A review of optimal planning of level and raise spacing in inclined narrow reefs

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Synopsis

The subject of optimal planning of level and raise spacing for inclined narrow reef deposits has received intermittent attention over the years because the subject matter is inherently complex. Previous work has approached the problem as simply that of simultaneously minimizing the total excavation and haulage cost associated with the development workings. However, when level and raise spacing are altered, other factors such as productivity are negatively affected, thus requiring a delicate trade-off of contradicting planning or optimization criteria. The paper concludes that the problem is actually of the multi-criteria decision analysis (MCDA) type, contrary to traditional thinking that the planning problem is achieved solely by minimizing waste development.

Keywords

Strategic mine planning, level spacing, raise spacing, inclined narrow reefs, optimization, half-level optimization model, multi-criteria decision analysis (MCDA).

Introduction

South Africa's Bushveld Complex and Witwatersrand Basin are the world's two largest precious metal ore deposits (Ryder and Jager, 2002). These deposits are inclined hard rock narrow tabular orebodies that extend over vast lateral extents and exceptional mining depths (Ryder and Jager, 2002). The Witwatersrand Basin is renowned for its gold production whereas the Bushveld Complex is known for hosting chromitite ore and the largest resources and reserves of platinum group metals (PGMs).

The extraction of these orebodies or reefs has been predominantly by conventional mining methods such as scattered breast mining, up-dip or down-dip mining, longwall mining, and sequential grid mining (York, 1999; Ryder and Jager, 2002; Egerton, 2004). The primary demarcation of mining areas or stopes in conventional mining is by means of a grid pattern defined by level and raise spacing. Main levels in conventional mining on inclined tabular reefs have been cut at vertical intervals in the 30 m–70 m range whereas raises have been spaced in the range 50 m–400 m, the lower raise spacing being typical for up-dip and down-dip mining methods (Jager and Ryder, 1999; Vieira, Diering and Durrheim, 2001; Fleming, 2002; Woodhall, 2002; Musingwini, 2009). Although level and raise spacing are dictated mainly by the practical limits of scraper winch reach, these wide ranges derive from the fact that level and raise spacing in conventional mining on the inclined narrow tabular reef mines varies from company to company and occasionally from operation to operation within the same company (Musingwini, 2009). A feasible explanation for this observation is that there has not been any scientifically proven optimal level and raise spacing for conventional mining, and mines select spacing based on company policy derived from empirical knowledge peculiar to the company. Additionally, it is not possible to have a 'one-size-fits-all' level and raise spacing because of the differing degree of geological complexity of each mine operation. It is therefore important that the optimal planning of level and raise spacing is more fully understood. This paper therefore explores literature spanning over decades in order to provide insight into the complexities of level and raise spacing planning in inclined reef deposits. Firstly it looks at the objectives in planning level and raise spacing, then explores the impact of varying level and raise spacing, and lastly it analyses and critiques some of the identified literature from as far back as the 1930s.

Objectives in planning level and raise spacing

Once level and raise spacing have been selected, medium to long-term mine plans are based on this selection; thus optimization of level and raise spacing becomes part of the strategic mine planning process. It is important therefore, that the selected level and raise spacing must satisfy long-term planning

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objectives which are financial, technical, and safety related. The financial objectives include the need to minimize operating costs (by spacing out development to minimize development cost per centare mined); minimize capital costs; maximize net present value (NPV), and minimize payback period (by having a short build-up period to full production).

The technical objectives include the need to maximize shaft head grade by minimizing dilution and selectively mining the orebody (by reducing level and raise spacing); maximize extraction ratio; maximize productivity (by reducing level and raise spacing); minimize build-up period to full production; minimize tailing-off period; and maximize replacement ratio or replacement factor (by spacing out levels and raises). For example, development is more expensive than stoping per m^3 of rock mined because blasting in stoping most often has a free breaking face, unlike in development ends where the free breaking face has to be created by initially blasting out a cut or utilizing a large diameter relief hole. Therefore it is desirable to minimize development which is most often done in waste rock from which no revenue is derived. For conventional mining in inclined narrow tabular reefs of the Witwatersrand Basin and Bushveld Complex of South Africa, this objective is measured using a metric called the replacement factor (RF) or replacement ratio (RR). The RF is a measure of the m^2 of stoping made available by a 1 m of development, implying that the RF can be maximized by minimizing development. A layout with a higher RF is more desirable.

The safety factors include the need to keep the line of sight as short as possible in order to reduce accidents (by reducing level and raise spacing), concentrate production to areas close to each other to improve supervision and minimize unsupported spans to achieve better geotechnical stability (by reducing level and raise spacing).

The above financial, technical, and safety related objectives indicate a contradiction between increasing or reducing spacing of development. In order to understand the interaction among these mine planning objectives when different level and raise spacing are assumed for a conventional mining operation, it is necessary to consider the impacts that arise from increasing level and raise spacing.

Effects of increasing level and raise spacing

When one considers increasing level and raise spacing, thousands of permutations of possible layouts can be designed, thus making the process an extremely complex one due to the large number of options that have to be considered. A single point estimate for level and raise spacing is therefore insufficient. Rather an optimal range is more appropriate in this case. When level and raise spacing are increased in a conventional mining layout, some of the associated desirable and undesirable impacts that occur concomitantly are outlined below:

- The stope size increases, resulting in a decrease in the number of stopes per unit area of the orebody. When the number of stopes per unit area decreases, this reduces the number of points of attack for production, making it more difficult to relocate production teams if, say, falls of ground (FOGs) occur in a stope or a stope area becomes unsafe. This is an undesirable outcome.
- The operating flexibility decreases as a result of reduced points of attack caused by fewer stopes per unit area. This is an undesirable outcome.
- The time to establish a stope is increased because the stope size has increased. This is an undesirable outcome because it slows the build-up period to full production for a stope.
- The RF increases since development is now more spaced out per unit area. This has a financially desirable outcome because the development cost per centare mined decreases.
- The mining of raises and winzes involves taking out a waste portion below the reef horizon to create adequate storage capacity for ore from production faces, therefore the dilution from raise and winze development ore decreases slightly because raises are more spaced out. This is a desirable outcome because it leads to slightly higher shaft head grades, thus improving revenues.
- The strike scraping distance is increased, resulting in a decrease in scraper productivity, as noted by Brassell (1964) and Lawrence (1984). This is an undesirable outcome because as Lawrence (1984) noted, the decrease in productivity offsets the potential saving in development costs.
- There is a reduction in the number of raises which are used for grade sampling of stopes to increase confidence in ore reserves estimation, thus underutilizing the exploratory value of development. This is undesirable because compromising the quality of ore reserves estimation can have serious implications at company board level.
- The line of sight for communication purposes is extended. This is undesirable because it compromises safety, particularly with 'blind' scraping as practised in conventional mining where communication is by 'pull wires' that send bell signals to the scraper winch operator.
- The production stopes are more spread out, making concentrated mining difficult to achieve and supervision becomes increasingly difficult. This is undesirable because, as Brassell (1964:461) noted, 'productivity can be improved by increased mechanisation and improved techniques but can best be gained by the concentration of mining activities on the minimum of working face'. Bullock (2001:17) also highlighted the need for concentrated production because, 'any entrepreneur planning a mining operation and who is not familiar with the problems of maintaining high levels of concentrated production at low operating costs per tonne over a prolonged period is likely to experience unexpected disappointments in some years when returns are low (or there are none).'
- The larger the stope size, the more cumbersome the logistics because crews have to travel longer distances within a stope. This is undesirable because it increases the risk of losing a blast, resulting in lower average monthly face advance rates per crew.
- The life of each stope or raiseline increases due to the combination of a decreased rate of face advance and increased stope size (Lawrence, 1984). This is

desirable because production crews can stay longer per raiseline, thus simplifying the logistics of moving crews to new raiselines.

From the discussion above it is evident that the main criteria that must be considered in optimizing level and raise spacing include development cost per centare mined, project net present value (NPV) that captures the interaction of cost savings against loss in productivity as spacing is increased, build-up or ramp-up, life of mine (LOM) and project payback period to capture the impact of timing associated with the changes, replacement factor or replacement ratio, dilution, shaft head grade, productivity, and production rate. These criteria are consistent with the criteria used by Egerton (2004) to compare different mining methods to mine the UG2 reef, except for extraction ratio, which was almost constant in this research study because the same mining method was used for all layouts. The above outcomes or decision criteria exhibit intricate interdependencies and in some cases outright contradictions. For example, by increasing level and raise spacing, the RF increases at the expense of flexibility, which becomes compromised because fewer blocks are now available for mining. Therefore, trade-offs have to be made among decision criteria in order to arrive at an optimal solution that satisfies all the criteria. The ideal solution should result in the minimization of undesirable impacts and maximization of the desirable ones. Optimizing level and raise spacing is therefore a complex multi-criteria decision-analysis (MCDA) exercise in which delicate trade-offs must be made between competing decision criteria depending on the importance attached to each criteria by the mine planners making the decision.

Review of previous work on level and raise spacing planning

Due to the complex nature of the planning of level and raise spacing for inclined narrow reef or vein deposits, the subject has received intermittent attention over the years, with generally inconclusive solutions being derived. Examples of such work include Eaton (1934), Lewis (1941), Brassell (1964), Zambó (1968), Lawrence (1984), and Anglo Platinum MTS (2005). Carter, Lee, and Baarsma (2004) similarly noted this observation and explained it by arguing that the design and planning engineer for underground metalliferrous mines has to rely on experience and a limited number of design heuristics in order to optimize underground mine plans because, unlike open-pit mine design optimization, the underground mine design optimzation problem has numerous permutations of possible mining layouts. The key findings of the literature identified above are discussed below.

Optimization of level spacing by Eaton (1934)

Eaton is one of the early researchers to focus on the subject of optimization of level spacing. Eaton (1934:29) argued that in order to 'keep down the cost per ton for development and level equipment, the interval between levels is made as large as is compatible with convenience, safety, and economy in mining'. It follows therefore when the cost of excavating and maintaining a level is high, then the level spacing should be made as large as possible. The current focus by mine planners on the Witwatersrand Basin and Bushveld Complex in advocating longer backlengths in the design of inclined narrow tabular reef mines concurs with this argument.

Eaton further argued that as the level spacing is increased, a point is reached where the saving per tonne of ore mined is more than offset by the cost of mining at longer distances. This argument can be deduced from Brassell (1964), who observed that mining at longer distances reduces productivity asymptotically, thus increasing the cost of mining at longer distances. From this perspective, Eaton was implicitly acknowledging that other factors other than the cost per tonne, affect the decision to select an optimal level spacing. Although Eaton did not quantitatively show how he arrived at optimal level spacing, he estimated the economic limit on level spacing to be 100 ft-200 ft (≈30 m–60 m) based on the mining practices on mines at that time. This range of values is consistent with current practices that were discussed above.

Eaton gave another hypothetical example of a mine where the orebodies were small and scattered, thus placing a demand for a large amount of haulage excavation to be done for a small tonnage throughput per level. In this example, the temptation is therefore to increase the level interval. This temptation, however, is at the expense of the exploratory value of development. For example, with increased level spacing it becomes more difficult to find the downward extension of the orebodies intersected on upper levels since veins can rapidly thin out and terminate. Therefore, Eaton's work highlights the importance of the role that geology plays in optimizing level and raise spacing, because more complex geology requires levels and raises to be spaced closer together, resulting in higher development cost per centare mined.

Although Eaton gives a compelling qualitative argument, the work does not provide a quantitative treatment on how the economic limit of 100 ft-200 ft (≈30 m–60 m) for level spacing was derived. The argument is also silent about the effect of the timing of the development costs, yet the timing of development changes once level spacing has been changed. Lastly, the approach considers the economic factor, represented by the cost per tonne ore mined, as the overriding factor, yet the problem is actually a multi-criteria decision analysis optimization problem.

Optimization of level spacing by Lewis (1941)

Lewis approached the optimal spacing of levels as an exercise to minimize the sum of excavation and haulage costs. When these two sets of costs are charged to a tonne of ore mined, the optimal level spacing is the one giving 'the least cost per ton of ore mined for the method of mining chosen' (Lewis 1941:416). Lewis adjusted these costs to account for interest that could have been earned on capital spent on developing stopes that are ready for mining but not being mined, thus accounting for the timing of development costs.

The cost analysis was done for a 4 ft (≈1.2 m) continuous thick vein of scheelite with an average dip of about 60°, serviced by an inclined shaft dipping at 75° in the same direction as the orebody. The overall cost per ton of ore mined decreased asymptotically with increasing level spacing following some nonlinear power function as depicted by Figure 1. The study underscored the economic motivation for choosing the largest possible level spacing. This finding concurs with Eaton's (1934) suggestion for longer level spacing and remains true today in mine planning on the narrow reef tabular platinum and gold mines of the Bushveld Complex and Witwatersrand Basin, respectively.

There are some shortcomings in the work by Lewis. Firstly, the work does not consider the impact of geological factors such as spatial grade variations and loss of mining areas due to geological discontinuities. These are important as they affect the net contribution in value from a development working. Secondly, the work is inconclusive on what would be an optimal level spacing for the scheelite vein deposit. Rather, Lewis (1941:417) concluded that:

'In the final analysis, the above comparative costs must be weighed against other factors, such as the relative advantages of various level intervals for prospecting, the time required to open the level before stoping can be started, the life of the level, and the structural features of the orebody and its environment, since these determine the method of mining and thus indirectly the distance between levels'.

In this comment Lewis was in fact acknowledging that optimization of development spacing should take geology into account and that the problem is in fact a multi-dimensional problem, yet he had solved it as a mono-criterion decision problem of minimizing the cost per ton of ore mined.

Scraper winch productivity and raise spacing by Brassell (1964)

Brassell carried out extensive stope productivity improvement field trials and related time studies at the then Vaal Reefs Exploration and Mining Company over a period of six years. The mine was a gold mine using conventional breast mining. Two of the several trials conducted are relevant to this paper. One of the trials was on panel face length variation and its corresponding effect on cleaning time using a 30 hp (≈25kW) scraper winch. In a 7-hour cleaning shift the effective cleaning time was about 3½ hours to 4 hours. The trial indicated that at typical slow-speed scraping, the optimum face length that could be cleaned in a single shift ranged between 100 ft (≈30 m) to 120 ft (≈36 m). This finding concurs with current conventional breast mining operations on narrow reefs in that panel lengths are kept in the range 25 m–40 m. The second relevant trial was on variation of advanced strike gulley (ASG) length as a panel face advanced away from the raise position. A 50 hp (≈37kW) scraper winch was used for strike gulley scraping. The results from this trial were tabulated by Brassell but are presented here in a graphical form (Figure 2). Figure 2 shows that scraper productivity decreases asymptotically with increasing ASG length or implicitly with increasing raise spacing, following some nonlinear power function. Brassell also noted that the breast stoping layout that evolved as a result of these trials, laid out raises 500 ft–600 ft (≈150 m–180 m) apart on strike, a raise spacing range which is currently used on some of the Witwatersrand gold mines and Bushveld Complex platinum mines.

However, the results from the Brassell study need to be understood in the context of present day conventional breast mining by noting that:

- Brassell's paper deals with a single panel in a raise connection. However, in current practice there could be up to five stoping crews in a single raise connection blasting up to five panels a day, resulting in the productivity being dependent also on the capacity of the centre gulley scraper winch to clean all the ore from the ASGs.
- Productivity will also be affected by the distance of the face scraper winches from the panel faces. Typically face scraper winches are 'leap-frogged' regularly so that they are not more than 30 m away from the panel face.
- Productivity will also depend on the scraper winch sizes used.
- The stope boxholes are cleaned by loco-and-hopper tramming systems on each level, which is a batch transportation system and therefore can reduce the cleaning capacity of the centre gulley winch.
- Productivity will also depend on how the full mining cycle for the raiseline is arranged. Poor shift arrangement and supervision negatively affect productivity even if scraping is being done at short scraping distances.

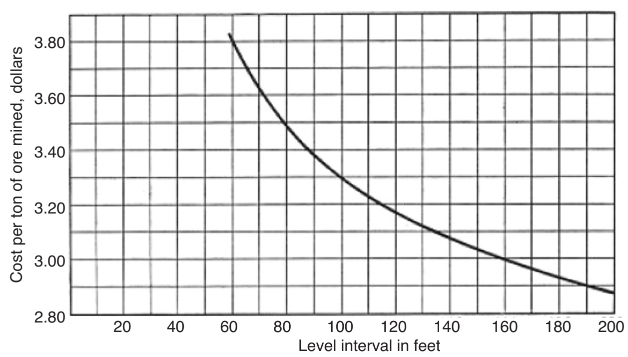

Figure 1—Variation of cost per tonne ore mined with level interval (Lewis, 1941)

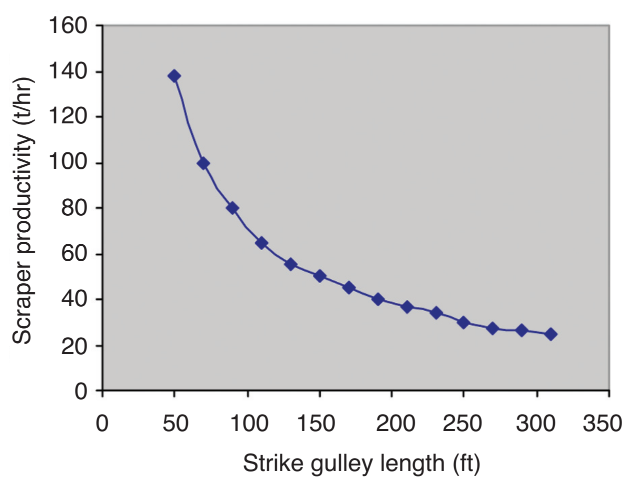

Figure 2—Variation of scraper winch productivity with increasing strike gulley length (adapted from Brassell, 1964)

- Productivity will also depend on the frequency of lost blasts, which dictate the balance between how much ore will be available per cleaning shift against how much the scraper can move in a shift. For example, Jiyana (2009) reported that the average lost blast frequency at Turffontein shaft currently averages at about 29%.
- The productivity will also depend on the geotechnical stability of the panels in the raise connection. Geotechnically poor ground conditions negatively affect productivity because significant shift time can be used for stope support, thereby compromising productivity.

Brassell's work has some implications for current optimization of level and raise spacing. Firstly, scraper productivity decreases with increasing scraping distance as raise spacing is increased, and so does panel face advance rate. Secondly, increased level spacing directly leads to longer backlengths, resulting in more panels per raise connection and longer centre gulley scraping distances, thus decreasing the centre gulley scraping productivity and panel face advance rate.

Optimization of level and raise spacing by Zambó (1968)

Zambó analysed the problem of optimizing level interval (which equivalent to level spacing) and panel strike length (which is equivalent to raise spacing), for tabular, gently-dipping vein deposits. Zambó used graphical and mathematical procedures to illustrate optimal spacing obtained by simultaneously minimizing excavation and haulage costs. Zambó used the Hungarian monetary unit, the forint (F) for all cost calculations. Zambó (1968:126) concurred with Eaton (1934) and Lewis (1941) in that:

'The greater the level interval, the less the specific investment expenditure, the smaller the number of levels to be kept open simultaneously, the more fully the hoist of the shaft can be exploited, and the less the mineral reserve to be tied down eventually in the pillars of the haulageways of the levels. Conversely, the less the level interval, the less the specific cost of displacing personnel, timber and supplies at large and between two levels in particular, the simpler the driving of raises and winzes... Of the possible level intervals, that one will be considered an optimum here which makes the specific production cost of the mine a minimum.'

By specific production cost, Zambó was referring to the cost per ton of ore mined. In deriving the optimum level and raise spacing, Zambó used data obtained from mines operating under similar geological and mining conditions. By applying the mathematical procedures developed in the study to a hypothetical mine and using typical industry data at that time, Zambó obtained the results shown by Figures 3 and 4.

Figure 3 shows the optimum level interval under different amortization conditions; h (=45 m) is the optimal level interval when the specific cost is not amortized; h_r (=54 m) is the optimal level interval when the specific cost is amortized at an interest rate of 5%; h' (=71 m) is the optimal level interval with uniform amortization without interest and h'_r (=81 m) is the optimal level interval with uniform amortization at 5% interest rate. By considering h and h_r it can be seen that a 5% change in interest rate results in a 20% change in level interval, which is quite significant. Similarly, a 15% change in optimal level interval is obtained when h' and h'_r are considered. Thus, the choice of the interest rate, or project discount rate, is important and should be done as carefully and realistically as possible to avoid erring on the choice of optimal level interval. Hajdasiński (1995) also

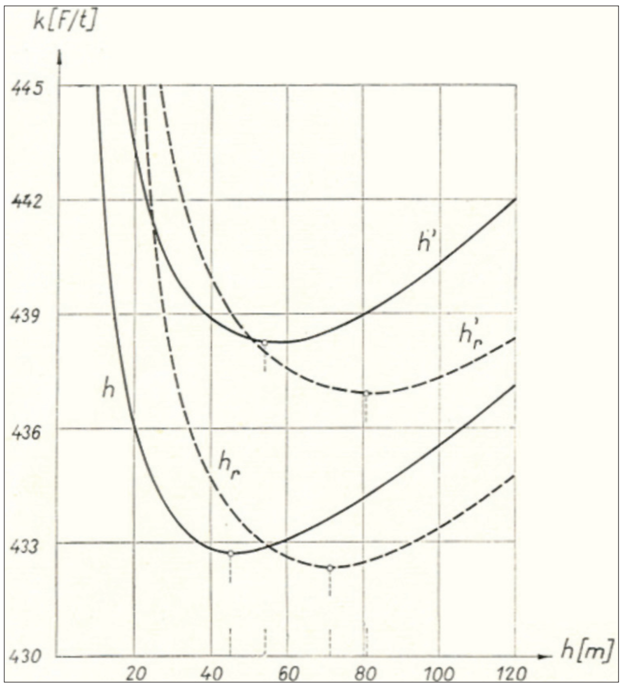

Figure 3—Variation of the specific cost function, *K*, with level interval, *h* (Zambó, 1968)

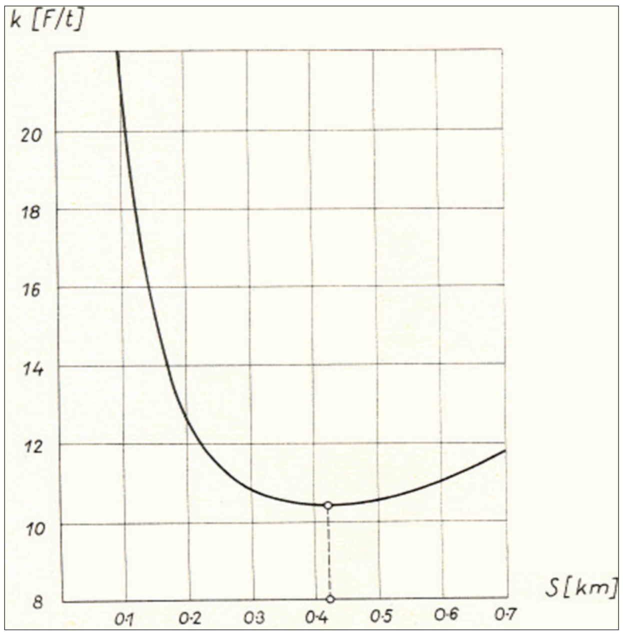

Figure 4—Variation of specific cost function, *K*, with cross-cut panel length, *S* (Zambó, 1968)

emphasized the importance of carefully and realistically selecting the interest rate when optimizing the location of mining facilities. Figure 4 indicates an optimum raise spacing of 0.46 km. This distance is in close agreement with the practical limit for level (or backlength) and raise spacing that was noted earlier. Again, the cost per ton varies with increasing raise spacing following some nonlinear power function (Figure 4). These findings concur with Eaton's (1934) argument that as the level interval is increased, a point is reached where the saving per ton of ore mined is more than offset by the cost of mining at longer distance and the overall cost per ton starts rising again, because other factors, such as the associated decline in productivity, negate the cost benefits derived from wider spacing of levels.

Zambó (1968:134) noted that the derived optimal level interval best served as a guide only, 'indicating that value of *h* in the vicinity of which a more detailed examination of the cost function may be worthwhile'. Zambó further noted that the specific cost function for both level interval and raise spacing 'varies rather slowly in the vicinity of the optimum point, while its rate of change increases quite rapidly with growing distance from the optimum', thus proving that 'it is not worthwhile to aim at an exaggerated accuracy in optimum computations' (Zambó, 1968:144). If this finding is interpreted within the context of this study, it implies that deriving a precise optimal level and raise spacing might be an exaggerated degree of accuracy, but rather deriving a range of optimal level and raise spacing may be more appropriate.

There are some shortcomings in Zambó's work. Firstly, Zambó did not jointly optimize level interval and panel strike length, yet the spacing selection of one will directly affect the spacing selection of the other; thus the solutions were sub-optimal solutions. Secondly, the approach structured the problem as a mono-criterion optimization problem based on cost per ton alone, yet the optimization problem is in fact a multi-criteria optimization problem.

Optimization of raise spacing by Lawrence (1984)

Lawrence developed a computerized method to calculate an economic optimum spacing of raise connections (i.e. raise spacing) in conventional 'scattered' (i.e. breast) mining layouts for shallow-dipping, narrow tabular gold reefs. In the computation, Lawrence considered only the cost saving associated with changing raise spacing as the key determinant in comparing different raise spacing. The savings were then converted to present value (PV) terms using opportunity interest rates between 3% and 7% applicable at that time, in order to draw up a meaningful comparison since changes in raise spacing affect timing of the development costs. The PV of cost savings were further annualized to give an equivalent annual cost saving by dividing by the annual tonn or centares mined and reported in R/t or R/ca, respectively. The calculation procedure was programmed in BASIC and the compiled model run on an HP9845 desktop computer.

Lawrence applied the model to a scattered mining layout for a hypothetical gold mine, using typical industry data prevailing at that time. All cost calculations were based on cost figures in 1982 monetary terms. The results of the analysis of PV cost savings are shown in Figure 5.

The dotted curve in Figure 5 is for an interest rate of 7% and the curve with a solid line is for interest rate of 3%. Figure 5 indicates that the relationship between the annualized PV of cost savings and raise spacing follows a quadratic function, which is some from of a power function. It is also discernible from Figure 5 that 'the economic optimum raise spacing would be either approximately 240 m or 250 m. For the purpose of this example, the economic optimum spacing is taken as 245 m.' (Lawrence, 1984:13). Strangely, this optimum does not seem to have been officially adopted, even to present day, by the Witwatersrand gold mines using conventional mining layouts, as indicated by the wide range

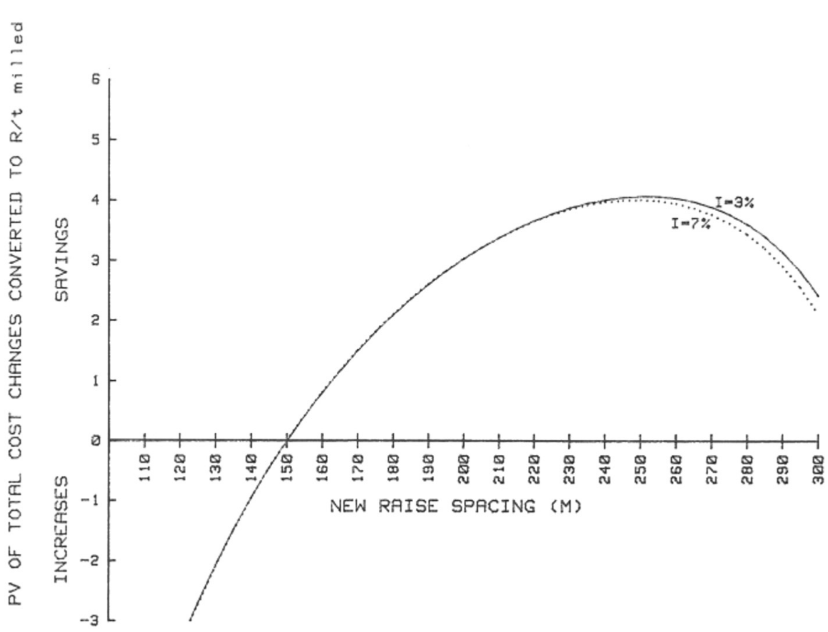

Figure 5—Variation of PV of cost savings with increasing raise spacing (Lawrence, 1984)

of level and raise spacing in use. The fact that the optimal raise spacing of 245 m has not been widely adopted by industry raises the question of its validity as an optimal spacing. Therefore the following opinions and criticisms on Lawrence's work are worth noting when interpreting the derived optimal raise spacing:

➤ The main constraint limiting raise spacing that was noted by Lawrence and which still remains true today was that, 'the most influential factor involved in the determination of the economic optimum raise spacing is the system used for strike tramming' (1984:17). The same sentiment was expressed by Woodhall (2002). The strike tramming system used when the study was undertaken was scraper cleaning, which is still used to the present day in conventional breast mining.

➤ Lawrence's work was based on varying raise spacing for a fixed level spacing that was equivalent to a backlength of 180 m, yet the mines practising conventional scattered breast mining use different level spacing as noted earlier on. Therefore a 'one-size-fits-all' solution as derived by Lawrence is inadequate under such circumstances, unless a mine is planned on the same fixed backlength of 180 m used by Lawrence. Additionally, when level spacing is fixed, individual backlengths between levels along raiselines are variable because the surface configuration of the orebody is not regular due to variable geology throughout the orebody. The fact of variable geology on a local scale within the orebody was noted by Schoor and Vogt (2004). Therefore it is incorrect to assume a fixed backlength as was done by Lawrence.

➤ Lawrence's model did not incorporate geological variations because it assumed a constant geology. Lawrence noted this weakness in the model by saying that, 'in a real situation, the ground would be divided into irregular blocks, each with a different strike width' (1984:16), therefore requiring that 'each block would be treated separately but in the same way as described above to give local optimum (economic and practical) spacings for raise connections'. Therefore, it is more appropriate to geological variability that closely follows real geology of the orebody when optimizing level and raise spacing in conventional mining layouts.

➤ Lawrence did not jointly optimize level and raise spacing, yet the spacing selection of one will directly affect the spacing selection of the other; thus the solution obtained can be considered to be sub-optimal.

➤ The model assumed that raise spacing is a mono-criterion optimization problem based on economics alone because, 'the economic optimum spacing is that at which the overall savings are at a maximum' (1984:11). This is inadequate because as was discussed earlier on, optimization of level and raise spacing is a multi-criteria optimization problem.

Anglo Platinum MTS (2005) half-level optimization model

When Anglo Platinum was formed through the unbundling of JCI, it acquired other PGM assets that were not part of the JCI group and in the process ended up with mines that had different standard operating procedures and mine planning guidelines (Rogers, 2005). In order to standardize the operations, the company has over the years developed the Group Guideline: Mine Technical Services manual for reference by individual mines. Part of the guideline addresses optimizing backlength (i.e. optimizing level spacing) for conventional breast mining and this is done through the Half-Level Optimization Model. Typical output from the model is illustrated by Figure 6. and provides justification for why longer backlengths are preferred in designing conventional breast mining. In fact, one of the sections in the Group Guideline: Mine Technical Services manual is, 'Why longer

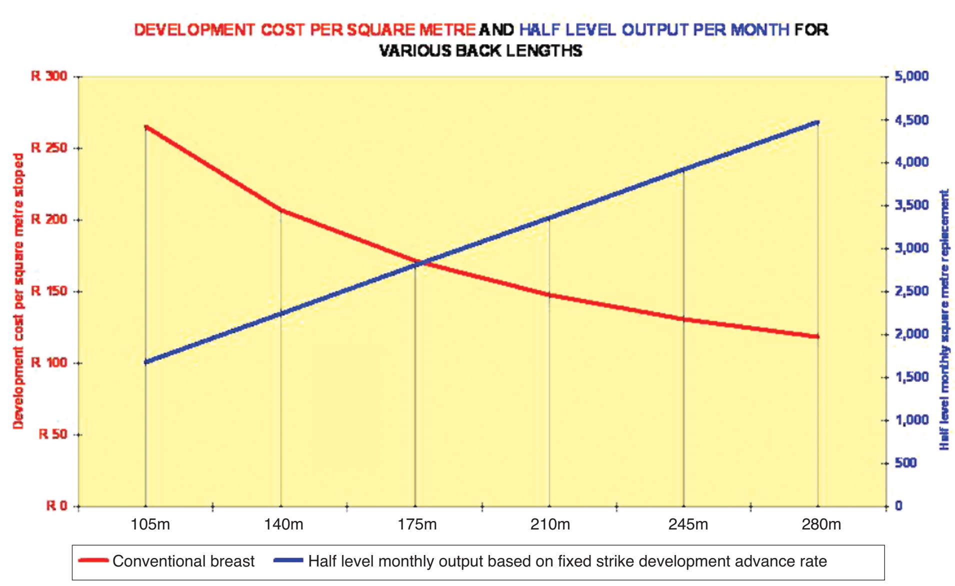

Figure 6—Typical half-level model output (Anglo Platinum MTS, 2005)

backs and development focus'. As Figure 6 indicates, the development cost per centare mined decreases asymptotically as backlength is increased, following some power function, further confirming the work of Lewis (1941) and Zambó (1968).

Other related studies on planning the location and timing of development

Other studies not specific to level and raise spacing optimization in inclined narrow reefs, but addressing the general planning of the location of underground mine development, include Young (1923), Lizotte and Elbrond (1985), Hjadasiński (1995), Macfarlane (1997), Kirk (1997), Diering (1997), Nilsson (1998), Bullock (2001), Brazil *et al.* (2003), Brazil *et al.* (2004), Brazil *et al.* (2005), and Ballington *et al.* (2005). The key issues coming from these studies that are relevant to this paper are:

- Economic and technical considerations sometimes tend to be contradictory when planning development for underground mining and a compromise must be made between these two to achieve optimal extraction. Financial wisdom demands that development, which is an expense and locks up capital, be deferred as far into the future as possible yet on the contrary technical knowledge suggests that developing well ahead of stoping is practically desirable because it generates additional geological information required to improve planning of the remainder of the unmined orebody thus, creating better operational flexibility. The concept of operating flexibility is discussed in the paper Musingwini, Minnitt, and Woodhall (2007).
- Mine operators and planners tend to focus more on costs than any other value drivers when looking at maximizing mineral asset value usually leading to sub-optimal solutions that are derived from minimizing the cost per unit of production, yet holistic optimization that considers multiple criteria would be more meaningful.
- The timing of development costs is critical to the economic success of a mining project because as Bullock (2001:18) contends, 'timing of a cost is often more important than the amount of the cost'. This is why in this paper the PV of development costs per centare and not development costs per centare was used as one of the optimization criteria.
- For an open pit deposit, the direction of mining is essentially down and an outward to the pit limits (Hatch Associates, 2004). The mining direction is the basis upon which the 'nested pit' approach in Whittle-4D was developed. However, for the underground mining situation, there are numerous permutations of the direction of mining, such as advance or retreat mining, depending on the chosen mining method (Carter, Lee, and Baarsma, 2004). The lack of extensive optimization analysis in underground mining layouts and schedules is largely attributable to the increased complexity of the problem due to the numerous permutations when compared to open pit layouts and schedules.
- Mining of a mineral block in an open pit is constrained by following relatively simple logical sequences rules for the removal of overburden and the mineral blocks above it and adjacent lateral blocks to form stable slopes. For an underground mineral block, there is no single logical sequence for tunnelling through the overburden and adjacent blocks can at times be left unmined only to be recovered later in a retreat sequence, thus sometimes making the problem an unconstrained optimization problem.

The foregoing observations explain why models, algorithms, and software are a common routine for the optimization of open pit mine designs, and have been well developed and been in use for many years. Examples include the Lerchs-Grossman algorithm and Whittle-4D commercial software. However, the design engineer for underground metalliferrous mines has had to rely on experience and a limited analysis of design alternatives due to the increased complexity of the underground optimization problem (Alford, 1995; Brazil *et al.*, 2004; Carter, Lee, and Baarsma, 2004; Ballington *et al.*, 2005; Smith and O'Rourke, 2005). A consequence of this difficulty has been that literature on the optimization of underground mine designs is relatively scanty and fragmented when compared to the abundant literature available on open pit optimization (Alford, 1995; Brazil *et al.*, 2004; Carter, Lee, and Baarsma, 2004). The literature review has demonstrated that optimizing level and raise spacing in a conventional breast mining method for the shallow-dipping narrow tabular reefs of the Bushveld Complex is a multi-criteria decision analysis (MCDA) problem. Additionally it has also shown that assuming constant geology throughout the orebody compromises the optimality of the derived solution.

Concluding remarks

The planning of level and raise spacing in inclined, narrow tabular reef deposits has received intermittent attention over the years, with generally inconclusive solutions being obtained, mainly due to the complexity of the problem. This paper has demonstrated that the underlying complexity of the planning of level and raise spacing is rooted in it being a multi-criteria decision analysis (MCDA) problem, which should be solved using MCDA techniques. Since each deposit is geologically unique, it is appropriate to derive deposit-specific optimal level and raise spacing.

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