Optimizing the Transition from Surface to Underground Mining

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Determine the horizontal levels (strata) in a mine that should be extracted via surface methods, and those that should be extracted underground.

A stratum can require more than one time period to extract, but is entirely extracted via at most one method.

Assumptions:
- Stratum and bench data are given
- A single underground method is employed
- Strata are mined continuously
Mine Configuration

- All surface strata are contiguous; all underground strata are contiguous
- Unmined strata can occur:
  - between surface and underground strata (crown pillar)
  - under the underground strata (footprint)
Figure: Surface-to-underground mine transition
Parameters

- \( r \): discount rate
- \( \hat{c}_s \) (\( \tilde{c}_s \)): profit from mining stratum \( s \) via surface (underground) methods (\$)
- \( \hat{\rho}_{st} t \) (\( \tilde{\rho}_{st} t \)): 1 if stratum \( s \) is still being mined at time \( t \) via surface (underground) methods given that it started to be mined in \( t' \), 0 otherwise
- \( T \): number of time periods in the horizon
- \( f_{st} \): fixed cost of going underground at \( s \) and time \( t \)
Variables

- $w_{st} = 1$ if we transition underground at stratum $s$ and time period $t$, 0 otherwise
- $\hat{y}_{st} = 1$ if stratum $s$ starts to be mined via surface methods in time period $t$, 0 otherwise
- $\tilde{y}_{st} = 1$ if stratum $s$ starts to be mined via underground methods in time period $t$, 0 otherwise
- $z_s = 1$ if stratum $s$ is never mined (and does not define a boundary), 0 otherwise
- $\hat{z}_s (\tilde{z}_s) = 1$ if stratum $s$ is the stratum at the top (bottom) of the crown pillar, 0 otherwise
- $\bar{z}_s (\underline{z}_s) = 1$ if stratum $s$ is the stratum at the top (bottom) of the footprint, 0 otherwise
Objective and Constraints

Maximize profits from each stratum mined either on the surface or underground less fixed infrastructure cost of going underground

Subject to

- A stratum can be mined at most once and via at most one method
- Surface sequencing constraints
- Underground sequencing constraints
- No simultaneous mining above and below ground
- Definition of crown pillar
- Definition of the footprint
- Allow at most one top of crown pillar, bottom of crown pillar, top of footprint, and bottom of footprint
- Relative placement of crown pillar and footprint
- Logic referring to fixed cost of going underground
- Mining commences on the surface
Solution Strategies

- Integer programming
- Dynamic programming
- Network modeling
Series of networks

Figure: Solution strategy via networks
Case Study: Palabora Mine

- Produces 30,000 tons per day via underground block caving
- Employs approximately 2,400 people and is expected to continue operations until at least 2020 based on proven reserves of 225 million tons of material with 0.7% copper grade
- Contains 87 strata requiring between 1 and 28 3-month time periods to extract (over 1700 meters from the surface to the deepest level being considered for extraction), 280 three-month time periods, one mining rate both above- and underground, and two cutoff grades, 0.4% and 0.6%
- Assumes that the same cutoff grade must be used for all strata extracted underground
Optimal Solutions for Various Copper Prices and Discount Rates

Table legend: strata mined on the surface; strata mined underground

<table>
<thead>
<tr>
<th>Annual Disc. Rate (%)</th>
<th>Ore Price (dollars per pound)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.00</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1-25; 87-26</td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
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<td>14</td>
<td></td>
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<tr>
<td>16</td>
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</tbody>
</table>
At higher copper prices, one should extract more strata

At higher discount rates, one should extract fewer strata

One may think that a higher discount rate might lead one to go underground earlier when much of the highest-ore-grade material is deep underground

One might think that it would be better to go underground earlier to reach those highly profitable strata earlier

It may be possible to find solutions that are fairly robust to forecast errors regarding ore prices and discount rates
Comparisons

- If we use an “adjacent” solution, differences in profit can be 1%

- **Myopic Heuristic 1** If we decide whether to extract the next stratum on the surface using the better of the two cutoff grades and then continue with the best possible underground extraction plan, or go underground now and continue with the best possible plan: 27%-53% from optimal

- **Myopic Heuristic 2** If we look ahead only one stratum at a time and greedily decide what to do next: whether to extract the next stratum on the surface using the better of the two cutoff grades, or whether to build the underground infrastructure and extract the best stratum underground, considering also the cost of the underground infrastructure

- **Palabora’s actual schedule and future plan** Strata 1-33 on the surface at a 0.4% cutoff grade and strata 53 to 34 underground at a 0.6% cutoff grade.
## Comparison of Solution Quality

<table>
<thead>
<tr>
<th>Annual Disc. Rate</th>
<th>Percentage Gap from Optimality Second Myopic Sol’n</th>
<th>Palabora Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%</td>
<td>25.1</td>
<td>24.7</td>
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<tr>
<td>4%</td>
<td>15.5</td>
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<td>6%</td>
<td>8.9</td>
<td>7.7</td>
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<tr>
<td>8%</td>
<td>5.0</td>
<td>4.1</td>
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<tr>
<td>10%</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>12%</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>14%</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>16%</td>
<td>0.3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Table:** Percentage Gap from Optimality for the Second Myopic Solution and Palabora’s Plan