

# Scheduling Tools for Open-Pit Mining Operations

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## Abstract

In open-pit mining operations, there are several levels of planning, each of which passes down restrictions to the level below. Each planning task is to determine the order in which material should be mined and how it should be processed, such that blending and utilisation targets are met. The mining operations are subject to various constraints on equipment use, maintenance and other resources. In this paper, we present a demo for two levels of planning: short-term scheduling and operations planning. The short-term schedule determines the blocks which should be mined, and when. The operational planners have the task of enacting the plans at a finer time horizon. Our system computes a set of schedules that can then be visualised in the form of tables, charts, and maps to support human expert planners.

## Open-pit Mining Operation Problem

In open-pit mining operations, there are several levels of planning, each of which pass down restrictions to the level below. In this paper, we present scheduling tools for two levels of planning in this application: short-term scheduling (13 week horizon) and operations planning (3 week horizon). Our tools are designed to aid decision making in the context of a single open-pit mine that produces a single product with desired bounds on its grade (percentage of metal) and quality (levels of a range of contaminants). The orebody of the mine is divided into a set of blocks, each associated with an estimated grade, quality, and tonnage. The scheduling problem can be heavily constrained. For example, truck and dig unit capacities must not be exceeded, all processing facilities must be utilised to their available capacity, in each week, and mining precedences have to be respected, constraining the order in which blocks of material can be extracted.

The *short-term scheduling* task is to (a) select a set of blocks to be mined in each week of a (typically) 13 week horizon, and (b) allocate routes from the mining source to a destination. The destinations may include processing facilities (crusher), stockpiles or ROM (run of mine stockpile), or waste dumps. The goals are (a) the correct blending of material to produce ore to a specification on average each

week, and (b) the appropriate utilisation of equipment using coarse estimates. The output of a short-term schedule is a set of blocks to be mined within that period, and an allocation of these blocks to weekly mining periods, such that each weekly period conforms with blending and utilisation constraints.

Given a weekly short-term schedule, *operational planners* have the task of enacting the plans—physically, with trucks and dig units—such that all mine performance goals are met. At the core of operational planning is a nonlinear scheduling problem with shared resources, blending, and maintenance constraints. The goals are to refine the blending and equipment utilisation estimates from the short-term schedule, and ensure that resulting plans are realisable. The output of an operational mine plan is a sequence of *builds* (i.e., small, short-term stockpiles) with an allocation of partial movements of material to builds such that the builds have the correct blend and crushers are maximally utilised. The key differences between the two levels of planning are that time units in the short-term schedule is a week, whereas in the operational plan the time unit is a minute—the latter permits a finer analysis of equipment utilisation.

We present, in this paper, a tool for the generation of multiple candidate solutions to the short-term scheduling task, given a priority ordering over a set of supported objectives, and a tool to enact these schedules, in the form of operational plans, taking into account the more complex constraints of daily operations.

## Short-term Scheduler

For the short-term scheduling problem, our system extends prior work, in which a rolling horizon based heuristic was presented for the generation of short-term schedules at single mine sites [(Blom et al. 2014), (Blom, Pearce, and Stuckey 2015)]. This heuristic splits a horizon of  $T$  periods into two periods of size 1 and  $T - 1$ . A mixed integer program (MIP) models the short-term scheduling problem across this two period horizon. Decision variables define which blocks are to be extracted in each period, and the destination of this material. Constraints place restrictions on the use of truck, dig unit, and processing resources. Given a solution to this two-period MIP, the activities of the first period are fixed, and we roll forward one period to consider the remaining horizon. A second two-time period MIP, covering periods 2 and 3 to  $T$ , is solved, and the activities of

period 2 fixed. This process continues until all  $T$  periods are scheduled.

An optimise-and-prune approach, is used to find a solution to our short-term scheduling problem, given a sequence of objectives  $\vec{O}$ , ordered from highest to lowest priority, to be optimised. Each MIP formed by our rolling horizon method is solved, with respect to each objective  $o$  in  $\vec{O}$ , in turn, to obtain a solution  $\vec{x}$  with objective value  $o(\vec{x})$ . Constraints are added to the MIP to prune from the space of feasible solutions all  $\vec{x}'$  for which  $o(\vec{x}') < o(\vec{x}) - \epsilon_o$  for a maximisation objective, and  $o(\vec{x}') > o(\vec{x}) + \epsilon_o$  otherwise, where  $\epsilon_o \ll 1$ . The final solution obtained to the MIP covering periods  $t'$  to  $T$ , after consideration of each objective, is used to fix the activities of period  $t'$ . We have found that this staged method of optimising with respect to a sequence of objectives  $\vec{O}$  is preferable to solving a single MIP whose objective is a weighted sum over  $\vec{O}$ .

A split-and-branch method is designed for the concurrent generation of multiple candidate schedules, each of which extracts blocks in a different sequence across the scheduling horizon. A split and branch factor,  $\alpha_s \geq 1$  and  $\alpha_b \geq 1$ , characterise the number of schedules generated by our solver and the manner in which they differ. Our approach maintains an initially empty set of *schedules in progress*,  $\mathcal{X}$ . We mark  $\alpha_s$  periods in our horizon, starting with  $t = 1$ , as *split points*, evenly distributing these points across the horizon. Starting with the first  $N$ -period MIP solved, covering split point  $t = 1$  and periods  $t = 2$  to  $T$ , distributed across  $N - 1$  period aggregates, we find  $\alpha_b$  distinct solutions. For each of these solutions, we add a new partial schedule to  $\mathcal{X}$  in which the activities of  $t = 1$  haven been fixed. For each schedule  $\vec{x}$  in  $\mathcal{X}$ , we fix the activities of each remaining period until we reach the next split point  $t'$ . At  $t'$ , for each  $\vec{x} \in \mathcal{X}$ , we find  $\alpha_b$  distinct solutions to the relevant MIP, generating and adding  $\alpha_b - 1$  new schedules to  $\mathcal{X}$ , each of which contain the same activities for periods  $t < t'$ , but varying activities in period  $t'$ . This process is repeated until all  $T$  periods, in all  $\vec{x} \in \mathcal{X}$ , have been scheduled, resulting in  $\alpha_b^{\alpha_s}$  distinct solutions to our scheduling problem.

## Operations Planning

At the operations planning level, we utilise event-based formulations presented in (Lipovetzky et al. 2014) and (Burt et al. 2015). The first of these considers state-dependent routing of dig units—as blocks are mined, new shorter paths may become available. We decompose the model into a blending problem (modelled as a mixed-integer program) and a state-dependent routing problem (modelled as a temporal planning problem). The first problem is solved using MIP technology. Given a set of material movements, our solver creates builds with correct blend bounds, while aligning the finish time of each crusher that contributes to the same build. For the small horizons considered, this decomposed approach solves efficiently.

We extend the event-based model to incorporate the utilisation of crushers. This important aspect of operational planning often dominates the impact of state-dependent routing, and so we relax the latter aspect in this model. How-

ever, considering the crusher utilisation still results in a non-linear problem. This version of the utilisation problem can be solved using Constraint Programming, MIP or Mixed-integer Nonlinear Programming algorithms. However, these methods are no longer effective when we wish to incorporate planned maintenance tasks, which may occur daily for trucks, dig units and crushers. To resolve this, we developed a heuristic based on outer-approximation and repair which utilises Mixed-integer Quadratically Constrained Programming algorithms. This heuristic solves also efficiently for the given horizon.

## Demo Scenario

With our short-term scheduling and operations planning tool, a human planner is able to create a variety of *optimisation scenarios*, where each scenario is a sequence of available objectives to consider, listed from highest to lowest priority. Given a split and branch factor,  $\alpha_s$  and  $\alpha_b$ , our solver generates, in parallel,  $\alpha_b^{\alpha_s}$  distinct schedules. The order in which blocks are extracted in each schedule, and the performance of these schedules with respect to the selected objectives, can then be visualised in the form of tables, charts, and maps. Furthermore, the human planner can quickly enact each schedule using the operations solver, checking that indeed the short-term schedule goals can be met when finer and more complex constraints are taken into account.

We demonstrate the use of this software tool for the short-term scheduling of an existing open-pit mine producing several million tonnes of ore per year. Two data sets have been provided by an industry partner for the purpose of demonstrating the tool's capabilities. Each data set relates to a distinct period, and describes the state of the mine, the blocks of ore, and waste available for extraction. This is a decision-support tool for expert human planners, as typically this process is time intense and requires many solving iterations.

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