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Setting Plant Capacity

By P L McCarthy [1]

Abstract

The optimum plant capacity for a new mine is usually based on empirical studies or "rules of thumb", subject to confirmation by detailed scheduling of the proposed mining operation. The mining industry has a record of poor returns on investment and a high rate of project failure using these methods, with under-performance in grade being a common experience.

The assumption that "economies of scale" will result from increasing throughput rates needs to be balanced by an awareness of the adverse effects of increasing the rate beyond a level that is supportable by the resource. For each scale of operation considered, it is a reality that for any intended head grade, at the associated intended cut-off grade, the actual head grade achieved will fall as the mining rate increases. This effect is known to people at operations but is not recognized in current ore reserve estimation methodology.

Once recognised, this dependency of head grade on mining rate can be quantified and used to establish the economically optimum mining and processing rate for a new project. A simple analysis is proposed, which may be extended to detailed spreadsheet modelling for financial optimisation.

Introduction

A design rate of mining and processing is selected in every mine feasibility study, although any attempt to optimize that rate is rarely documented. To maximise return on investment, it has long been recognised that both the capital investment per unit of output and the operating cost per unit of output should be minimised. In general, both of these cost measures decrease as the scale of the project increases, so the initial temptation is to "push the orebody to the limit".

However, the technical and commercial risk both increase as the scale of the project increases. Hoover (1909) said "The lower the production rate, the lower the required investment, the longer the income stream and the lower the risk to the investor". While this was well before the advent of Discounted Cash Flow ("DCF") analysis, the point made by Hoover remains a good one.

A study reported by Tatman (2001) compared the final feasibility study production rate with the average sustained production rate from sixty steeply dipping tabular deposits. Tatman found that 35% of the mines did not achieve their planned production rate, and was able to derive an empirical formula relating the risk of failure to the geometry of the deposit and the rate of mining. Tatman's conclusions are consistent with the author's observations for underground mines (McCarthy, 1993) that in general there is a limiting rate of mining advance (typically about 60 vertical metres per year) beyond which either the ore tonnage or head grade, or both, cannot be sustained.

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The physical limit to the rate at which any orebody can be mined is dictated by the possible rate of development, available face length (in a pit) or available stopes (underground), grade control turnaround, and so on. There is also an economically optimum rate, which is lower than the physical limit of mine production, beyond which the negative influences of a high rate of mining begin to outweigh the incremental cost advantages.

It is also clear that mining slowly is more predictable, while attempting to mine quickly leads to greater production volatility and a less certain outcome. As more capital is invested in the larger operation, it has a higher commercial risk.

An empirical study by Taylor (1976) further refined in Taylor (1986) provided a surprisingly simple relationship between mine life (hence mining rate) and ore reserve tonnage for open pit porphyry copper mines. McSpadden and Schaap (1984) extended this work to other types of ore deposit and both surface and underground mines.

These studies were based on what mines were doing at the time but there was no claim made that the resulting mining rates were optimal. However, Smith (1997) observed that "The production rate from Taylor's Law appears to provide a reasonable starting point for a project evaluation". Smith (ibid) presented a number of other commercial "rules of thumb".

The empirical studies are very useful in setting guides to production rates based on industry practice, but offer no fundamental principles that can be applied. In most feasibility studies, there is an implicit attempt to maximise production within "safe" limits. This may not be the optimum strategy. In particular, the negative impact on head grade of a high mining rate is well known in operations but is ignored in the literature on mine optimisation.

This paper presents the first steps in developing a rational basis for optimising the production rate that recognises, in particular, the relationship between mining rate and head grade.

Orebody Size and Mining Rate

Let us consider orebodies of increasing size, excluding flat tabular orebodies, which are a special case. Usually, as the orebody gets bigger:

- The available tonnes per vertical metre increases
- For a pit, the stripping ratio to a particular depth decreases
- For an underground mine, the development efficiency (tonnes per metre) increases
- Possible stope sizes get bigger (to a geotechnical limit)
- Lower-cost and more productive mining methods become possible
- The average capital investment per tonne of eventual production decreases
- The physical limit of mine production increases
- The economically optimum mining rate increases

For any particular orebody we may choose any mining rate up to the physical limit of mine production. Experience and analysis suggest that as we increase the chosen mining rate:

- The required total capital investment increases
- The required working capital, including pre-stripping or advance development, increases.
- The fixed component of operating cost is spread over more tonnes
- Step capacity limits are reached, requiring further capital investment
- Head grade to the mill decreases, for reasons discussed below
- Control of the mining process begins to deteriorate after some point
- The physical limit of production from the orebody is approached
- Potentially negative social and environmental impacts increase
- The rate of waste production and disposal increases

In the author's experience mining and processing rates are set in the following ways:

- To satisfy economic criteria (eg return on investment), often with inadequate regard to what the orebody will sustain
- To match existing installed capacity (eg when a pit is converted to an underground mine)
- Using "rules of thumb" such as the equivalent vertical advance rate limit, or Taylor's rule.
- By detailed "paper" or computer scheduling of mine production to establish the physical limit, then designing at the physical limit or with some "margin of comfort".
- To meet corporate goals such as ounces per year of gold production

Experience with feasibility studies and a survey of the literature have not given an example of a quantitative approach that optimises production rate based on the physical influences on the mining process discussed above. There may be an assumption by metallurgical and process engineers that the mine planners have ways of optimising the rate, or alternatively that they can deliver whatever rate is needed to meet economic criteria. Neither assumption is true.

The track record of mine feasibility studies is poor. The 35% failure rate (to achieve production targets) observed by Tatman (2001) may be compared with the observation that only 50% of underground base metal mines and mills reach design throughput by Year 3 and 25% never reach design throughput (Ward and McCarthy, 1999). In an earlier study of 35 Australian gold mines (Burmeister, 1988), 68% of mines failed to deliver the planned head grade, while a review of nearly 50 North American projects showed only 10% achieved their commercial aims with 38% failing within about one year (Harquail 1991).

The Process of Optimisation

Ideally, a feasibility study would result in an optimised design for the mine and processing plant. In reality, most studies are constrained by time, budget and data to achieve a minimum economic hurdle, without really determining how much better the project could be with further study. The gross variables under the designer's control are the cut-off grade, production rate, mining method and process design. Of these, the mining method and process design can be selected using well-established criteria based on experience, field data and test work.

The sensitivity of project value (however defined) to the key parameters of production rate and cut-off grade is illustrated in Fig. 1. Various combinations of these two parameters give a three-dimensional "value surface" which has one or more zones of maximum value. For each combination, it is necessary to design and schedule the mine, estimate costs and evaluate the financial result. A discreet (although perhaps daunting) set of combinations is sufficient to estimate the shape of the entire surface and to identify the optimum.

The objectives of optimisation must be aligned with the corporate objectives of the owner. Some stated corporate objectives, such as maximising annual ounces of gold production or maximising mine life, cannot be optimised. Clearly, increasingly large sub economic projects will satisfy the former objective while decreasingly large sub economic projects will satisfy the latter.

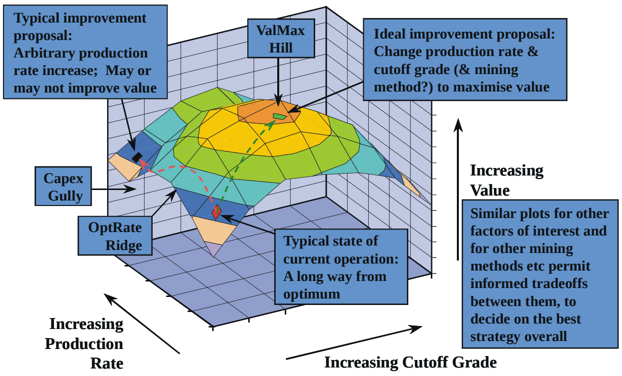
For short-life projects, increasing the mining rate increases the risk that most of the production will be delivered into a trough in the product price. Sensitivity analysis based on a range of price scenarios will identify the rate that yields an acceptable risk.

There is also the problem of capital allocation between competing projects. If there is no restriction on the available capital then corporate value is maximised by maximising the Net Present Value (NPV) of every available viable project and carrying all of them through to production. In the real world, where available capital is restricted, the corporation must select projects for investment using some ranking technique. Economic theory says that projects should be ranked using the Present Value Ratio (PVR), which is the ratio of NPV to initial capital investment. For simplicity, the capital investment is usually taken to be the total of negative cash flows prior to achieving positive cash flows.

If the perceived risks are similar, projects with higher PVRs are selected before those with lower PVRs. A project with a high NPV but a low PVR may require more capital than the corporation (or the investment community) is able or willing to risk, or if developed it may displace alternatives which would have provided a better aggregate return on investment.

From the above, the mining rate should be optimised to maximise the project NPV at the corporation's agreed discount rate, provided that this leaves it with a PVR that will make it an attractive investment. Arguably, the mining rate should be changed (and possibly reduced) to improve the PVR, even at the expense of NPV, if this will allow the project to proceed in competition with others. This observation emphasises the importance of right-sizing the operation rather than pushing throughput into the limiting range.

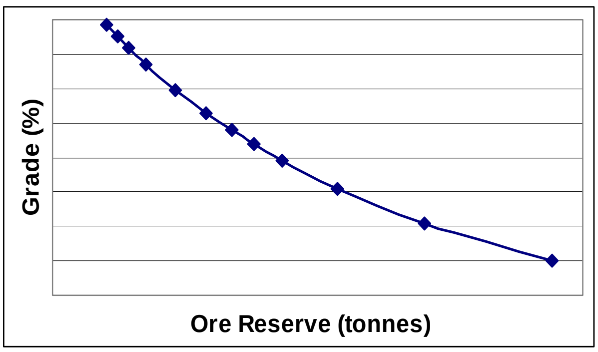
Figure 1 – *Finding and Climbing the Hill of Value (after Hall, 2002)*



Head Grade and Mining Rate

The grade-tonnage curve is an essential tool in mine planning, allowing the designer to choose a small, high-grade option or a large, low-grade option, or any option in between these limits (Fig 2). For each option there is a set of corresponding cut-off grades used in planning and operations. The size referred to here is the tonnage of ore that can ultimately be extracted from the resource.

Figure 2 – *the Grade Tonnage Curve*

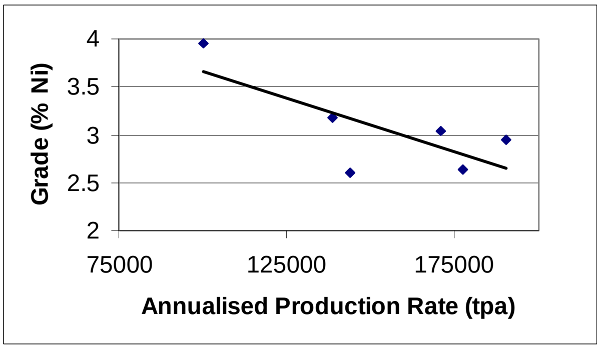


Different mining and processing rates can be applied to each size option, each having a different NPV. Taylor (1997) describes the NPV maximum value as a "failure point", noting that it is an upper economic limit for the possible range of production rates rather than an optimum rate. Taylor's paper deals with economic criteria and not with the practical implications of high mining rates. The practical issues usually become important well before the NPV maximum value is reached.

For each size of operation considered, it is a reality that for any intended head grade, at the associated intended cut-off grade, the actual head grade achieved will fall as the mining rate increases.

Once recognised, this dependency of grade on mining rate has a profound effect on mine planning. Fig. 3 shows the actual relationship between mining rate and head grade for an underground nickel mine, based on attempts over several years to mine at varying rates into a shared treatment facility. If life-of-mine plans are developed for a new mine using this relationship for grade, instead of a "base case" head grade assumption, the optimum mining rate turns out to be considerably less than what is physically possible in the orebody with the available equipment.

Figure 3 – *Head Grade and Mining rate*



In mining terms, the production rate can be expressed as the "effective vertical advance rate", or the relationship between actual mining rate and the "tonnes per vertical metre" available in the deposit. It turns out that underground mines designed for advance rates of 40 to 50 vertical metres per year are most often successful, whereas those attempting 60 vertical metres or more per year are most likely to fail.

The failures are due to over-capitalisation of plant and inadequate advanced development, coupled with an inability to maintain the intended grade at an excessive production rate. The grade problem is as much due to human nature as it is to technology; if people are set unrealistic goals then "waste plus ore equals more ore".

Production Variability and its Implications

The variability of production, head grade, recovery, throughput or output can be measured hourly, daily, monthly etc. The more variable this measure, the less use is being made of the installed capacity and hence of the capital invested and of the fixed component of operating cost. One of the key symptoms of a system that has been pushed beyond its stable capacity is an increase in production variability.

A mining project designed for a 1.0Mtpa rate with 5% variability needs an installed capacity of 1.05Mtpa. If a decision to increase the rate by 10% to 1.1Mtpa leads to an increase in variability to 15%, then the installed capacity must be increased to 1.27Mtpa, an increase of 20%. If the capacity is only increased by 10%, the increased variability will lead to a slight reduction in output.

The Temptation of Tonnage

In general industry practice, the tonnage capacity of the process plant sets the rate. If the plant has been constructed with surplus capacity or expanded to that point then great pressure is put on the mine to fill the mill, often with scant regard for the effect on the quality of the material delivered. The author recently reviewed a mine where the stope designs included large quantities of hard, abrasive waste rock. Upon suggesting that a smaller, more selective stope design would be advantageous he was told, “We looked at that but we couldn’t get the scheduled tonnes”. The mill throughput has since been reduced and the stopes redesigned, for a substantial improvement in mine NPV.

Both owners and designers of process plants seem to pride themselves on building plants that substantially exceed “nameplate capacity”. This excess capacity is soon converted into a demand for the mine, with the consequences already noted. The existence of this excess capacity implies that the design engineers are not particularly competent, or they are overly conservative. Having specified a particular design throughput, the owner has been obliged to pay for something greater, increasing the capital investment and reducing the return on assets.

There may be some second-guessing happening here. The plant designers don’t really believe the optimisation and mine scheduling work done by the mining engineers, and expect that they will actually deliver more ore than the design. Excess capacity may also be useful in responding to variations in resource grade or product price. If that is the reason for building in excess capacity then the specifications should say so, along with the circumstances under which the excess capacity will be utilised. The owner has paid for an option to expand production, and the value of that option can be estimated.

What is needed is an optimisation procedure that is reasonably rigorous and transparent and that identifies any factors of conservatism built into the mine and process plant.

A Simplified Optimisation Model

We will consider the objective to maximise the annual surplus of revenue over costs. This ignores the time value of money, but offers useful insights into the importance of the grade-rate relationship. We will assume that a preliminary mining rate somewhere near the physical limit for the resource has been chosen, a corresponding cut-off grade has already been selected, and therefore the total tonnes available over mine life can be estimated.

First consider revenue. The most important aspect of this model, and the key to right-sizing our mine, is to establish that, for any given cut-off grade, the head grade declines as we increase the mining rate. This is because we push progressively harder to win tonnes within the confines of our orebody. We can describe this effect by the equation

$$G = g - ht \quad \text{…………………(1)}$$

Where
G is the realised head grade (in % metal)
g is the grade we would achieve if we mined slowly and selectively
h is a constant, unique for each orebody
t is the mining rate in tonnes per annum

Note that this is a marginal analysis, and the value of h applies only in a relatively narrow range, near the limiting rate of practical mining (in other words, h is a function of t). While a form of this relationship is shown in Fig 3, the slope of the curve could be steeper at the limit.. We can calculate the annual revenue D from

$$D = v\,(g - ht)\,t \quad \text{………………..(2)}$$

Where
D is the annual revenue in dollars
v is the realised value of the product in dollars per tonne

We will consider both the annual operating cost (including sustaining capital) and the annualised capital cost, which we obtain by amortizing total project capital over the mine life. The annual operating cost P can be modelled as a typical “fixed and variable” cost of the form

$$P = a + b\,t \quad \text{………….(3)}$$

Where a and b are constants

The project capital cost C is also of the “fixed and variable” form when related to tonnes per annum of installed capacity, hence

$$C = c + d\,t \quad \text{………..(4)}$$

Where c and d are constants.

This is a simplification, as real capital costs increase as a step function in relation to capacity, but the series of steps may be approximated in this way.
If R is the total ore (in tonnes) available over the mine life, then the amortized capital cost per tonne C/R is given by

$$C / R = c / R + (d\,t) / R \quad \text{…………..(5)}$$

and the annualised capital cost A is

$$A = (c / R)\,t + (d\,t^2) / R \quad \text{………(6)}$$

We seek the mining rate t that maximises the annual surplus of revenue minus annual costs.

The annual surplus = D – P – A

$$= v\,(g - h\,t)\,t - (a + b\,t) - (c / R)\,t - (d\,t^2) / R \quad \text{….(7)}$$

This will be a maximum when

$$t = (v\,g - b - c / R) / 2\,(v\,h + d / R) \quad \text{………….(8)}$$

For example, if R = 10Mt, v = \$800/t, g = 12%, h = 2 x 10-8, a = \$6M, b = \$54/t, c = \$5M and d = \$7.50/t, then the optimum rate is t= 1.24 Mtpa. Changing h to zero (ie ignoring the grade-rate effect) allows t to run away to a very large and meaningless number.

This result is a simplification, but similar calculations can be put into spreadsheet form with any desired level of detail and used to optimise NPV. It is clear that understanding the grade-rate relationship (ie the likely value of h) is the key to optimising the mining and treatment rate.

Estimating the Grade-Rate Relationship

Because the significance of the grade-rate relationship at the limiting rate has not been previously considered in the literature, there is no published data to support an estimate of the value of h. However, the author is involved in current benchmark and other studies that are collecting raw data that can be analysed for various mining methods and deposit types so that in future it will be possible to better quantify the value of h, or a corresponding non-linear function.

It is possible to say that h cannot exceed a value of g / t,because that is the value obtained when the marginal tonne of material added to t is pure waste. Thus h is itself a function of t, and iteration is required to complete the optimisation.

As a first approach to estimating the grade-rate relationship, it is possible to estimate the head grade that would result from applying the selected cutoff grade at specific mining rates as follows:

- Assuming that the exploration drilling is representative, at a mining rate of zero (ie with infinite selectivity) the head grade would be close to the average grade of the above-cutoff drill intercepts.
- Using the most selective practical mining method the resulting head grade can be estimated from the dilution history of similar operations. Such selective methods might include the use of a 1.0m wide bucket on a 60t excavator in an open pit, or hand-held cut and fill underground mining. In either case intensive grade control would be assumed and a vertical advance rate of around 30m per year might be expected.
- Using a conventional approach to planning with a vertical advance rate of around 50m per year, the head grade at the chosen cutoff grade can be estimated.
- An upper limiting case occurs in an open pit when the rate is limited by the largest equipment that can operate within the pit.

In an underground mine, the limit might occur using sublevel open stoping with a highly regularised stope shape and unlimited advanced development. In either case a vertical advance rate approaching 100m per year would apply. The geometric dilution would be substantial and grade control would be ineffective.

Using the above point estimates, a curve can be fitted to give a grade-tonnage relationship, or to estimate the value of h, for any selected cutoff grade.

An example is provided by the history of one high-grade gold deposit. Highly selective mining in the 19th century gave a head grade of 90 g/t Au, whereas modern hand-held cut and fill methods gave a head grade of 30 g/t Au. This fell to 15-20 g/t Au using mechanised cut and fill and would have fallen further, to an estimated 10 g/t Au, if sublevel benching had been attempted. The cut-off grade was about the same for each period; only the rate of mining changed, with an associated impact on dilution.

Conclusion

The optimum plant capacity should be based on appropriate studies, which will identify the maximum return on investment over a range of sensitivity scenarios. While unit capital and operating costs are reduced as the mining and processing rate is increased, other negative influences become important. The influence of the mining rate on head grade is a key consideration.

Once the design capacity is set, including any intended over-capacity, the plant should be constructed to conform to the design. Any subsequent decision to exploit excess capacity should take into account the ability of the mine to deliver feed of the required quality.

To reduce the incidence of under-performance of mines relative to their feasibility studies, the plant throughput should not be increased beyond a point where the diminishing head grade becomes more significant than any reduction in direct costs and amortization.

References

Burmeister B.B., From Resource to Reality: A Critical Review of the Achievements of New Australian Gold Mining Projects During the Period January 1983 to September 1987, Macquarie University, 1988.

Hall B.E. 2002, Optimising the Mine Plan to Achieve Corporate Goals, *AusIMM Underground Operators Conference* Townsville Qld, 29-31 July (in preparation).

Harquail D., 1991. Investing in Junior Mining Companies. *Proceedings of the 6th Mineral Economics Symposium of CIM.* CIM Montreal Canada.

Hoover H.C 1909 Principles of Mining, McGraw-Hill, New York, pp. 153-160

McCarthy P.L., 1993, “Economics of Narrow Vein Mining”, seminar *Narrow Vein Mining*, AusIMM Bendigo, pp 89-97

McSpadden G.M. and Schaap W. “Technical Note – A Test and Comment on Taylor’s Rule of Mine Life”, *Proc. AusIMM No 289*, Aug/Sep 1984

Smith L.D., 1997 A Critical Examination of the Methods and Factors Affecting the Selection of an Optimum Production Rate. *CIM Bulletin* Vol 90 No 1007 February.

Tatman C.R. 2001 “Production Rate Selection for Steeply Dipping Tabular Deposits” *Mining Engineering* October 2001 pp. 62-64

Taylor H.K., 1978, Mine Valuation and Feasibility Studies, in *Mineral Industry Costs* (Ed. J.R. Hoskins and W.R. Green), pp. 1-17 (Northwest Mining Association, Spokane)

Taylor H.K. , 1986 Rates of Working Mines – A Simple Rule of Thumb., Technical Note. Transactions IMM Vol 95 Oct. pp A203-204

Ward D.J. and McCarthy P.L. 1999 Startup Performance of New Base Metal Projects in *Adding Value to the Carpentaria Mineral Province,* Mt Isa, Qld, Australian Journal of Mining, April 1999.