Effect of stope size on sustainable steady-state production rates in a sub-level open stoping system

Julian Poniewierski

An orebody utilising sub-level open stoping can have an intrinsic constraining limit in the production rate achievable that relates to the number of stopes that can be in some phase of the stope cycle at any one time. This constraining limit, the number of stopes, can be changed by decreasing the cut-off grade or by decreasing the stope size. Examples of the effects of using both methods are presented, but in particular the effects of changing the stope size. While smaller stopes will result in a lower average production rate per stope and a higher cost per tonne operating cost, the production rate for the mine when considered as a system can increase. Potentially, this can result in a higher NPV for the operation. The nature of the production rate increase has been investigated and reported for an idealised orebody. For example, for the orebody investigated, the 8-year sustainable steady-state production rate can be increased by 20% by reducing the stope size from 40 m x 40 m (in plan) to 34 m x 34 m (including consideration of pertinent size scaling effects). The orebody example investigated illustrates the need for the production limits of the physical mining system to be understood before making production level assumptions for mine infrastructure.

Julian Poniewierski is a senior mining consultant with Runge Limited, Level 17, Central Plaza One, 345 Queen Street, Brisbane, Australia (Tel: +61 7 3100 7244; Fax: +61 7 3100 7297; web: www.runge.com; E-mail: jponiewierski@runge.com.au).

 Manuscript received 18 February 2005; accepted in final form 9 November 2005.

Keywords: Underground mining, open stoping, production rate, stope size, scheduling, cut-off grades, mining constraints, XPAC, simulation

INTRODUCTION

It is a commonly held belief amongst underground mine planning and design engineers that in a sub-level open stoping mine, the bigger the stopes – up to the geotechnical limits – the greater will be the production rate and hence, the more cost efficient the mine. This paper shows that this can be a fallacy – it is usually true for the individual stope but may not be true for the mine when considered as a system of inter-related stopes.

In a fixed size orebody that utilises sub-level open stoping, there is an intrinsic constraining limit in the production rate achievable that relates to the number of stopes that can be in some phase of the stope cycle (preparation, production, filling or curing) at any one time. Once this limit is reached, there are no more stopes that can be brought into production. This is a physical constraint, which places a limit on the production rate achievable for the stoping system. The effects of such limiting constraints is in alignment with the theory of constraints as known in manufacturing industries (for example, Goldratt and Cox[1]), where it is well known that a system or a process cannot be more efficient than its limiting factor. In this case, the limiting factor is the number of stopes in the system.

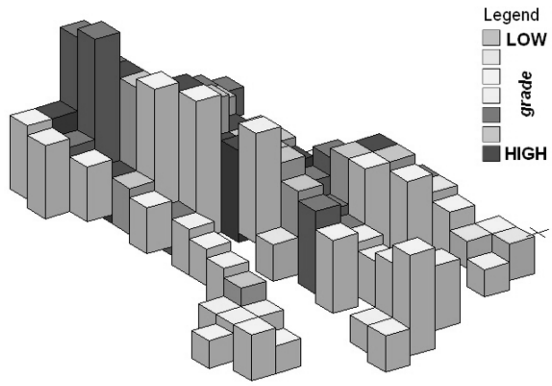
However, this constraint, the number of stopes, can be changed. This can be accomplished by either altering stope size or cut-off grade. Altering stope size and the resulting effects on potential production rates for an idealised orebody has been investigated and the results are reported below. For the case of altering cut-off grade to change the number of stopes, data from a study on changing cut-off grades for a large open stoping mine were available to the author from work reported in Poniewierski *et al.*[2,3] The pertinent data have been extracted and summarised.

A scheduling model was built using XPAC AutoScheduler™ to investigate the effect of stope size on potential production rates and included due recognition and allowance for the major scaling effects of stope size that affect the various elements of the stope cycle times.[4]

EFFECT OF CHANGING STOPE NUMBER BY CHANGING CUT-OFF GRADE

The process of evaluating different cut-off grades for the large sub-level open stoping mine discussed by Poniewierski *et al.*[2,3] resulted in different layouts for different cut-off grades – each with a different number of stopes of different sizes. An example of two such different layouts is shown in Figure 1.

Figures 2 and 3, show how a sustainable steady state production rate varies for layouts with different numbers of stopes, due to different cut of grades.



1 Two different stope layouts for two different cut-off grades (after Poniewierski *et al.*[3])

Note that the production rates plotted in Figure 2 are the sustainable steady-state production rates for a minimum period of 5 years – implying that they can be sustained for each and every month of the 5 years. As described in Poniewierski *et al.*,[2,3] increasing the target production rates will result in fewer years being sustainable at that rate.

As shown in Figure 3, the steady state production rate (in this case expressed as a multiple of the average stope size) increases linearly with increasing number of stopes regardless of the minimum number of years of steady state production required.

SIMPLIFIED EXAMINATION OF THE PROBLEM

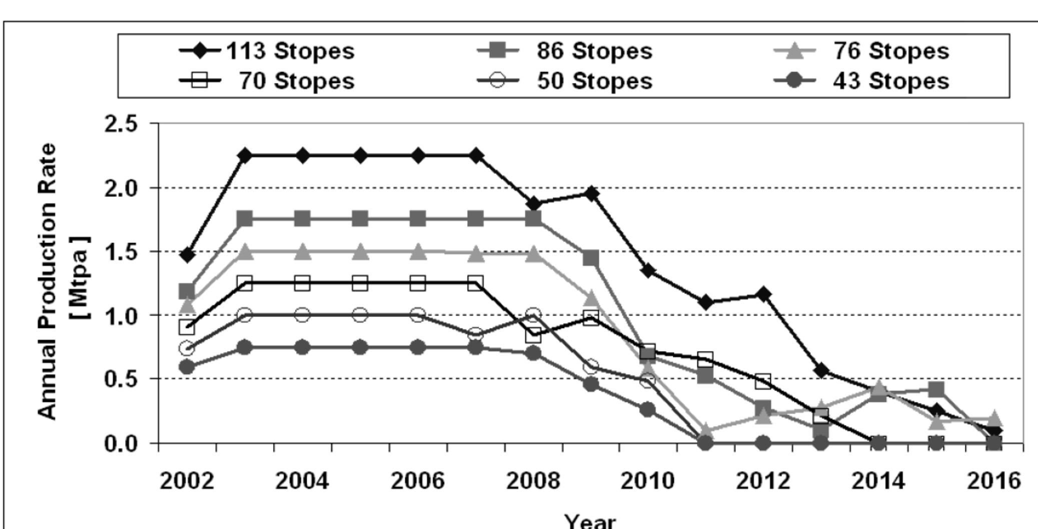
Decreasing the stope size in a fixed size orebody will increase the number of potential stopes that can be brought into production at any one time. A significant second effect is that the stopes surrounding an active stope, which are temporarily unavailable for rock stability reasons, will be inactive for a shorter period of time. This is a result of the stope cycle time being smaller, *i.e.* quicker to drill, quicker to produce, quicker to backfill.

This principle can be explained by examining the effect shown in Figure 4, which shows a portion of an idealised orebody of plan area size 120 m x 120 m, and in which two of many stope size options is shown – 30 m x 30 m and 40 m x 40 m. In Figure 4, for each size case, one stope is actively in part of its production cycle (shown hatched) and the resulting stopes that are excluded from being in their production cycle are shown in grey.

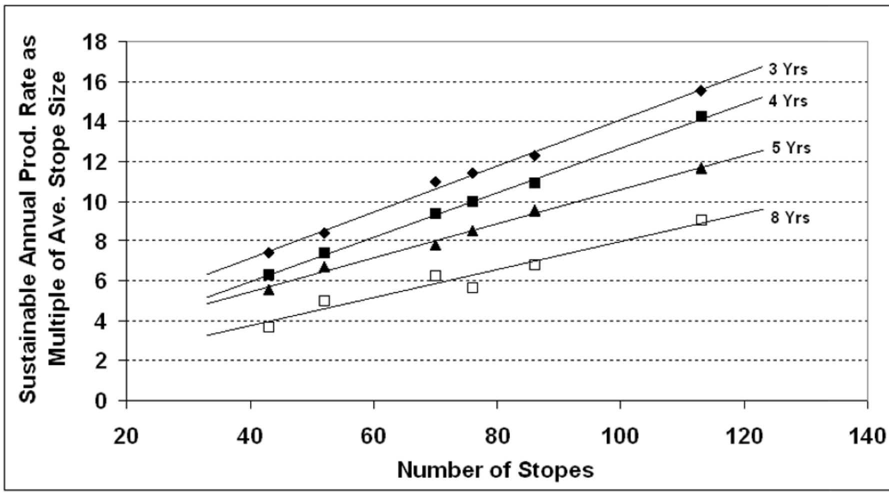
The following simplified stope cycle component rates, which are in units of metres squared per month rather than tonnes per month in order to illustrate the principle, are assumed without considering the scaling effects on production for stopes of different size:

Stope preparation rate = 250 m^2 $month^{-1}$
Stope production rate = 200 m^2 $month^{-1}$
Stope fill rate = 300 m^2 $month^{-1}$

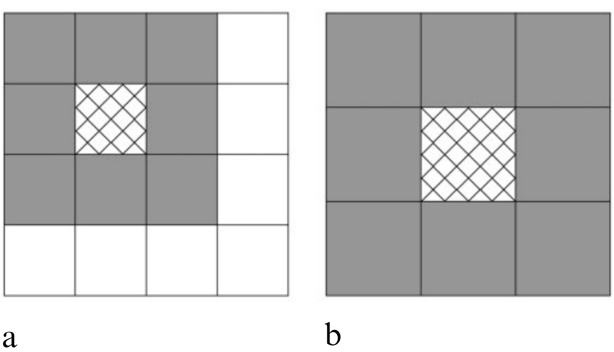
These rates result in the production and utilisation statistics shown in Table 1. The important statistic to note from Table 1 is the efficiency of orebody utilisation, *i.e.* the production achieved per year for the percentage of orebody utilised (either in production or made unavailable by a producing stope). For the smaller stope, there is an 81% greater



2 Variation of sustainable steady-state production rate for a different number of stopes (resulting from changes in cut-off grade) for one of the Enterprise Mine orebodies



3 Sustainable steady-state production rates (as multiples of average stope size) determined for one of the Enterprise Mine orebodies versus number of stopes (effect of cut-off grade changes)



4 Effect of an active stope on a section of an orebody for different size stopes. (a) 30 m x 30 m; (b) 40 m x 40 m

efficiency in orebody utilisation for this simplified example. Hence, the smaller stope size has the potential to have a higher production rate for the whole orebody due to the possibility of having more stopes producing at any one time and, therefore, tying up less of the orebody per stope for a smaller length of time.

A higher production rate will result in fixed time costs for the mine being spread over more tonnes, resulting in a lower cost per tonne for these fixed time costs.

On the negative side of the equation are the following factors:

(i) A lower average stope production rate. Each stope has a production rate build-up during the slot creation, a steady state maximum production rate and a production decrease during the stope clean-up, which involves long distance remote mucking. The time that the stope is at its maximum production rate is lower, yet the time taken for the production increase and decrease phases will be only slightly reduced. The result is a lower average production rate.

(ii) A higher unit cost per tonne for a small stope. Each stope has a number of fixed costs. For example, each stope will require a slot raise. For a given vertical height this is the same cost per stope regardless of the tonnage of the stope. Slot blast-hole drilling will form a greater proportion of the stope drilling required for smaller stopes and will, therefore, increase the drilling cost per tonne for each stope. Other fixed costs will include backfill walls and preparation and ventilation requirements. Therefore, smaller stopes will have a higher cost per tonne.

CURRENT PRODUCTION RATE PREDICTION METHODS

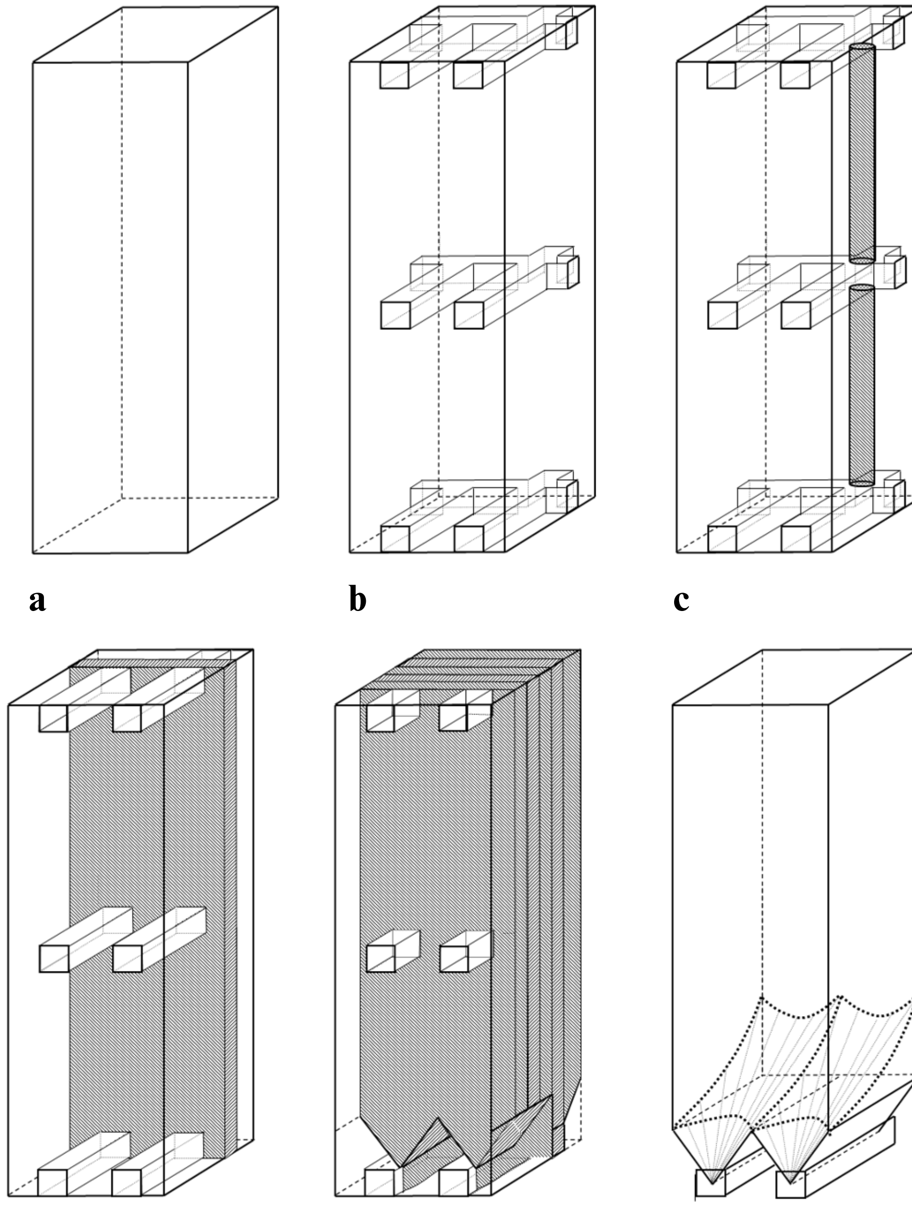
There are a few rules-of-thumb and guidelines currently used by many engineers in determining a suitable production rate for an orebody. These include:

(i) Taylor's law[5] – a rule-of-thumb that states that the daily production rate should be approximately equal to 0·014 x (reserves)$^{0.75}$ tonnes per day.

(ii) Vertical advance rate rules-of thumb – for example, production should be equivalent to

Table 1 Production and utilisation statistics for two different stope sizes for a section of an orebody

	30 m x 30 m stopes	40 m x 40 m stopes
Stope size area (m^2)	900	1600
Stope size as a percentage of the orebody portion size	6·3%	11·1%
Percentage of orebody portion utilised (*i·e·* either in production or unavailable because of stope in production)	56·25%	100%
Time of orebody portion utilisation (preparation, production & filling)	11 months	20 months
Efficiency of orebody utilisation (production units per year per percent of orebody utilised)	1745 m^2 year^{-1} per % of orebody used	960 m^2 year^{-1} per % of orebody sed



5 Single stope development sequence

30–55 m of vertical development per year for a vertically dipping orebody.[6]

(iii) Empirical geometry based relationships – for example, production rate equals a rate factor (vertical tonnes per metre) multiplied by a rate multiplier (being a function or orebody thickness).[7]

For projects involving potentially hundreds of millions of dollars of investment, it is surprising to note that many projects choose the production rate based on these rules-of-thumb. This is particularly the case in studies prior to the development of a bankable feasibility study, although sometimes this also applies to the bankable feasibility study.

As Smith[8] states: 'the selection of the production rate is one of the most crucial decisions to be made in the development of a mineral property, as this single factor determines the capital costs, operating costs, and mine life, all of which influence the project economics and the viability of the project. Using rates determined by rules-of-thumb can result in a mining and processing facility that is inappropriately sized for the deposit, which when too large will burden the project owner with costs that the deposit cannot support.'

Smith[8] discusses the selection of the production rate (and mine life) with respect to the economic characteristics of the project – a production rate that is not necessarily achievable when the physical characteristics of the ore-body in question are considered. Tatman[7] concurs with Smith stating that optimising a project's production rate for net present value will fail to 'fully consider the geological environment and the geometry of the deposit and can lead to overly optimistic production rates for underground mines'. In a study of 60 deposits, Tatman found that 35% of the mines did not achieve their planned production rate.

The production rate assumptions made for a project are invariably that the production rate can be maintained for the mine life. This is usually not the case and a high sustainable steady-state production rate can generally only be achieved for a percentage of the mine life, particularly for large scale sub-level open stoping mines, as was seen in Figure 2.

DESCRIPTION OF PROBLEM INVESTIGATED AND PRODUCTION RATE PREDICTION METHOD

In order to determine the effect of stope size on the production rate, an idealised orebody has been designed and scheduled for a primary–secondary sub-level open stoping system. This orebody is a simple prismatic orebody 240 m x 240 m in plan, and 100 m high, with a specific gravity of 2·9 and constant grade throughout the orebody.

Stopes have been designed as rectangular prisms with shaped trough undercuts (TUCs) – a design feature used at large open stoping mines such as Mount Isa Mine and Olympic Dam Mine to minimise remote mucking and reduce loss of broken ore stocks. (The use of TUCs does, however, increase design losses as stopes get larger). The sequence of development of a single stope has been shown in Figure 5 in a sequence of six steps: (i) the orebody rectangular prism in which the stope resides; (ii) the access development mined for drilling out of the stope; (iii) the cut-off raise developed to commence opening of the stope; (iv) the slot developed by firing into the cut-off raise; (v) the main rings that are fired into the slot, which also form the V-shaped trough undercuts; and (vi) the state of the broken ore in the stope at commencement of remote mucking of the stope.

In plan, the stopes have been set as square shaped, but each with a height of 100 m. Four stope sizes were investigated: 40 m x 40 m; 34·3 m x 34·3 m (referred to as 34 m x 34 m); 30 m x 30 m; and 20 m x 20 m. The stope plans for the 40 m and 20 m size options are shown in Figure 6 along with the naming convention used for the stopes.

The scheduling of these stope layouts has been undertaken using an XPAC AutoScheduler model[4] specifically built for this investigation, but similar in structure to the model used for the Enterprise Mine investigations reported in Poniewierski *et al.*[2,3] Use of XPAC AutoScheduler has effectively allowed a discrete event simulation of the schedule, following all stope cycle scheduling rules, and obeying all rules defined for the interaction of stopes with each other. Dynamic updating of the stope scheduling rules and quantities and qualities can take place based on the status of a stope with respect to other stopes, which are already scheduled.

The stope cycle components modelled were the stope preparation activities (final operating development, raise-boring and production drilling), stope production, preparation for backfilling, backfilling and fill curing. Realistic quantities and rates (given below) have been used for each element of the stope cycle based on rates and quantities that occur at a number of Australian operations that have stoping operations of similar type and dimensions. The scheduling model was built to ensure that all stopes remain accessible from either the externally accessible areas (in this case the east, west and southern edges) or via other unmined stopes.

STOPE SIZE AFFECTED FACTORS

An important aspect of evaluating the effect of stope size changes on the production rate is to account properly for the aspects of the stope cycle that are affected by stope size and will, therefore, affect the scheduled quantities and timing. As stope size is changed a number of factors affecting production will change. These include:

(i) Production rate profiles.
(ii) Design extraction percentages (in particular the ratio of development ore tonnage to stope tonnage and the amount of ore lost in shaped trough undercuts).
(iii) Rock mechanics' behaviour, in particular dilution and loss from overbreak into the stope of adjacent stope walls and exposed fill walls (assumed to be paste fill in the XPAC model built).
(iv) Development and drilling quantities and rates.

F1	F2	F3	F4	F5	F6
E1	E2	E3	E4	E5	E6
D1	D2	D3	D4	D5	D6
C1	C2	C3	C4	C5	C6
B1	B2	B3	B4	B5	B6
A1	A2	A3	A4	A5	A6

L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12
K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12
J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12
I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12
H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12
G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12
F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12
E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12
A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12

6 Stope plan layouts for 40 m (left) and 20 m (right) stoping size options

Table 2 Assumed average in-stope development requirements for each stope size option

	Drill level (3 of)			Extraction level				
Stope size	Slot drive	Main ring drive	Total (m)	Slot drive	Main ring drive	Total (m)	5-m allowance per level	Total in-stope development (m)
40	35	40	75	30	80	110	20	355
34·3	29·3	34·3	64	24·3	68·6	93	20	305
30	25	30	55	20	60	80	20	265
20	15	20	35	10	40	50	20	175

Suitable assumptions about how these factors relate to the stope size have been made in order to enable scaling of these effects. Some of the scaling methods and results are discussed below.

PRODUCTION RATES AND STOPE SIZE

Stope production rate is a major factor requiring appropriate scaling for different stope sizes. Stope production rates gradually increase as the slot is blasted and the stope is brought into production, followed by a period of relatively steady-state production for the main ring blasts, with production rates gradually decreasing as the stope is cleaned with remote mucking, which is initially easy but becomes slower during final clean-up.

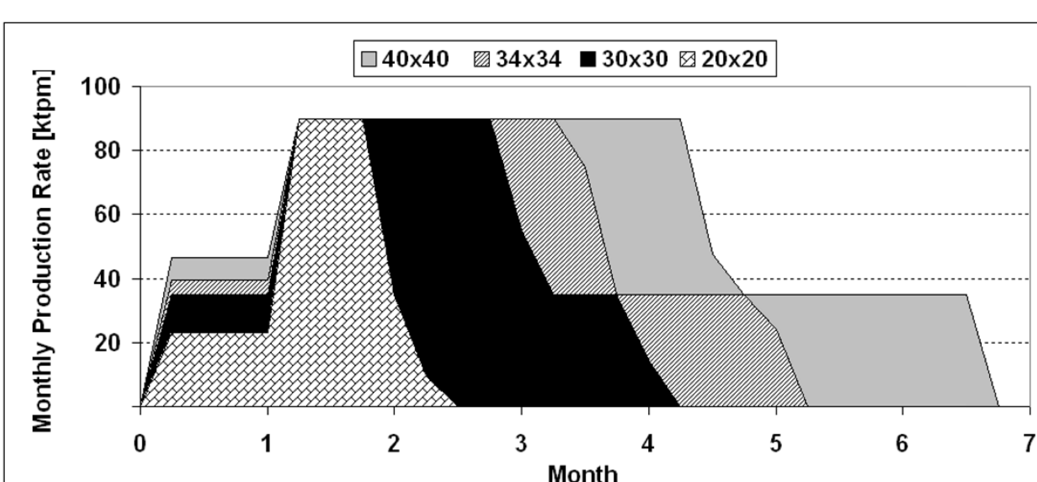
For the XPAC model built for this study, the steady-state production rate for main ring production was assumed to be at a rate equivalent to 90 kt month^{-1}. The slot length has been assumed to be equal to the full stope width, with the slot width at an effective 4·0 m (after over-break), with 10 days taken to pull the slot up to each of three drilling levels. This effectively equates to 1 month to pull the slot through the full height of the stope. For a 40 m x 40 m stope this equates to slightly over 46 kt mined in the first month (4 m x 40 m x 100 m x 2·9 t m^{-3}). For a 20 m x 20 m stope this equates to approximately 23 kt mined in the first month.

The resultant production profile in terms of equivalent monthly production rate for each of the four stope sizes investigated is shown in Figure 7. The average production rate over the production component of the stoping cycle, achieved by each stope size, is shown in Figure 8, along with the total stope cycle time (including stope preparation, backfilling and curing) for each stope size. The average production rate results shown in Figure 8 is in alignment with the generally held belief that 'bigger is better' with respect to stope production and stope size (recognising of course that this is for a single stope and not the stoping system in totality).

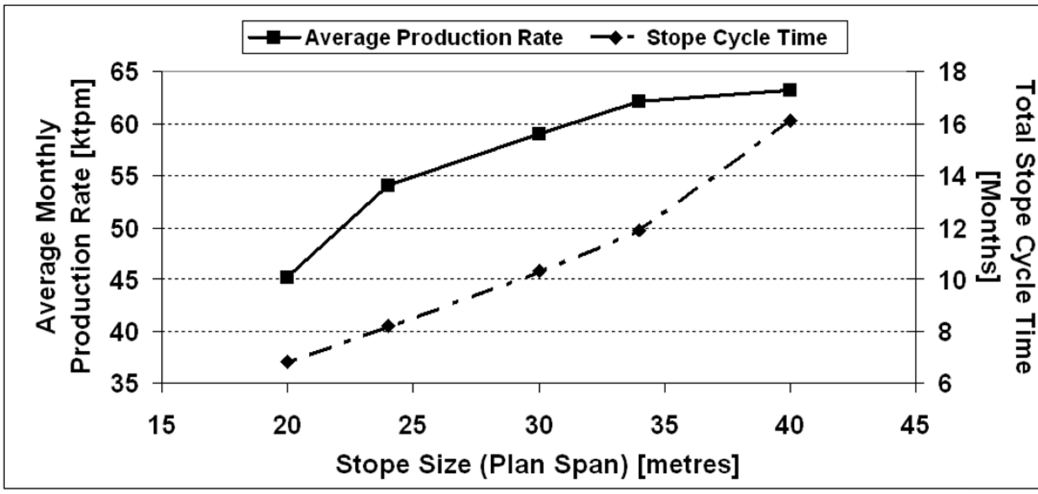
IN-STOPE DEVELOPMENT AND STOPE SIZE

The focus of the XPAC scheduling model that has been built is on stope production; however, ore produced from in-stope development cannot be ignored. Horizontal development is one of the major factors requiring appropriate scaling for different stope sizes, with the percentage of development ore as a percentage of total stope ore varying with stope size.

Development has been assumed to be 5 m x 5 m square in cross-section and all within the orebody, with each stope requiring a total of four development levels, including the extraction level and a top of stope drilling level. The assumptions made on the development design (as schematically indicated in Figure 5b) for each level resulted in total development requirements for each size of stope as given in Table 2, including an allowance of five metres per level for miscellaneous auxiliary development for drainage and power.



7 Effective monthly production profiles for the primary stopes of various sizes



8 Average monthly production rate for the primary stopes and average stope cycle times of various size stopes

The stope tonnage extracted as development, expressed as a percentage of the stope primary design tonnage is shown in Figure 9.

The scheduling model has been set-up such that the relevant monthly ore targets are divided into stope ore and development ore according to their relevant percentages. Therefore, stoping targets are adjusted in accordance with the difference between the total ore targets and the development ore percentage.

Table 3 Tonnage loss in shaped trough undercuts (TUCs) for the different stope sizes

Stope size (m)	Enclosing rectangular prism tonnage (t)	TUC tonnage loss (t)	TUC tonnage as % of enclosing stope prism
40	464 000	12 100	2·6%
34·3	340 898	8300	2·4%
30	261 000	5800	2·2%
20	116 000	1500	1·3%

DESIGN LOSSES AND STOPE SIZE

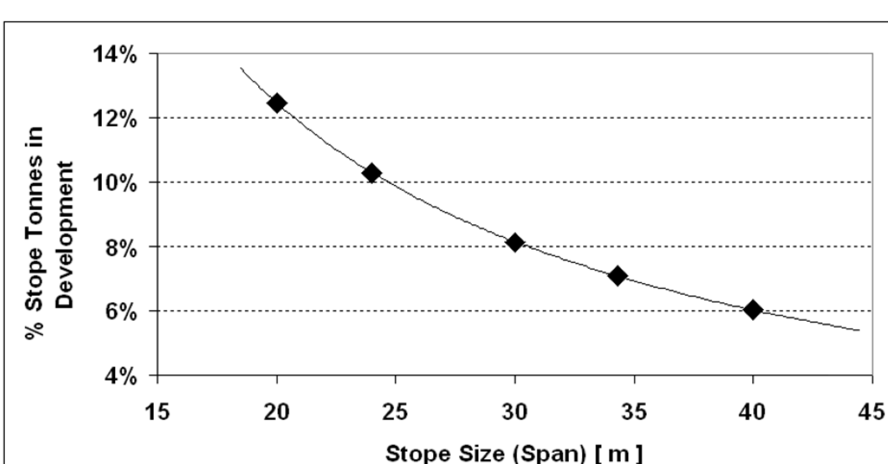
A major item of design tonnage loss is the tonnage lost by use of shaped trough undercuts on the extraction horizon as shown in Figure 5e, designed using an active rill angle of 55°. This results in a loss of ore, which is a different percentage for each stope size, which is shown in Table 3.

NUMBER OF STOPES, PRIMARY STOPE TONNAGE AND STOPE SIZE

As stope size is changed, the number of stopes that the orebody can be divided into changes, as does the tonnage of the stope. These values are given in Table 4, along with the ratio of development ore to stope tonnage derived for each stope size, which is expressed as a percentage and shown earlier in Figure 9.

OVER-BREAK DILUTION AND LOSS, AND STOPE SIZE

Over-break dilution and loss is a major parameter requiring scaling for different stope sizes. For the scheduling model built, the over-break has been assumed to be hyperbolic in shape in both plan and cross-section as shown in Figure 10.



9 Tonnes in development as a percentage of the primary design stope tonnes for five different stope sizes (four of which were scheduled)

Table 4 Stope number and primary design tonnage for the different stope sizes

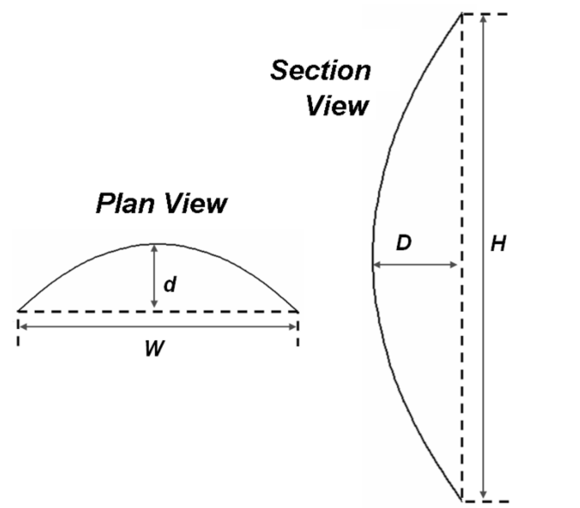
Stope size (m x m)	Number of stopes	Enclosing rectangular prism tonnage (t)	In-stope development tonnage (t)	TUC tonnage loss (t)	Primary stope design tonnage (t)	Development as % of primary stope tonnage
40 x 40	36	464 000	25 700	12 100	426 200	6·0%
34 x 34	49	340 898	22 000	8300	310 598	7·1%
30 x 30	64	261 000	19 200	5800	236 000	8·1%
20 x 20	144	116 000	12 700	1500	101 800	12·5%

The maximum depth of over-break has been assumed to be linear with increasing horizontal stope span (size) beyond a critical length (in accordance with the author's past observations during an over-break measurement study). The actual values used in the study are shown in Figure 11. Note that there is no attempt in this study to vary dilution values for different lengths of fill wall stand-up time.

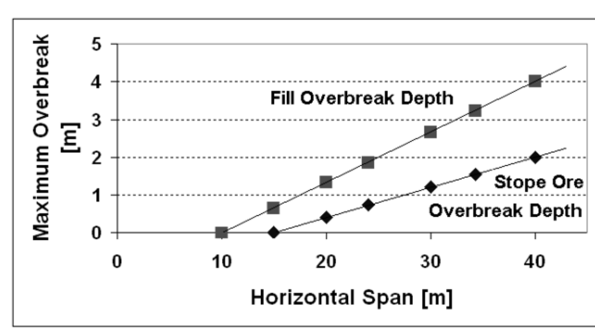
Using the assumptions of a hyperbolic over-break shape (in plan and in section), and the maximum overbreak depths as shown in Figure 11, values of over-break for use in dilution calculations for various stope spans for both rock and fill walls were calculated and are shown in Figure 12.

The actual diluted tonnage for each stope (and the concomitant loss for adjacent stopes) is calculated for each stope dynamically during the schedule by XPAC AutoScheduler, using the volume of over-break as shown in Figure 12. Account is taken of the nature of each of the stope walls by considering the status of each side adjacent stope. Either it has not yet been stoped, therefore, rock dilution is at the grade of the adjacent stope, or it has been filled, and fill dilution is at a grade of zero.

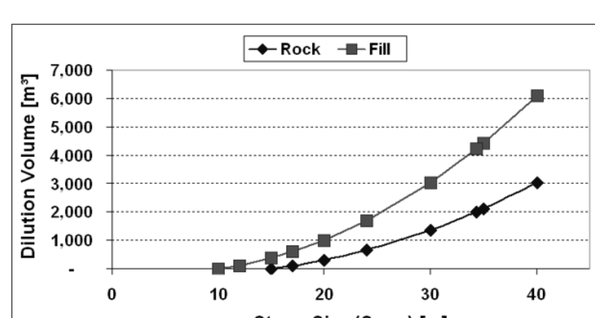
Tonnage and grade extraction factors calculated using the above dilution and loss parameters for each type of stope (classified by the number of fill walls at the time of stoping) and each stope size are shown in Table 5. The tonnage and grade extraction factors are used to determine the tonnage and grade extracted from a particular stope by multiplying the appropriate extraction factors (for the stope's particular fill exposure status) by the primary stope design tonnage and grade.



10 Schematic of assumed hyperbolic pattern of over-break: plan view (left) and cross-section view (right) for a stope span of *W* and stope height of *H*, with *D* being the maximum over-break depth



11 Maximum depth of stope over-break for a rock wall and a fill wall a function of horizontal span



12 Volume of stope over-break for a rock wall and a fill wall as a function of horizontal span

SCHEDULING RESULTS

About 30–40 different schedules were run for each of the stope sizes modelled. Each schedule was incremented for a different production rate and the schedule results examined for the number of years at which the target production rate was achieved in a sustainable manner. The target production rate versus the resulting number of sustainable steady-state production years is presented in Figure 13.

Additionally, in Figure 13, a line is plotted to represent the production rate for a simple division of the orebody tonnes by the desired target production rate and, for reference, the point representing the production rate from Taylor's law.

The implications of the results are that for production rates higher than that predicted by

Table 5 Tonnage and grade extraction factors for various numbers of fill wall exposures and for the different stope sizes

	Primary stope design		Primary stope extracted		1-Fill wall stope extracted		2-Fill walls stope extracted		3-Fill walls stope extracted	
Stope size (m)	Tonnage	Grade	Tonnage factor	Grade factor	Tonnage factor	Grade factor	Tonnage factor	Grade factor	Tonnage factor	Grade factor
40	426 200	3·0%	1·083	1·000	1·032	0·979	0·982	0·955	0·932	0·929
34	310 600	3·0%	1·075	1·000	1·030	0·980	0·986	0·957	0·941	0·933
30	236 000	3·0%	1·067	1·000	1·028	0·981	0·989	0·960	0·951	0·937
20	101 800	3·0%	1·035	1·000	1·020	1·006	1·005	0·969	0·990	0·953

Taylor's law rule-of-thumb, the stope size can have a significant effect on achievable sustainable steady-state production rates. For example, for the orebody modelled, if a production rate of 2·0 Mt year^{-1} had been selected, from a simple division of orebody size by target production rate, the expected mine life would be about 8 years. However, if the mine was subsequently designed using 40 m x 40 m stopes, the desired 2·0 Mt year^{-1} production rate would only be achieved for less than 5 years, resulting in a much longer time period required to extract the resource and a poor utilisation of the associated capital plant built to treat the extracted ore. However, if the mine design used 30 m x 30 m stopes or smaller, the target design production rate is likely to be achieved for most of the mine life.

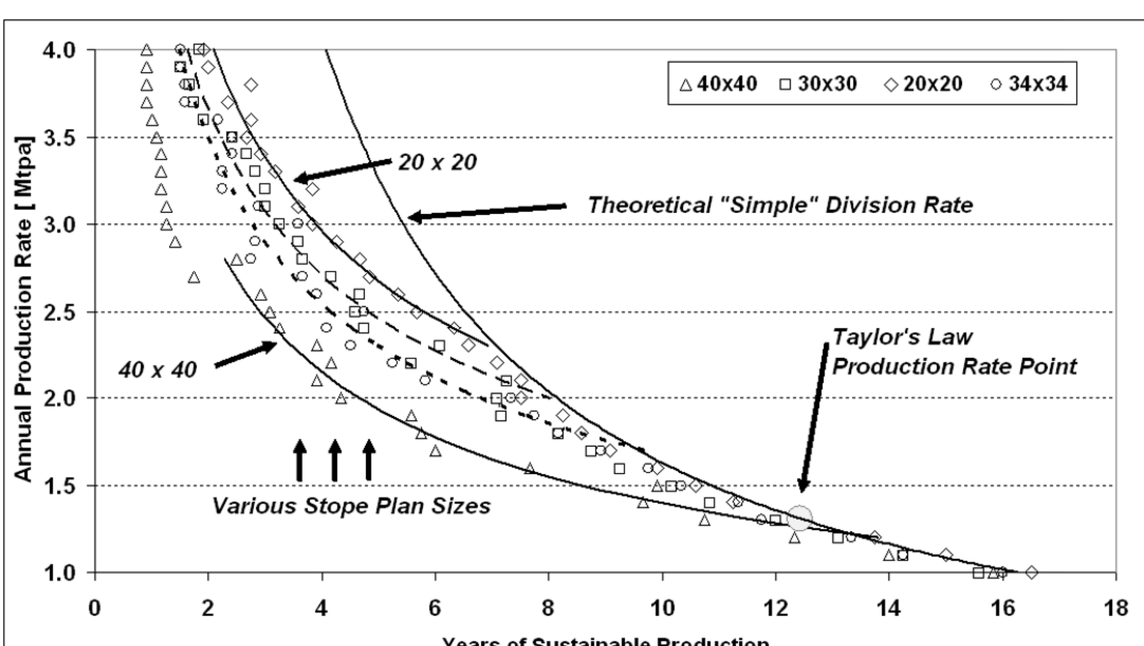
Similarly, from Figure 13, for the 8-year sustainable steady-state production rate, the 40 m x 40 m stopes will give a sustainable steady-state production rate limit of 1·55 Mt year^{-1} whereas the 34 m x 34 m stopes will give a sustainable steady-state production rate limit of 1·86 Mt year^{-1} – an increase of 20%.

It is also noticeable in Figure 13 that significant scheduling artefacts (a jump in the deviation of the plotted scheduling rates from a smoothed line of best fit) can occur when the number of stopes required to maintain a production rate increases, *e.g.* from two stopes at any one time to three stopes at any one time, as seen in Figure 13 for the 40 m x 40 m size stopes at the production target rate of around 2·6–2·8 Mt year^{-1}.

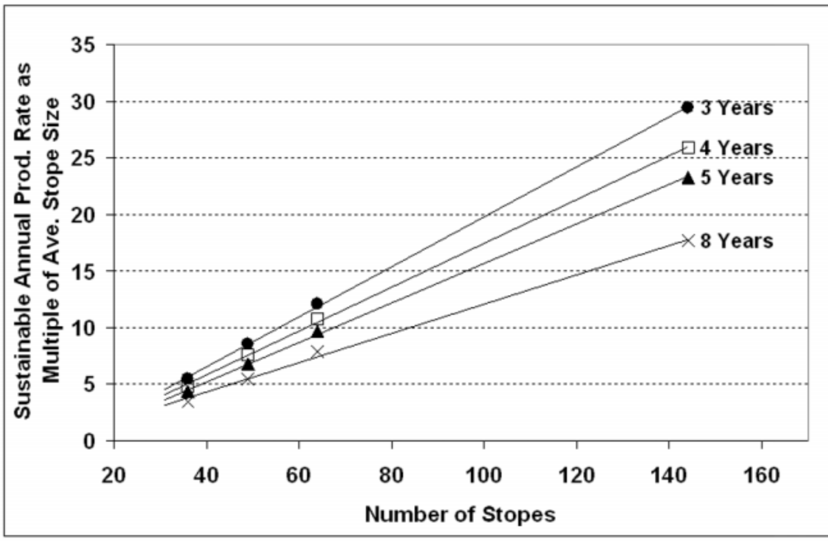
Similar to Figure 3, but as a result of changing stope size, Figure 14 shows the sustainable steady-state annual production rates achievable (in terms of a multiple of the average stope size) as a function of the number of stopes in the orebody.

CONCLUSIONS

In a mine where the production limiting constraint is the mining system itself, which is caused by a constraint in the number of stopes in the mining system, assuming other constraints such as shaft capacity, mill capacity and smelter capacity have not been reached,, it may be cost beneficial to decrease the size of the stope in order to increase the overall production rate from the system. This is initially counter-intuitive to the situation for the single stope production rate for which bigger stopes give higher average production rates.



13 Effect of stope size on sustainable steady-state production rates for various number of years compared to a simple theoretical production rate



14 Sustainable steady-state production rates determined for modelled orebody versus number of stopes (effect of stope size change)

Operating cost increases caused by the decrease in stope size may well be more than offset by an increase in the revenue stream caused by an increase in the total system production rate, along with the potential benefits of lower dilution with the smaller stopes. For a mine with high fixed costs and high initial capital costs, as may be generated by the construction and on-going support of multiple stage shaft hoisting, refrigeration plants for ventilation and paste backfill plants, there is a higher likelihood of increased production rates more than compensating for the higher operating costs of smaller stope sizes. This will result in a higher net present value for the operation. Only a full investigation of potential rates, using a schedule simulation and an evaluation of costs and revenues for each specific project, will determine if this is the case.

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Author

Julian Poniewierski is a senior mining consultant with Runge Limited. He graduated from the University of Queensland in 1982 and gained an MAppSci from the University of NSW in 1987. He has worked for underground mining operations in Mount Isa, Kalgoorlie, and Cobar. He has also worked in research and technical service roles with the Julius Kruttschnitt Mineral Research Centre and with ICI Explosives. His main area of interest is investigation of value adding through the understanding of mining systems and design.