Optimisation in a Coal Export Supply Chain

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Thanks also to: Jonathan Vandervoort, Janelle Endacott, the HVCCC Annual Capacity Planning Team, Craig Long, PWCS Terminal Managers, and the support of ARC LP 0990739
• The Hunter Valley coal chain: an overview

• Coal chain planning at the HVCCC
  - History
  - Operations planning

• Optimisation so far: overview

• Maintenance scheduling

• Conclusions and future directions
The World’s Largest Coal Export Operation

- 35 coal mines
- 14 producers
- 24 load points
- 80 different brands

2 above-rail operators
15,000+ train trips per year
2 track owner/operators
Haulage distances up to 350km

3 coal loading terminals
Exporting around 100 MTPA, increasing
Trains and Dumpstations
Stockpiles, Stackers and Reclaimers
Stockpiles, Stackers and Reclaimers
Stockpiles, Stackers and Reclaimers
Stockpiles, Stackers and Reclaimers
Conveyors
Berths, Shiploaders and Ships
Berths, Shiploaders and Ships
The Hunter Valley Coal Chain

- Consumption is
  - 10% domestic
  - 90% export, of which 65% goes to Japan

- Just-in-time cargo assembly
  - Multiple components per cargo

- Turn of arrival loading port

- No control over demand
  - Two weeks visibility
  - Highly variable volumes

- How to
  - Maximize throughput
  - Drive efficient asset utilization?

- Plan and operation as though a single shareholder!

16 independent organisations required to move each tonne of coal
The Hunter Valley Coal Chain Coordinator

HVCCCLT

Provides centralised planning services on behalf of its members:

1. **Short term objective** – focus on maximising daily capacity and throughput
2. **Long term objective** – assist members with investment planning

Established as a trial in 2003 and formalised with governance arrangements under an MoU in July 2005 – operates on a premise of cooperation between member organisations

- 35 employees seconded from member organisations
- $5 million investment in state-of-the-art planning technology and models

HVCCC

- Initially an MOU between the organisations that own the train, track, terminal and port infrastructure
- From Sep 2009, an independent company now including the coal producers
- The movement of every tonne of domestic and export coal is planned via the HVCCC
- HVCCC provides a ‘system wide’ forum for pursuing operational improvements and efficient decisions about future investment
## HVCCC Functional Roles

### Strategic Capacity Planning
- Developing a rolling annual 10 Year Master Plan
- Advising on capacity constraints
- Reporting progress against planned capacity expansion

### Annual Capacity Alignment
- Provision of a co-ordinated annual Coal Chain capacity plan
- Provision of an aligned, monthly capacity plan with daily targets

### Operations Planning and Scheduling
- Provision of rolling monthly, optimised and co-ordinated delivery and loading plans
- Provision of daily centralised delivery and loading schedules
- Assist with daily schedule recovery

### Monitoring, Analysing and Reporting
- Monitoring utilisation of Coal Chain capacity
- Monitoring and reporting on daily, weekly, monthly and year-to-date planned and actual Coal Chain performance
- Development and maintenance of support services and systems
Old system limitations threatened the HVCC Logistic Team’s ability to plan throughput efficiently.

“Ouija Board”
Scheduling of trains for coal delivery to the port using a magnetic board.

Stockpile management required pen and paper.
**Planning System Overview**

**Step 1:** An order is placed with PWCS to load a vessel. PWCS accept or decline the request.

**Vessel Nomination:** Size, Type, Arrival Date, Cargoes, Components, Rail Operator, Load Plan, etc.

**Step 2:** A vessel stem is prepared that allocates vessels to berths and sets loading time and sailing times.

**IPS: Vessel Stem**

**Step 3:** The stockpiles at the port are planned to ensure the cargo is assembled ready to load the vessel at its appointed time.

**IPS: Stockpile Plan**

**Step 4:** A first cut of the Cargo Assembly Plan is prepared which identifies how many tonnes and on which days the coal will be moved from the mines into the port.

**IPS: CAP**

**Step 5a:** The Cargo Assembly Plan is turned in a rail schedule which specifies exactly what trains will run at which times to which load points – this is the plan that is handed over each day to the train operators.

**IPS: Cargo Assembly Schedule**

**Step 5b:** A set of plans are provided each day to identify exactly what assets are required to do what task at what times in order to maximise system throughput. This includes everything from stackers to assemble stockpiles through to reclaimers, shiploaders and requests to the Newcastle Port Corp to move vessels.

**IPS: Resource Utilisation Plan**

Coal Chain plans are continuously revised in response to:
- Changes and events that occur during the Live Run
- Changes (e.g. to blends) initiated by customers
A VESSEL STEM IS PREPARED THAT ALLOCATES VESSELS TO BERTHS AND SETS LOADING TIME AND SAILING TIMES.
A first cut of the cargo assembly plan is prepared which identifies how many tonnes and on which days the coal will be moved from the mines into the port.

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THE STOCKPILES AT THE PORT ARE PLANNED TO ENSURE THE CARGO IS ASSEMBLED READY TO LOAD THE VESSEL AT ITS APPOINTED TIME.
THE CARGO ASSEMBLY PLAN IS TURNED IN A RAIL SCHEDULE WHICH SPECIFIES EXACTLY WHAT TRAINS WILL RUN AT WHICH TIMES TO WHICH LOAD POINTS – THIS IS THE PLAN THAT IS HANDED OVER EACH DAY TO THE TRAIN OPERATORS.
A set of plans are provided each day to identify what assets are to do what task at what times to maximise system throughput: everything from stackers to assemble stockpiles through to reclaimers, shiploaders and requests to the port corp to move vessels.
TRIMS (ARTC VALIDATION OF COAL DELIVERY PLAN), FOLLOWING VALIDATION COAL DELIVERY PLAN GOES LIVE AND IS THEN EXECUTED BY LIVE RUN OPERATIVES
• Arena Simulation Model: several modules that cover the logistics related activities of the HVCC
• Each of the 3 Terminal Modules includes a number of sub-modules, namely;
  – *ETL Vessel Estimator Sub-Module*: Used to generate a rail schedules
  – *Stockpile Allocation Sub Module*: To allocate stockpile space for each vessel
  – *In Loading Sub-Module*: Models the rail unloading at the port.
  – *Out Loading Sub Module*: Models the ship loading
Optimisation Models: Overview 1

• Strategic planning model (CSIRO)
  - whole-of-coal chain model with variable resources
  - to determine least cost infrastructure required to meet the coal throughput in the master plan
  - MIP models and heuristics

• Shipping data generator (Newcastle)
  - Optimization and simulation models need arrival streams of ships at the port as input, known as shipping “stems”
  - Stems should accurately forecast future demand
  - Sequence of QP, MIP models with hierarchical goals

• Integrated train and vessel scheduler (Newcastle)
  - Detailed 6-week out planning, looking at precise timing of trains (train path) and accurate vessel schedules (MIP model)

• Operational train scheduling (CSIRO)
Optimisation Models: Overview 2

- **Stem-based capacity assessment (Newcastle)**
  - Whole-of-coal chain model with daily time granularity
  - Can the given infrastructure handle the demand (stem)?
  - If it can, minimise the demurrage (delays)
  - MIP models, strengthened formulations, cuts

- **Stockyard-centric planning (Newcastle)**
  - 6-week out detailed planning of stockyard allocation
  - Location and start build time for each stockpile decided
  - Reclaiming equipment and vessels scheduled to the hourly level
  - Inbound capacity (load points, trains, stackers) modelled at the daily level
  - 2D packing of stockyards (oriented, strip packing), but unconstrained direction is variable, dependent on allocation of inbound resources, objective driven by stockpiles combined on vessels, plus schedules
  - Greedy heuristics combined with IP
Planned maintenance scheduling

• Planned maintenance of track and terminal equipment:
  – Track sections, e.g. rail grinding, Speno car inspection
  – Stackers/reclaimers
  – Dumpstations, conveyor belts
  – Shiploaders
  – Berths (e.g. rails for shiploaders)

• This maintenance causes temporary reductions in the system capacity, and therefore throughput

• Improvements in the system throughput can be realised by appropriately timing maintenance jobs (aligning)

• Objective is to schedule maintenance jobs so that the total system throughput is maximized
Why alignment?

Capacities: max throughput = 12 (per day)

Aligned!
Why alignment?

Capacities: max throughput = 12 (per day)

Aligned!
Schedulers from rail and each terminal construct preliminary schedules of maintenance in isolation.

These schedules are submitted to HVCCC, which mediates changes to the schedules in order to better align maintenance jobs.

This process is iterated until a consensus is reached.
Calculating annual capacity

- Between start and end times of maintenance jobs, (during each time slice), the network state is constant
- Calculate available capacity in each time slice
- Add up over all time slices to get annual capacity
• The HVCCC calculated available capacity in each time slice via a set of if-then type rules, capturing interaction effects of different types of equipment being off or on at the same time

• **Key insight:** all aspects of the operation can be represented as max flow through a network
Network structure for a terminal outbound stream

• Terminal outbound impact calculation

StreamsAvailable = \min\{ReclaimersAvailable, ShiploadersAvailable\}
OutboundCapacity = ShiploadingCapacity - Inefficiency

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Network structure for a terminal outbound stream

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# Network structure for a terminal outbound stream

![Network Diagram](image)

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### Network structure for a terminal outbound stream

![Diagram of network structure](image)

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Combined rail and terminal networks
Measuring schedule quality

- Measure the available capacity in each time slice by solving a *maximum flow problem* in the network
- Capacities of arcs in the network for each time slice are determined by the scheduled maintenance
- Annual capacity (measure of schedule quality) is the sum of the flows over the time slices
- Storage of coal at the stockyard pads means that the problem cannot be decomposed by time slice, so in fact annual capacity should be measured by solving a single *dynamic maximum flow problem over time*
- This is linear program, which solves in 30 seconds using standard technology – dual values indicate bottleneck jobs
Scheduling rules and features

- Job durations range from hours to days, start times are at the hourly level
- Certain jobs are fixed
- Remaining jobs can be moved within a ±7 day window about the input initial start time
- Some jobs must not overlap in time
- Some jobs have to be moved together with “companion” jobs
- Some jobs scheduled on the weekend must remain on the weekend, and some on a weekday have to stay on a weekday
- Some jobs can be done on different days, but must be at the same time
- Don’t move jobs unnecessarily
Optimizing the maintenance schedule

- Network \((N,A)\), start node \(s\), end node \(e\)
- \(u_a\) capacity of arc \(a\) (max flow per unit time)
- \(S\) set of storage nodes
- storage capacity range \([l_v,u_v]\) for node \(v\)
- Time horizon \(\{0,1,...,T\}\)
- \(J\) a set of maintenance jobs, job \(j\) specified by
  - arc \(a_j\) it applies to
  - processing time \(p_j\)
  - set of possible start times \(R_j \subseteq \{0,1,...,T\}\)
- \(C\) is maximal set of pairs of incompatible jobs
- \(\mathcal{T} = \{t_0 < t_1 < ... < T_M = T\}\) set of all relevant times
  \(\mathcal{T} = \{0,T\} \cup (\bigcup_j (R_j \cup (R_j + p_j)))\)
Optimizing the maintenance schedule

Variables

• $f_{ai} = \text{flow on arc } a \text{ in time interval } [t_{i-1}, t_i]$
• $h_{vi} = \text{storage at node } v \text{ in time interval } [t_{i-1}, t_i]$
• $x_{ai} = 1 \text{ if arc } a \text{ available in time interval } [t_{i-1}, t_i], 0 \text{ otherwise}$
• $y_{jt} = 1 \text{ if job } j \text{ starts at time } t \in R_j , 0 \text{ otherwise}$

Objective (Hierarchical)

1. $\max \sum_i (\text{total flow out of node } s \text{ in interval } i)$
2. $\min \# \text{ jobs moved from initial scheduled time}$
Optimizing the maintenance schedule

Constraints

• Network flow constraints in $f_{ai}$, $h_{vi}$
  - Flow conservation, bounds

• Flow subject to arc available: $f_{ai} \leq u_{a}(t_{i} - t_{i-1})x_{ai}$

• Must do each maintenance job: $\sum_{t} y_{jt} = 1$

• If do maintenance job $j$ on arc $a$ starting at time $t$ with $t_{i} \in [t, t+p_{j}]$ then arc $a$ it is not available at time $t_{i}$:
  $x_{ai} + \sum_{\{t:t<t_{i}\leq t+p_{j}\}} y_{jt} \leq 1$

• Conflicting jobs can’t overlap: $\sum_{j \in C} \sum_{\{t:t_{i}<t\leq t+p_{j}\}} y_{jt} \leq 1$
Related literature

• Dynamic network flow problems: large literature, recent survey Nasrabadi, Koch, Skutella, MMOR, to appear

• Scheduling: very large literature e.g. Pinedo’s book, however all scheduling focusses on standard objectives such as makespan, overdue time (methods very much depend on the nature of the objective) and where jobs must be done on machines, limiting how many can be done simultaneously

• Recent work on infrastructure restoration (power, water, sewerage) by Nurre, Sharkey and others, see Sharkey’s website at Rensselaer Polytechnic: scheduling (restoration) jobs on arcs subject to maximum flow, however scheduling aspect = usual machine scheduling

• There appears to be no work at all done on scheduling arc outages over maximum flow in a network over time
• **Theorem:** even when start time sets are intervals, there is no storage at nodes, and no incompatible jobs, the problem is NP hard

• There are some easy special cases, depending on network structure (e.g. path), or job properties (e.g. unit processing times)
• Issue: $|\mathcal{A}|$ is impractically large

• **Theorem**: If no storage is allowed, then there is an optimal solution in which all jobs start times are either as early as possible, as late as possible, or aligned with the start or end time of other jobs

• Experiments showed that storage made little difference to the optimal maintenance schedule generated
  - Restrict to recursively generated set of possible start times that align jobs starts or ends
  - Still impractically large
  - Restrict start times for each job to the earliest and latest start times of every other job that coincides with this job’s start time window
• Size of network: 37 nodes, 69 arcs
• Number of maintenance jobs: 1,296 (197 fixed)
• Duration 90 mins – 28 days, average 18 hours
• Number of start times 17-31, average 30.5
• $|\mathcal{F}|$ used = 8,254
• Number of variables: $\approx 862,000/496,000$
• About 25% of variables are binary
• Number of constraints: $\approx 1.6$ million/344,000
• MIP solved with Gurobi 3.0, single thread Dell PowerEdge 2950, 3.16 GHz, 64Gb RAM
• Time to solve: 18 hours per objective
Results for the network based MIP

<table>
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<th></th>
<th>Sign Off 2010</th>
<th>Optimized</th>
<th>Benefit</th>
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<tr>
<td></td>
<td>Inbound</td>
<td>Outbound</td>
<td>Inbound</td>
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<tr>
<td>Q1</td>
<td>30,008</td>
<td>29,972</td>
<td>30,883</td>
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<tr>
<td>Q2</td>
<td>30,535</td>
<td>30,504</td>
<td>31,316</td>
</tr>
<tr>
<td>Q3</td>
<td>30,611</td>
<td>30,646</td>
<td>31,480</td>
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<tr>
<td>Q4</td>
<td>29,705</td>
<td>29,737</td>
<td>30,319</td>
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<tr>
<td>Total</td>
<td>120,861</td>
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</table>

Jobs moved

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<tr>
<th></th>
<th>Rail</th>
<th>Terminal 1</th>
<th>Terminal 2</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Inbound</td>
<td>Outbound</td>
<td>Inbound</td>
<td>Outbound</td>
</tr>
<tr>
<td>Q1</td>
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<td>7</td>
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<tr>
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<td>9</td>
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<tr>
<td>Q4</td>
<td>29</td>
<td>0</td>
<td>0</td>
<td>5</td>
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<tr>
<td>Total</td>
<td>191</td>
<td>8</td>
<td>0</td>
<td>31</td>
</tr>
</tbody>
</table>
Conclusions for maintenance scheduling

• Mixed integer programming can be used to successfully optimize maintenance schedules of critical infrastructure

• Key is selection of a restricted set of possible job start times to obtain practical solutions

• Benefits to the company:
  – Potential to release more capacity by optimized alignment
  – Reduced time invested by the Annual Capacity Planning Team compared to the purely the manual process
  – Potential use for quarterly or monthly planning
  – Value for “what-if” analysis
Future work for maintenance scheduling

- More detailed rail network models, directional up and down flow on network arcs taking into account travel times
- Managing multiple optimal solutions, and stability of solutions under small changes
- Decomposition and sophisticated MIP techniques to prove optimality over full set of possible job start times
- Develop faster methods for MIP solution
- Fast heuristics – e.g. rolling time horizon
- Theoretical results for specific network structures
The Hunter Valley coal chain has established a unique and highly effective approach to planning and coordination of shared infrastructure.

Modelling, simulation and optimisation tools are critical to ongoing planning.

These represent significant challenges in terms of scale, complexity of important subsystems, integration and coordination of planning activities.

The HVCC has made a significant investment in research activity to support this, which we look forward to continuing.