Solving Large-Scale Production Scheduling Problems in Underground Mining

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Linear Optimization

- The problem possesses a set of decision variables, $x$
- and an objective function comprised of (some of) these variables, which we maximize (or minimize)
- subject to a set of linear constraints, i.e., equalities
- and, in our case, binary restrictions on the variables:

\[
\max cx \\
\text{subject to } Ax = b \\
x \text{ binary}
\]
Solution Techniques

- Instances are large: We may have tens to hundreds of time periods, and thousands to tens of thousands of activities.
- We must use problem structure!
  - Variable Elimination
    - Aggregation
    - Early start times
  - Bienstock-Zuckerberg algorithm
  - Heuristics
LKAB’s Kiruna Iron Ore Mine†

- The mine is above the Arctic Circle in northern Sweden
- It is the second largest underground mine in the world
- The orebody is a world-class high-grade magnetite deposit, approximately 4km long and about 80m wide
- The mine employs about 600 workers and produces about 24 million tons of iron ore per year in the form of three ore products
- Initially, the deposit was mined via surface methods. In 1952, underground mining operations (sublevel caving) began

†Michael Martinez, LtCol - United States Air Force (PhD CSM)
Kiruna’s Location and History

Figure: Northern Europe

Figure: History of Kiruna’s Operations
Sublevel Caving

- Used for vertically-positioned, vein-like deposits
- Horizontal sublevels on which to mine are created
- Ore passes extend vertically down to the sublevels, and access routes run lengthwise on a sublevel
- Crosscuts are drilled perpendicular to the access routes from which the ore is blasted and removed
- Load haul dump units remove the ore and transport it to the ore passes
- The site on which each load haul dump unit operates is referred to as a machine placement
**Figure: A Sublevel Caving Operation**

**Figure: Mine Configuration and Operations**
Long-term Integer Programming Model

- Determine the start date for each machine placement
- Minimize deviation from preplanned production levels for each ore type in each month
- Observe operational constraints:
  - Demand
  - Vertical and horizontal sequencing between machine placements
  - Shaft group
Sequencing Machine Placements

Figure: Machine Placement Sequencing and Detail
Combined Model

- Must account for much more detail than the long-term plans
- There are entities smaller than machine placements
- Each machine placement contains 5-10 production blocks
- The resolution of the near-term part of the schedule must be at the production block level
- Sequencing constraints hold between production blocks
- There is the added complexity of a draw-down line
Sequencing Production Blocks

Figure: Relationship between production blocks, machine placements, and drawdown lines
Results

Figure: Depiction of total deviation (ktons of ore) as a function of the monthly time periods in the planning horizon for both the long-term and combined models.
Lisheen’s Lead/Zinc Mine, Thurles, Ireland

- Located in Europe
- Zn/Pb in hard rock deposit with varied thicknesses
- Situated well below the earth’s surface with difficult ground conditions, e.g., uneven terrain, groundwater
- Partially mined (suboptimally)
- 995 ore areas (blocks)
- Complex and area-specific mining methods: room-and-pillar, long-hole stoping, drift-and-fill

‡Dónal O’Sullivan, Galt and Associates (PhD CSM)
Mining Methods

Figure: Room-and-Pillar
(Hamrin, 2001)

Figure: Long-hole Stoping

Figure: Drift-and-Fill
Motivation for Mine Scheduling Optimization

- Optimize the value of the mine by maximizing discounted metal through the mill
- Determine high-grade ore to bring forward into the 2013-2014 life-of-mine schedule
- Avoid any suboptimal ore sterilization
- Create an objective schedule quickly and run scenario analysis
Mining Requirements

- An area can be mined and backfilled at most once
- Ore production cannot exceed a maximum (per month)
- Average ore grade cannot exceed a maximum (per month)
- Amount of paste cannot exceed a maximum (per month)
- Number of areas being backfilled cannot exceed a maximum (per month)
- Precedence constraints between mining-mining, mining-backfilling, backfilling-mining, and backfilling-backfilling exist
Pillars’ Precedence and Depiction of Haulage Route
Mine Complexity

Mining design is inconsistent:

- Some areas are very large (68,000 Tonnes) while others are very small (71 Tonnes)
- The same block can appear in two geographically distant areas of the mine
- Parts of the mine are on three levels
- Some areas need to be backfilled, while others do not
- Different areas of the mine have different precedence requirements even if the areas appear to be similar
- Some currently enforced precedence rules seem illogical
- The timing of the extraction of high-grade haulage pillars is a critical aspect of the mine schedule
Results: Metal is Brought Forward in the Schedule

- Manual Schedule
- Integer Program Schedule

<table>
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<th></th>
<th>Year 1</th>
<th>Year 2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal (Tonnes)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manual</td>
<td>1,200</td>
<td>1,100</td>
<td>2,300</td>
</tr>
<tr>
<td>Integer</td>
<td>1,300</td>
<td>1,000</td>
<td>2,300</td>
</tr>
</tbody>
</table>

Total Metal: 4,600 tonnes (Manual: 2,300, Integer: 2,300)
Comparison of Manual and Optimized Schedule

Graph showing the comparison of manual and optimized schedules in terms of tonnes of ore produced over weeks. The graph includes a line for manual schedule, a dashed line for IP schedule, and a dotted line for minimum production.
Lisheen Added a Bypass for High-Grade Pillars
An American Gold Mine: Collaborators

- Andrea Brickey, Professor, Mining Engineering, South Dakota School of Mines
- Barry King, PhD Candidate, ORwE, CSM
- Daniel Espinoza, Professor, Department of Industrial Engineering, Universidad de Chile
- Eduardo Moreno, Professor, Faculty of Engineering and Science, Universidad Adolfo Ibañez
- Marcos Goycoolea, Professor, School of Business, Universidad Adolfo Ibañez
- Orlando Rivera, PhD Student, Industrial Engineering and Operations Research, Universidad Adolfo Ibañez
Introduction

- Determine development, mining, and backfilling activity start dates
- Maximize “discounted” gold extracted
- Adhere to resource and precedence constraints
Data consist of 24,000 individual activities that require from 1 to 78 days to complete.

All activities correspond to one of 46 design elements.

Design elements are categorized into 10 activity types based on required constraints.

Constraints apply to individual or multiple activity types.
Mine Layout

Figure: Overall Layout

Figure: Detailed Layout
Activity Types

- **ED**: exploration development activities
- **DL**: drilling activities
- **JM**: jamming activities
- **VD**: vertical development activities
- **PD**: primary development activities
- **SD**: secondary development activities
- **SM**: stope mining activities (stopes, cut-fill, up-hole, floor pull)
- **PB**: paste backfill activities
- **CB**: cemented rock backfill activities
- **RB**: unconsolidated rock backfill activities
Results: Cumulative Metal Production
Monthly Ventilation Levels
Where is the Math?