Rail scheduling for the Hunter Valley Coal Chain

Andreas Ernst , Antonio Gomez-Iglesias, Gaurav Singh

OPERATIONS RESEARCH GROUP, CMIS
www.csiro.au

CSIRO

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.

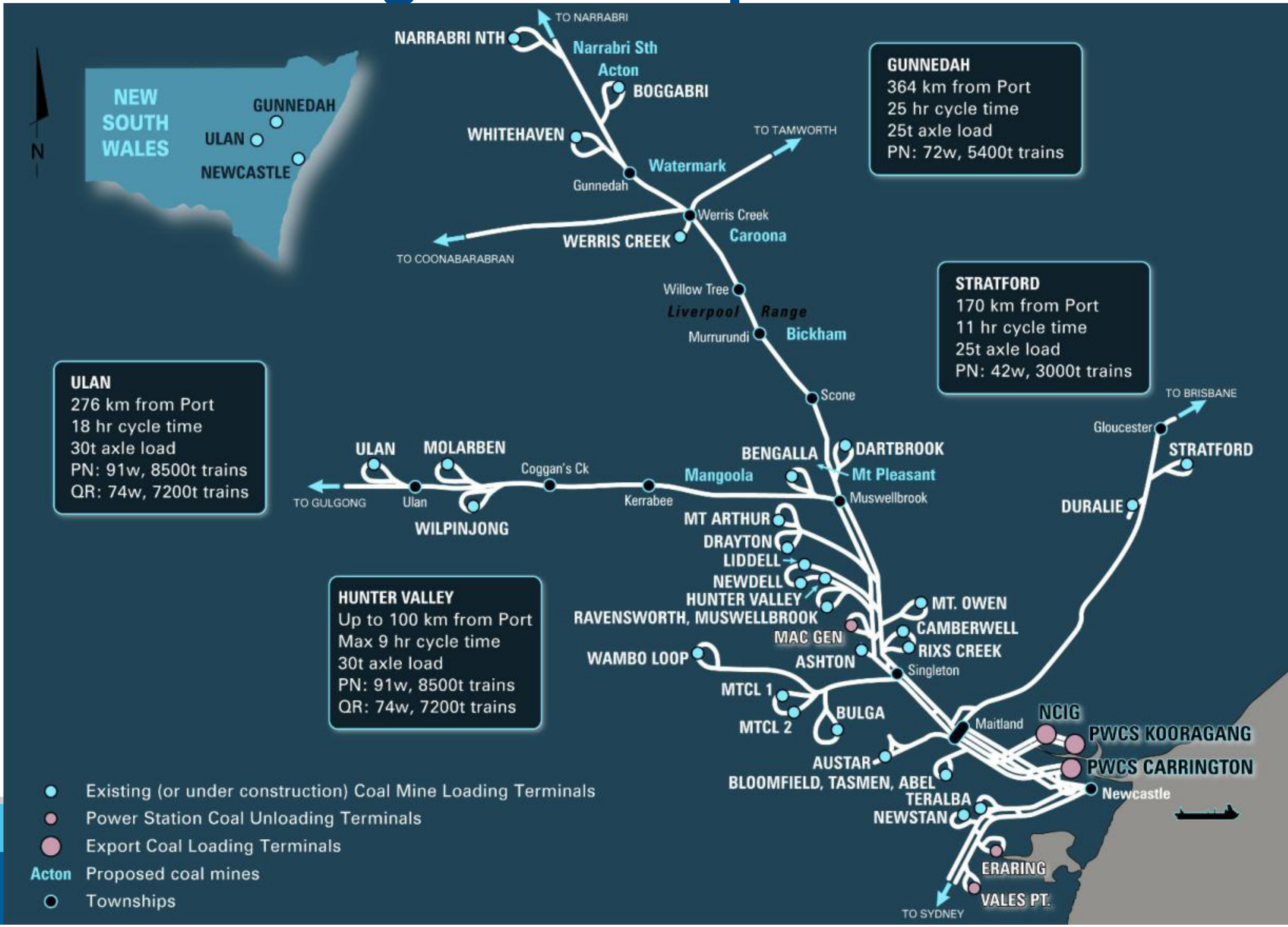
Biggest contributor in Australian GDP. Exports worth more than $50 billion in 08-09.

Trains transporting coal are among the longest in the world.

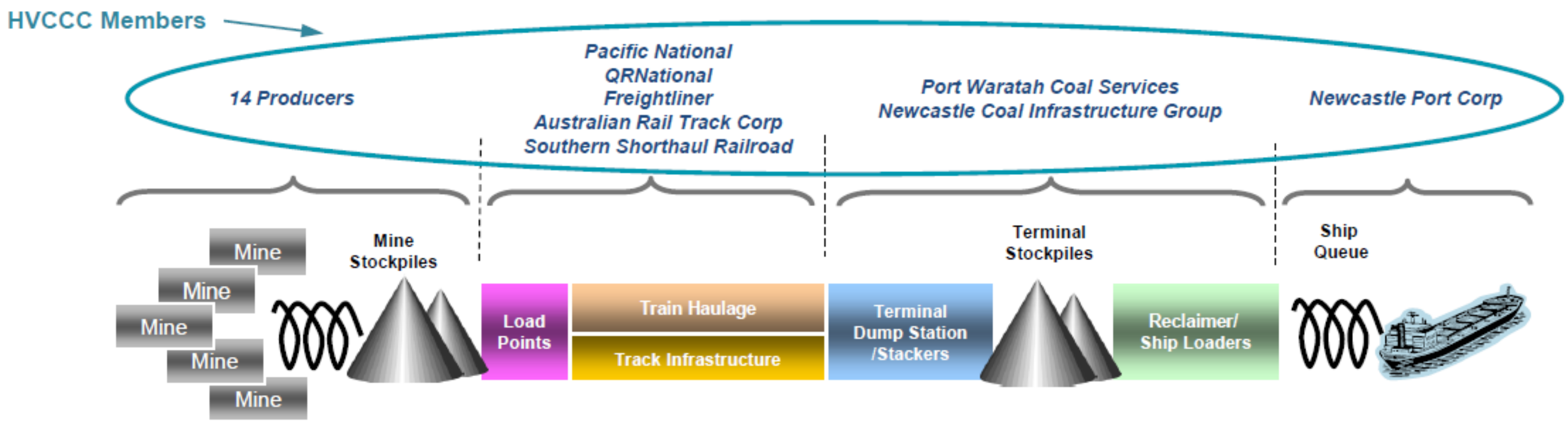
8500 tonnes train has as many as 6 locomotives and 148 wagons amounting to a length of more than 2 kilometres.

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



Hunter Valley Coal Chain Coordinator



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 364km

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

Antiene Domestic Terminal

- Muswellbrook Power Stations

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
http://www.hvccc.com.au/AboutUs/Pages/MapOfOperations.aspx

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

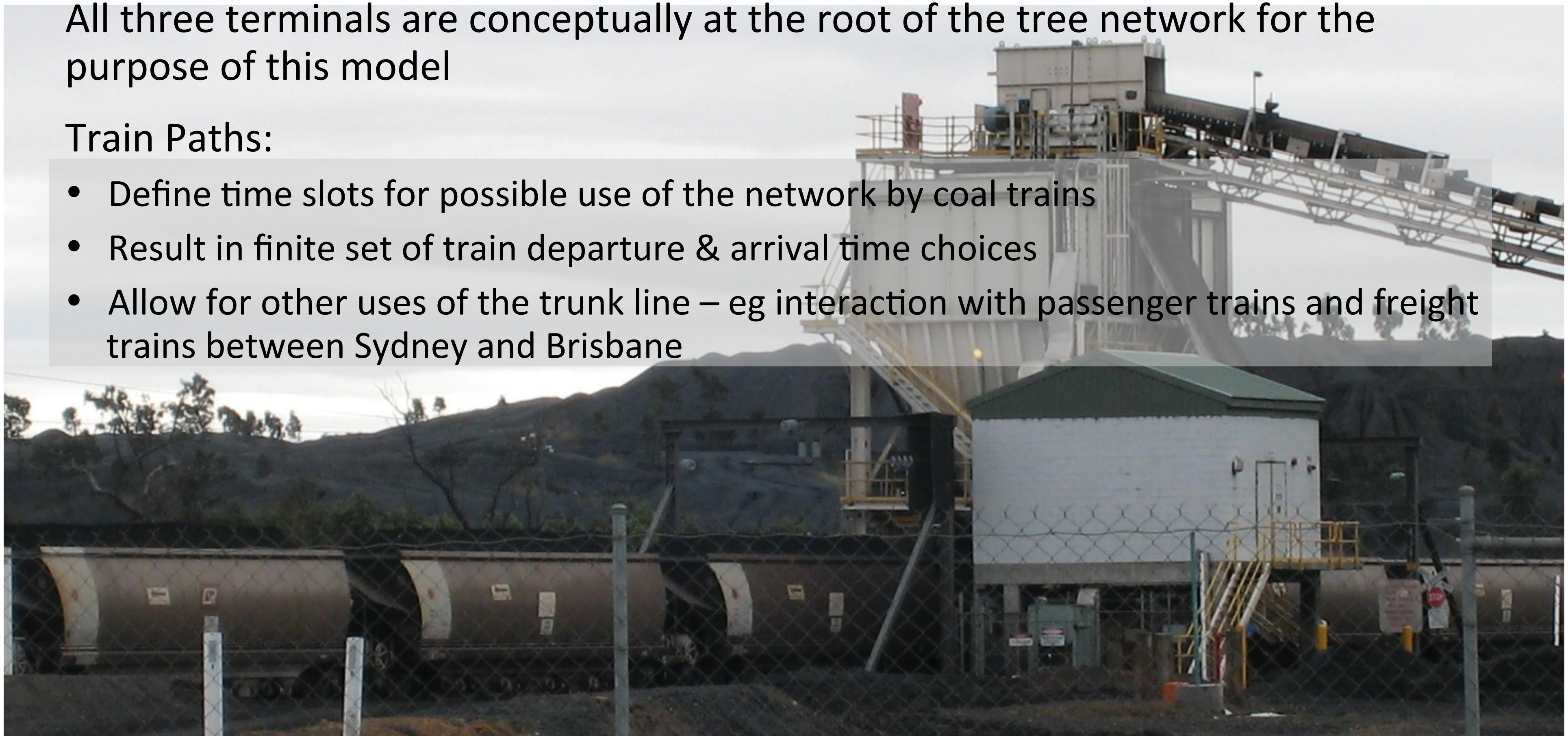
Tree structure with trunk line up the Hunter Valley and branches to mines

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

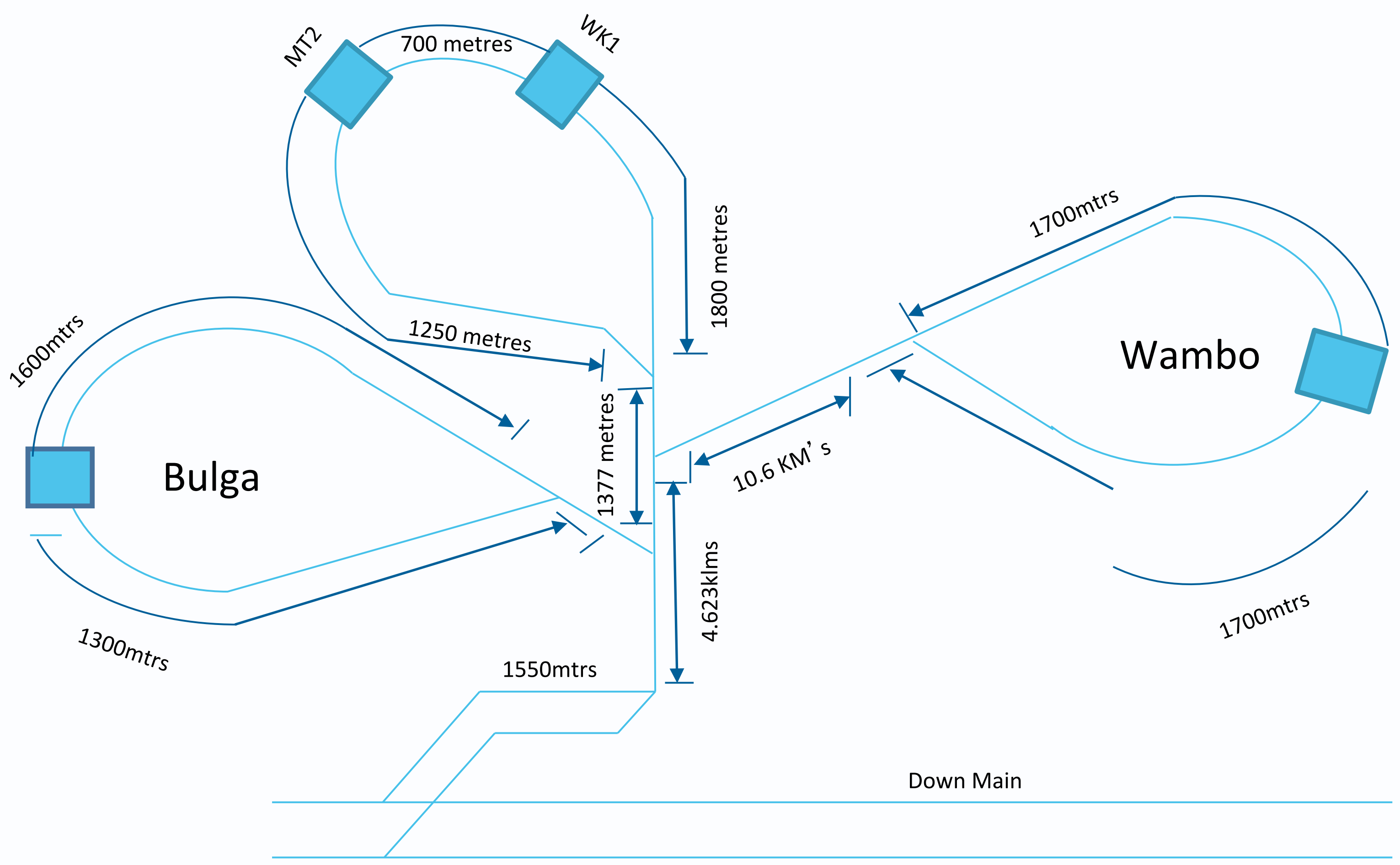
Train Paths:

- 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



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 → multiple cargos

1 stockpile → 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:

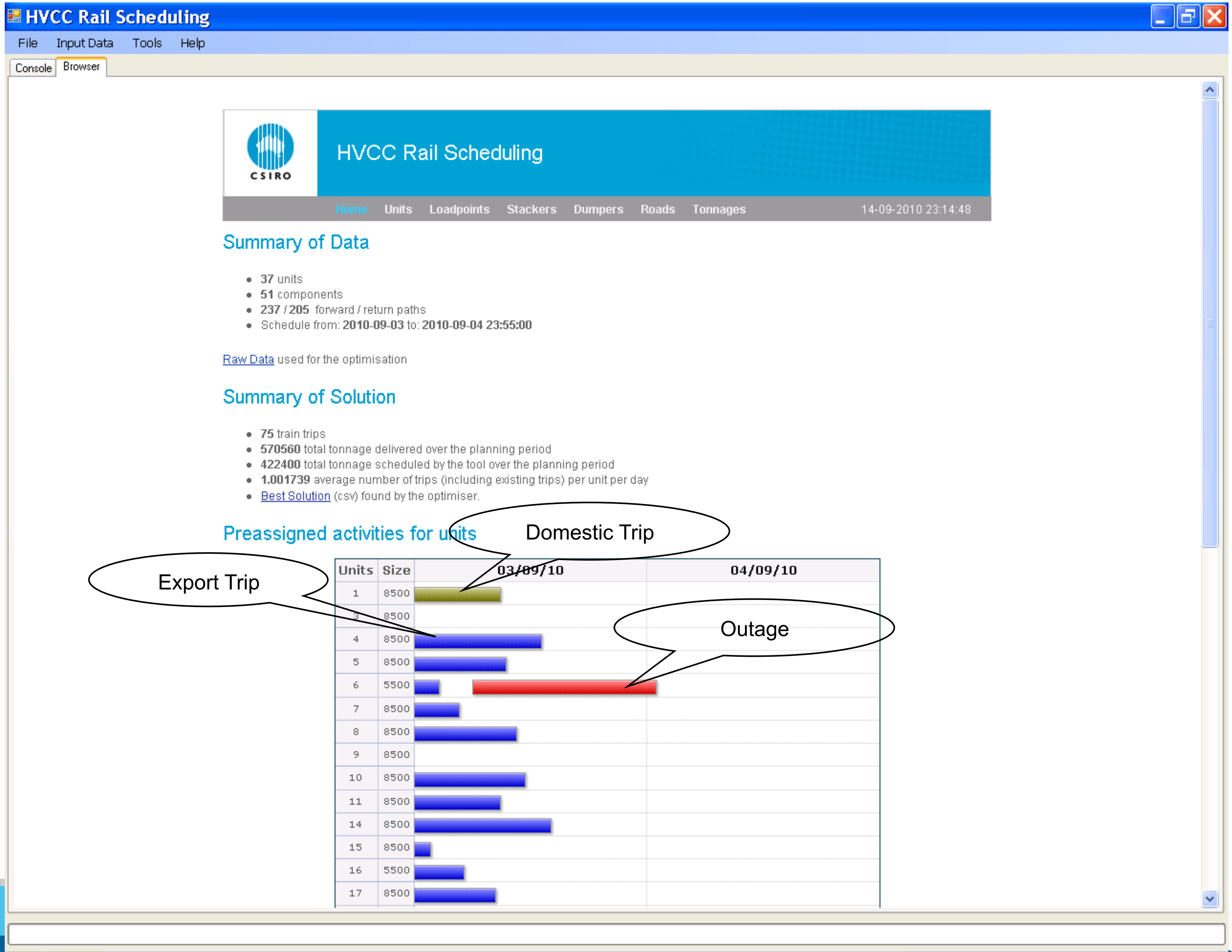
- Departure time from a terminal at Newcastle (forward path)
- Start & end loading at mine loadpoint (fixed duration)
- Departure time from mine loadpoint (return path)
- Start & end unloading at a dump station
- *Maintenance times*
- *Refuelling times*

Resources to assign:

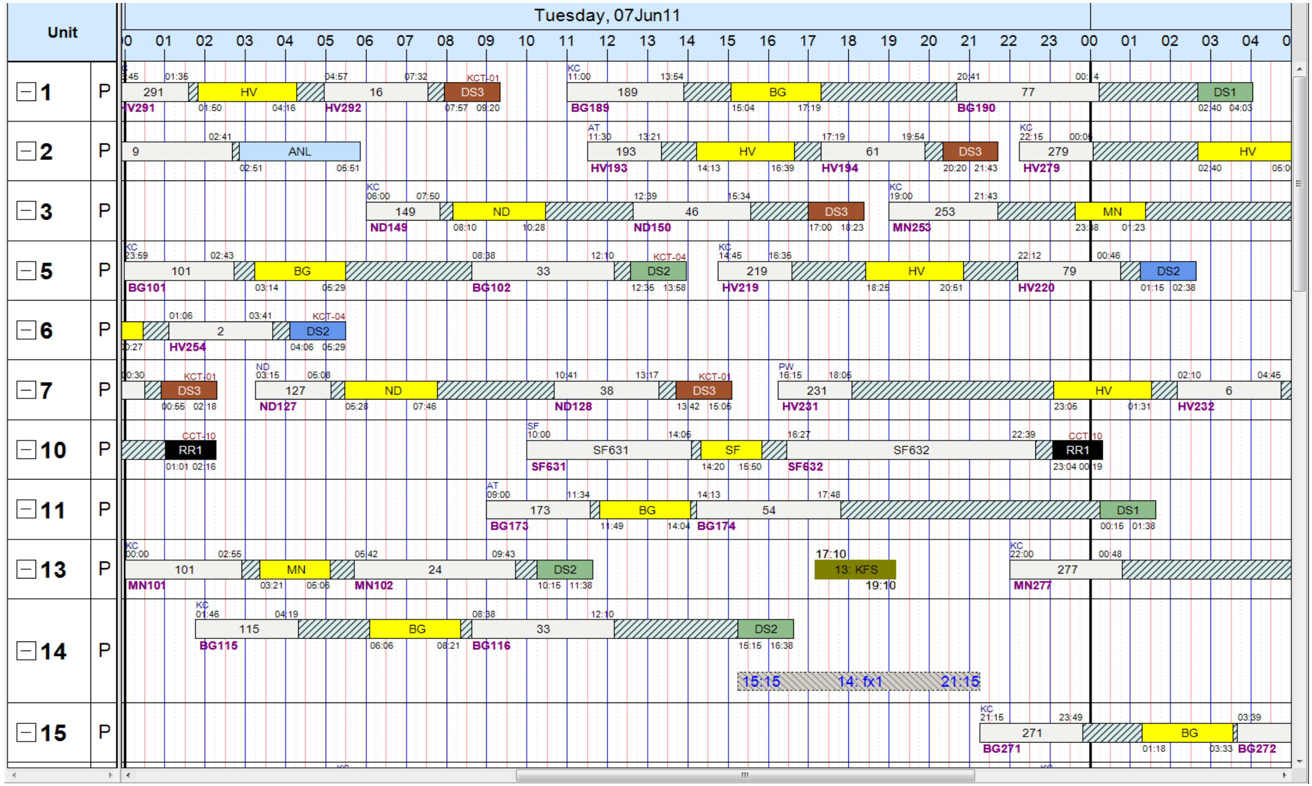
- Which unit to use for each roundtrip
- What mine to go to
- Dump station for unloading
- Stacker for unloading
- *Arrival & departure roads (tracks) at the terminals*

CSIRO

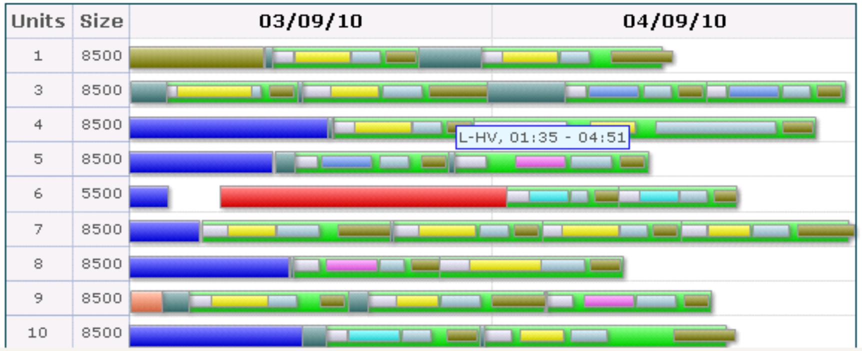
Summary of outputs



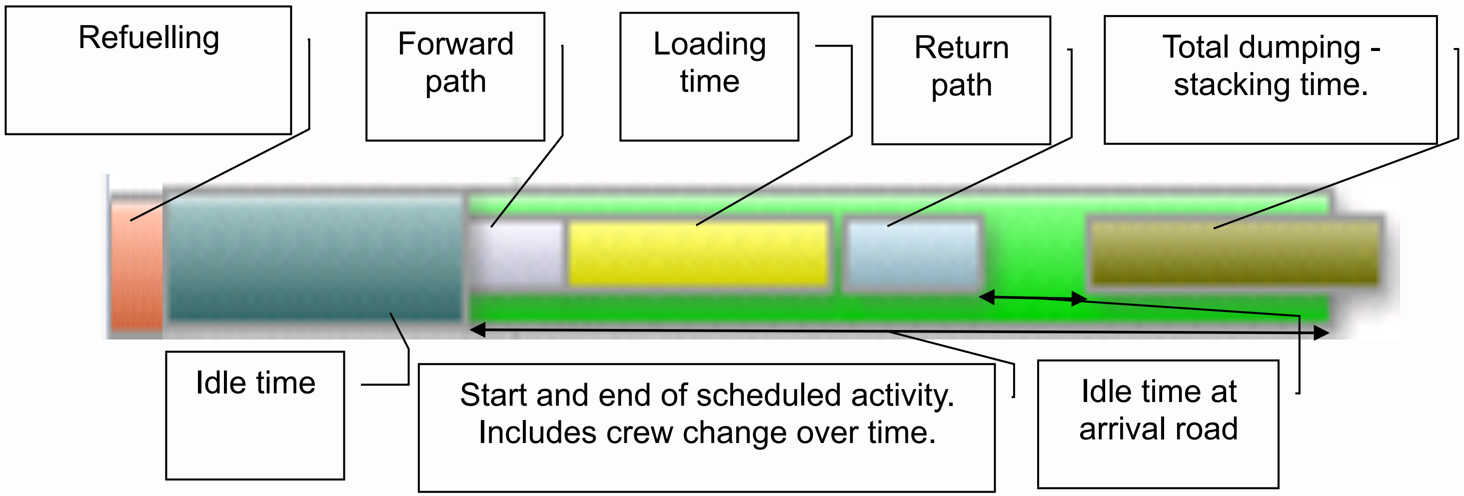
Unit schedule



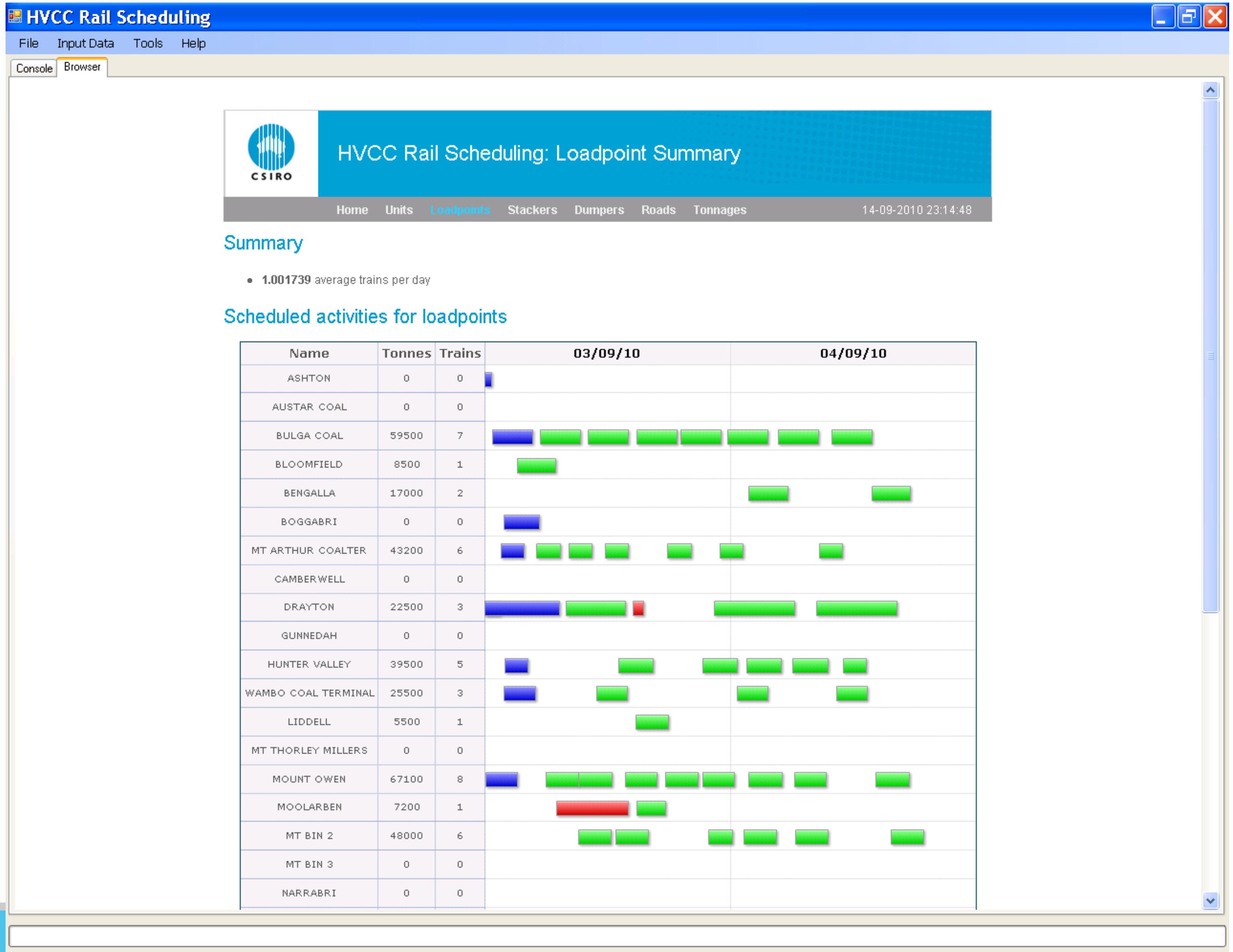
Scheduled activities for units



Train activities



Summary - loadpoint



HVCC Rail Scheduling

File Input Data Tools Help

Console Browser

HVCC Rail Scheduling: Loadpoint Summary

Home Units Loadpoints Stackers Dumpers Roads Tonnages 14-09-2010 23:14:48

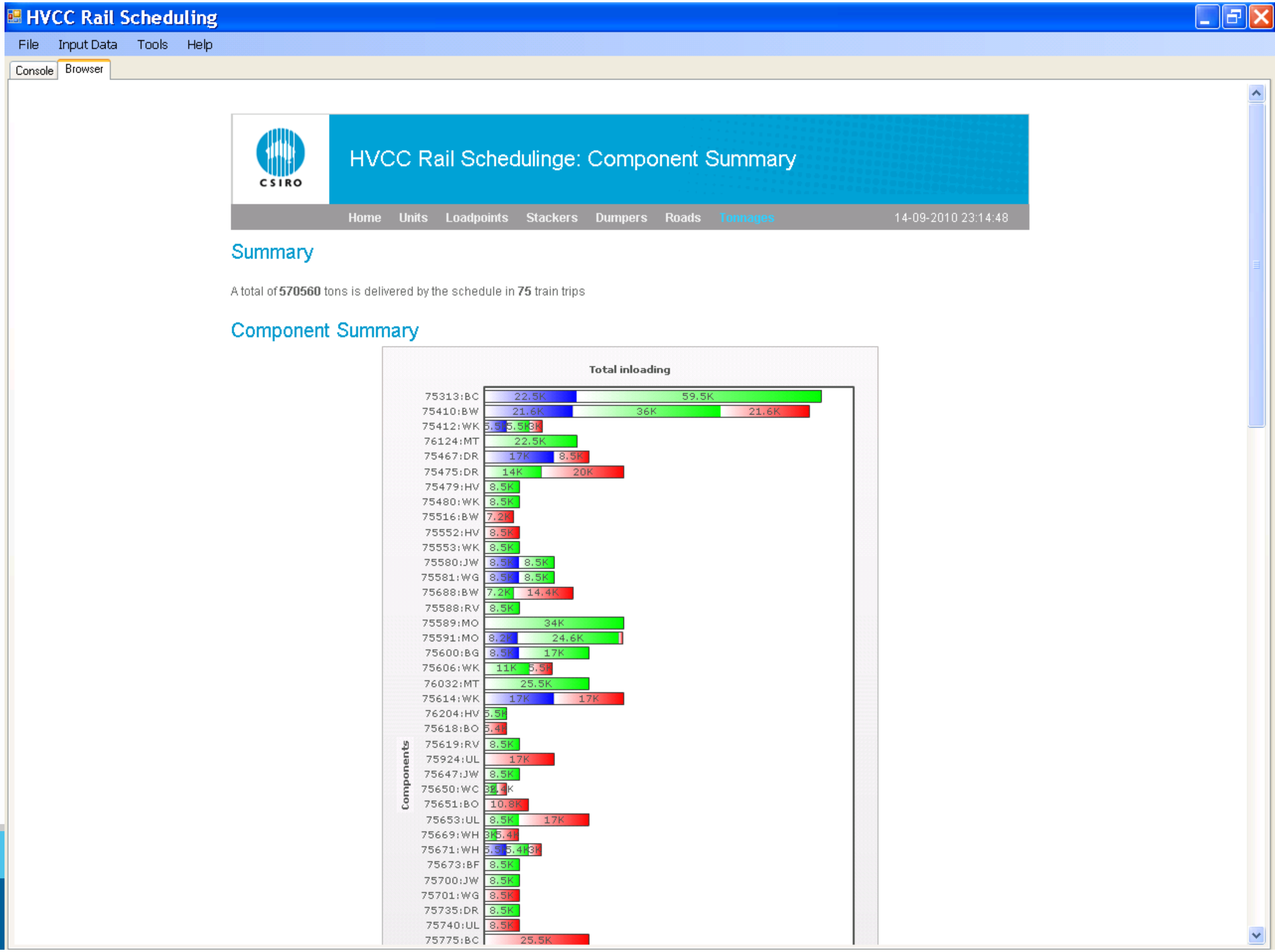
Summary

- **1.001739** average trains per day

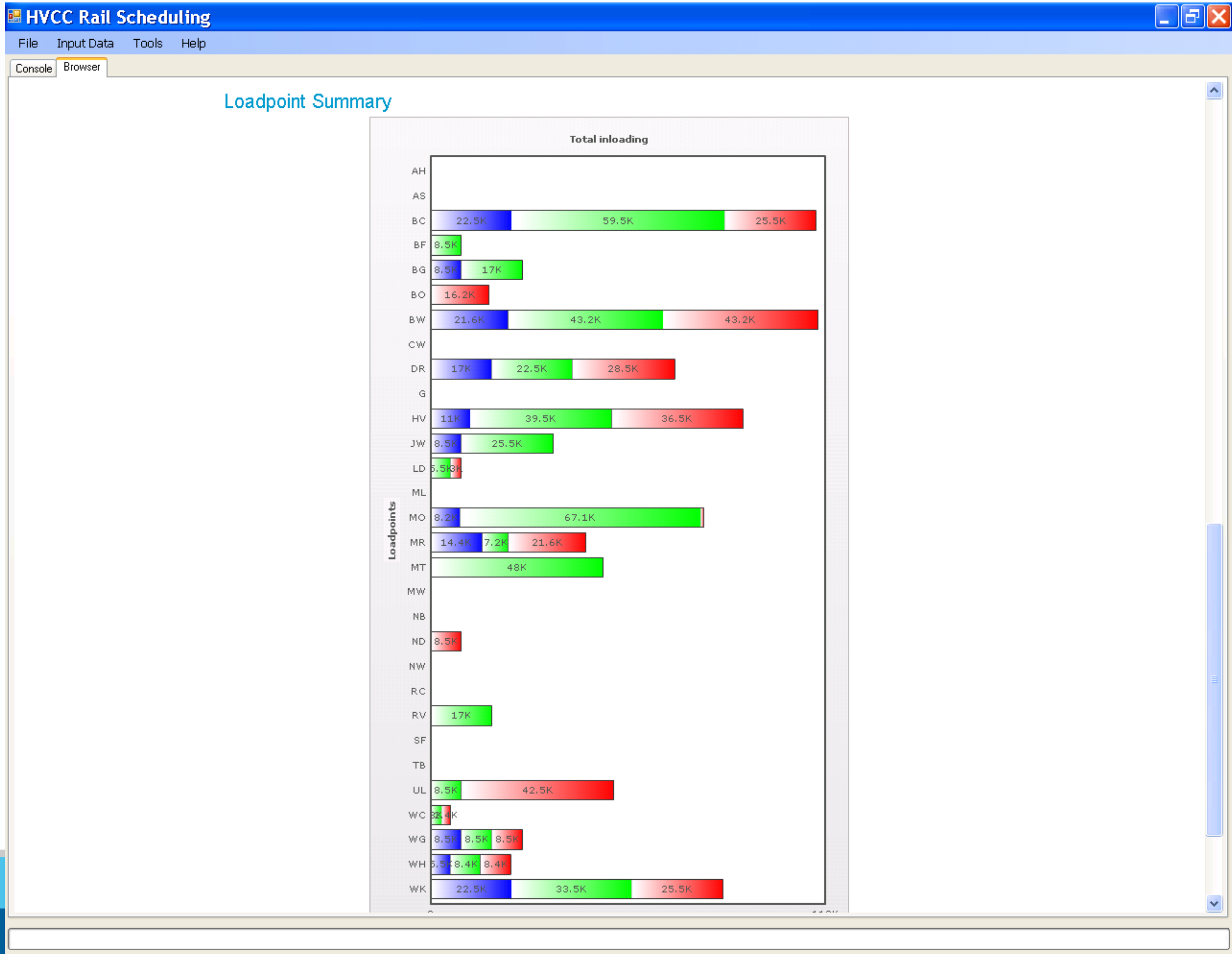
Scheduled activities for loadpoints

Name	Tonnes	Trains	03/09/10	04/09/10
ASHTON	0	0		
AUSTAR COAL	0	0		
BULGA COAL	59500	7		
BLOOMFIELD	8500	1		
BENGALLA	17000	2		
BOGGABRI	0	0		
MT ARTHUR COALTER	43200	6		
CAMBERWELL	0	0		
DRAYTON	22500	3		
GUNNEDAH	0	0		
HUNTER VALLEY	39500	5		
WAMBO COAL TERMINAL	25500	3		
LIDDELL	5500	1		
MT THORLEY MILLERS	0	0		
MOUNT OWEN	67100	8		
MOOLARBEN	7200	1		
MT BIN 2	48000	6		
MT BIN 3	0	0		
NARRABRI	0	0		

Summary- Tonnages



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
- Unloading time at terminal
- Dump station
- Stacker stream

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

$$\text{Max } \Sigma_i \, v_i \, x_i$$

$$\text{S.t.} \quad \Sigma_{i \text{ uses } r \text{ at } t} \, x_i \leq 1 \qquad \text{for all resources } r \text{ and times } t$$

$$x_i \in \{ 0,1 \}$$

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

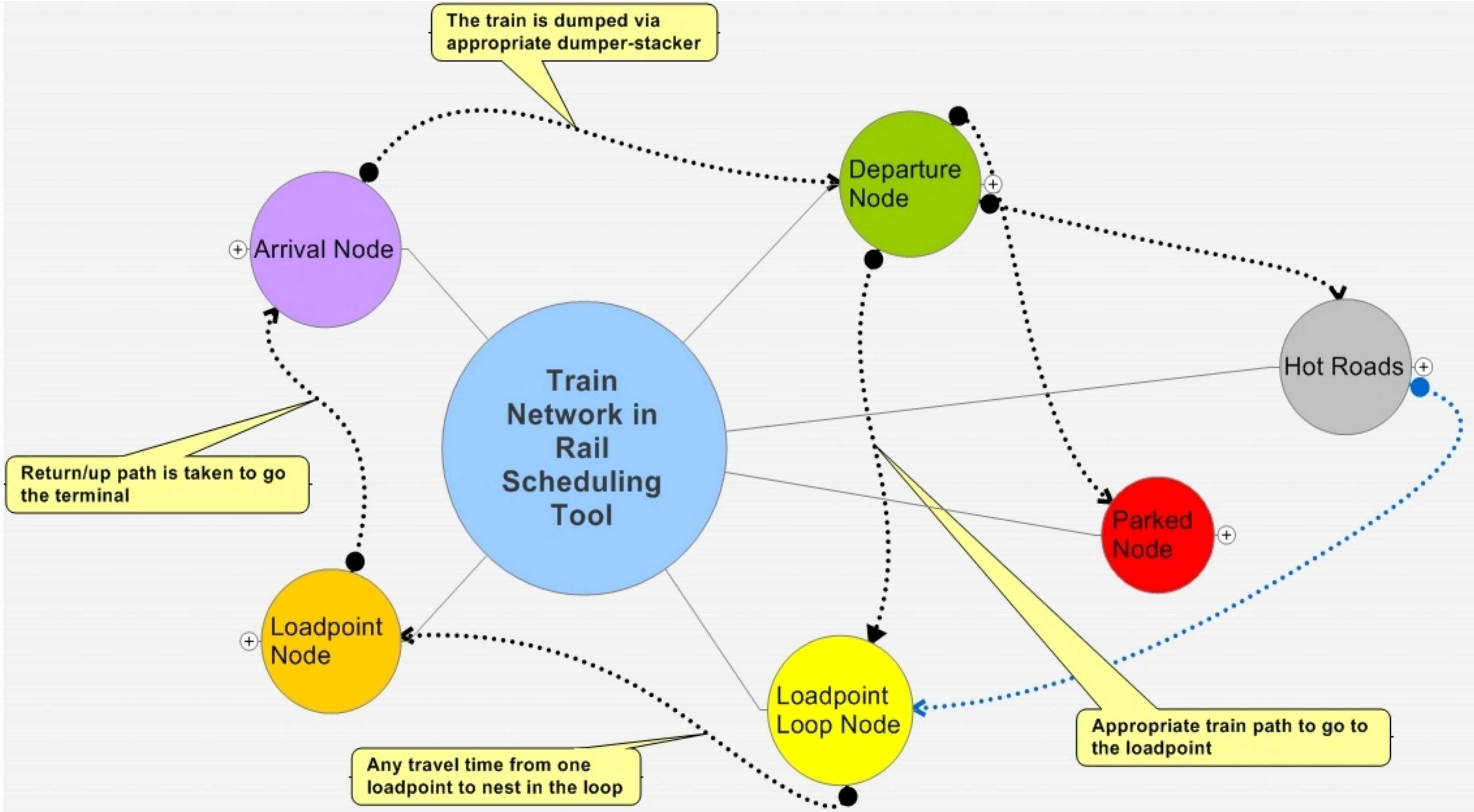
Represent what a train can do as a time-space network with additional resources

- Nodes = location in space and time
- State = coal loaded, fuel level, maintenance state
- Edges = activities that a train can carry out

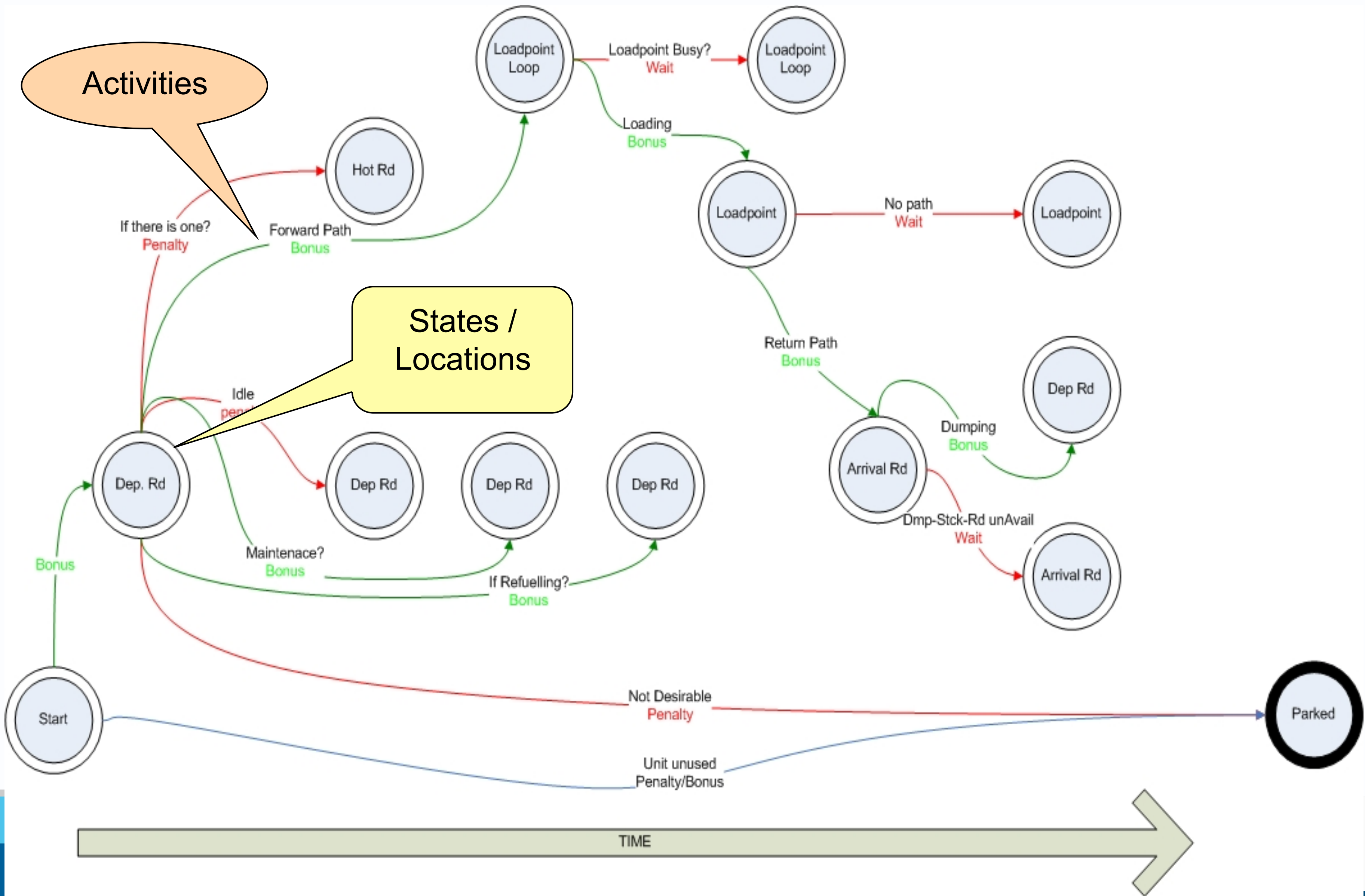
Solve resource constrained shortest path problems as Lagrangian sub-problems

Effectively an extended version of Model 1 with a set of roundtrips for a unit generated on the fly.

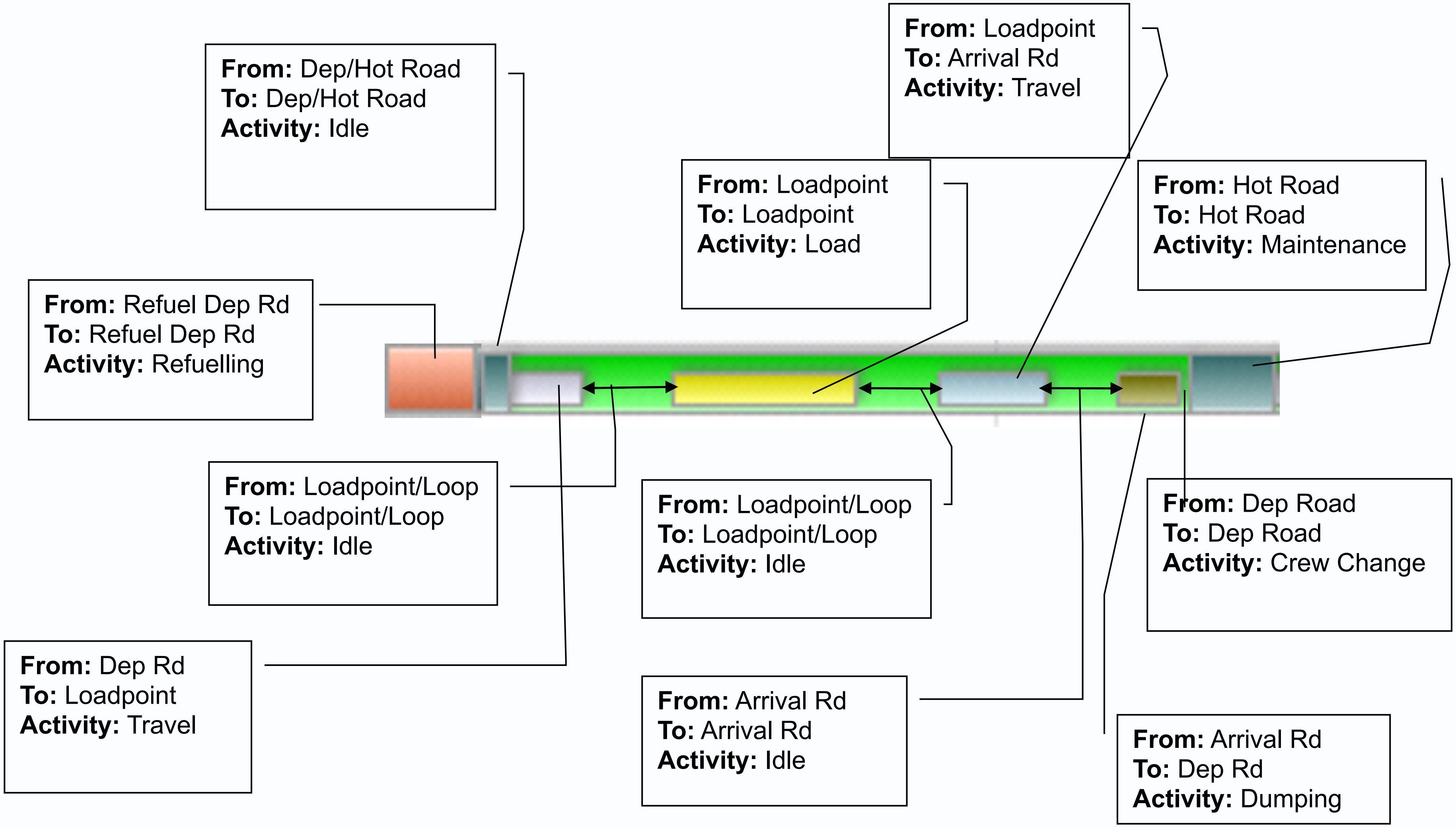
High level view of the network



Network Graph for a Unit



Activities for a unit



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

$x_{us} \in \{0,1\}$ for all feasible schedules s 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

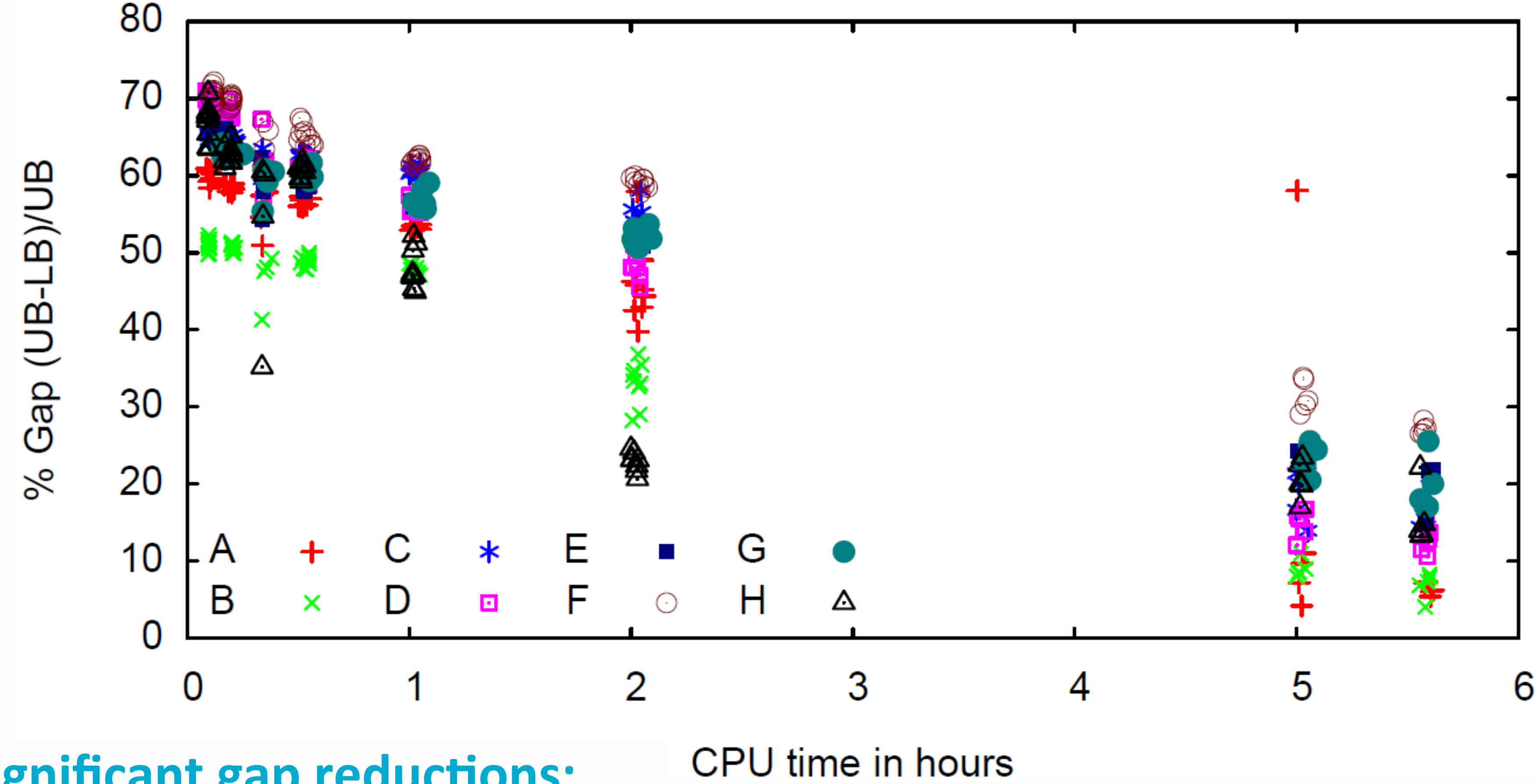
	Dataset:	A	B	C
	Columns (M)	2.1	4.8	2.1
	Non-zeros (M)	129.9	338.6	131.5
1 hour run	Lag.Heur (1hr) LB/UB	**240.9** / 272.8	**177.5** / 329.9	**183.1** / 215.3
1 hour run	Gurobi (1hr) LB / UB	231.1 / inf	157.0 / inf	177.0 / inf
1 hour run	CPLEX (1hr) LB / UB	0.0 / inf	--- / inf	0.0 / inf
10 hr run	Lag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

16 core CPU with 100Gb RAM Lag. Heur. run serial only

Data Sets for Model 2

Instance	No. of relaxed Constraints	No. Trains	No. Trips requested	Pre-assigned activities
A	37,267	64	43	31
B	38,323	60	40	27
C	30,692	61	45	26
D	38,108	63	45	34
E	38,096	61	50	27
F	37,120	60	78	1
G	49,605	38	120	22
H	33,360	38	48	12

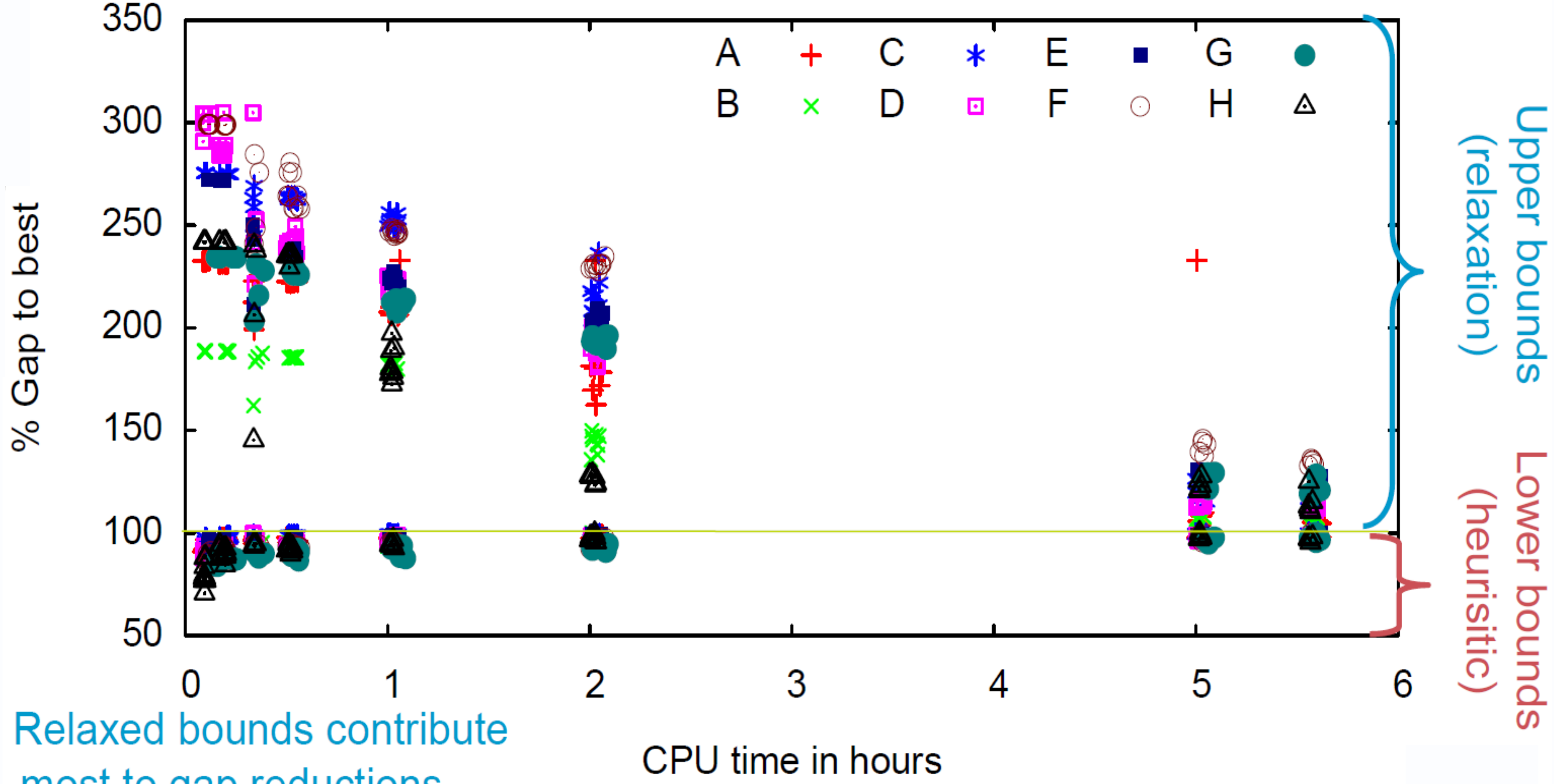
Gap achieved with increasing CPU time



Significant gap reductions:

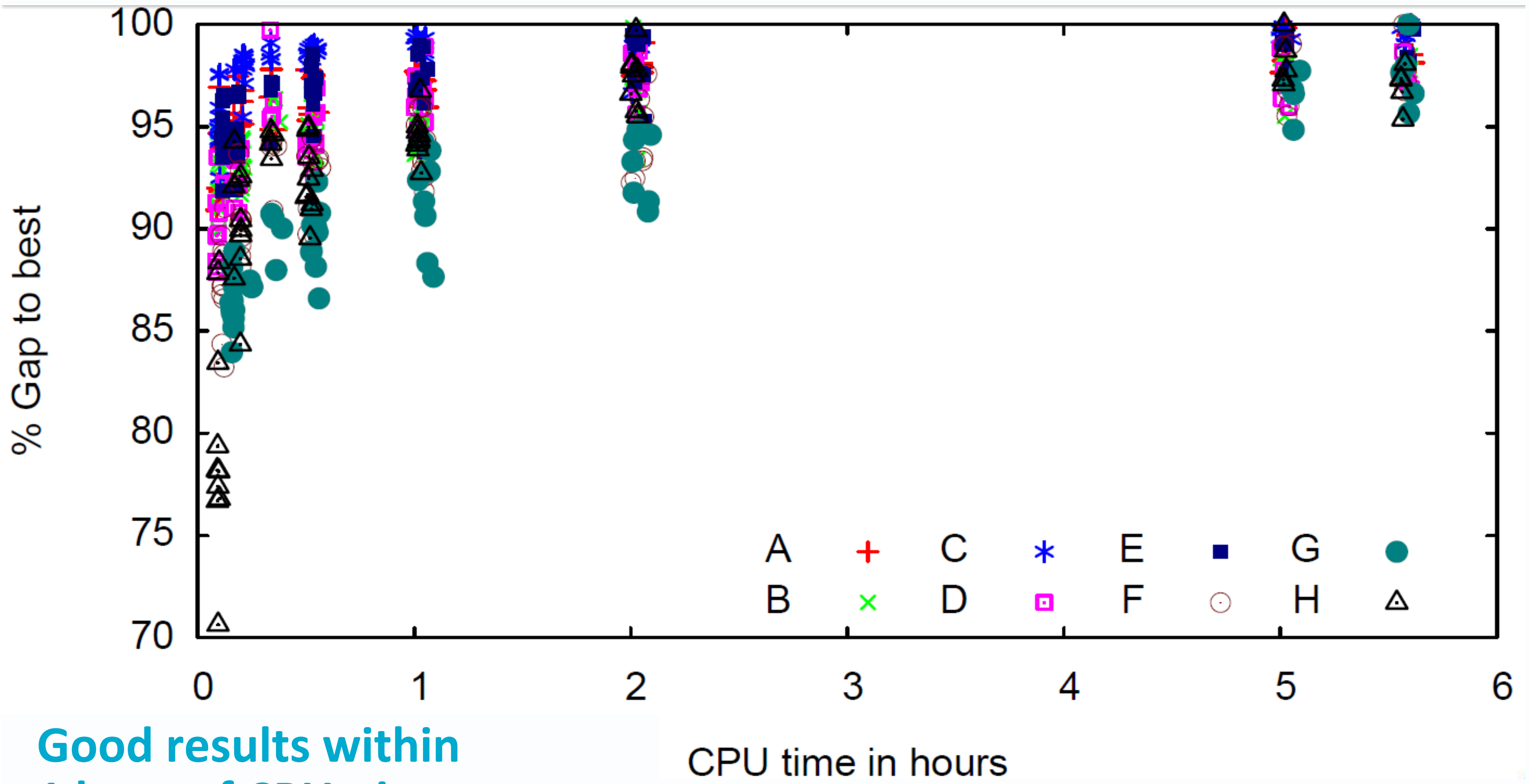
Due to better bounds or better solutions?

Gap to best solution found



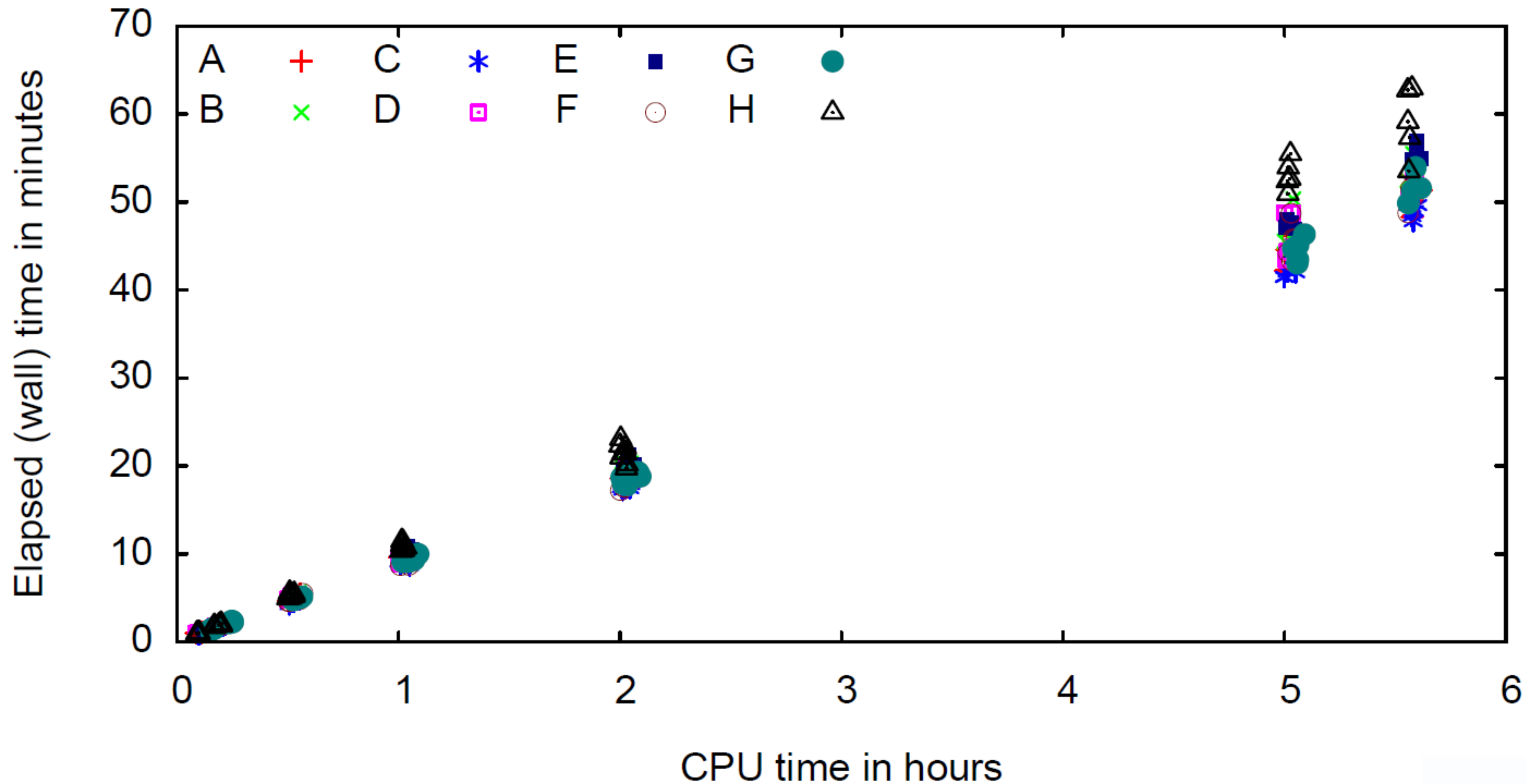
Relaxed bounds contribute most to gap reductions

Improvements to schedule quality

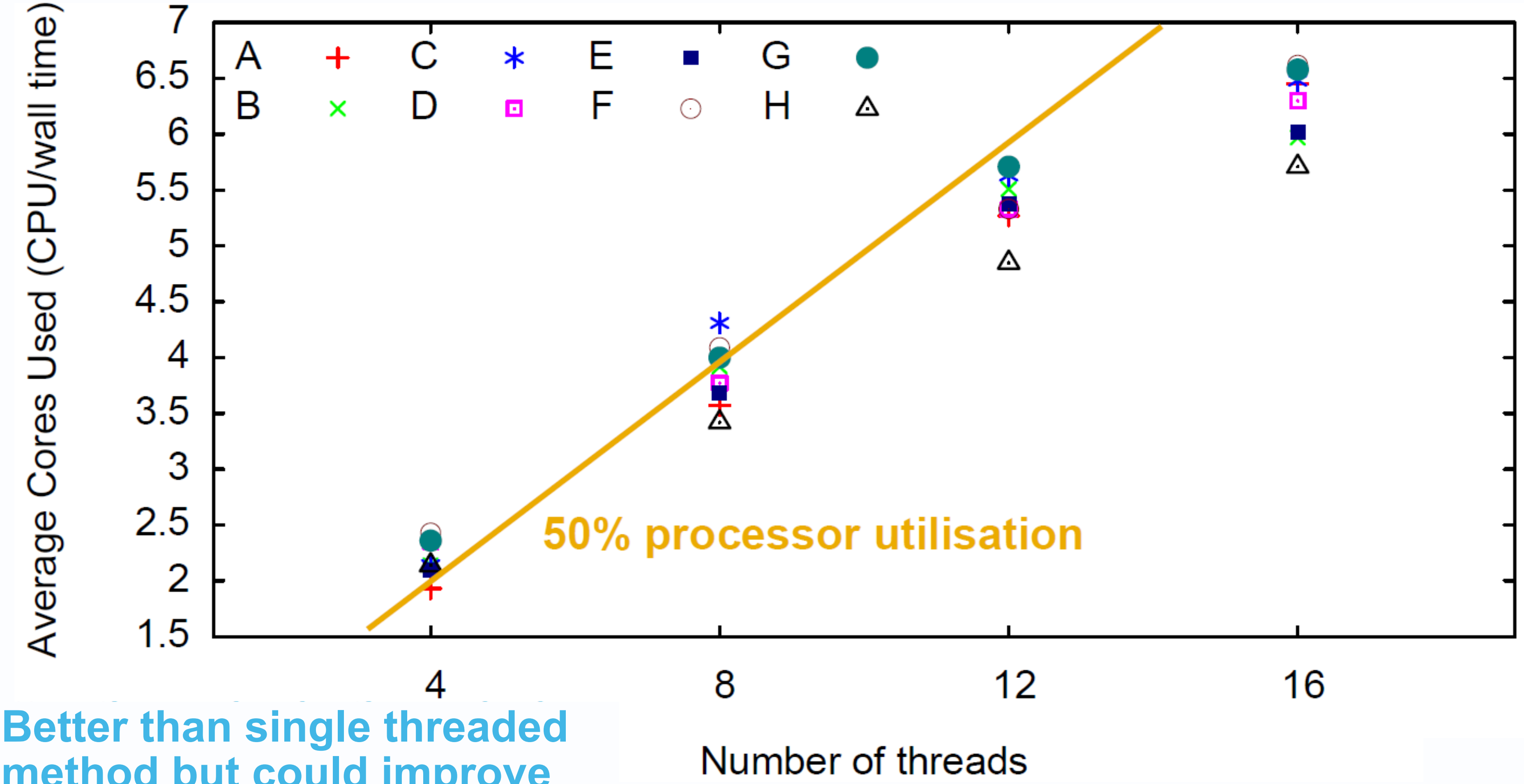


Good results within
1 hour of CPU time

Runtime as function of CPU time



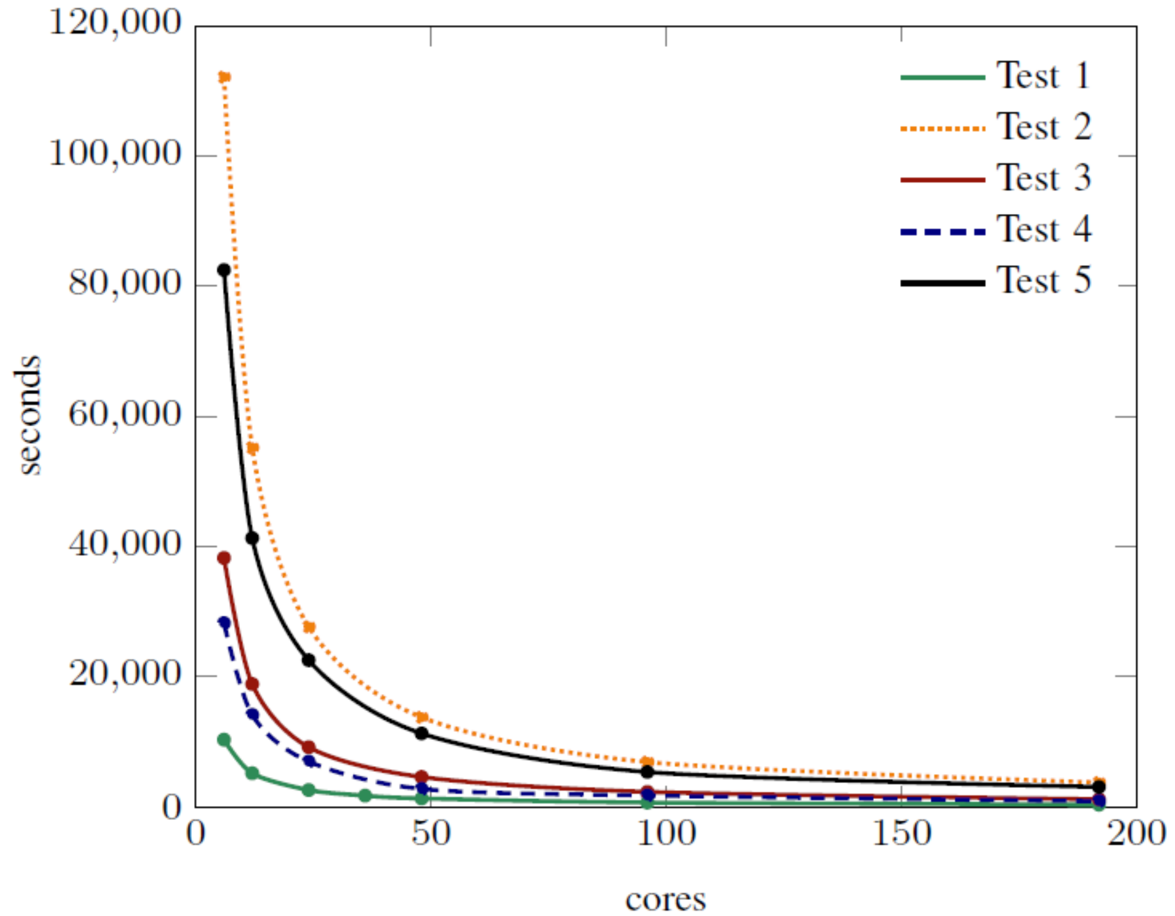
Processor utilisation



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

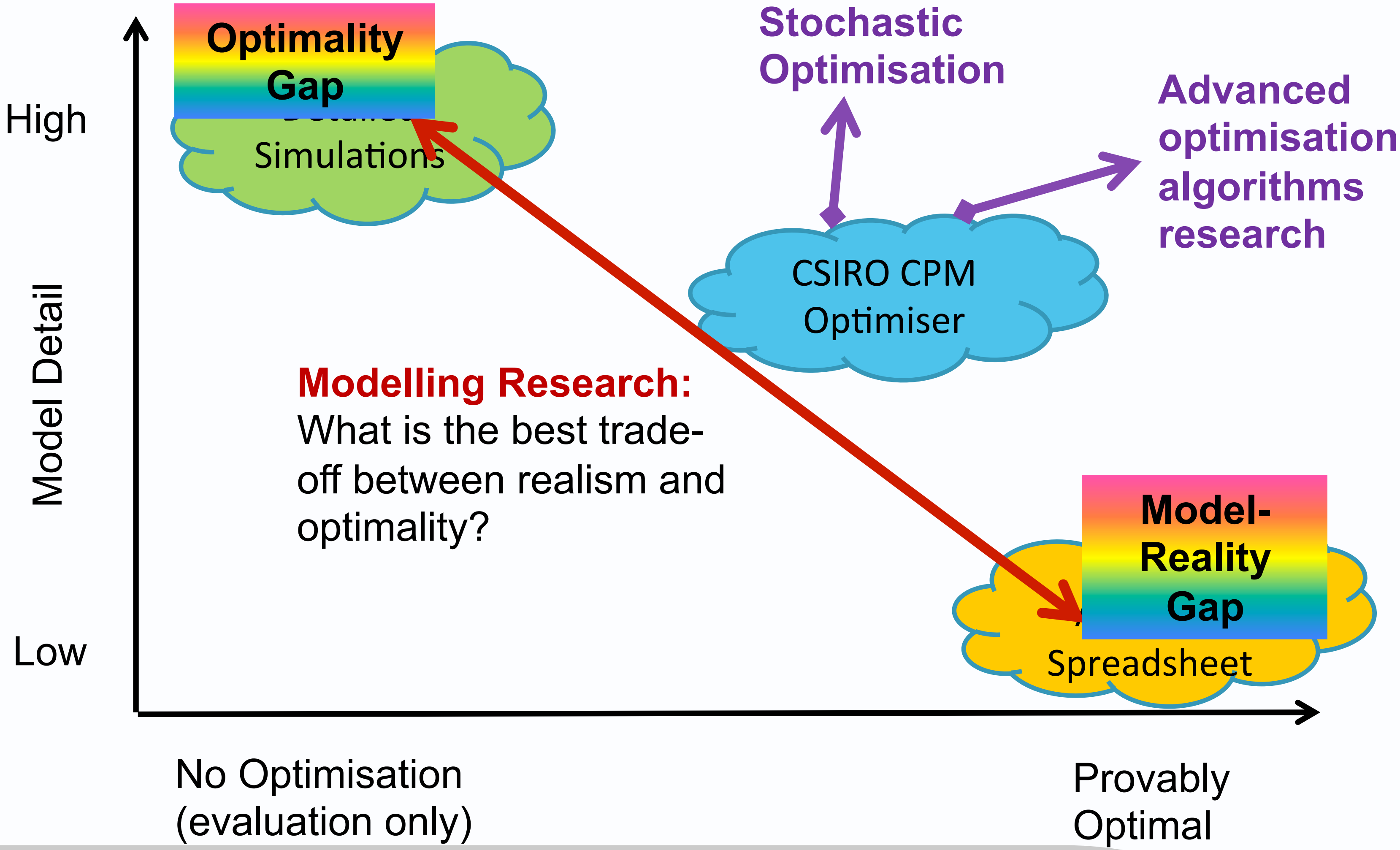
1. Challenging scheduling problem
2. Fixed time points from paths allows set packing style formulation with Lagrangean relaxation based solution approach
3. Time-space network based solution method allows more sophisticated Lagrangean approach
4. Reasonable solution quality in acceptable run time
5. 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

Modelling approaches for strategic planning

What is the best way to model the Hunter Valley supply chain?



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)

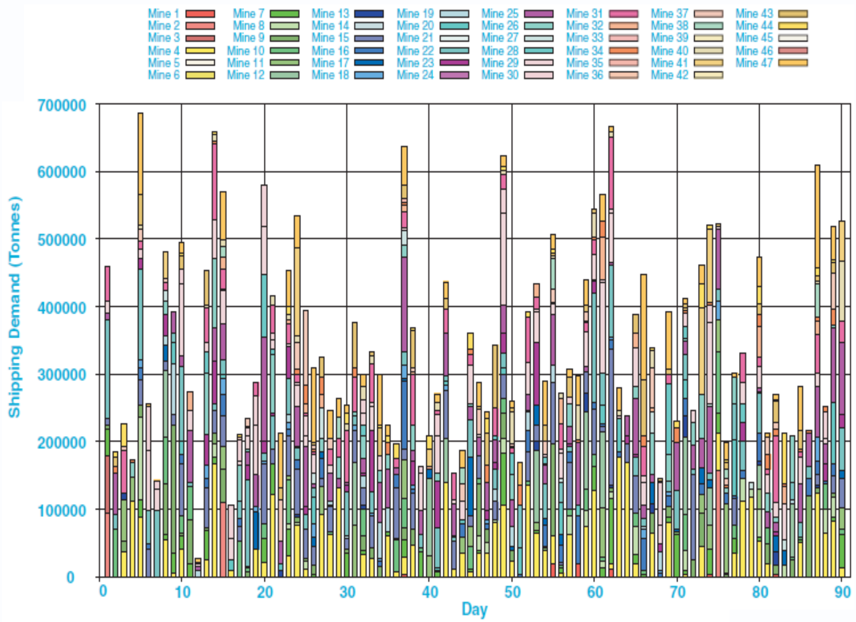
HVCC Capacity Planning Model in Practice

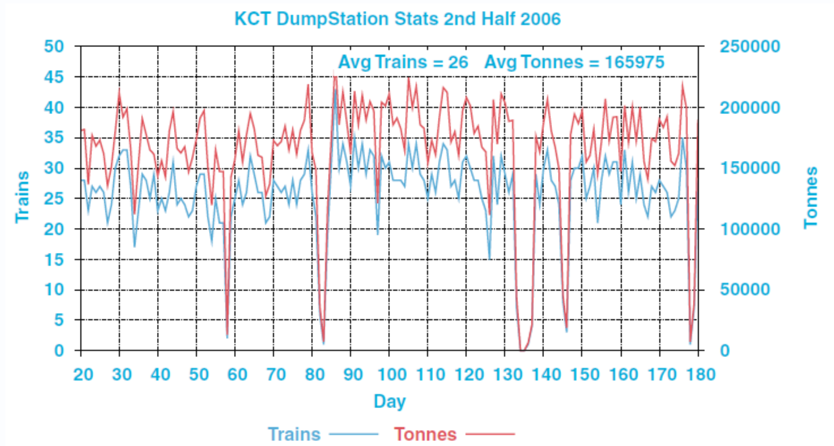
Used in conjunction with existing simulation model

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