Scenario evaluation through Mine Schedule Optimisation

Lorrie Fava, Dean Millar
MIRARCO, Laurentian University, Canada

Bryan Maybee
Curtin University, Australia

ABSTRACT

The Schedule Optimisation Tool (SOT) is a software that identifies the sequence (schedule) of mine development and the ore production activities that maximise the Net Present Value (NPV). A case study exercise in a live mine planning process found that SOT added over a hundred million dollars of value to the orebody. SOT has been enhanced to allow automated generation and evaluation of mine design parameters.

The first enhancement allows the automated evaluation of schedules over a range of operational resource constraints. Heuristics can be used to seed the starting point of the search; for example, by prioritising production from specific stopes based on their mineral grades. The second enhancement allows a user-specified ranking to be applied as a seeding heuristic. A third enhancement allows automated application of sequencing rules for primary and secondary stopes. SOT provides substantial assistance to the mine planner, allowing for strategic decisions based on a thorough evaluation of mine design parameters.

INTRODUCTION

Ideally, at the time of each critical decision, a mine planner should be able to carry out comparative evaluations of competing options between which he or she must decide. In practice, for underground mine design, mine planning teams have a limited opportunity to review alternatives, due to the time it can take to prepare the alternatives for analysis. Decisions on stope or development layouts made during the early parts of a round of mine planning can be difficult to reverse due to the time required to revise them if they are subsequently found to be inappropriate, or it becomes apparent that they will lead to a sub-optimal extraction plan. Frequently, the deadlines associated with the mine development process itself impose the time constraints that make revisions to mining plans difficult in the later stages of a planning round. Consequently, it is important to explore competing alternatives that arise early on in a planning round as completely as is practical. Software tools that automate or semi-automate the process of formulating the underground mining plan thus have potential to add appreciable value to a given orebody by allowing more extensive appraisal of the competing options early in the design process, or by allowing rapid revision of a mining plan, later on in a planning round, following discovery of an adverse outcome.

There is a recognised [1] lack of general purpose mine planning software tools for underground mining. The delay in the emergence of appropriate software tools for underground mine planning has been attributed to the additional complexity, and the uniqueness of each underground operation. The need for decision support tools in underground mining that lead to added value and time savings being realised will become increasingly acute in view of the current and projected shortage of skilled personnel [2].

SOT

These needs have driven the development of software that has been called the Schedule Optimisation Tool (SOT) to assist with mining plan formulation and evaluation for the long-term planning of underground mines. The initial version of this software tool is presented in [3]. At present, SOT is deployed at the time development opening alignments have been specified, individual stopes have been identified over a block model and this realisation of the desired end state of orebody extraction has been discretised into a set of mining activities.

Each activity has properties specifying, inter alia, mineral grades, total tonnes, length and equipment required so that the costs and revenues associated with any given activity can be computed. Equipment and/or manpower resources can be allocated to activities, so that constraints that relate to, for example, fleet sizes can be enforced by the scheduler.

Activities have predecessor links to other mining activities. For example, the activity of extracting a stope cannot be executed before the stope's access drive is created; the access drive development activity is the predecessor of the stope extraction activity. The link between two activities may have an associated lag, with a duration and a type. If a successor activity may not begin before the predecessor activity is completed, the lag type is finish-start. If a successor activity may begin as soon as the predecessor activity begins, the lag type is start-start. If a successor activity may begin as soon as a specified percentage of the predecessor activity is completed, the lag type is percentage-overlap.

SOT uses an evolutionary algorithm to conduct a search for the sequence, or schedule, of these development and stoping activities that yields the maximum net present value of the cash flows (assuming a given discount rate), subject to each activity's predecessor constraints and a set of operational resource constraints for the mining operation. The resulting schedule of activities effectively forms a mining plan that maximises the value of the orebody, for the given development alignments and configuration of stopes. An evolutionary algorithm, although it does not provide a certificate of optimality, can solve problem instances that are intractable with exact optimisation methods. SOT generates in minutes an optimised schedule, adhering to all operational resource constraints, for thousands of activities. Typically, the mine planner will let SOT run for a few hours, and can then decide, as improved schedules are being generated, whether the improvements warrant allowing additional running time.

A case study [4] was conducted for a real mine, depicted in Figure 1, with 1,591 development and stoping activities. It is a narrow vein gold and copper mine with shaft and ramp access, and a mine life of approximately 40 years; the name of the mine cannot be disclosed for confidentiality reasons. Two examples of the results of scheduling this mine with SOT are shown in Figure 2. The NPV of the schedule of activities produced by a mine planning software package was evaluated, subject to constraints limiting the annual ore production of the mine and the resources allocated to those activities. This is shown as point A of Figure 2. A mining plan was also independently produced by an experienced mine planner, and the NPV of this schedule was assessed too, subject to the same constraints (point B of Figure 2). SOT was used to improve both of these initial mining plans. From the schedule generated by the mine planner with three months of effort, SOT generated an improvement of $121 million (point C of Figure 2). From the lesser-constrained starting schedule from the mine planning software, SOT generated an improvement of $174 million (point D of Figure 2). The case study exercise undertaken with SOT added over a hundred million dollars of value to the orebody.

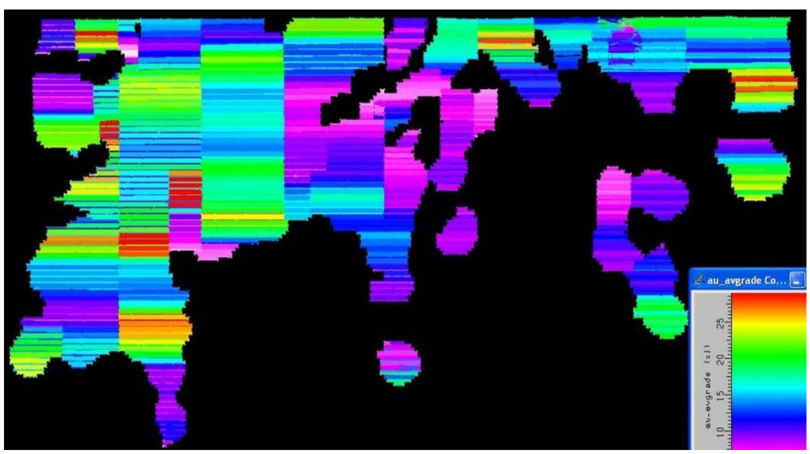

Figure 1 Stoping layout of the case study mine, coloured according to gold grade

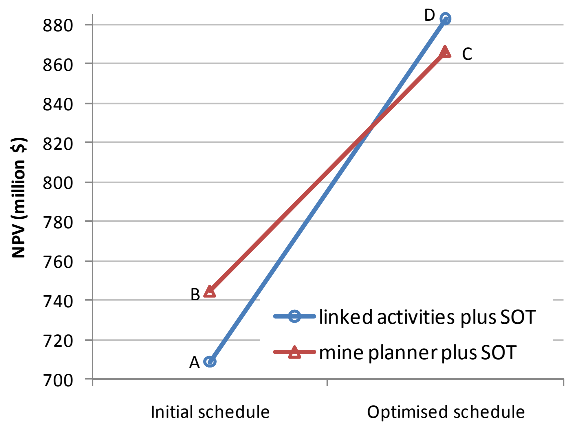

Figure 2 NPV improvement generated by SOT for a case study of a real mine. A: default schedule of activities from mine planning software subject to annual production and activity resource constraints; B: mine planner's schedule subject to annual production and activity resource constraints; C: mine planner's schedule improved by SOT; D: default schedule improved by SOT

STRATEGIC MINE PLANNING

During the mine planning process, planners must make decisions on the following (non-exhaustive) list of parameters that are critical to the determination of the value ultimately realised in a mining project:

- mining method
- cut-off grade
- access method
- mill capacity
- hoisting capacity
- fleet sizes
- scheduling strategy and
- life-of-mine schedule.

Ideally, for each of the above parameters, all feasible alternatives should be compared on the basis of their influence on the NPV, which expresses the ultimate project value. Within current practices, the time required to follow through with detailed mining plans associated with all the feasible alternatives precludes the preparation of more than only a few detailed mine plans. Decisions for the values of these parameters are then frequently informed by experience from past or similar projects, or are based on 'rules of thumb' that do not necessarily lead to the optimal mining plan. Some strategic studies have shown that following the conventional wisdom can lead to mine plans that are far from optimal [5], and it is difficult to establish what project value may have been destroyed in the process.

For a given set or subset of the above-listed strategic mine planning parameters, we refer to each combination of parameter values as a scenario. For example, a scenario may comprise a specification of a cut-off grade of 2.5 grams per tonne and a prescription that a longhole mining method be adopted.

Automation of the formulation of mining plans associated with the specification of a particular scenario provides an objective basis for strategic decision making, especially if the corresponding mining plans are optimised, as is the case with a tool such as SOT. For a comparison among scenarios to be meaningful, it is essential that a consistent financial model is applied, and a consistent set of practical constraints is adhered to in each scenario evaluation.

Automating aspects of mine planning for the purpose of scenario evaluation also provides the opportunity to:

- Rapidly re-analyse, given an updated financial model or a revised set of practical constraints, to assess whether such updates will change the ranking of the scenarios under consideration.
- Undertake a type of sensitivity analysis that flexes, for example, the exchange rates used in evaluation, to observe whether they have the potential to change the decision variables (*e.g.*, the mining method). If so, the exchange rates could then be subjected to additional analysis and refinement.
- Vary financial parameters to reflect, for example, varying projections of metal prices, inflation rates and capital costs, so that the robustness of a given set of mining plans to varying economic circumstances can be appraised [6], and economic risk can be mitigated in mine design.

In the following sections we highlight features of SOT that can be useful for mine planning scenario evaluation, with brief illustrations from case studies. Automated flexing of options for scenario generation and evaluation is discussed in the sections Scheduling Strategy, Resource Capacities and Stope Sequencing. The section Other Strategic Decisions discusses how the mine planner can use SOT for areas of decision making where SOT cannot automatically flex options.

SCHEDULING STRATEGY

Table 1 SOT seeding heuristics

Seeding Heuristic	Ranking Factor	Spatial Domain of Evaluation
1	highest mineral mass	activity
2	highest mineral grade	activity
3	least cost by mineral mass	activity
4	highest mineral mass	mine area
5	highest mineral grade	mine area
6	least development distance by mineral mass	mine area
7	least cost by mineral mass	mine area
8	highest mineral mass	activity and area
9	highest mineral grade	activity and area
10	least development distance by mineral mass	activity and area
11	least cost by mineral mass	activity and area

Table 1 lists 11 alternative seeding heuristics implemented in SOT. With a seeding heuristic, particular stopes are scheduled as soon as practical, according to the ranking factor, where this is computed over the spatial domain of the evaluation.

When a seeding heuristic is selected, a score is assigned to each stope in the mine. For example, if seeding heuristic 8 is selected, the score assigned to a stope will be calculated as a combination of the total mineral mass contained in the stope's mine area relative to other mine areas, and the total mineral mass contained in the stope. The score of a stope will be taken as its priority by SOT. A parameter, typically set at about 80%, specifies the degree of seeding, so that the evolutionary algorithm can produce an initial population with some variation. No such variation would be possible if the scores of all stopes were unique, and seeding was applied with degree 100%.

The mine planner can provide a ranking of the stopes, and use that ranking as the seeding heuristic 12. This ranking could reflect a scheduling strategy based on expert knowledge, or on circumstances particular to a project and not reflected in the built-in methods. Most simply, it could order areas or sections of the mine (within which stopes are defined as activities) according to the planner's scheduling strategy. Where the assigned ranking of two stopes is the same, a secondary score can be adopted. The options for this second score are the mineral grade or mineral mass, corresponding to seeding heuristics 13 and 14 respectively.

SOT automatically flexes seeding heuristics. Schedule optimisation is conducted independently with each seeding heuristic in turn, and the best schedules are reported. The application of automated flexing of seeding heuristic to an actual case study orebody is given in Figure 3. In this case, the scheduling strategy brought in as seeding heuristic 12 was obtained through a mixed-integer programming tool, LOBOS [7]. LOBOS generated an optimal high-level schedule of aggregated stopes (a strategy), and this strategy was mapped directly to a score for each stope. Alone, this strategy performed comparatively poorly, but better in combination with secondary criteria, as seeding heuristics 13 and 14. The built-in SOT seeding heuristic 9, which is based on the mineral grade of the mine area and the stope, resulted in the highest NPV schedules.

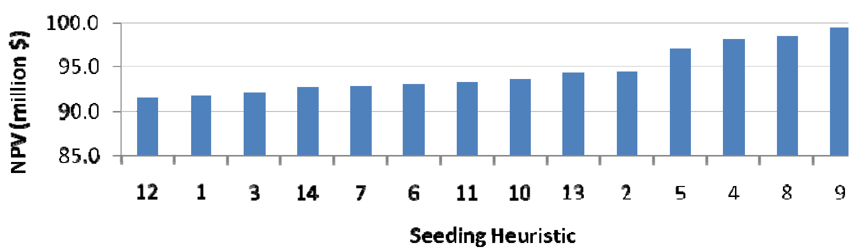

Figure 3 Flexing of seeding heuristic, applied at 80%

OPERATIONAL RESOURCE CONSTRAINTS

Exemplar mine design parameters that can be treated as operational resource constraints include:

- hoist capacity
- mill capacity and
- fleet size and equipment productivity.

SOT has a facility for the automated flexing of operational resource constraints. The mine planner decides the range of capacities to be considered, and the step size within that range. This is done independently for each operational resource that is to be constrained. SOT will automatically perform a separate optimisation run for every combination of operational resource capacities. This feature can be used, for example, to find the best combination of hoist capacity, mill capacity, jumbo drill fleet size and jackleg drill fleet size. For each operational resource scenario, the appropriate capital expenditures and operating costs are applied, as provided by the mine planner. By comparing the NPV determinations of the optimised schedules, the mine planner can empirically determine the best among the scenarios considered, and, if more decision support is required, choose new ranges and step sizes for a follow-on study of additional operational resource scenarios.

A simple example of the results of operational resource flexing with SOT is shown in Figure 4, where the annual production intensity of the mine was constrained: for each point of Figure 4, the production rate was held at the indicated threshold, and then the mining plan was reoptimised. Repeating the process across a range of threshold production rates generates the graph of NPV shown. Figure 4 shows that a production rate of 1.8 million tonnes per annum was found to be the best among the selected scenarios.

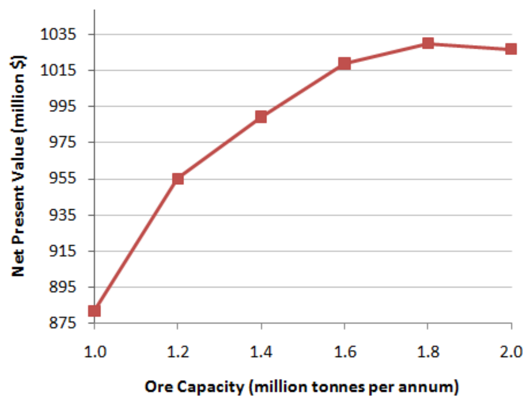

Figure 4 Strategic analysis of production rate

As a second example, two operational resource constraints were automatically flexed, and the results are reported in Table 2. The annual production intensity and the annual access development metres were constrained, with the relevant costs varied appropriately. (For example, a higher production rate requires more or larger equipment, with increased capital expenditure.) These constraints were set by the mine planner to represent mill sizes and drill fleet sizes, in order to find the best combination of constraints (*i.e.*, scenario). For each scenario, SOT automatically recalculated an optimised mining plan. Table 2 shows that the best scenario was found to be the largest mill size and the second largest fleet size.

Table 2 Simultaneous flexing of two operational resource constraints

NPV (million $)		**Level and Ramp Development (metres per annum)**			
		3,000	4,000	5,000	6,000
Ore Capacity (tonnes per annum)	**1.00**	59.25	57.54	62.05	59.27
	1.25	126.48	134.82	141.66	139.52
	1.50	132.94	134.65	141.89	138.21
	1.75	162.41	166.92	170.02	170.13
	2.00	166.74	170.73	172.40	169.93

STOPE SEQUENCING

Due to geotechnical considerations, some sequencing of stopes must often be prescribed. This can be done by designating stopes as primary, secondary or tertiary, and applying sequencing rules that reference these designations, resulting in fixed stoping sequences. Instead, SOT allows sequencing rules to be prescribed rather than the rigid specification of stoping sequence. As a schedule is being generated, a rules engine (expert system) automatically designates primary, secondary and tertiary stopes, and generates predecessor constraints that satisfy the prescribed sequencing rules. In this way, the stope sequences may vary from one schedule to the next as the optimisation proceeds, without violating the imposed sequencing rules. Figure 5 shows that this automated flexing of stope sequencing was able to add value of between $11 and $18 million in each of the four scenarios studied, corresponding to four combinations of cut-off grade and access method.

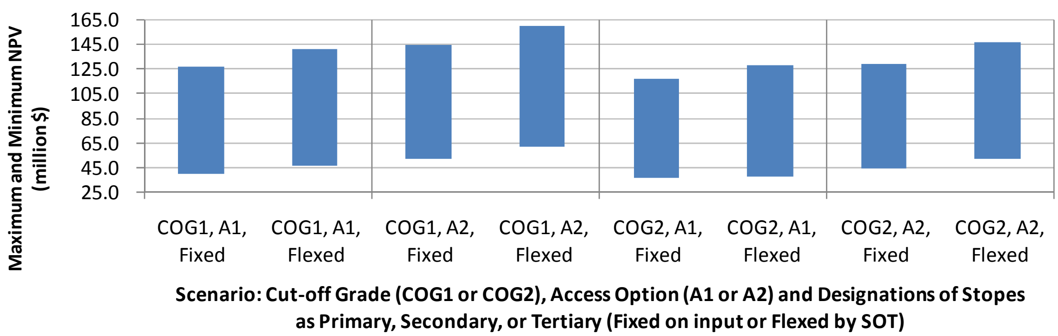

Figure 5 Automated flexing of stope sequences

OTHER STRATEGIC DECISIONS

Some strategic parameters are not amenable to automated flexing within SOT. These can be varied as appropriate, and analysed by the mine planner through separate runs of the tool. Such parameters include:

- mining method (because stope design is not yet an automated process)
- cut-off grade (because variation of this parameter admits and removes blocks to be stoped), and
- access method (because development design is not yet an automated process), for example, ramp or shaft.

Referring back to Figure 5, eight different SOT runs are represented. The focus of the previous section was on the automated flexing of stope sequences that occurred within four of the runs. By examining the results from a different point of view, it can be seen that they also allow the mine planner to investigate the best combination of cut-off grade and access method. The best among the selected scenarios was found to be cut-off grade 1 with access method 2.

The mine planner's effort is required to set up the different design options. SOT's rapid schedule optimisation allows the comparative evaluation of all resulting scenarios, enabling superior strategic decision-making practices.

SUMMARY AND FUTURE WORK

We have proposed that a comparative evaluation of alternative scenarios is an essential component of optimised mine planning, and that automation and optimisation software are necessary to carry out these evaluations.

Several instances have been presented, showing the use of the Schedule Optimisation Tool for scenario evaluation, assisting with strategic decisions relating to:

- scheduling strategy through seeding heuristics
- resource capacities, and
- sequencing of primary, secondary and tertiary stopes.

Other strategic parameters, such as mining method and cut-off grade, can be evaluated through separate runs of the tool.

Several research directions arise from the current work:

- The closer integration of mine design and scheduling is expected to result in improved optimisation of each, with an automated iteration between the software tools, rather than sequential optimisation, first of the design and then of the schedule.
- The early consideration of geomechanical issues will allow the optimisation process to produce feasible outcomes, so that the resulting mine plan is more achievable.
- The early integration of ventilation considerations into the mine planning process is expected to result in improved optimisation through trade-offs between increased development costs and reduced life-cycle operating costs.

ACKNOWLEDGEMENTS

Enhancements to SOT for scenario evaluation have been funded through PRIMO, AMIRA's project P884. Valuable contributions to the case studies have been made by Darren Janeczek, Bob Anderson, Kiel Daoust and Annie Tousignant.

REFERENCES

Newman, A., Rubio, E., Caro, R., Weintraub, A. & Eurek, K. (2010) *A Review of Operations Research in Mine Planning*. Interfaces, vol. 40(3), pp. 222-245. [1]

Stacey, T.R., Hadjigeorgiou, J., & Potvin, Y. (2008) *Technical skills — a major strategic issue*. Journal of the Southern African Institute of Mining and Metallurgy, vol. 108(12), pp. 775-782. [2]

Fava Lindon, L., Goforth, D., van Wageningen, A., Dunn, P., Cameron, C., & Muldowney, D. (2005). *A parallel composite genetic algorithm for mine scheduling*. In: Proceedings of the 9th IASTED International Conference on Artificial Intelligence and Soft Computing, pp. 245-250. [3]

Maybee, B., Fava, L., Dunn, P.G., Wilson, S. & Fitzgerald, J. (2010) *Toward Optimum Value in Underground Mine Scheduling*. CIM Journal, vol. 1(3), pp. 176-182. [4]

Hall, B.E. (2009) *Short-Term Gain for Long-Term Pain – How focusing on tactical issues can destroy long-term value*. Journal of the South African Institute of Mining and Metallurgy, vol. 109(3), pp. 147-156. [5]

Smith, G.L., Surujhlal, S.N. & Manyuchi, K.T. (2008) *Strategic mine planning — communicating uncertainty with scenarios.* Journal of the Southern African Institute of Mining and Metallurgy, vol. 108(12), pp. 725-732. [6]

Smith, M.L. (2011) *Strategy Optimisation for the Prominent Hill Mining Complex*. To appear in: Proceedings of the 2nd International Seminar on Mine Planning. [7]