. Sometimes physical conditions prevent the firm from realizing an output equal to the level of capacity. Frequently, it is observed that production trails off toward the end of a mine’s life. This may be because marginal costs are increasing, so that planned output is declining near $T$. It may also be because the reserves pinch out over time. Sometimes output may be at capacity, but grade fluctuations cause fluctuations in output of metal or concentrate. It may also happen that reserves unproved at the time of investment can be exploited toward the end of production, or that reserves are in reality lower than anticipated at the start. At the point of investment, the quality and level of reserve are not known with certainty, but are revealed only by extraction.

Still, extractive capacity per unit time, $K$, is chosen by the mine operator with the expectation that production will remain at capacity throughout the life of the mine, and usually in the planning exercise it is assumed that $T = T$. In this case it is anticipated that $T = S/K$, and the level of cost is $C(K, K)$, i.e., $C(q, K)$, $a = C(K, K)$. Average cost is constant at $a = C(K, K)K$.

Getting to the valuation problem, consider a mine with a sunk capacity of $K$ and which holds reserves $S_t < S$ at time $t > 0$. Assuming production at capacity, the remaining life of the mine is $T - t = S/K$. The remaining present value of the mine, given a constant price, average cost, and interest rate, is

$$V(S_t, K) = \int_0^T [p - a]Ke^{-r(s-t)}ds$$

$$= [p - a]K \frac{1 - e^{-r(T-t)}}{r}$$

$$= \omega S_t \frac{1 - e^{-r(T-t)}}{r(T-t)}, \tag{4}$$

where we have written $\omega$ for the average operating profit, or modified net price, $[p - a]$, and have used the relationship $S_t = K(T - t)$. Equation (4) holds for any installed level of the capital stock, even if this is not necessarily the (currently) optimal one, and conforms to the formulation $V = \lambda S$ used by mining industry analysts, with $\lambda = \omega (1 - e^{-r(T - t)})/r(T - t)$.

Under our assumption that price is constant and that production proceeds at capacity for the remaining life of the mine, the value of the mine, with an installed capacity $K_t$ is given by a mine-specific number less than one, $(1 - e^{-r(T - t)})/r(T - t)$, multiplied by the reserves valued at the modified net price, $\omega$, where the average cost replaces the marginal cost of the Hotelling valuation principle. As with the Hotelling valuation principle, equation (4) requires only contemporaneous price and reserve data, highlighting Miller and Upton’s intuition about net price as a valuation tool. Contrary to Miller and Upton’s view, however, equation (4) does not mirror Hotelling’s rule. In the development of Hotelling’s rule (as modified to account for rising costs through time, taxes or other features mentioned by Miller and Upton and others, including Hotelling himself), output is not constrained. This is why, in intuitive explanations, producers can be held to be indifferent to producing at different points in time, so that a rule for net price holds. In equation (4), with output constrained, the shadow value of reserves rises at the rate of interest, but that shadow value is only a component of net price and not the whole net price. Net price, in fact, is assumed constant.

Strictly speaking, valuation equation (4) represents the present value of the mine only if production is optimally planned to be constant over the life of the mine, which, as we note above, will be the case when marginal cost is constant and hence equal to average cost (i.e., $\omega$ is constant). Bradley (1985) claims that marginal cost is approximately constant. If marginal cost is not constant, than average cost is not. But it varies only for $t \in (\theta, T)$. Before time $\theta$, average cost is constant at $C(K, K)$. Since $\theta$ is usually close to $T$, the error in using equation (4) to value mines with nonconstant marginal costs and substantial reserves compared to production, assuming optimal extraction by the operator, is small.

While of the same functional form as the Hotelling valuation principle, equation (4) demonstrates the error in the use of $\omega S_t$ (which is the equation (3) version of the Hotelling valuation principle with $F = 0$) to value producing mines, as is the practice in environmental-accounting exercises worldwide. Taking a discount rate of 8% and an average mine life of fifteen years, the factor $(1 - e^{-r(T - t)})/r(T - t)$ equates to 0.58, implying that $\omega S_t$ overvalues mining reserves by about 70% if net prices do not escalate over time. Such overvaluation has been recognized in the literature (Davis (1996)) and observed by national-income accountants (Bartelmus et al. (1994), World Bank (1997, p. 19)). Constrained capacity and constant prices do, therefore, create a valuation rule that is consistent with the empirical evidence.

Adjustment for drifts in the price or cost is easy to add for completeness. Suppose (unlike in equation (3)) that the analyst expects price to rise autonomously at rate $\gamma_p$, and average extraction cost to rise autonomously at rate $\gamma_c$, then

\[ (p - a) \text{ at } \gamma_p \text{ and } r \text{ at } \gamma_c \text{ then} \]

\[ \gamma_c \text{ at } \gamma_p \text{ and } r \text{ at } \gamma_c \text{ then} \]
the anticipated value of the program is

\[ V(S_i, K) = \int_{s_i}^s \left[ p e^{(r-\gamma)T} - ae^{(r-\gamma)T} \right] K_e^{-r(t-s)} ds \]

\[ = pS_i \left[ 1 - e^{-(r-\gamma)(T-t)} \right] - aS_i \left[ 1 - e^{-(r-\gamma)(T-t)} \right] \]

\[ = \omega S_i \left[ 1 - e^{-(r-\gamma)(T-t)} \right] \]

Equation (5) is similar to the equation (3) version of the Hotelling valuation principle, but with an easily calculated intercept term. Moreover, price and cost inflation is easily accounted for in equation (5), whereas equation (3) does not permit the analyst’s price expectations to diverge from the Hotelling rule and be reflected in asset value.

Equation (5) reemphasizes the error in using only \( \omega S_i \) to value hard-rock mineral properties. If \( \gamma_p > r \), as observed in the past for most minerals, the term multiplying \( \omega S_i \) is again less than one. If \( \gamma_e = \gamma_p \), then the second term on the righthand-side of (5) will be close to zero.\(^7\) If, on the other hand, \( \gamma_e \neq \gamma_p \), price and cost inflation are the source of an intercept term.

III. Empirical Verification

It is possible to test assertions for the value of producing mines using either imputed valuation data, as in Miller and Upton (1985), or transaction data, as in Adelman and Watkins (1995, 1996) and Watkins (1992). Transaction data are preferable, but not always available in sufficient numbers to allow econometric testing.

A. The Data

We have collected international transaction data for 35 producing gold deposits that traded over the period December 1985 through December 1996.\(^8\) The data consist of the transaction price, quantity of reserves transacted, current average extraction cost, average gold price in the month of the sale, and current production level. Four observations were removed because the transaction included associated nongold assets, and one Papua New Guinea transaction was removed because of the influence of political risk in the transaction price. Two observations had extraction costs greater than the current gold price, making the assets valuable only as options on gold production. We therefore also excluded these from our analysis. The remaining 28 observations, with an average transaction value of $28.5 million, were used to test the validity of the various proposed valuation equations. The data are presented in the appendix.

The results. We begin by testing equation (3) via the regression

\[ V_i = \beta_0 + \beta_1(\omega S_i), \]

where \( i \) indexes the transaction. Since \( F \) in equation (3) is indeterminate, we can say nothing about the expected sign of \( \beta_0 \) and the null hypothesis is simply \( \beta_1 = 1 \). The regression results, shown in table 1, indicate that we can reject this null at the 95% level (one-tailed test), while the intercept is not significantly different from zero.\(^9\) The regression coefficient estimate on \( \omega S_i \) of less than 1.0 matches similar empirical tests rejecting the Hotelling valuation principle using oil and gas data. Table 1 also reports several performance measures. The root mean-squared (RMS) percent error of the valuations calculated using equation (3), based on the usual assumption that \( F = 0 \), is 291%, the mean absolute percent error is 142%, and only 75% of the estimated values are within 100% of the transaction values, lending little credibil-

\(^7\) If \( \gamma_e = \gamma_p = 0 \), equation (5) simplifies to equation (4).

\(^8\) The data, originally from publicly available sources, were provided by Onstream Resource Managers, and were supplemented from Mining Business Digest.

\(^9\) We cannot reject homoscedasticity at the 97.5% level in any of the four regressions reported in table 1.
ity of the formula as a mine-valuation tool. For comparison, equation (2) with \( V_i = 100S_i \), as used by some mineral industry appraisers when valuing producing gold reserves, gives an RMS percent error of 257\%, less than this version of equation (3) used by national-income accountants.10

The regression slope estimate of 0.72 and the absence of a significant intercept term is consistent with our derivation of valuation equation (4). We test equation (4) via the regression

\[
V_i = \beta_0 + \beta_1 \left( \frac{1 - e^{-r(T-t)}}{r(T-t)} \right),
\]

with \( r_i \) equal to the treasury-bond yield for bonds of comparable maturity to the remaining mine life up to a maximum of thirty years.11 By our analysis in Section 2, we would expect to find \( \beta_0 = 0 \) and \( \beta_1 = 1 \) in this equation. As shown in table 1, we cannot reject the joint null hypothesis at the 5\% level. The RMS percent error of valuation equation (4) has dropped to 120.9\%, and the mean absolute percent error has dropped by almost half.

Equation (5) allows for drifts in price and cost over time. The average rate of gold price increase between 1985 and 1996, \( \gamma_p \), was 1.1\% per year. The corresponding value for \( \gamma_c \) was 2.8\% per year.12 Using these constant price and cost inflation values, equation (5) is tested using the regression

\[
V = \beta_0 + \beta_1 \left[ \frac{1 - e^{-\gamma_p(T-t)}}{\gamma_p(T-t)} \right] - \gamma_c \left[ \frac{1 - e^{-\gamma_c(T-t)}}{\gamma_c(T-t)} - \frac{1 - e^{-\gamma_p(T-t)}}{\gamma_p(T-t)} \right].
\]

Again, by our analysis in section II, the joint null hypotheses are \( \beta_0 = 0 \) and \( \beta_1 = 1 \). As with equation (4), we cannot reject the joint null at the 5\% level (see table 1). The use of these inflation variables has raised the RMS percent error slightly, to 122.4\%, and lowered the degree of fit as measured by the adjusted R-squared.

We also allow for prices and costs to inflate at the general rate of inflation, as is implicit in valuations that are conducted in “real” terms using constant real prices and costs and a real discount rate (Gentry and O’Neil (1984)). Using the average inflation rate of 3.4\% during the sample period, we regress equation (5) with \( \gamma_p = \gamma_c = 0.034 \), and obtain a higher adjusted R-squared, but mixed changes in performance.

Thus, in our sample, there is no clear improvement in valuation accuracy by including price and cost inflation, and equation (4) is appropriate. However, if the analyst has expectations about rates of price and cost increases, then the impact of these expectations on value can be accounted for in equation (5). Neither the original Hotelling valuation principle (equation (1)), nor its modified version (equation (3)), allows for these expectations to be easily reflected in value.13

IV. Conclusion

The Hotelling valuation principle has been promoted as a method for valuing producing mineral properties, and has been taken up in various fashions by national-income accountants, among others. However, the principle provides that the relevant net price is the difference between price and marginal cost, and marginal cost is usually not available. Many analysts have replaced marginal cost with average cost, which is readily available in accounting statements, but which creates a measurement bias, which they ignore. We find that neither the marginal-cost version of the formula (equation (1)) nor the average-cost version (equation (3) with \( F = 0 \)) provides an accurate theoretical valuation of a hard-rock mineral deposit; indeed, the latter is likely to overvalue reserves by around 70\%. Empirically, equation (3) is rejected in a test involving transactions data for producing gold mines. In fact, an ad hoc formula used by industry analysts, equation (2) with a constant reserve coefficient of $100/oz., values with less error.

Taking mining-engineering practice into account, we propose alternative formulas for calculating the value of a mine, by equations (4) and (5). Our derivations stress the constraints that mining capacity places on a firm’s extraction decisions. Yet the equations retain the flavor of Miller and Upton’s Hotelling valuation principle, with contemporaneous price, cost, and reserve data being central valuation parameters. The valuation equations do not rely on Hotelling’s rule, but rather allow valuers to incorporate their own expectations about price and cost inflation.

Because production is expected to be at capacity for most of a mine’s life, average cost—not marginal cost—naturally emerges as the appropriate variable to use in valuation. However, because the firm is constrained, its value is less than would be predicted if the constraint were not modeled. Contrary to Miller and Upton’s derivation, the modified net price (average operating profit) is multiplied by a factor—which is mine-specific to the extent that it involves remaining mine life—that is strictly less than one, typically around 0.6.

Empirically, these formulas outperform the version of the Hotelling valuation principle currently recommended by the World Bank (Bartelmus et al. (1994)) and used by the Bureau of Economic Analysis (1994) in its recent valuation

10 The mean absolute percent error is 155.8\%, and 67.9\% of estimated values are within 100\% of the transaction values.

11 The results were virtually unchanged when we used a constant interest rate of 8\%, the average thirty-year treasury-bond rate over the sample period. We use the risk-free rate because gold is thought to be a zero-beta asset. This is confirmed in recent empirical work by Schwartz (1997), who finds that the market risk premium associated with gold price uncertainty is zero.

12 Marshall and Swift cost index, mining and milling, published in Chemical Engineering.

13 One would have to adjust the current net price up or down to reflect price and cost expectations that are not consistent with Hotelling’s rule.
of the stock of U.S. mineral reserves. Since the results of these accounting exercises may have implications for sustainability and possibly environmental policy, these are important adjustments to the Hotelling model of resource value.

REFERENCES


APPENDIX

GOLD MINE TRANSACTION DATA, DECEMBER 1985–DECEMBER 1996

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