Rail scheduling for the Hunter Valley Coal Chain
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www.csiro.au

Mathematics of Transportation Networks, June 2013
Coal Supply Chain in Australia

Australia produced 446.17 (08-09) and 471.09 (09-10) million tonnes of coal. 60-62% of coal is exported.

Biggest contributor in Australian GDP. Exports worth more than $50 billion in 08-09.

Trains transporting coal are among the longest in the world.

8500 tonnes train has as many as 6 locomotives and 148 wagons amounting to a length of more than 2 kilometres.

Forecast of 390Mt by 2015, to support increasing coal demand from the emerging economies, China and India.
Hunter Valley Coal Chain – World’s Largest Coal Operation

- **Gunnedah**: 364 km from Port, 25 hr cycle time, 25t axle load, PN: 72w, 5400t trains
- **Stratford**: 170 km from Port, 11 hr cycle time, 25t axle load, PN: 42w, 3000t trains

**Hunter Valley**
- Up to 100 km from Port, Max 9 hr cycle time, 30t axle load, PN: 91w, 8500t trains, QR: 74w, 7200t trains

**Ulan**: 276 km from Port, 18 hr cycle time, 30t axle load, PN: 91w, 8500t trains, QR: 74w, 7200t trains

- **Existing (or under construction) Coal Mine Loading Terminals**
- **Power Station Coal Unloading Terminals**
- **Export Coal Loading Terminals**
- **Proposed coal mines**
- **Townships**
Hunter Valley Coal Chain Coordinator

HVCCC Members

14 Producers

Pacific National
QR
National
Freightliner
Australian Rail Track Corp
Southern Shorthaul Railroad

Port Waratah Coal Services
Newcastle Coal Infrastructure Group

Newcastle Port Corp

Producers
- 40 coal mines
- 14 producers
- 27 load points
- > 80 different brands of coal

Track
- 3 large train haulage operators
- Further 2 smaller train haulage operators
- 45+ trains / 16,000 trips per year
- 2 track owner / operators
- Haulage distances up to 384km

Export Coal Terminals
- 3 coal loading terminals
- 6 dump stations
- 6 ship berths and loaders
- 1.8 Mt of rapid cargo build stockpiles at PWCS
- Longer horizon dedicated stockpiles at NCIG

Port/Vessels
- Approx 1,200 vessels per year
- Average vessel size is 89,000 tonnes
- Average 1 to 4 cargoes per vessel
- Tidal constrained river port

End Buyers
- 10% domestic consumption
- 90% export – mostly thermal
- 79% to Japan and Korean markets

Courtesy HVCCC

Planning

Hunter Valley Coal Chain Coordinator
• Responsible for planning and scheduling of all coal exports from the Hunter Valley supply chain
• Separate company that is owned by and accountable to all of the major players in the supply chain (mining companies, ports etc)

Planning Horizons:
• Strategic: Capacity expansion and changes to business rules looking at 2-10 year horizons
• Tactical: Maintenance planning, capacity allocation (to different companies), etc looking at periods of up to 1 year
• Operational: Managing ship queue, stockpile allocations, train scheduling etc for 1 day to maximum 2 weeks out
• Live run: day of operations disruption management

IPS Software: Shared view of planning and scheduling related data
• Currently being re-built
• Rail Scheduling Tool is first major optimisation component – expected to go live later this year
Rail Scheduling Context

- Need to plan train trips for typically 1 day – maximum 2 days in advance
- Ship loading sequence and stockpile allocations already decided in a previous phase
- Stockpile plans include approximate time of railing
  - number of train loads to be brought in from each mine per day
- Main aim is to schedule all of the planned trains
  - several additional objectives and soft constraints
- Current manual process (point-and-click software) takes approximately 1 working day to prepare schedule for 1 day
  - Extensive software for managing schedules, plans and related data currently being re-written by 3rd party software company (QMastor)
- Need to work around availability of trains, mines, terminal machines etc
Rail Scheduling Tool Requirements
Trains

1. Trains (aka units) come in a range of sizes (2000t to 8500t)
2. May be operated by one of multiple companies:
   • Pacific National, Queensland Rail,
3. May have pre-assigned activities
   • “current” roundtrips to deliver coal to terminal: determines starting position of trains
   • Domestic trips – providing coal for local power plants
   • Outages
   • Maintenance – some flexibility to determine timing
4. Perform cycles of travelling to mine, loading, returning to Newcastle and unloading at one of the terminals
5. Operate 24 hours per day
6. Need to refuel after every 1-2 trips (depending on distance)
7. Crews change at the terminal after unloading and for longer trips also at inland points
   • Crew scheduling implications are not considered during rail scheduling
Train Network

Tree structure with trunk line up the Hunter Valley and branches to mines
Single track sections with limited opportunities for passing near the mines
All three terminals are conceptually at the root of the tree network for the purpose of this model

Train Paths:
• Define time slots for possible use of the network by coal trains
• Result in finite set of train departure & arrival time choices
• Allow for other uses of the trunk line – eg interaction with passenger trains and freight trains between Sydney and Brisbane
Example of loadpoint loop

Whittingham Branch

Bulga

MT2

WK1

1600mtrs

1300mtrs

1550mtrs

1250 metres

700 metres

1377 metres

10.6 KM’ s

4.623klns

1000mtrs

1800 metres

1250 metres

1700mtrs

1700mtrs

Wambo

Down Main
Mines

Often several mines owned by same company
May produce several coal “products”
Restrictions on types of trains accepted based on:
  • Train size – physical restriction
  • Train operator – contractual restriction
Outages – maintenances or other restrictions
Tend to have uneven usage depending on shipping demand
Change-over time:
  • Need to “recharge” train loaders
  • May need a coal change-over time if two consecutive trains are loading different coal products (not currently implemented)
  • Sometimes on separate loops or may have several mines on the same loop off the main line
    • In extreme cases loading of trains at one loadpoint can interfere with other trains loading at another mine
Terminal Resources

Dump station
• Unload trains by opening bottom of train as it drives through the station allowing coal to into a bin

Conveyor to stacker

Stacker
• Places coal onto stockpile
• May be connected to multiple dump stations at a terminal
• Restriction on which stacker can be used based on stockpile where coal is to be stacked (normally 1 or 2 choices)

Stacking may interfere with reclaiming for ships
• some stackers are also reclaimers
• physical safety distance restrictions between different machines
• this interaction is not explicitly modelled in the rail scheduler

Reclaimers, ship loaders, berths, ships
• out of scope for the rail scheduler
Shipping Demand

1 ship $\rightarrow$ multiple cargos
1 stockpile $\rightarrow$ multiple components
may require coal from different mines
to be loaded onto the same stockpile

Tried to let the optimiser decide on train sizes, but
• Solutions were not much better
• The problem became harder to solve
• Planners were unhappy. They just want to see schedules with train sizes as they had originally planned

Need to have all coal for a ship at port before ship is allowed to berth

Typically takes 5-10 days to assemble stockpiles for a ship
more time required for mines further from port with longer cycle times

Stockpiles completely cleared when a ship is loaded
Aim of Rail Scheduling

Reduce time spent by planners

Schedule all planned train trips to units

Create a “good” schedule:

• As much coal scheduled as possible – components are prioritised
• Minimum delays
• Minimum train idle time – and where possible keep trains waiting at the mines not near the terminals
• Preferred dumper-stacker combinations used at the terminals
• Minimise (or maximise) the number of units used

In the short term finding places to “park” trains can be difficult so maximising utilisation makes sense.
Rail schedule

Create roundtrips to collect planned coal. Need to schedule:

- Departure time from a terminal at Newcastle (forward path)
- Start & end loading at mine loadpoint (fixed duration)
- Departure time from mine loadpoint (return path)
- Start & end unloading at a dump station
- Maintenance times
- Refuelling times

Resources to assign:

- Which unit to use for each roundtrip
- What mine to go to
- Dump station for unloading
- Stacker for unloading
- Arrival & departure roads (tracks) at the terminals
Summary of outputs

Summary of Data
- 32 units
- 51 compartments
- 237/208 forward return paths
- Schedule from 2016-09-03 to 2016-09-04 2350:00

Preassigned activities for units

Domestic Trip
Export Trip
Outage
Unit schedule

Scheduled activities for units
Train activities

- Refuelling
- Forward path
- Loading time
- Return path
- Total dumping - stacking time.

- Idle time
- Start and end of scheduled activity. Includes crew change over time.
- Idle time at arrival road.
Summary - loadpoint

Summary

- 1.00/17/39 average trains per day

Scheduled activities for loadpoints

<table>
<thead>
<tr>
<th>Name</th>
<th>Tonnies</th>
<th>Trains</th>
<th>03/09/10</th>
<th>04/09/10</th>
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<tr>
<td>ASHTON</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
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<tr>
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<td>BALGA COAL</td>
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<tr>
<td>BLOOMFIELD</td>
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<td></td>
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</tr>
<tr>
<td>BONGALLA</td>
<td>17000</td>
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</tr>
<tr>
<td>BOOYABALE</td>
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<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MT ARTHUR COALTER</td>
<td>43200</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CARELSWELL</td>
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</tr>
<tr>
<td>DRAFTON</td>
<td>22500</td>
<td>3</td>
<td></td>
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<tr>
<td>G imperson</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
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<tr>
<td>HACTER VALLEY</td>
<td>59000</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAMBO COAL TERMINAL</td>
<td>25800</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEEDELL</td>
<td>5500</td>
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<td></td>
<td></td>
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<tr>
<td>MT THORLEY MILLERS</td>
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<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOUNT OWEEN</td>
<td>67100</td>
<td>8</td>
<td></td>
<td></td>
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<tr>
<td>MOLLARDEEN</td>
<td>7200</td>
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<td>MT BIN 2</td>
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<td></td>
</tr>
<tr>
<td>MT BIN 3</td>
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<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NARRABRI</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Summary- Tonnages

Summary

A total of 570560 tons is delivered by the schedule in 75 train trips

Component Summary

[Diagram showing tonnage data with numerical values]
Summary – Loadpoint Demand
Mathematical Formulation
Model 1: Roundtrip packing

Define a roundtrip by:

- Unit that is carrying out the trip
- Departure on a particular forward path
- Loading interval at mine
- Return path

Each roundtrip has a value:

- amount of coal delivered, idle time included, etc

Select (pack) the maximum set of roundtrips that can be accommodated without resource conflicts

- Create a discrete set of times when conflicts may occur (cliques)
- Constraints: no. roundtrips using resource \( r \) at time \( t \) at most 1

\[
\text{Max } \sum_i v_i x_i \\
\text{S.t. } \sum_{i \text{ uses } r \text{ at } t} x_i \leq 1 \\
x_i \in \{0, 1\}
\]

- Unloading time at terminal
- Dump station
- Stacker stream
Model 1: Roundtrip packing

Requires artificial restriction on maximum idle time to make number of roundtrips manageable
  • Still get millions of potential roundtrips

Formulation too large to solve with CPLEX on a 32 bit computer

However can get good solutions with Lagrangian approach
  • Use Lagrangian relaxation of all of the constraints
  • Volume algorithm for determining good Lagrange vector
  • Repair heuristic to get feasible solutions

Pros:
  • good solution with relatively tight bounds in reasonable amount of time
  • Can accommodate reasonably complicated roundtrip restrictions

Cons:
  • Can’t account for resource usage between roundtrips
  • Limited flexibility for waiting at loadpoints & arrival roads – otherwise size explodes
  • Refuelling requirements based on previous trips can’t be accommodated
Model 2: Train network model

Represent what a train can do as a time-space network with additional resources
• Nodes = location in space and time
• State = coal loaded, fuel level, maintenance state
• Edges = activities that a train can carry out

Solve resource constrained shortest path problems as Lagrangian sub-problems

Effectively an extended version of Model 1 with a set of roundtrips for a unit generated on the fly.
High level view of the network
Network Graph for a Unit

Activities

States / Locations
Activities for a unit

- From: Dep/Hot Road
  To: Dep/Hot Road
  Activity: Idle

- From: Refuel Dep Rd
  To: Refuel Dep Rd
  Activity: Refuelling

- From: Loadpoint/Loop
  To: Loadpoint/Loop
  Activity: Idle

- From: Loadpoint
  To: Loadpoint
  Activity: Load

- From: Loadpoint
  To: Arrival Rd
  Activity: Maintenance

- From: Loadpoint
  To: Loadpoint
  Activity: Travel

- From: Loadpoint
  To: Loadpoint
  Activity: Load

- From: Arrival Rd
  To: Arrival Rd
  Activity: Idle

- From: Arrival Rd
  To: Dep Rd
  Activity: Dumping

- From: Dep Rd
  To: Loadpoint
  Activity: Travel

- From: Dep Road
  To: Dep Road
  Activity: Crew Change
States of a Train

Location:
- Any of the departure roads, load points or arrival roads

Time:
- Generally discretised in steps of no more than 5 minutes
- Effectively a train will only “reconsider” its decision as to what to do next every “time-step” minutes, also the resource usage is in multiples of this time-step

Loaded state:
- Whether the train is full or empty. For full trains the state also specifies the loadpoint it was loaded at.

Fuel:
- The amount of “fuel” left in the tank – determines what loadpoints can be reached without refuelling (relaxed to a soft constraint)

Maintenance:
- Whether any moveable (FX) maintenances for the unit have already been carried out
Formulation

Let $x_{us}$ be a binary variable for selecting schedule $s$ of unit $u$
Let $B_{us}$ be the benefit of carrying out schedule $s$ on unit $u$
Solve

$$\text{Max } \sum B_{us} x_{us}$$

Subject to:

$$\sum_{s \text{ uses } r \text{ at } t} x_{us} \leq 1 \quad \text{for all resources } r \& \text{ times } t$$

$$x_{us} \in \{0, 1\} \quad \text{for all feasible schedules } s \text{ of } u$$

Note that there are an extremely large number of possible schedules but we never enumerate these
• Column generation but without use of a column pool.
• Only 1 schedule per unit considered at any one time
Algorithm

Lagrangian relaxation of all resource constraints

Solve resource constrained longest path problem in the acyclic train state-space network for each unit to generate one schedule at a time

Volume algorithm for optimising dual values
- Like subgradient ascent but with bundle-method like stabilisation of the search direction

Lagrangian repair heuristic for finding optimal solutions
- Iteratively construct schedule one roundtrip at a time and fix out edges in train network based on roundtrips already scheduled for other units
- Ant colony optimisation method for selecting optimal order in which to construct roundtrips

Parallelisation:
- Solve longest path sub-problems for each train in parallel in the Lagrangian iterations
- Run ant construction in parallel in the ant colony optimisation
Indicative Results
Model 1

Maximisation with up to 2 hours of idle time for 3 datasets

<table>
<thead>
<tr>
<th>Dataset:</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns (M)</td>
<td>2.1</td>
<td>4.8</td>
<td>2.1</td>
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<tr>
<td>Non-zeros (M)</td>
<td>129.9</td>
<td>338.6</td>
<td>131.5</td>
</tr>
<tr>
<td>Lag.Heur (1hr) LB/UB</td>
<td>240.9 / 272.8</td>
<td>177.5 / 329.9</td>
<td>183.1 / 215.3</td>
</tr>
<tr>
<td>Gurobi (1hr) LB / UB</td>
<td>231.1 / inf</td>
<td>157.0 / inf</td>
<td>177.0 / inf</td>
</tr>
<tr>
<td>CPLEX (1hr) LB / UB</td>
<td>0.0 / inf</td>
<td>--- / inf</td>
<td>0.0 / inf</td>
</tr>
<tr>
<td>Lag Heur (10hr) LB/UB</td>
<td>240.9 / 259.2</td>
<td>178.7 / 191.7</td>
<td>184.9 / 199.1</td>
</tr>
<tr>
<td>Gurobi (10hr) LB/UB</td>
<td>255.9 / 258.9</td>
<td>157.0 / inf</td>
<td>196.4 / 198.9</td>
</tr>
<tr>
<td>CPLEX (10hr) LB/UB</td>
<td>227.9 / 258.9</td>
<td>0.0 / inf</td>
<td>0.0 / inf</td>
</tr>
</tbody>
</table>

16 core CPU with 100Gb RAM Lag. Heur. run serial only
# Data Sets for Model 2

<table>
<thead>
<tr>
<th>Instance</th>
<th>No. of relaxed Constraints</th>
<th>No. Trains</th>
<th>No. Trips requested</th>
<th>Pre-assigned activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>64</td>
<td>43</td>
<td>31</td>
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<tr>
<td>B</td>
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<td>27</td>
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<td>C</td>
<td>30,692</td>
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<td>26</td>
</tr>
<tr>
<td>D</td>
<td>38,108</td>
<td>63</td>
<td>45</td>
<td>34</td>
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<tr>
<td>E</td>
<td>38,096</td>
<td>61</td>
<td>50</td>
<td>27</td>
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<tr>
<td>F</td>
<td>37,120</td>
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<td>78</td>
<td>1</td>
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<tr>
<td>G</td>
<td>49,605</td>
<td>38</td>
<td>120</td>
<td>22</td>
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<tr>
<td>H</td>
<td>33,360</td>
<td>38</td>
<td>48</td>
<td>12</td>
</tr>
</tbody>
</table>
Gap achieved with increasing CPU time

Significant gap reductions:
Due to better bounds or better solutions?
Gap to best solution found

Relaxed bounds contribute most to gap reductions
Improvements to schedule quality

Good results within 1 hour of CPU time
Better than single threaded method but could improve
Cluster based distributed method

Initial experiments using a heterogeneous distributed method based on Ant Colony + Bee Colony + Lagrangean Optimisation

Wall time on a Linux cluster with increasing number of cores (12 per node)
Conclusions

1. Challenging scheduling problem
2. Fixed time points from paths allows set packing style formulation with Lagrangean relaxation based solution approach
3. Time-space network based solution method allows more sophisticated Lagrangean approach
4. Reasonable solution quality in acceptable run time
5. Can gaps be improved?
   - Longer/faster runs, better formulations, ...
   - Branch & Bound for exact solutions
6. Better heterogeneous parallel search methods
Questions?

Andreas Ernst
Operations Research Group Leader
CSIRO Mathematics, Informatics & Statistics
What is the best way to model the Hunter Valley supply chain?

Modelling Research:
What is the best trade-off between realism and optimality?

- High Model Detail
  - Optimality Gap
    - Simulations
  - Stochastic Optimisation
  - Advanced optimisation algorithms research

- Low Model Detail
  - No Optimisation
    - (evaluation only)
  - Provably Optimal

CSIRO CPM Optimiser

Model-Reality Gap

Spreadsheet
Hunter Valley Coal Chain: Capacity Planning

Question:

- As the demand is expected to increase, what are the optimal expansions required to satisfy the demand at minimum delay?

CSIRO developed a capacity planning library, which is useful for modelling all the operations and complex constraints of a supply chain

- Creates long term infrastructure investment plans based on historical or future throughput demand for a 3-12month period
- Identify bottlenecks in the supply chain
- Shows minimum cost additional facilities/expansion required to cope with proposed throughput and trades this off against delays.
- Can be used in conjunction with simulation systems.
HVCC Capacity Planning Model

**Inputs:**
1. Shipping demand – scenario including variability over ~6 months
2. Existing infrastructure – rates and efficiency/utilisation factors
3. Relative costs of upgrades

**Outputs**
Lowest cost expansion to process demand:
- Increased train loading rates at any of the loadpoints
- Increased junction capacities
- Additional wagons/trains
- New dump stations at any of the terminals
- Additional stackers or reclaimers at any of the yards
- Ship loading infrastructure

Operational plan – day by day usage of infrastructure

Trade-off with shipping delay (controllable via input parameters)
HVCC Capacity Planning Model in Practice

Used in conjunction with existing simulation model

Good agreement between simulation & optimisation models

Optimisation guides selection of scenarios to analyse in more detail with simulation

Useful insight into combination of expansions that is most cost-effective for dealing with significantly increased throughput.
Tactical Planning
Train Network

Tree structure with trunk line up the Hunter Valley and branches to mines
Single track sections with limited opportunities for passing near the mines
All three terminals are conceptually at the root of the tree network for the purpose of this model
Tactical Planning: Train Path Optimisation

- Repeating daily pattern of train paths
- Maximise number of up and down paths available
- No conflicts with existing/pre-allocated trains
- All train paths mutually compatible
  - Can select any subset of these train paths for our final schedules
Path planning solutions

1. Looking for regular daily pattern
2. Blocked externally imposed train paths.
3. 33 track segments with limited passing loops (stations with capacity 2)

Optimisation finds significantly more paths than solution generated manually