Optimize Earthwork Hauling Plan with Minimum Cost Flow Network

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Outline

- Background
- Minimum Cost Flow Based Method
- Case Study & Validation
- Conclusion
Background

Site grading design completed

- Cut fill balance
- Quantity takeoff

Major tasks in earthwork planning:

- Material Earthwork Allocation
- Temporary haul road design
- Equipment Fleet optimization
Background

Earthwork allocation:
Find the most economic combination of haul jobs to move the material from section to section

<table>
<thead>
<tr>
<th>Job</th>
<th>Cut</th>
<th>Fill</th>
<th>Volume (bcm)</th>
<th>Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job-A</td>
<td>20</td>
<td>19</td>
<td>8100</td>
<td>-</td>
</tr>
<tr>
<td>Job-B</td>
<td>20</td>
<td>18</td>
<td>16700</td>
<td>[19]</td>
</tr>
<tr>
<td>Job-C</td>
<td>21</td>
<td>18</td>
<td>5500</td>
<td>[20, 19, 17]</td>
</tr>
<tr>
<td>Job-D</td>
<td>21</td>
<td>17</td>
<td>4400</td>
<td>[20, 19, 18]</td>
</tr>
<tr>
<td>Job-E</td>
<td>33</td>
<td>17</td>
<td>18600</td>
<td>[21, 20, 19, 18]</td>
</tr>
<tr>
<td>Job-F</td>
<td>33</td>
<td>16</td>
<td>36000</td>
<td>[21, 20, 19, 18, 17]</td>
</tr>
<tr>
<td>Job-G</td>
<td>33</td>
<td>15</td>
<td>8400</td>
<td>[21, 20, 19, 18, 17, 16]</td>
</tr>
</tbody>
</table>
Problem

Limitations of earthwork allocation optimization by linear programming

1) Time consuming to establish and solve equations
2) Generate Haul jobs with conflicts:
   Hard blocks: Can be identified before hand, but cannot be eliminated.
   Soft blocks: Embedded within haul jobs, can be eliminated.
3) Cannot provide job sequence
Simulation Methods

Construction Operations Simulation

Operation oriented: fleet selection

Limitations:
Simulation is separated from earth work allocation

1) User specify the route manually
   (Hajjar and AbouRizk 1997, Marzouk, and Moselhi 2004)

2) Simulate with non-optimal heuristic approach
   (Morley, Lu, and AbouRizk 2014)
Minimum Cost Flow (MCF) Based Method

Research objective

1) Easy to use tool

2) Accommodate “hard blocks”

3) Avoid “soft blocks”

4) Integrate time (job sequence) into earthwork planning
Minimum Cost Flow (MCF) Based Method

Framework

Earthwork Allocation with Flow Network Optimization

- Existing Roads
- Reserved Areas
- Accessibility
- Base Speed Between Sections
- Cut/Fill Volume and Layout
- Flow Network Construction
- Minimum Cost Flow Optimization

Optimal Earth Flow Network

Earthwork Plan Generation

- Heuristic Rules
- Layout/Order constraints

Earthwork Plan

8
Minimum Cost Flow (MCF) Based Method

Minimum cost flow network

\[
\text{minimize } \sum_{(i,j) \in A} c_{ij}x_{ij}
\]

\[
\sum_{j:(i,j) \in A} x_{ij} - \sum_{j:(j,i) \in A} x_{ji} = b(i) \quad \text{for all } i \in N
\]

\[
l_{ij} \leq x_{ij} \leq u_{ij}
\]

for all \((i,j) \in A\)

N is a set of \(n\) nodes
A is a set of \(m\) directed arcs
Minimum Cost Flow (MCF) Based Method

Flow network construction

<table>
<thead>
<tr>
<th>Arcs</th>
<th>Directions</th>
<th>Unit costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area A</td>
<td>fill</td>
<td>Area B</td>
</tr>
</tbody>
</table>

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 37133 | 14846 | 5013 | 1065 | -7288 | -9169 | -2661 | 16089 |
| 24797 | 4497 | -17920 | -26853 | -27369 | -21327 | -4500 | 11153 |
| 21111 | 3339 | -4915 | -8243 | -8123 | -8382 | -3025 | 10732 |

Area A is a negative net volume area (fill);
Area B is a positive net volume area (cut).
Minimum Cost Flow (MCF) Based Method

Earth Flow Network
Turning optimum material network flows into ready-to-execute haul jobs

**Heuristic rules**

1) Maximum flow first
2) Minimize mobilization of excavators
Haul jobs derived from optimum material flows

<table>
<thead>
<tr>
<th>Sub Flow</th>
<th>Job</th>
<th>Cut</th>
<th>Fill</th>
<th>Volume</th>
<th>Route (R)</th>
<th>Predecessor</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>10</td>
<td>11</td>
<td>1065</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>22</td>
<td>19</td>
<td>2661</td>
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<td>-</td>
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<tr>
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<td>22</td>
<td>16</td>
<td>9169</td>
<td>[19]</td>
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<td>[19,16]</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
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<td>6</td>
<td>23</td>
<td>17</td>
<td>6653</td>
<td>[20]</td>
<td>5</td>
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<td>5</td>
<td>8</td>
<td>4497</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2</td>
<td>8</td>
<td>13423</td>
<td>[5]</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>2</td>
<td>11</td>
<td>5929</td>
<td>[5,8]</td>
<td>8</td>
</tr>
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</table>
## Validation & Evaluation

### Optimal validation & evaluation

<table>
<thead>
<tr>
<th>Method</th>
<th>Average weighted haul distance (m)</th>
<th>Haul effort (bm4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morley, Lu, and AbouRizk (2014) Heuristic rules</td>
<td>411</td>
<td>165,805,946</td>
</tr>
<tr>
<td>Morley, Lu, and AbouRizk (2014) Random rules</td>
<td>431</td>
<td>173,790,000</td>
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<tr>
<td>Proposed Method</td>
<td>401</td>
<td>161,543,988</td>
</tr>
<tr>
<td>Improvement compared to Random Rules</td>
<td>7%</td>
<td>8%</td>
</tr>
<tr>
<td>Improvement compared to Heuristic Rules</td>
<td>3%</td>
<td>3%</td>
</tr>
</tbody>
</table>
Validation & Evaluation

Block removal validation & evaluation

Layout 1

Layout 3
Validation & Evaluation

Block removal validation & evaluation

Mutual reliance of shortest path based method reaches up to 60%.

Mutual reliance is eliminated in proposed research.

<table>
<thead>
<tr>
<th>Layout</th>
<th>Percentage of Jobs with Mutual Reliance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Liu and Lu (2014) (Original) with Floyd’s Algorithm</td>
</tr>
<tr>
<td></td>
<td>Proposed Method</td>
</tr>
<tr>
<td>Layout1</td>
<td>34/57 = 60%</td>
</tr>
<tr>
<td>Layout3</td>
<td>30/56 = 54%</td>
</tr>
</tbody>
</table>
Conclusion

The paper proposed an approach which:

1) Provides an intuitive graph based interface.

2) takes job sequence and constructability into consideration.

3) Is able to generate multiple optimal solutions – practically feasible.

4) Eliminates “soft blocks”
Questions ?