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Estimating Australian Commodity Freight Movements: A Linear Programming Approach

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Abstract

Increased policy focus on freight, and the adequacy of infrastructure to support Australia's growing freight task, is increasing the demand for more detailed information on where and how freight moves. Detailed data on freight movements, however, is either expensive to collect or restricted by confidentiality concerns and, as a consequence, generally little data or only partial data is publicly available on the volume of current freight movements.

BITRE is attempting to fill this data gap for major commodities, using a (linear) programming approach. The methodology estimates freight flows by modelling commodity movements between sources of supply (e.g. mines, farms, quarries) and intermediate production facilities (e.g. mills, refineries) to points of final demand (e.g. ports, for commodity exports, power stations, domestic manufacturing plants) across domestic transport networks. Input data is drawn almost entirely from publicly available information. As far as practicable, the model incorporates commodity-specific supply chain characteristics (e.g. intermodal terminals, collection and storage facilities), providing scope to not only estimate freight movements, but also simulate the impact of potential changes to critical infrastructure links or new network infrastructure proposals.

The model has been developed entirely in R—the free software environment for statistical computing and graphics. Modelled freight flows are presently obtained as the linear programming solution to the problem of minimising the total cost of transport between all possible origins and destinations for individual commodities. The model incorporates multiple transport modes—presently road, rail, sea and conveyor. The paper briefly outlines the results of the model for iron ore—the model produces freight movement estimates for these commodities to within 2 to 3 per cent of industry-reported aggregate freight volumes. The model methodology is also readily extensible to other commodities. and BITRE has already developed modules for other commodities including coal, grains, cotton, rice and sugar.

1. Introduction

A competitive, efficient and productive national land freight system underpins Australia's economic growth and prosperity (Standing Council on Transport and Infrastructure 2013). Understanding the size and scope of Australia's current freight task is a key element in evaluating the adequacy and efficiency of transport infrastructure to support freight movements. However, the last comprehensive survey of regional origin–destination (OD) freight movements across Australia was undertaken was 2001 (Australian Bureau of Statistics 2002), and is now quite dated.[1] While that survey provided valuable information on OD road freight movements between regions, for major commodities at Statistical Division level and for all commodities at Statistical Subdivision level, OD information that could be released for rail and sea freight transport modes was limited to only state and territory level,

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[1] The ABS is currently processing results from a comprehensive survey of road freight movements undertaken in 2013–14, and funded by Commonwealth, state and territory transport agencies. Survey results are expected to be published in late 2015.

due to commercial confidentiality. Moreover, while the data was valuable at a regional level, it was not able to provide any information about the pattern of freight movements at a sub-regional level.

BITRE is attempting to fill this data gap for major commodities, using a (linear) programming approach. The methodology estimates freight flows by modelling commodity movements between sources of supply (e.g. mines, farms, quarries) and intermediate production facilities (e.g. mills, refineries) to points of final demand (e.g. ports, for commodity exports, power stations, domestic manufacturing plants) across domestic transport networks. Input data is drawn almost entirely from publicly available information. As far as practicable, the model incorporates commodity-specific supply chain characteristics (e.g. intermodal terminals, collection and storage facilities), providing scope to not only estimate freight movements, but also simulate the impact of potential changes to critical infrastructure links or new network infrastructure proposals. The information requirements of the model depend on the size and structure of the particularly industry, but typically include:

- commodity supply point information—location, production volume and transport access arrangements
- commodity demand point information—including location, usage, transport access arrangements and type of use, e.g. domestic use or port for export
- intermediate product handling/processing facility locations—e.g. intermodal terminals, mills, storage facilities
- transport network information—including detailed transport network information and the costs of transporting goods between each OD pair across the different modes. The model presently includes road, rail, sea and conveyor transport network layers.

The linear programming (LP) approach then allocates goods' movements in order to minimise an objective function, usually to minimise total transport costs (Reeb and Leavengood 2002).

Similar approaches have been used by other agencies, such as CSIRO, Transport for New South Wales (TfNSW) and the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES).

In particular, CSIRO's TRANSIT[2] tool has implemented an optimising approach to modelling livestock movements in northern Australia (Higginson 2013) and is currently being extended to cover livestock movements across all of Australia. Under the Australian Government's agricultural competitiveness agenda, the model is to be extended to cover 25 separate agricultural commodities (Australian Government 2015). Our understanding is that the TRANSIT model currently relies on detailed proprietary data of individual livestock origin–destination movements through different parts of the supply chain and has hitherto focussed only on road transport. Our approach, on the other hand, seeks to estimate such movements, admittedly not in as much detail, from entirely publicly available data sources.

TfNSW's Strategic Freight Model (SFM) covers the movement of over 72 different commodities between 230 origin and destination regions across New South Wales, and includes the capacity to forecast future inter-regional freight movements (TfNSW 2013, Appendix A). The model is built at a strategic level but covers only freight movements in New South Wales. Publicly available information about the TfNSW Strategic Freight Model does not elaborate on its capacity to model point-to-point movements or capture multi-modal freight movements through various parts of the supply chain.

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2. TRAnsport Network Strategic Investment Tool (TRANSIT) – www.csiro.au/en/Research/LWF/Areas/Landscape-management/Livestock-logistics/TRANSIT.

The BITRE's approach to date has focussed on major primary industry export commodities and has not considered significant import supply chains and manufactured commodity freight. The broader context of Australia's freight task is not covered in this paper, but is briefly covered in BITRE's *Freightline* series. The purpose of this paper is to provide a technical description of our scientific approach to estimating freight movements for Australia's major commodities.

The structure of the paper is as follows. Section 2 describes the use of linear programming to solve transportation problems and outlines the model structure. Section 3 outlines the BITRE's implementation of the linear programming approach to modelling freight movements. Section 4 presents model results for several selected commodities. Section 5 discusses some limitations and potential future extensions. Finally, we make some concluding remarks in Section 6.

2. Modelling origin–destination freight movements

The LP model formulation has long been used in modelling transport problems. The method is relatively straightforward to implement and mathematically simple to solve—the simplex method (Dantzig 1951) is the most common solution method, whereby the objective function and linear constraints are specified in matrix form, and solution by repeated 'pivots' to steps.

Suppose there are a set of freight origins, denoted by index i, and a set of freight destinations, represented by index j, connected by a transport network comprising m alternative transport modes. Each origin is assumed to produce a given amount T of commodity k (T_i^k) and each destination demands a given amount Q an amount of commodity k (Q_j^k). The total amount of commodity k supplied from origin i to all j destinations must be not greater than available supply at i (equation 1). Similarly, the total amount of commodity k supplied from all i origins must at least satisfy total demand at destination j (equation 2).

$$\sum_j x_{ij}^k \leq T_i^k \quad \text{for all } i \tag{1}$$

$$\sum_i x_{ij}^k \geq Q_j^k \quad \text{for all } j \tag{2}$$

Equation 1 is the supply constraint and Equation 2 the receival constraint. The linear programming problem is to choose the set of network paths (route) between from origin i to destination j (x_{ijr}^k) that minimises the total cost of transport, subject to the supply and recieval constraints, above. The objective function is

$$\min_{x_{ij}^k} \sum_r \sum_{i,j} c_r^k \cdot x_{ijr}^k \tag{3}$$

where x_{ijr}^k denotes the volume of commodity k transported between i and j by route r and c_r^k denotes the unit transport cost for commodity k along route r. The cost minimising network path between nodes i and j may involve multiple transport modes.

Equations 1, 2 and 3 comprise the general model specification. However, there are other potential constraints that may apply to particular commodities. These may include:

- storage site capacity constraints
- intermodal terminal constraints
- rail capacity constraints
- contractual arrangements, which dictate transport movements between particular node pairs.

The general specification described above is a ‘balanced transportation’ problem, where the total output from all sources is equivalent with the total demand at the destinations. Where the problem is unbalanced, e.g. total production exceeds demand transportation, the constraints are specified as inequality constraints, and slack variables need to be included to account for the imbalance. (A wider range of slack variables are also included in the model to ensure a feasible solution and assist with model validation.)

3. Commodity freight movement implementation

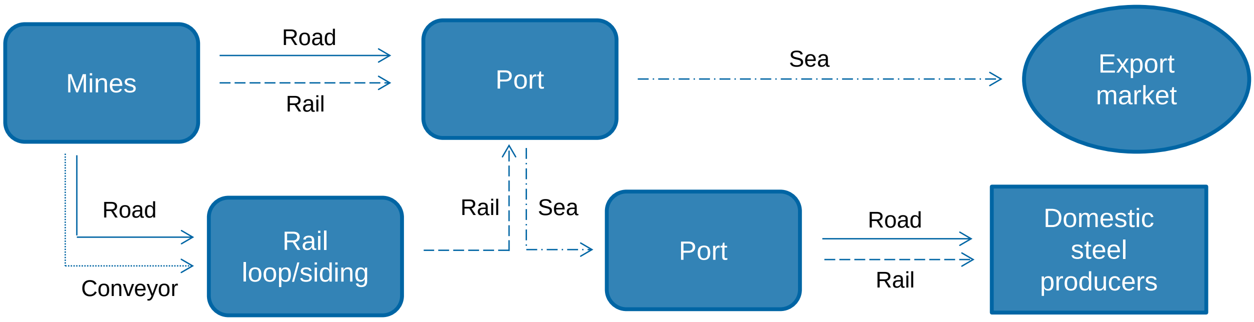
3.1 Commodity supply chain characteristics

The general model specification outlined in Section 2 can be readily applied to various commodities, albeit with slight modifications to handle differences in supply chain composition across different commodities.

For example, the iron ore supply chain (Figure 1) involves the transport of mined ore to port for export, with a small amount shipped around the coast to supply domestic users, and is a relatively simple supply chain. (The iron ore model does not extend to include steel product flows.) By contrast, the sugar supply chain (Figure 2) includes two intermediate production stages, sugar mills, where sugar cane is milled to produce raw sugar, and sugar refineries, which process raw sugar into refined sugar products. For the sugar supply chain, the general model specification, outlined in Section 2, has to be customised to handle flows of essentially four different ‘commodities’—i) cane sugar, from farms to mills; ii) raw sugar, from mills to refineries/ports; iii) refined sugar products, from refineries to ports/domestic users; and iv) cane sugar by-products, such as molasses and bagasse (not shown in Figure 2).

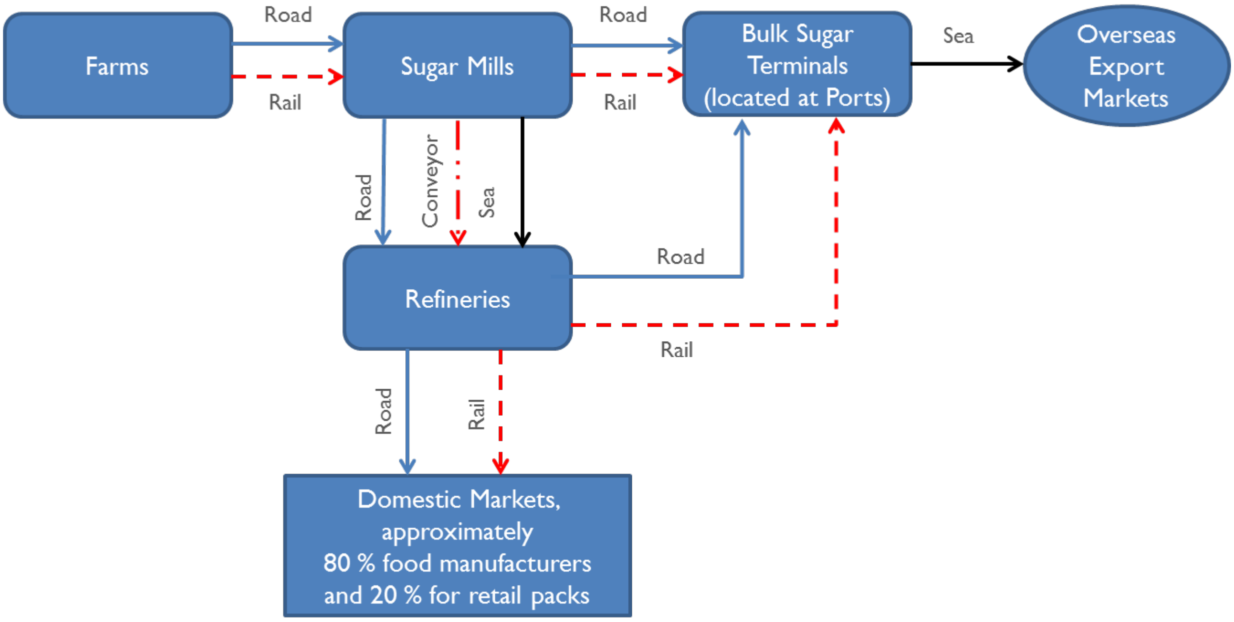
Customising the model to handle different supply chain characteristics broadly involves inclusion of additional constraint sets for each additional facility type. For example, for sugar, there are separate constraint sets for farms, sugar mills, refineries and bulk sugar terminals. For each of mills and refineries, the constraints need to take account of the in-plant transformation, i.e. from cane sugar to raw sugar at mills and from raw sugar to refined sugar products at refineries.

Figure 1: Australian iron ore supply chain



Source: BITRE (2014b).

Figure 2: Australian sugar supply chain



Source: BITRE (forthcoming).

3.2 Software

The model is presently implemented in R—the free software for statistical computing and graphics (R Core Team 2014). Various proprietary software packages could also be used to implement the model, for example a combination of ArcGIS, to handle spatial data, and GAMS, for linear programming, could be used.

The main advantage of R is that the entire modelling process can be handled in the one software tool. This includes:

- raw data processing
- handling spatial (GIS) data inputs
- computing network shortest paths
- linear programming (LP)—model uses *lpSolve* (Berkelaar et al. 2004)
- graphical outputs (including maps of commodity flows across transport networks).

The potential limitations of the current implementation revolve mainly around the LP model component—Meindl and Templ (2012), for example, report that open source solvers are not yet as fast and have lower solution success rates than commercial solvers, such as *Cplex* and *Xpress*. For the present, the models that we are solving do not appear large enough to run up against size and speed constraints identified by Meindl and Templ (2012).

3.3 Data requirements

The key data requirements for the model include:

- transport network data
- production facility locations and selected characteristics, including production volumes and transport network access
- processing and storage facility locations and selected characteristics, including processing/storage capacity, transport network access, loading/unloading rates

- domestic facility locations, covering places of domestic commodity consumption and use (e.g. steel mills or iron ore, power stations and cement plants for coal, etc.)
- port locations and selection locations, including commodity export volumes, processing/storage capacity and transport network access
- modal transport costs.

The amount of data required varies by industry, more or less according to the number of domestic industry-related establishments across the supply chain.

3.3.1 Transport network data

The road, rail and conveyor transport network layers used in the model are presently based on Geoscience Australia's vector topographic 250k scale data set (GA 2006). Some minor modifications were made to the GA road and rail layers—e.g. separating multilinestring road segments into single linestring segments and splitting rail segments at each railway station/siding. The domestic and international shipping lane network layer is a BITRE-digitised representation of aggregate ship GPS locations reproduced in AMSA (2010).

The model presently relies only on a minimal set of transport layer characteristics—length, road standard and surface type (road) and gauge (rail)—so that any topologically consistent and complete network data set could be readily substituted into the model, such as OpenStreetMap or commercial mapping data sets.

3.3.2 Commodity production, consumption and export data

Collection and validation of commodity production, consumption and export data for each domestic industry site and exporting port is integral to the specification of the LP model constraints, and is often the most labour-intensive component of model construction. The data has been sourced from public-sector statistical collections as well as from publicly-available private sector company annual reports. Key public-sector commodity production, consumption and/or trade data sources include:

- Regional agricultural output data – ABS, ABARES, State agriculture agencies
- Mineral output data – ABS, BREE, State and territory mining and resources agencies
- Port commodity export volumes – ABS, BITRE, Ports Australia
- Small-area land use information – Geoscience Australia, ABARES.

Where data that is required for the model is not available from public-sector statistical collections, it must be augmented using industry sources. For example, mineral production volumes are generally not reported at mine-level in public-sector statistical collections, and have had to be sourced from mining company annual reports. Similarly, grain handling and storage network location information, required for modelling grain supply chains, has been sourced from bulk grain handlers' websites. As far as possible, direct industry-source data is validated against statistical sources, at least at an aggregate level, to ensure total domestic commodity production and imports match total domestic commodity consumption and exports.

3.3.3 Transport costs

Transport costs considerably influence the estimated modal allocation and route assignment of model-estimated commodity movements and are a key model input. However, freight rates/transport costs are typically commercially sensitive and not generally publicly available. For those commodities modelled to date, we have relied on what information is publicly available about typical average costs to make informed judgement about relative modal transport costs.

The road transport sector is strongly cost competitive, featuring a large number of operators and minimal entry/exit barriers, so average road transport costs tend to closely reflect average total factor input costs. Presently, road transport costs for each network segment are set equal to the product of assumed average costs per (net) tonne kilometre and segment distance. (It is intended to add multiple heavy classes to the model, and develop an input-based cost module to differentiate average freight costs between different classes.)

Rail freight rates/operating costs are generally highly sensitive, and average costs will tend to vary across rail systems and with the volume of freight. The iron ore railways of the Pilbara, for example, tend to be very cost efficient with average operating costs of around 1–2 c/ntkm (cents per net tonne kilometre) and 2.5 c/ntkm for other bulk railways (Laird et al. 2005, p. 3). The low average operating costs of the Pilbara rail networks are attributed to world class track (good alignment, excellent formation, complete with sleepers and weight of rail capable of high axle loadings), up-to-date locomotives and well-maintained wagon fleets, as well as high average energy efficiency (e.g. 0.002 litres of diesel per 1 tonne kilometre of iron ore). For other commodities, rail transport volumes are much less and average transport costs generally far higher.

Over very long distances, coastal shipping average transport costs are generally less than those for road and rail. In any case, for long-distance bulk freight movements between coastally accessible locations, coastal shipping is generally the only feasible transport option.

3.4 Implementation

Implementation of the model involves the following steps:

- import transport network, and commodity production, consumption, export port and other supply chain site location and characteristics data
- match production, consumption, export port and other supply chain site locations to nearby transport network nodes, for all transport modes
- generate a matrix of modal transport costs for every network node pair
- formulate the LP model, taking account of all relevant supply chain constraints. As previously noted, additional constraints are generally included so that the freight movement model more closely represents actual supply chains—e.g. constraints to reflect the impact of contractual obligations on supply chain configuration, constraints that ensure total inflows and outflows balance at intermodal terminals, etc.

  In the iron ore supply chain model, for example, there are also constraints to ensure that iron ore only flows from mines to ports or domestic steel production facilities, and that iron ore does not flow between mines.
- finally, solve the LP model.

The LP model solution comprises a set of flows between every network node pair for which there is a non-zero freight volume, identified by OD pair. The outputs enable the results to be verified against available published statistics. For example, we have validated estimated iron ore and coal rail freight volumes against estimates reported by the Australian Railway Association (ARA 2012).

4. Model results

4.1 Iron ore freight movements

This section briefly outlines application of the model to estimating iron ore freight movements, particularly key data sources and special features of iron ore supply chains.

Iron ore mine locations were sourced from Geoscience Australia's *Operating Mines Dataset* (Geoscience Australia 2012). Iron ore mine production estimates were obtained from mining company annual reports and/or quarterly or semi-annual public statements. Identification of transport access arrangements for each mine was included in this step. Total iron ore production in 2011–12 was approximately 510 million tonnes. Port iron ore exports were sourced from Ports Australia (2012), and augmented and cross-checked individual port authority annual reports. Total iron ore exports were just over 500 million tonnes in 2011–12.

There are two major domestic users of iron ore—BlueScope Steel's Port Kembla steelworks and Arrium's Whyalla steelworks. Between them, they used approximately 6.5 million tonnes of domestic iron ore to produce approximately 4.6 million tonnes of steel.

The iron ore LP model constraint set includes:

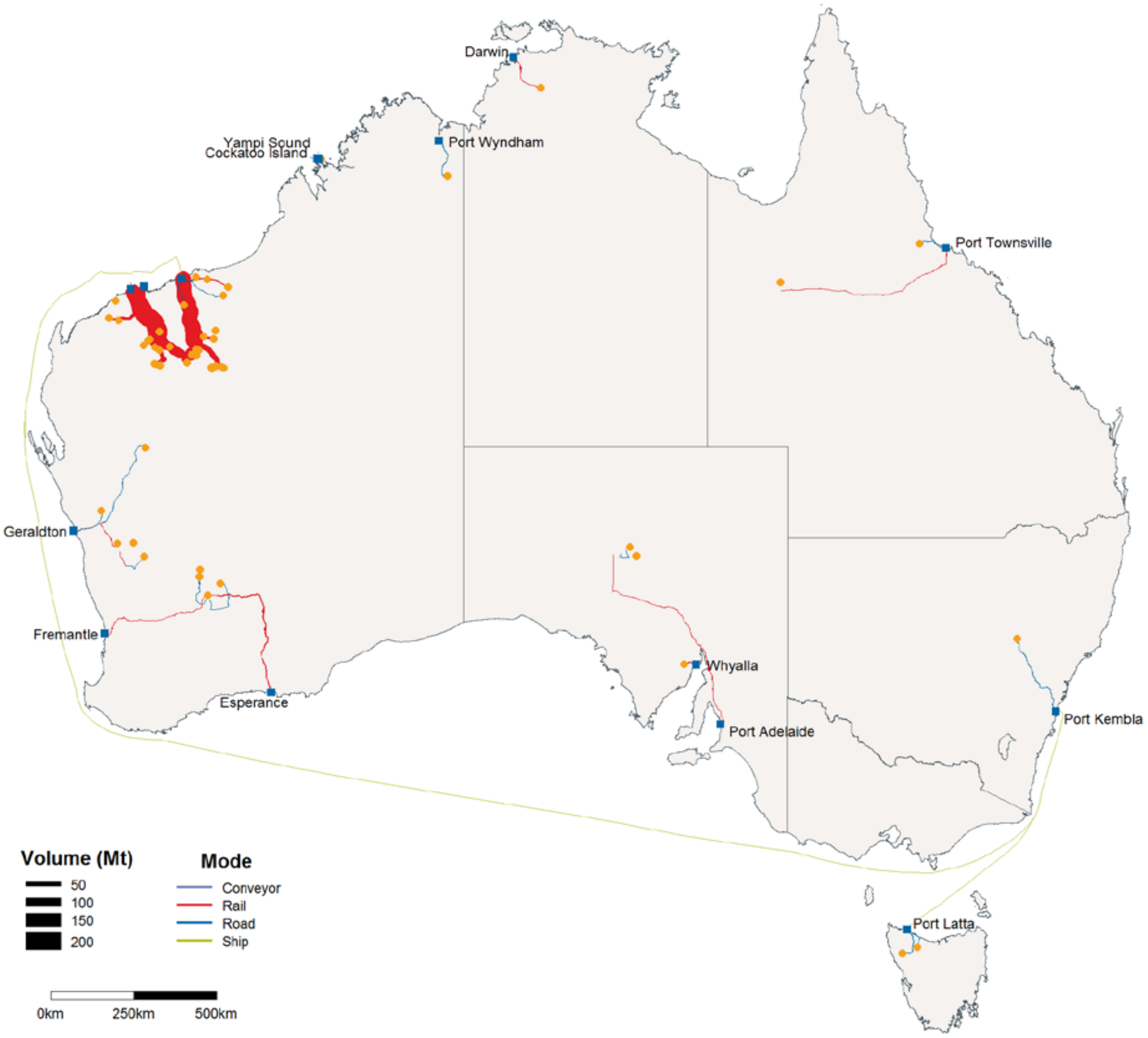
- mine production constraints
- domestic steel input constraints
- port export volume constraints
- intermodal node constraints
- additional supply-chain specific constraints.

Intermodal nodes are those points in the network where freight transfers from one mode to another, with no change in volume. Ports are essentially intermodal nodes, but are treated separately to other intermodal nodes in the model as they are a source of information on freight throughput. Apart from ports, there are few intermodal nodes in Australian iron ore supply chains. In 2011–12, these were limited to conveyor–rail connections servicing a few of the larger iron ore producers' mines, and the transfer of ore between road and rail for ore from Cairn Hill mine (mid-north SA), for export from Port Adelaide, Carina mine (Southern WA), for export through Fremantle, and from Cliffs Natural Resources' mines, near Koolyanobbing (WA), to Esperance for export.

Iron ore supply-chain specific constraints are included so that the LP model more closely reflects actual transport arrangements. For example, iron ore supplied to BlueScope Steel's Port Kembla facility in 2011–12 came from BHP Billiton Pilbara mines, via Port Hedland, and the Savage River mine in north-west Tasmania, via Port Latta. Absent these constraints, that capture specific contractual arrangements, the model would produce inaccurate transport flows.

Figure 3 illustrates the model-estimated domestic iron ore freight transport flows for 2011–12. Most immediately apparent is the large volume of iron ore transported by rail from the Pilbara to export ports at Port Hedland, Dampier and Port Walcott. Figure 3 also shows smaller volumes of iron ore from mid-west and south-west Western Australia, and in New South Wales, Queensland, South Australia, Tasmania and the Northern Territory.

Figure 3: Estimated iron ore freight transport flows, by transport mode, 2011–12



Source: BITRE (2014b).

Table 1: Estimated iron ore freight transport flows, by jurisdiction[a] and transport mode

Jurisdiction	Road	Rail	Sea	Other	Total	Road	Rail	Sea	Other	Total[b]
	(billion tkm)					*(million tonnes)*[a]				
NSW	0.03	0	0	0	0.03	0.07	0	0	0	0.07
Qld	0.02	0.51	0	0	0.53	0.17	0.7	0	0	0.85
SA	0.13	1.87	0	0	2.00	1.73	9.6	0	0	9.6[c]
WA	3.09	167.99	23.62	0.44	195.14	9.73	483.3	4.1	53.9	491.6[c]
Tas.	0.33	0	0.44	0	0.77	2.07	0	0.8	0	2.07
NT	0	0.20	0	0	0.20	0	1.1	0	0	1.09
Total	3.62	170.57	24.06	0.44	198.67	13.77	494.7	4.9	53.9	505.3

a. Jurisdictional allocation of road, rail and other transport volumes based on administrative boundaries. Jurisdictional allocation of sea freight transport volumes based on port of loading.

b. Tonnages presented on a total uplift/discharge basis. Modal volumes do not sum to total tonnages.

c. Intermodal transport counted only once in the total.

Source: BITRE (2014b).

Table 2: Estimated regional origin–destination iron ore freight volumes, 2011–12[a]

	Destination – SA3 region											
Origin – SA3 region	**Daly - Tiwi - West Arnhem**	**Esperance**	**Illawarra Catchment Reserve**	**Kimberley**	**Mid West**	**Outback - North and East**	**Pilbara**	**Port Adelaide - West**	**Townsville**	**West Coast**	**Wheat Belt - North**	**Total**
						Road (*million tonnes*)						
Charters Towers-Ayr-Ingham									0.17			0.17
Dubbo			0.07									0.07
Kimberley				1.50								1.50
Mid West					1.45							1.45
Outback - North and East						1.73						1.73
Pilbara							6.78					6.78
West Coast										2.09		2.09
Total			0.07	1.50	1.45	1.73	6.78		0.17	2.09		13.79
						Rail (*million tonnes*)						
Katherine	1.08											1.08
Mid West					5.26							5.26
Outback – North									0.68			0.68
Outback - North and East						7.87		1.73				9.60
Pilbara							467.35					467.35
Wheat Belt – North		8.90									1.82	10.72
Total	1.08	8.90			5.26	7.87	467.35	1.73	0.68		1.82	494.69
						Sea (*million tonnes*)						
Pilbara			4.10									4.10
West Coast			0.80									0.80
Total			4.90									4.90
						All modes (*million tonnes*)						
Charters Towers-Ayr-Ingham									0.17			0.17
Dubbo			0.07									0.07
Katherine	1.08											1.08
Kimberley				1.50								1.50
Mid West					6.71							6.71
Outback - North									0.68			0.68
Outback - North and East						9.60		1.73				11.33
Pilbara			4.10				474.13					478.23
West Coast			0.80							2.09		2.89
Wheat Belt - North		8.90									1.82	10.72
Total	1.08	8.90	4.97	1.50	6.71	9.60	474.13	1.73	0.85	2.09	1.82	513.38

a. ASGS 2011 SA3-level regions (ABS 2011).

Source: BITRE (2014b).

Table 1 shows the model-based estimates of domestic iron ore freight volumes for 2011–12, by jurisdiction and transport mode. The model implies the total iron ore freight task was approximately 198.7 billion tonne kilometres, nearly one-third of the total Australian freight task (approximately 599 billion tonne kilometres in 2011–12) and the iron ore rail freight volumes are nearly 60 per cent of total Australian rail freight volumes (approximately 290.6 billion tonne kilometres in 2011–12).

The model-based iron ore rail freight task estimates—494.7 million tonnes and 170.57 billion tonne kilometres—closely accord with the Australian Railway Association's (ARA 2013) reported estimates—496.3 million tonnes and 175.4 billion tonne kilometres in 2011–12 (ARA 2013, pp. 22 & 27). The slight difference in the estimated rail freight task are most likely due to slight differences in the distribution of mineral outputs across BHP Billiton and Rio Tinto's mines, and approximation of actual rail distances using digital network data.

The model also facilitates production of regional OD freight movement estimates at any desired geographical area level. Table 2 shows estimated OD iron freight movements at Australian Statistical Geography Standard (ASGS) Statistical Area 3 (SA3) level (ABS 2010).

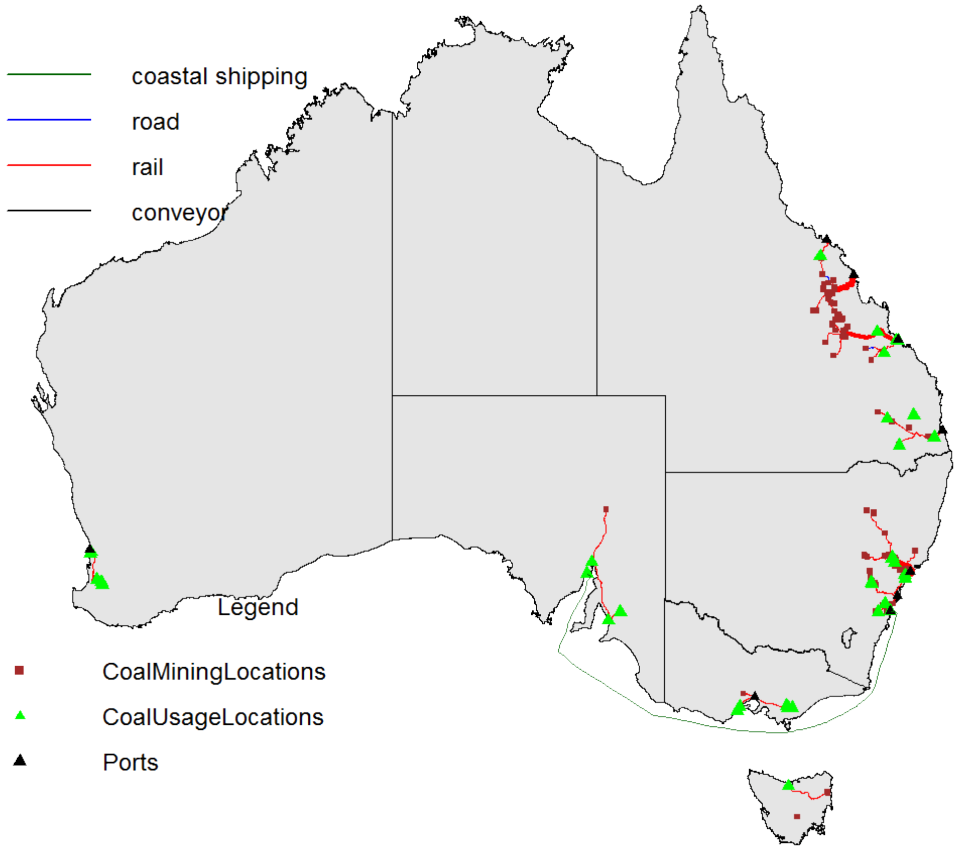
4.2 Other commodities

Other commodities that BITRE has or is in the process of modelling include:

- Grains (wheat, coarse grains & pulses)
- Coal
- Sugar
- Cotton and rice

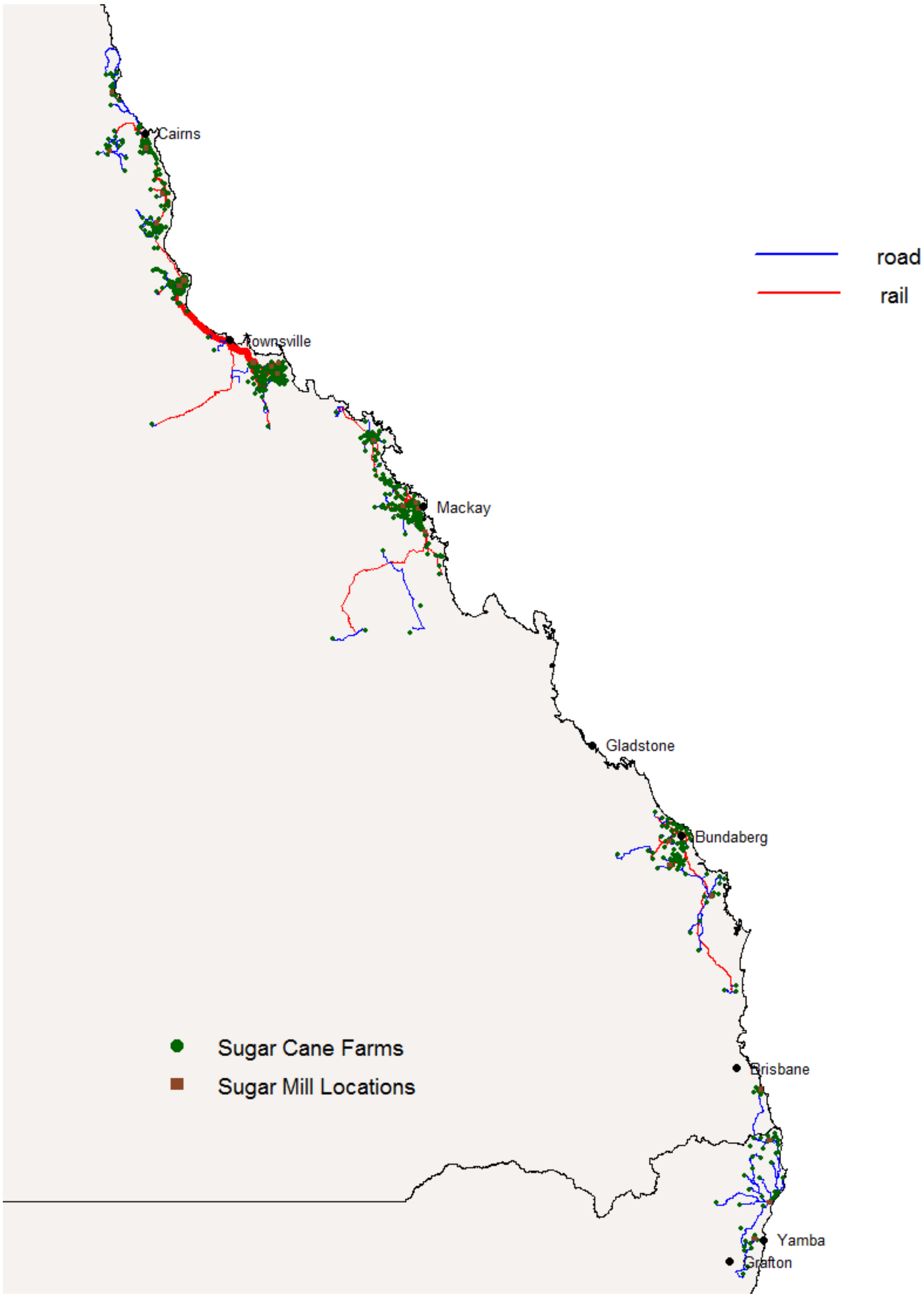
Figure 4 illustrates model-estimated domestic coal transport flows for 2011–12 and Figure 5 shows model-estimated domestic sugar transport movements for 2011–12.

Figure 4: Estimated coal freight transport flows, by transport mode, 2011–12



Source: BITRE estimates.

Figure 5: Estimated sugar cane freight transport flows, by transport mode, 2011–12



Source: BITRE estimates.

5. Model limitations and potential extensions

The present model specification either applies a simplified approach or does not explicitly model particular aspects of transport supply chains. In particular, the current optimisation function is a simplification of how supply chains decisions are made, and the model currently includes only a single heavy vehicle type.

5.1 Optimisation specification

The linear programming approach minimises the total cost of transport across the entire commodity supply chain. It is akin to a single decision maker optimising across all different entities in the supply chain. However, in the real world supply chain decisions are made by multiple entities, and a more realistic approach would have each separate entity (agent) in the model optimising (either minimising cost or maximising profit) across their own supply chain(s). The simple LP model does not reflect this multiplicity of objectives.

The other shortcoming of the LP model is that it does not allow for costs to vary with transport volumes. For bulk rail freight, particularly iron ore and coal, average transport costs generally vary with transport volumes, implying a non-linear transport cost function. However, correctly specifying the cost function is problematic because of the limited amount of publicly-available rail cost information, and further non-linear programming problems are more computationally intensive.

5.2 Multiple vehicle types

The present model specification includes a single, generic road freight vehicle type, which is assumed to have access to the entire road network. In practice, there are many different heavy vehicle configurations, ranging in size from two-axle rigid trucks of 4.5 tonnes up to triple trailer road trains, all with different cost structures and each subject to different road network access restrictions. Future development of the model is planned to include allowance for multiple heavy vehicle classes, which take account of varying costs and network access restrictions.

5.3 Scenario analysis

A common use of network models is to be able to simulate the likely market response to changes in market conditions or network disruptions. Though not considered here, the model structure readily enables consideration of different scenarios, including the impact of potential disruptions to critical infrastructure links or new network infrastructure proposals.

6. Concluding Remarks

This paper has outlined a general methodology and model framework for estimating inter-regional commodity movements in Australia. The paper also presents some sample estimates of multi-modal freight movements of iron ore, coal and sugar, that have been produced using the model, derived from commodity production origin location and output data and destination location and demand data. Specific supply chain characteristics need to be incorporated to each model of freight movements for each commodity. As far as possible, practical and existing unique transport arrangements for each commodity need to be integrated to the models that allocate origin destination freight movements based on the lowest transport cost. The estimates need to be verified with aggregate or known freight movement data for a particular commodity to ensure the appropriateness of the models and their results. The approach can be readily extended to estimate other commodity freight movements, primarily agricultural and mining commodities, such as sugar, cotton, rice, grain (wheat) and coal.

This approach to estimate freight movements also allows sensitivity analysis to be performed, in particular where investigation (through simulation) on the impact of potential disruptions to critical infrastructure links, or new network infrastructure proposals, is required.

Improved transport network and transport cost data, as well as more accurate origin destination data from a freight movement survey, would allow improved accuracy as well as expansion of the freight movement information. This would significantly support policy development and infrastructure investment decisions.

References

Australasian Railway Association (2013), *Australian Rail Industry Report 2011–12*, Report prepared for the ARA by the Apelbaum Consulting Group, Melbourne. URL: www.ara.net.au.

Australian Bureau of Statistics (2002), *Freight Movements, Australia, Summary (Re-issue)*, September 2002, Catalogue no. 9220.0, ABS, Canberra. URL: www.abs.gov.au.

Australian Bureau of Statistics (2010), *Australian Statistical Geography Standard (ASGS): Volume 1 - Main Structure and Greater Capital City Statistical Areas, July 2011*, Catalogue no. 1270.0.55.001, ABS, Canberra. URL: www.abs.gov.au.

Australian Government (2015), *Agricultural Competitiveness White Paper*, Commonwealth of Australia, Canberra. URL: agwhitepaper.agriculture.gov.au.

Australian Maritime Safety Authority (2010), *Navigational Safety in Australian Waters 2010–2025*, AMSA, Canberra. URL: www.amsa.gov.au.

Berkelaar M, Eikland K and Notebaert P (2004), *lp_solve* (Version 5.1.0.0), Open Source (Mixed-Integer) Linear Programming System. URL: lpsolve.sourceforge.net.

Bureau of Infrastructure, Transport and Regional Economics (2014a), *Freightline 1 – Australian freight transport overview*, BITRE, Canberra. URL: www.bitre.gov.au.

Bureau of Infrastructure, Transport and Regional Economics (2014b), *Freightline 2 – Australian iron ore freight transport*, BITRE, Canberra. URL: www.bitre.gov.au.

Cherny D, Denton T and Waldron A (2013), *Linear Algebra,* Retrieved from www.math.ucdavis.edu/~linear/.

Dantzig G B (1951), 'Application of the Simplex Method to a Transportation Problem', Paper presented at the Activity Analysis of Production and Allocation.

Geoscience Australia (2006), *GEODATA TOPO 250k Series 3* [Data], Geoscience Australia, Canberra. URL: www.ga.gov.au.

Geoscience Australia (2012), *Operating Mines Dataset* [Data], URL: www.australianminesatlas.gov.au/mapping/downloads.html#ozmin, Accessed: August 2013.

Heizer, J and Render, B (2014), *Operations Management*, 11th Edition: Prentice Hall.

Higginson A J (eds) (2013), *Livestock Industry Logistics*: *Optimising Industry Capital Investment and Operations*, CSIRO Sustainable Agriculture Flagship, CSIRO, Canberra.

Laird P G, Michell M, Stoney A and Adorni-Bracessi G (2005), *Australian Freight Railways for a new century*, AusRail Plus 2005, 22–24 November 2005, Sydney, Lloyd's List Daily Commercial News. URL: ro.uow.edu.au.

Meindl B and Templ M (2012), 'Analysis of commercial and free and open source solvers for linear optimization', Technical Report CS-2012-1, Institute for Statistics and Probability Theory, Vienna University of Technology. URL: www.statistik.tuwien.ac.at/forschung/CS/CS-2012-1complete.pdf.

Transport for New South Wales (2013), *NSW Freight and Ports Strategy*, TfNSW, Sydney.

Ports Australia (2012), *Trade Statistics 2011–12 [Data]*, Ports Australia. URL: www.portsaustralia.com.au.

R Core Team. (2014). *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna. URL: www.R-project.org.

Reeb, J E and Leavengood S A (2002), 'Transportation problem: a special case for linear programming problems', Performance Excellence in the Wood Products Industry, EM(8779).

Standing Council on Transport and Infrastructure (2013), *National Land Freight Strategy: A place for freight*, URL: www.transportinfrastructurecouncil.gov.au/publications/files/National_Land_Freight_Strategy_Compressed.pdf.

Transport for New South Wales (2013), *NSW Freight and Ports Strategy*, TfNSW, Sydney.