Integrated pit, dump and haulage network optimisation for mine scheduling - a linear programming approach

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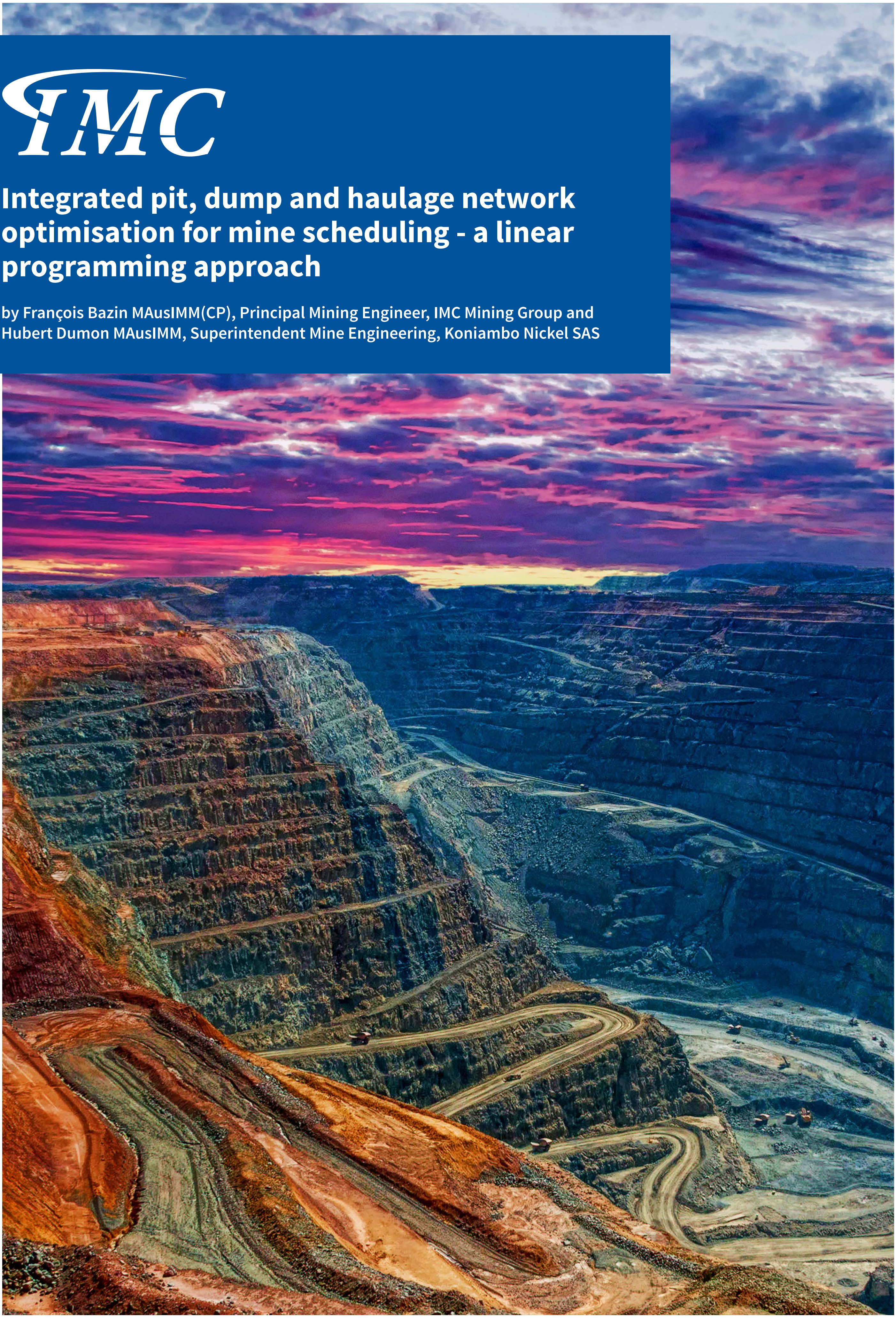

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ABSTRACT

The use of linear programming (LP) to identify optimal solutions for a mine production schedule is a powerful yet under-utilised method for improving project value.

This paper explores a laterite nickel mine case study of a production schedule that optimises the project net present value of an integrated network of mining areas, roads and waste dumps.

Commercially available mixed integer linear programming software has been used to model the data and the production constraints. The LP model simultaneously considers the optimal mining sequence, haul road and waste dumping sequence while maximising the project net present value (NPV).

This integrated approach to mine scheduling effectively bridges the gap between tactical and strategic mine planning and ensures that a mine production schedule is both feasible and optimal.

ABOUT THE AUTHORS

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Hubert Dumon is the Superintendent of Mining Engineering at Koniambo Nickel in New Caledonia and is tasked with implementing long and medium term planning processes. He has a Master's degree in Engineering and Management from the Ecole Nationale Supérieure des Mines de Paris. His experience includes operational roles at Rio Tinto in Italy and strategic planning roles at Areva. Hubert speaks fluent French, English, Italian and is a member of the AusIMM

INTRODUCTION

Mine planning and production scheduling are fundamental to realising the value of an in situ asset. Mining projects are complex systems including dynamic digging locations, haul routes and waste dumping locations. During a typical mine life, pits get deeper, haul roads are cut off or established, waste dumps grow and backfilling opportunities are created.

In conventional mine production scheduling, the main focus is on ensuring that the correct quantity and quality of material is delivered to the ore processing facility while honouring total movement constraints. The sequencing of the waste dumps and the subsequent truck hours required to haul the material from the mining locations to the dump(s) is often completed post-scheduling. The shortfall of this approach is the disconnect between the digging and the waste dumping sequence that will invariably lead to sub-optimal mine plans.

Mixed-integer linear programming (MILP) can be used to model complex mine scheduling systems to identify feasible solutions while maximising the schedule NPV. In this case study, five laterite nickel mines in New Caledonia have been scheduled in an integrated model to produce a combined on-spec Saprolite ore stream for a nickel refinery.

The objective of the integrated production schedule is to find the highest present value solution while honouring the many constraints imposed by operating five mines in a mountainous, tropical and high-rainfall environment.

The fundamental point of differentiation for the mine scheduling approach described in this paper is the simultaneous modelling and optimisation of the digging sequence, haul route and the waste dumping locations.

The linear programming constraints in the scheduling model have been set up to ensure that material mined from the pit locations also accounts for truck hours required to arrive at the final destination; run-of-mine (ROM) pad or waste dump. Additionally, the waste dump construction sequence has been modelled to ensure that the waste volumes and waste truck hours are correctly accounted for in 'real time' during the construction of the dump in the schedule.

This integrated approach to mine scheduling, that effectively bridges the gap between tactical and strategic mine planning ensures that a mine production schedule is both feasible and optimal.

THE MINE PLANNING PROBLEM

Commonly, base metal projects' laterite nickel production schedules are driven by the requirement to provide a blended product at a certain chemical specification. These specifications include:

- nickel and cobalt grade
- Fe:Ni ratio
- MgO:SiO2 ratio.

Laterite nickel orebodies are generally highly variable in terms of chemical composition both vertically and laterally while the process plants (pyrometallurgical or hydrometallurgical) tend to demand very tight chemical specifications.

Figure 1 shows the process plant target specification limits as well as the pit-by-pit Fe:Ni and MgO:SiO2 ratios for the case study. This demonstrates the

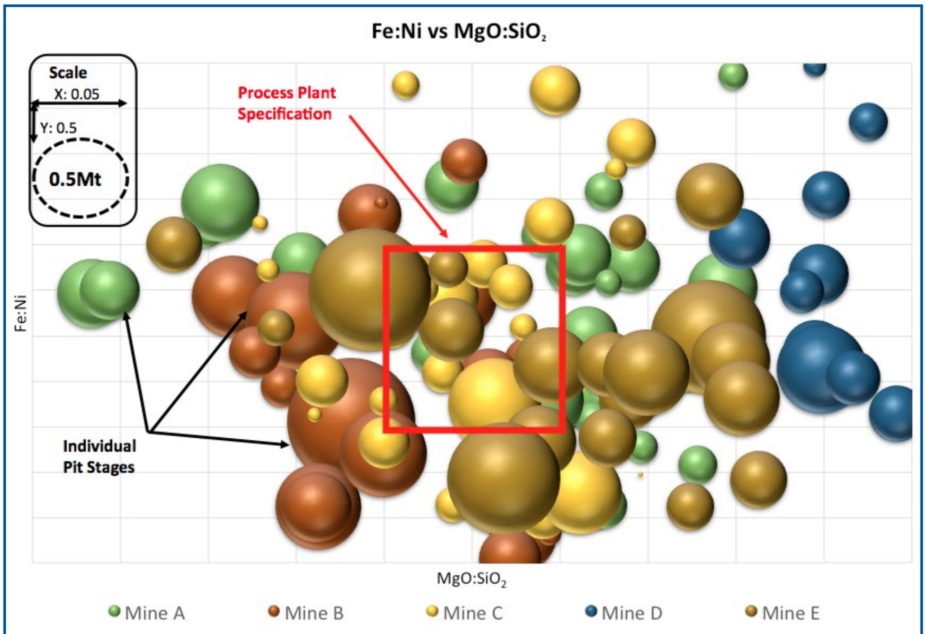

Figure 1. An interesting blending problem. Pit constellation charts (bubble size denotes ore tonnage).

importance of mine planning to achieve the process plant specifications.

In addition to ensuring the blended product meets the process plant's chemical specification the mine schedule needs to adhere to practical mining constraints while also finding a solution that optimises the NPV.

Due to the shallow nature of the laterite nickel pits, many sequencing options are feasible in terms of access and development. The preferred development sequence should take into account the following issues:

- optimise present value or cash flow
- ensure that sufficient waste dump capacity exists for each solution
- account for truck hours and constrain if required
- account for excavator hours and constrain if required
- stage capital expenses when the outlay returns a higher NPV solution (ie additional trucks or additional ore processing capacity)
- practical mining constraints, for example:
  - maximum excavator hours per mining location : models equipment separation
  - maximum volume per waste dump per period : models waste dump construction delays in terms of geotechnical and drainage time per lift
  - minimum and maximum excavator and truck fleet hours : smooths out truck hours against available capacity.

In a conventional mine schedule, each scenario tends to be based on a static set of block destination assumptions, ie a block has a predefined or a not-yet defined final destination in terms of ROM pad or specific dumping area.

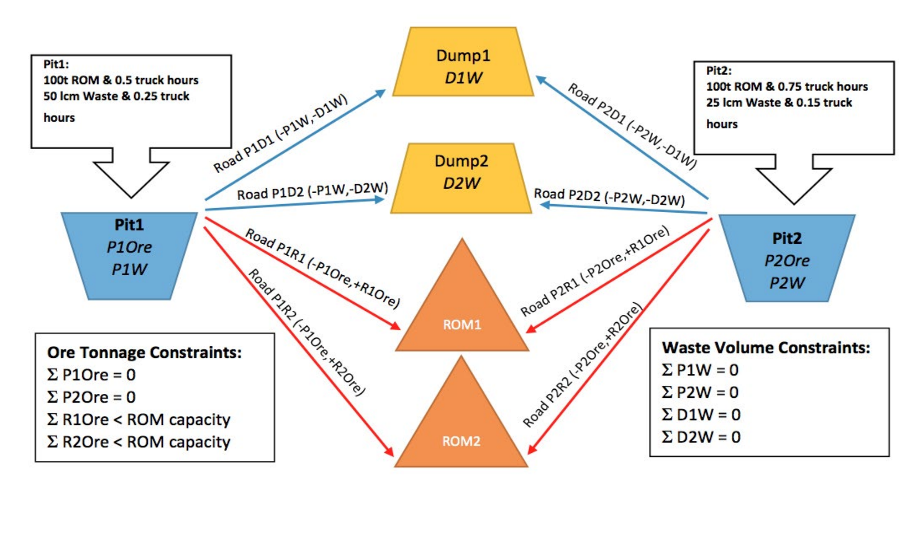

Figure 2. Simplified mine schedule network diagram.

Typically, engineers design waste dump stages and evaluate the truck hours after a schedule has been completed. If there is an excess of truck hours in a particular period, the engineer must go back and re-run the schedule to meet this constraint. These mine planning iterations can take several weeks to fine-tune and will result in a sub-optimal solution.

This case study is based on an integrated mine plan with five operating mines creating a single blended product that must honour the process plant specification in each quarter.

Each mine is a separate production facility and has between 15-30 possible mining areas, many of which can be backfilled after an area is depleted.

The scheduling complexity arises because each block in the schedule can be assigned to many different ROM pads and external waste dumps. In the sequencing plans, the pit blocks are connected to the ROM pads and external waste dumps via a large network of haul routes to estimate the required truck hours (and therefore variable cost) associated with each feasible solution.

The linear programming model is tasked to find a feasible and optimal solution in the context of manning and equipment constraints. A simplified network diagram (Figure 2) demonstrates the ore and waste tracking principles.

LINEAR PROGRAMMING FOR MINE SCHEDULING

Linear programming is commonly used to find solutions in complex systems found in logistics, transportation and manufacturing. A linear programming system can be described as having three key components:

- set of decision variables
- an objective function that is used to measure the quality of the feasible solutions
- a set of constraints.

The objective function and the constraints are linear functions of the decision variables.

For a mining schedule modelled using linear programming, the decision variables represent the various quantities that can be mined in each digging location in each period (eg truck hours, ore tonnes, waste tonnes, etc). Linear equations can then be modelled to represent the capacity constraints in each period (Table 1).

The objective function is the estimated NPV and is used to rank all the feasible solutions. The solution with the highest NPV becomes the optimal solution.

In the case study the estimated NPV includes all fixed and variable costs associated with mining, hauling and waste dumping to arrive at comprehensive ranking of all feasible solutions.

Linear programming can find optimal solutions to complex systems such as an integrated pit, dump and haulage network.

	Capacity constraint	Represented as
Condition 1	Truck hours must be less than 5000 hrs	$\sum$ Truck hours – 5000 < 0
Condition 2	Ore tonnes must be between 2000 t and 2500 t	$\sum$ Ore Tonnes – 2000 > 0 and $\sum$ Ore Tonnes – 2500 < 0
Condition 3	Total movement must be less than 8000 t	$\sum$ Total movement – 8000 < 0

Table 1. Linear equations representing capacity constraints in each period.

MINE SCHEDULING

Software

Minemax Scheduler is a schedule optimising tool that uses a MILP model of the constraints and the financial and production targets of a project. It uses the CPLEX branch and cut algorithm to optimise

Scheduling database

In order to simultaneously model the pit and dumping sequence as well as the road network, the mine scheduling database is made up of three types of blocks:

1. Pit blocks – blocks that contain ore, waste and grades from the diluted reserve model. These blocks also contain the required truck hours from the block to the pit exit along the designed ramp.

2. Road blocks – dummy blocks that must be 'mined' to keep track of the truck hours required to haul the ore and waste along each road segment. These blocks link the pit exit to the ROM pad or waste dump entry point.

3. Waste dump blocks – blocks that contain the dump volume and the required truck hours from the dump entry point to the actual dump block centroid. Backfill blocks are treated the same as waste dump.

Waste

For the schedule to correctly account for the placement of waste, several quantities and constraints must be modelled.

Waste volumes are tracked in terms of loose cubic metres (LCM) in the schedule. When pit blocks are mined, a positive waste LCM quantity is created: P1W and P2W for Pits 1 and 2 respectively (Figure 2).

Pit 1 waste has a choice of two roads leading to two waste dumps, Dump 1 and Dump 2. Road P1D1 takes waste from Pit 1 to the Dump 1 entry point. This road is treated as a dummy block with a large negative quantity for the Pit 1 waste (P1W) and the Dump 1 waste (D1W). The dummy road block also carries the correct number of truck hours required to haul the waste from

Pit 1 to the Dump 1 entry point.

Similarly, the Dump 1 blocks contain the capacity of the actual volume that can be placed in the dump block (in LCM) and the truck hours required to travel from the dump entry point to the dump block centroid.

In order to account for the truck hours utilised on the road network, in every scheduling period the following constraint must be honoured:

$\sum$ P1W = 0 and $\sum$ D1W = 0 where P1W = D1W.

With both of these equations satisfied, if 50 LCM of waste is mined from Pit 1 (P1W = 50) then this creates a negative 50 LCM P1W and a negative 50 LCM D1W quantity on Road P1D1.

The negative D1W quantity is then correctly placed in the dump with the corresponding positive D1W from the dump blocks. Once there is no longer any D1W capacity on Dump 1 then the P1D1 road is effectively unusable for the remainder of the schedule. The Pit 1 waste will then be forced to use the P1D2 road to Dump 2 (Figure 3).

Ore

Ore truck hour modelling is very similar to the waste example above but a little simpler. Ore mined from Pit 2 for example creates a positive P2Ore quantity that can only be evacuated by the P2R1 or P2R2 roads.

The P2R1 road has a large negative quantity of P2Ore that is 'mined' as required to satisfy the constraint $\sum$ P2Ore = 0. In this example, if 100 t of ore is mined from Pit 2, then P2Ore becomes 100 t and in order to satisfy the scheduling constraint, negative 100 t must also be 'mined' from either the P2R1 or P2R2 road.

The truck hours required to haul the -100 t of ore along the road network is then correctly accounted for. At the

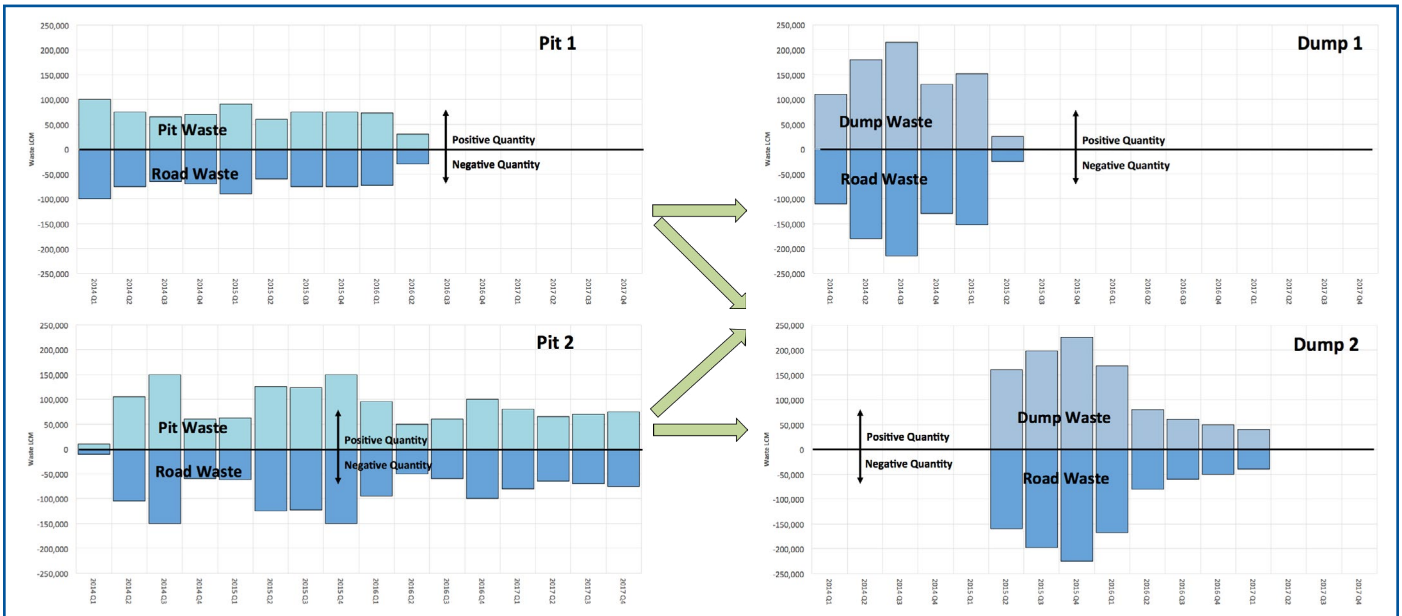

Figure 3. Pit, road and dump waste accounting.

destination, a maximum capacity for the R1 ROM area per period can be modelled by tracking an additional quantity of R1Ore or R2Ore. If the ROM capacity was 50 000 t per period, the scheduling constraints could be modelled as:

$\sum$ R1Ore < 50 000 and

$\sum$ R2Ore < 50 000

Equally, a minimum amount could be modelled to force ore along a particular road or to a specific ROM pad. Once the R1Ore capacity is reached for the R1 ROM pad, then the R2Ore would be the only remaining destination for the ore. In this example, the P1R1 and P2R1 roads would effectively be unusable for the remainder of the scheduling period (Figure 4).

Truck hour cost-based decisions

Now that truck hours are accurately modelled for ore and waste in the pit, along the chosen haul road and in a chosen waste dump, we can introduce the concept of modelling truck costs. As discussed previously, Minemax Scheduler is set up to find the highest

Figure 4. Pit, road and run-of-mine ore accounting.

NPV solution given a set of constraints.

If every truck hour consumed by the schedule costs $150 per hour (for example) and we are looking for a solution that maximises the NPV, the cost of truck hours for each pit/road/dump combination will be evaluated accordingly when identifying the optimal solution.

In the case presented above, if 50 LCM of waste is mined from Pit1 and both Dumps 1 and 2 are available, the haul route chosen by Minemax will be the route that consumes the fewest truck hours from the Pit 1 exit to the final destination in either dump. As the dumps increase in height and the haul distances increase, the truck hours required to place a block in the dump also increases and the dump becomes less attractive.

Similarly, excavator hour costs can be modelled. In material that is harder or slower to dig, the consumption of excavator hours may be greater and therefore the unit cost ($/op hr) can be applied to each consumed excavator hour. The cost of digging will then be taken into account when finding the optimal solution. The same reasoning would apply to material that requires a higher powder factor or consumes more mill hours to process due to ore hardness.

Precedences

Once the key scheduling constraints have been modelled, standard scheduling precedences can be applied. The most obvious precedences prevent a backfill area from being used as a dump until the pit itself has been mined out. Pit-to-pit and pit-to-dump precedences are also added in areas where a certain development sequence must be honoured.

With the dynamic modelling of waste dumping locations, precedences can also be set up between dump locations or within dump cells to model the construction sequence of the waste dump.

Operating cost modelling

As in most mines, operating costs vary with depth, material type, hardness and drill and blast requirements.

In the case study, two types of variable costs have been simulated: volume variable and block variable costs. The total mining cost is the sum of the volume variable and the block variable operating costs.

The volume variable costs (defined as $/t) that have been modelled in the laterite nickel case study include: waste mining, ROM mining, run-of-process ore haulage and ship-loading. These volume variable costs include ancillary, support-fleet costs and overheads but exclude block variable costs.

Block variable costs (defined as $/ hour) vary on a per block basis and include the load and haul costs for the primary fleet. Loading costs vary by material type (softer materials consume fewer excavator hours). Haulage costs vary according to the time taken to haul a block from the bench to the pit exit, along the chosen road and to its final destination (ROM or waste dump).

Capital cost modelling

In addition to simultaneous optimisation of pits, dump and road networks, capital investment decisions can also be assessed as part of the optimal solution.

For example, it may be an option to start production at a satellite mine but to account for the upfront capital cost of building the access roads, infrastructure and pre-strip, a capital outlay may be modelled to create a ‘capital hurdle’ before starting production. When assessing all feasible options, the capital expense of commencing mining operations at the satellite mine (or not) will be utilised in the NPV calculation to assess the optimal solution.

Similarly, additional trucks can be ‘purchased’ during a schedule. For example, if the maximum truck capacity for a particular site is 20 000 hours per year (four trucks), a capital expenditure of one truck (or say $1.5 M) can be modelled that will increase the truck hour capacity per year by 5000 hours from that point onwards.

As the feasible solutions are ranked by NPV, the decision to purchase the additional truck will be based on being able to generate a scheduling solution that has a higher NPV (by mining more ore or hauling further to mine higher-grade ore). If purchasing the truck leads to a lower NPV solution this would not be presented as the optimal solution.

Another application of capital cost modelling to increase the capacity of a process would be for a heap leach operation or mill expansion. The capital expense to expand the processing capacity can be modelled which will enable the timing of the expansion to be determined concurrently among the many other variables that influence the optimal solution.

Revenue modelling

In order to optimise the NPV an assessment of the mining revenue needs to be made. In the case of the laterite nickel mine, the FOB revenue has been modelled. Subsequently all the costs from the mine to FOB have been included in the capital and operating cost estimate.

In other commodities such as copper and gold, the mine gate revenue or the net smelter return is often used as the revenue basis when scheduling.

Scalability

The scheduling example shown in Figure 2 is for illustrative purposes and only considers two pits, two dumps and eight roads. In the case study completed by the authors, the scheduling database contained:

- five mine sites
- 135 pits

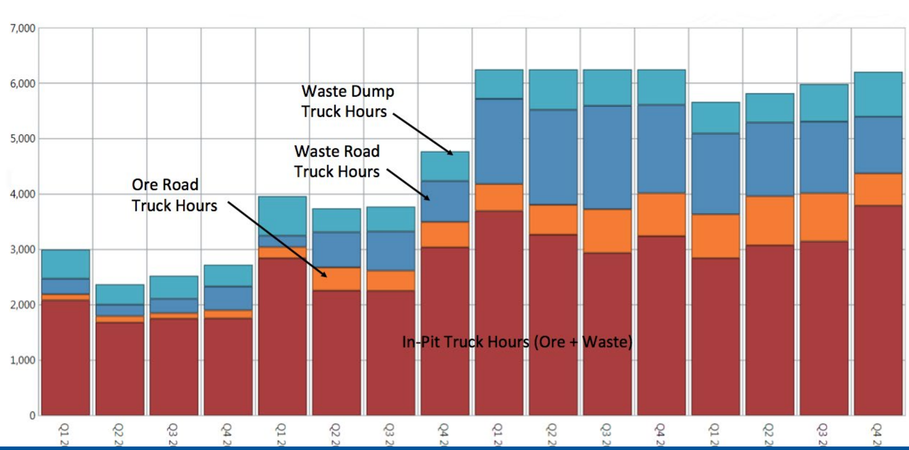

Figure 5. Truck hour accounting.

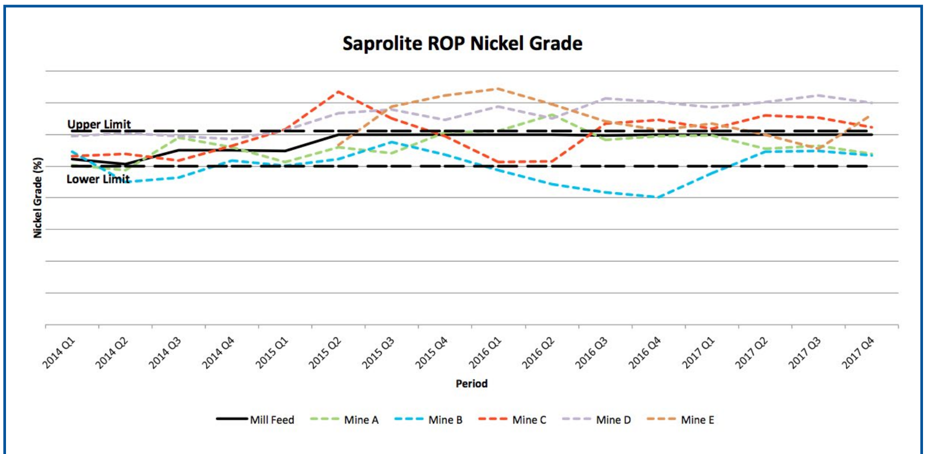

Figure 6. Ore blend specifications – nickel grade.

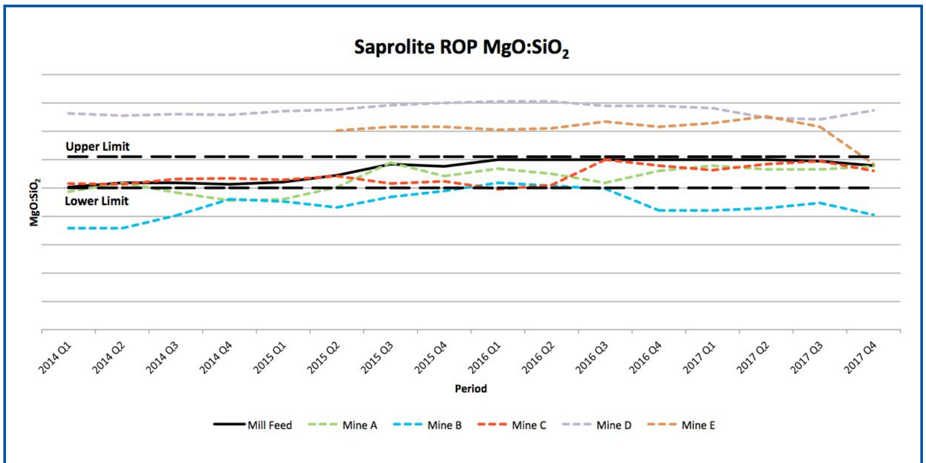

Figure 7. Ore blend specifications – MgO:SiO2.

- 144 waste dumps (including backfill locations)
- 300 possible ore roads
- 390 possible waste roads.

More than 750 constraints were required to track the ore and waste quantities in the schedule. Once set up, each scheduling scenario took between 10-15 minutes to find a solution for 16 quarterly periods.

Mixed-integer linear programming for mine scheduling is not limited to long-term planning applications. Often in short-term mine planning, the feasible solution is harder to identity because there are more constraints.

As planners, we tend to rely on experience and intuition when using a conventional mine planning approach to find an acceptable solution for short-term problems and this invariably leads to sub-optimal solutions. A much simpler scheduling model could be created to assist short-term planning engineers to find the optimal solutions in a matter of minutes.

Integrated schedule output

The validation of the schedule involves ensuring that the solution is practical and honours all of the chemical, physical and social constraints.

Minemax Scheduler is well-suited to finding optimal solutions to complex systems with many constraints within a reasonable processing time. The following figures show a few of the outputs from the integrated production schedule used in the case study. Figure 5 shows the truck hour accounting for a particular pit stage. Figure 6 and Figure 7 demonstrate the suitable solution found to the complex chemical specifications required from a five mine and 135 pit schedule.

OTHER APPLICATIONS

As demonstrated in this paper, highly complex systems can be modelled to simultaneously schedule pit and waste dumping sequences while taking variable haulage costs into account.

While the case study discussed in this paper is a laterite nickel case, there are many other applications where modelling a complex mine scheduling problem using linear programming would improve the present value of the outcome, for example:

- integrated landforms – competing tailings storage facility (TSF) and waste dump construction schedules where a minimum amount of waste rock is designated for TSF construction
- fleet and processing expansion decisions – milling versus heap leach and truck purchasing decisions
- cut-off/over grade and stockpiling decisions – is targeting a higher-grade ore feed really worth the extra mining and stockpiling cost?
- waste landform construction schedule versus truck fleet size – defining a waste landform construction sequence that minimises the operating cost but also maintains a uniform truck hour requirement
- complex blending and stockpiling sequences – what is the optimal blending solution in a multiple element and multiple mine system?

CONCLUSION

Integrated mine production scheduling requires detailed design work to be completed before scheduling can commence. Waste dumps and haul road networks need to be mapped out and assigned to mining locations. Equipment productivities and variable costs also need to be estimated. An integrated mine production schedule expressed as a linear programming problem results in a solution that is both feasible and optimal.

Communicating a mine plan that has clearly honoured the production capacity of the mining fleet along a designed road network, honoured the drill and blast capacity and any waste dump constraints gives the mine planning engineer a very powerful tool to make a case for change at a mine.

Operational teams using the integrated mine production schedule will appreciate the much higher degree of realism involved in producing a mine plan that satisfies both the tactical and strategic mine planning objectives. What-if scenarios can also be evaluated quickly and ranked by NPV or other measures.

It is the authors' opinion that this more realistic and optimal mine scheduling method will result in a greater buy-in of the mine plan from mine operations and senior management. Time will tell whether it will also lead to better compliance to the schedule!

GET IN TOUCH WITH THE AUTHORS

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REFERENCES

Chinneck J, 2001. 'Practical Optimization: A Gentle Introduction'. Available from www.sce.carleton.ca/faculty/chinneck/po.html.

Butler J and George T, 2013. 'Simultaneous Pit and Waste Dump Schedule Optimization'. SME Annual Meeting, Denver. Available from www.minemax.com/downloads/minemax-metal-mining-sme-2013.pdf.