

# Estimating Freight Movements using Dijkstra's Algorithm

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## Abstract

The demand for more detailed information on Australia's freight movement is increasing due to more policy focus on freight and the adequacy of infrastructure to support Australia's growing freight task. 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 related to current freight movements.

With this lack of data availability, Dijkstra's algorithm is well suited to be used in deducing freight movements due to the simplicity of its 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 across domestic transport networks. Apart from the transport network and the cost of freight between identified locations, the only data needed is the production data of a commodity. It incorporates two or more possible transports modes, as per the individual commodity scenario, in the model.

This modelling approach is applied to the commodities of rice and cotton and results presented.

## 1. Introduction

Knowledge of freight movements within Australia is one of the most important pieces of information required for the informed planning of Australian infrastructure needs. The majority of freight transport models that have been proposed are usually designed for specific scenarios. The main obstacle in the development of more elaborate freight models is the limited availability of data (Ben-Akiva et al., 2008). A linear programming (LP) approach was presented in Mitchell & Kurniawan (2015), which also noted that data is scarce due to commercial confidentiality issues and the need to fill in the data gaps. This paper presents an application of Dijkstra's algorithm that works with minimal data and can generate reasonable modelled freight movement outputs. The structure of the paper is as follows. Section 2 describes the Dijkstra's algorithm. Section 3 outlines the implementation of Dijkstra's approach to modelling freight movements and describes the data requirements. Section 4 presents the model formulation and results for two specific commodities—cotton and rice. Finally, we make some concluding remarks in Section 5.

## 2. Dijkstra's Algorithm

Dijkstra's algorithm is classified a greedy algorithm, that is it solves a problem by building its solution set one element at a time. Once an element is added to the solution, it will not be

removed, so that there is no backtracking. The rule that adds elements to the solution set is generally fairly simple. Greedy algorithms are very sequential since the decision whether to add an element to the solution set depends on all previous decisions.

Dijkstra's algorithm is one of the most popular algorithms in computer science and operations research (Sniedovich 2006) and can be used to determine the shortest path from one node in a graph to every other node within the same graph data structure, provided that the nodes are reachable from the starting node.

A graph is a data structure with two distinct parts: a finite set of vertices, which are also called nodes, and a finite set of edges, which are references/links/pointers from one vertex to another. Graphs are represented as  $G = (V, E)$ , where  $V$  is the set of vertices or nodes, and  $E$  is the set of edges. There are two ways of representing this set of edges either as unordered pairs, or ordered pairs based on whether the graph's edges are directed or undirected. An undirected graph's edges have no order to them, hence it is possible to travel from one vertex to the other. However for the directed graph, there is directional flow.

Let:

$u$  or  $v$  be vertices or nodes in a graph;

$o$  be the source node (origin);

$m$  be the destination node;

$(u, v)$  denote an edge from  $u$  to  $v$ ;

$w(u, v)$  denote the weight of the edge that connects  $u$  and  $v$ ;

$dist(v)$  be the distance from the source (starting node) to node  $v$ ;

$Q$  be a queue of all nodes in the graph (at the conclusion of the algorithm, it will be empty);

Dijkstra's algorithm finds a shortest path tree from a single source node  $o$  to  $m$ , by building a set of nodes that have minimum distance from the source as follows:

Given: origin node =  $o$  and destination node =  $m$ ;

Initialization:  $dist(o) = 0$  and  $dist(v) = \infty$  for all other nodes

Iteration:

While ( $v \neq m$ , take the node  $v$  from  $Q$ , with the smallest  $dist(v)$ . [Note that for the first iteration, the source node,  $o$  will be chosen because  $dist(o) = 0$  and  $dist(v) = \infty$  for all other nodes]

Step 1: remove  $v$  from  $Q$  to indicate that node  $v$  has been visited;

Step 2: Update  $dist$  values of all nodes *directly connected* to  $v$ , by using:

If  $dist(v) + w(u, v) < dist(u)$

then  $dist(u) = dist(v) + w(u, v)$ ;

otherwise  $dist(u)$  is unchanged.

The algorithm terminates if either  $v \neq m$  or  $v = \infty$  are not satisfied. Thenafter the shortest path can be traced back by following the nodes' parents from the destination node up to the starting node.

The pseudocode for the above is provided below:

```

function Dijkstra (Graph, sourceNode, destinationNode){
    dist[sourceNode] = 0
    for each node v in Graph {
        if (v ≠ sourceNode){
            dist[v] = ∞
        }
        add v to Q
    }
    while (v ≠ destinationNode or v = ∞) {
        v = node from Q with min dist[v]
        remove v from Q
        for each neighbour u of v{
            if (dist(v) + w(u, v) < dist(u))
                dist(u) = dist(v) + w(u, v)
        }
    }
    return dist[]
}

```

### 3. Freight Movement implementation

#### 3.1 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 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;
- applying Dijkstra's algorithm; and
- graphical outputs (including maps of commodity flows across transport networks).

### **3.2 Data Requirements**

The required input for Dijkstra's approach to solving freight modelling are:

- Transport network data (road/rail);
- Commodity production; and
- Transport costs (for applicable modes) between identified locations (Eg. For cotton: farms, gins, warehouses & ports);

#### ***3.2.1. Transport network data***

The road, rail and conveyor transport network layers used in the model are based on Geoscience Australia's vector topographic 250k scale data set (GA 2006). Some minor modifications, such as separating multilinestring road segments into single linestring segments and splitting rail segments at each railway station/siding, were made to the GA road and rail layers.

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, such as OpenStreetMap or commercial mapping data sets, could be readily substituted into the model.

#### ***3.2.2. Commodity production***

Collection and validation of commodity production 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 data sources include:

- Regional agricultural output data – ABS, ABARES, State agriculture agencies
- Mineral output data – ABS, State and territory mining and resources agencies
- Port commodity export volumes – ABS, Ports Australia
- Small-area land use information – GA, 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, grain handling and storage network location information 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.

#### ***3.2.3. 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 cost are assumed to be between 15 and 20 c/ntkm (cents per net tonne kilometre). This is based on an estimated average operating cost of between 10 and 15 c/ntkm for a fully laden B-double, plus the cost of the empty return leg. By way of comparison, Freight Metrics' online Truck Operating Cost Calculator<sup>1</sup> implies an average cost of 10.9 c/ntkm for a B-double carrying an average of 24 tonnes and travelling just over 207,000 kilometres per year. For the purposes of our modelling, we used 12.5 c/ntkm<sup>2</sup>

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 and 2.5 c/ntkm for other bulk railways (Laird et al. 2005, p. 3). For other commodities, rail freight volumes are much less and average transport costs generally higher—BITRE (2017), for example, estimates average rail freight rates for intermodal freight at around 4 c/nktm in 2016<sup>3</sup>. The rates used for our modelling purposes are based on the grade of the railway lines. The rates were 6, 7, 8, 9.5 and 10.5 c/ntkm for grades A,B,C,D and E respectively.

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.

### 3.3 Implementation

Implementation of the model involves the following steps:

- import transport network, and commodity production and other supply chain site locations including ports characteristics data;
- match production 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;
- use Dijkstra's algorithm to find cheapest path from origin (production) to destination (usually export ports) via required production facilities;
- refine results in reference to known paths of delivery; and
- cross-check exports data (if available) with the modelling results

## 4. Modelling results of Cotton and Rice freight movements

For the purposes of this paper, the freight movement for cotton and rice commodities will be considered, for the financial year of 2015-16.

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<sup>1</sup> Source: [www.freightmetrics.com.au/Calculators/TruckOperatingCostCalculator/tabid/104/Default.aspx](http://www.freightmetrics.com.au/Calculators/TruckOperatingCostCalculator/tabid/104/Default.aspx).

<sup>2</sup> Cotton fibre has a relatively lower volumetric density compared to rice—cotton lint's density is approximately 472 kg/m<sup>3</sup> while that of milled rice is approximately 780kg/m<sup>3</sup>. A standard six-axle or B-double articulated truck carrying rice is likely to be mass-constrained before being volume constrained. Even for cotton, however, mass constraints are not immaterial—for example, Cotton Australia's Bale Restraint Guide 2013 implies that high density cotton bales can be loaded on conventional 12.2 meter a semi-trailer up to a payload of approximately 25.2 tonnes, which would be close to the theoretical maximum allowable mass for a six-axle articulated truck with GVM 42.5 tonnes and tare weight of around 16 tonnes.

<sup>3</sup> Rail freight rates applying to transport of cotton and rice to port for export, traverse routes with more limited rail backhaul opportunities and hence freight costs are likely to be higher than for intercapital rail.

## 4.1 Cotton

### 4.1.1. Background

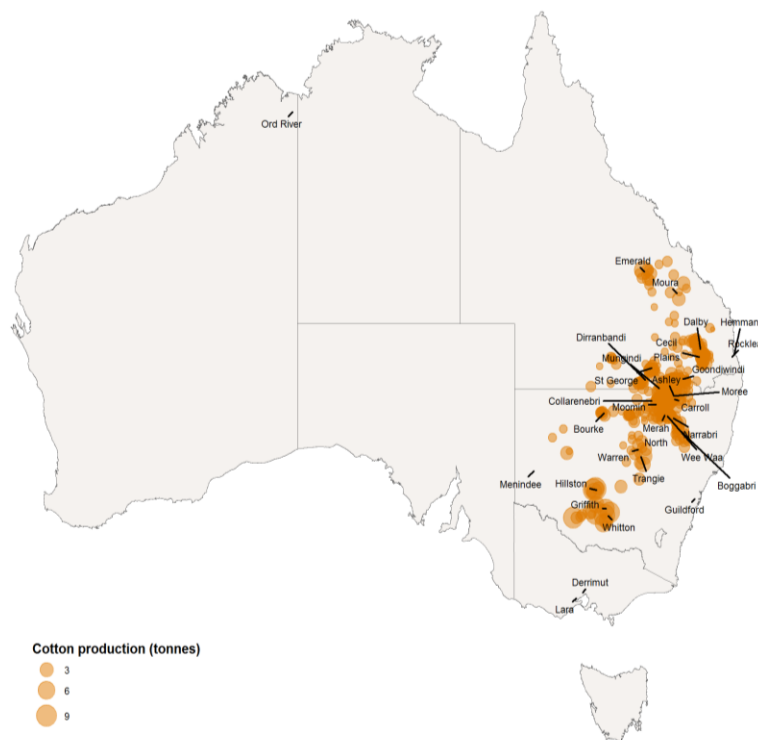
Cotton is an annual, summer crop. Beginning in August, soil is prepared for planting. From September to November, cottonseed is planted and the growing season lasts from November through to February. It takes approximately four months for the cotton bolls to split open. From March to May, cotton is picked and transported to gins for processing, before classing—the grading of cotton fibre based on quality—and marketing activities are undertaken from May to August. Australian cotton is predominately grown in New South Wales and Queensland (see Figure 1 and Table 1 for details on production regions and quantity for the year 2015-16).

**Table 1: Australian cotton lint production for the year 2015–16**

Area	Production (kt)
New South Wales	362.8
Queensland	188.1
Australia (Total)	550.9

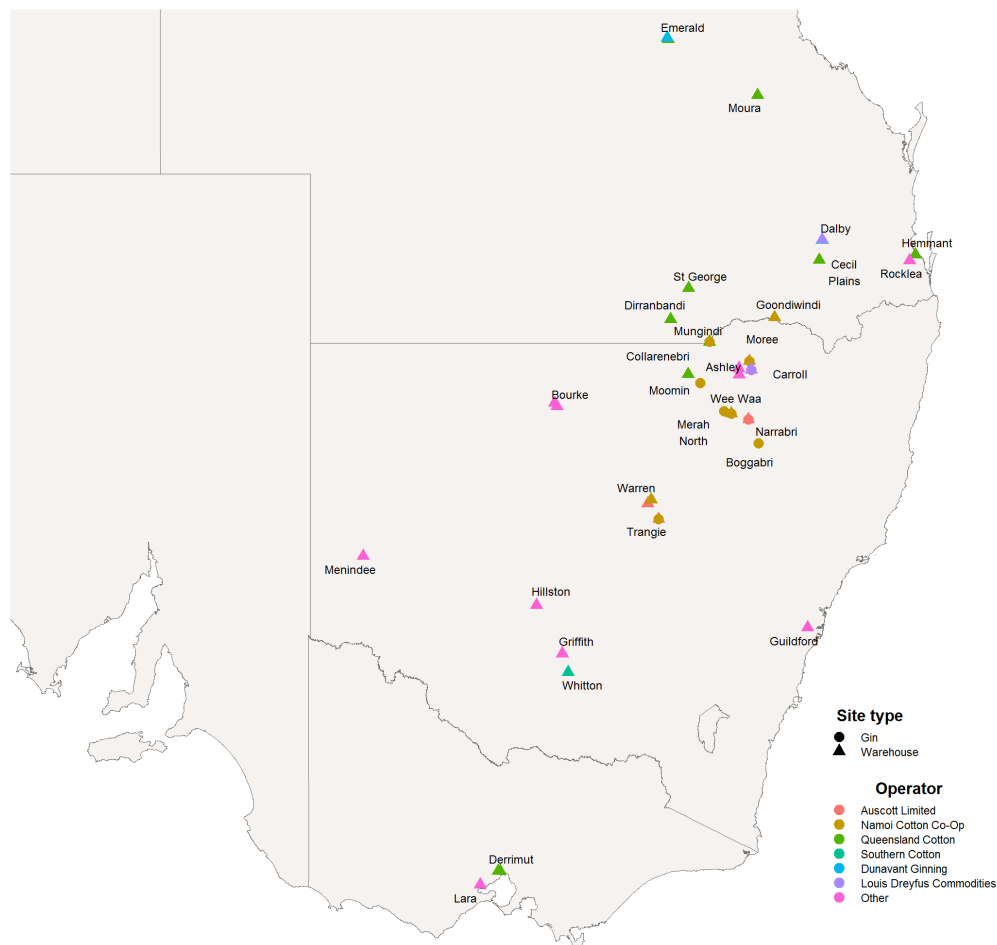
Sources: ABARES (2017) and ABS (2017a).

**Figure 1: Cotton growing areas, Australia, 2015–16**



Once picked, cotton is pressed into large rectangular modules or round bales on the farm. The bales and modules are then transported to a cotton gin for the first stage of processing. Cotton gin factories separate cotton lint—the raw cotton fibre—from the cottonseed and trash—stalks and seed hulls. Large mechanical saws strip the cotton lint from the seeds, and blowers remove as much trash as possible. The lint is then pressed into cotton bales for sale. Each cotton bale weighs 227 kilograms (Cotton Australia 2013c). Gins are located in regional areas where cotton is grown. Figure 2 shows the location of Australia’s cotton gins and warehouses. Note that some of the gins also operate as warehouses.

**Figure 2: Location of cotton gins and warehouses, Australia**



Cotton transport arrangements are influenced by the location of ginning and storage facilities, and nearby transport links. Figure 3 provides a simple schematic diagram of the Australian raw cotton supply chain.

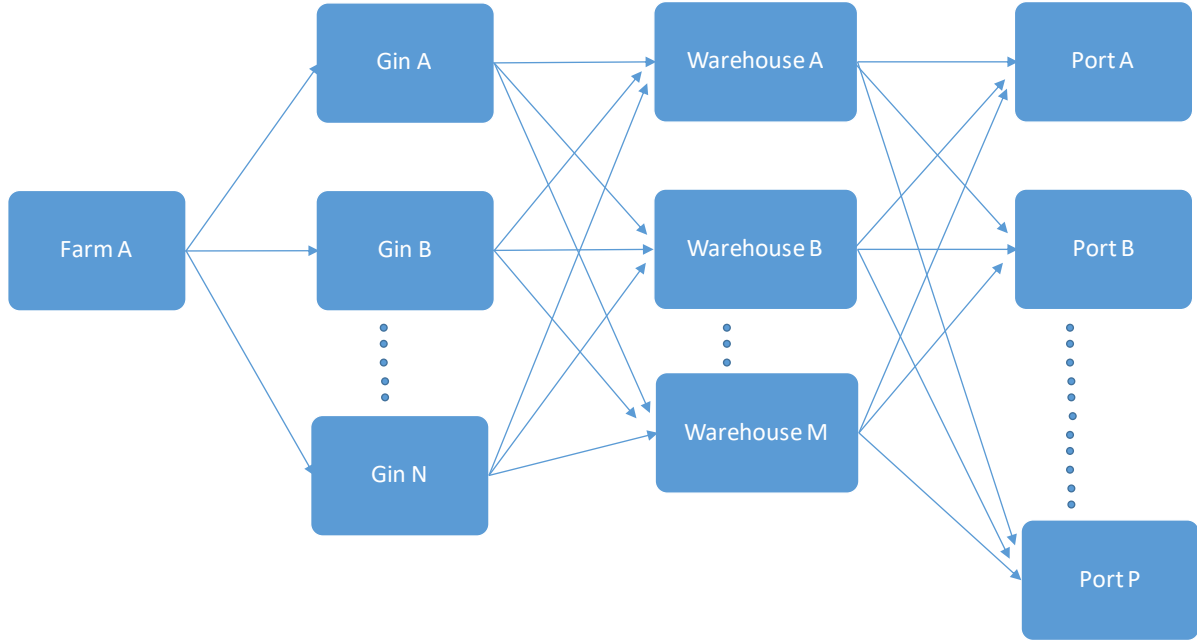
**Figure 3: Simplified cotton supply chain**



Hence to solve the cotton freight movement problem within Australia, the task is to find the “shortest” (cheapest) path from *each* farm to a gin, and then to a warehouse and finally to export ports. The farms, gins, warehouses and the ports would be the nodes and the weights applied to the edges would be the two costs - cost of transportation (rail or road). The cotton transport task considered in this paper only examines cotton lint – the raw cotton fibre. Cotton by-products including cottonseed, cotton linters—the fine fibres that remain on the cottonseed after processing—and the trash products from the ginning process are not considered.

For instance, for a particular Farm A, the path finding problem could be illustrated as in Figure 4, below. A similar graph would apply to each cotton production farm. Notice that gins, warehouses and the ports are inter-linked and directed but not intra-linked because this is not a requirement for cotton freight movement between like stages, i.e. there is no need to go from one gin to another, etc.

**Figure 4: Dijkstra's algorithm solution space**



#### 4.1.2 Model formulation

Let:

- $F_i$ : ( $0 < i \leq q$ ): denote farms, where  $q$  is the total number of farms, which in our case is the total number of clusters that was implemented to reduce complexity, i.e. 500;
- $G_j$ : ( $0 < j \leq n$ ): denote gins, where  $n$  is the total number of gins;
- $W_k$ : ( $0 < k \leq m$ ): denote warehouses, where  $m$  is the total number of warehouses;
- $P_x$ : ( $0 < x \leq p$ ): denote ports, where  $p$  is the total number of ports; and
- $F_i 2 G_j, G_j 2 W_k, W_k 2 P_x$ : denote the cost of travelling from  $F_i$  to  $G_j$ ,  $G_j$  to  $W_k$  and  $W_k$  to  $P_x$  respectively

Hence the problem is to minimize the cost function below for each farm,  $F_i$ : ( $0 < i \leq q$ ):

$$[F_i 2 G_j]^M + [G_j 2 W_k]^M + [W_k 2 P_x]^M \quad (1)$$

where  $M \in \{1, 2\}$ , where 1 denotes rail transport and 2 denotes rail transport.



## 4.2 Rice

### 4.2.1. Background

The Australian rice industry has the capacity to produce up to approximately one million tonnes of rice each season, under favourable growing conditions. In 2015–16, total rice production was 274 kilotonnes, which is about 23 per cent of recent domestic production peak—approximately 1161 kilotonnes in 2012–13. Although Australian rice producers use 50 per cent less water than the global average, production is highly dependent on the amount of water available to irrigators (RGA 2017a). Table 2, below, shows rice production by state in 2015–16. For production of previous years, please consult ABARES 2017.

**Table 2: Australian rice production for the year 2015–16**

Area	Production (kt)
New South Wales	262.4
Queensland	9.6
Victoria	0.2
Australia (Total)	274.0

Sources: ABARES (2017)

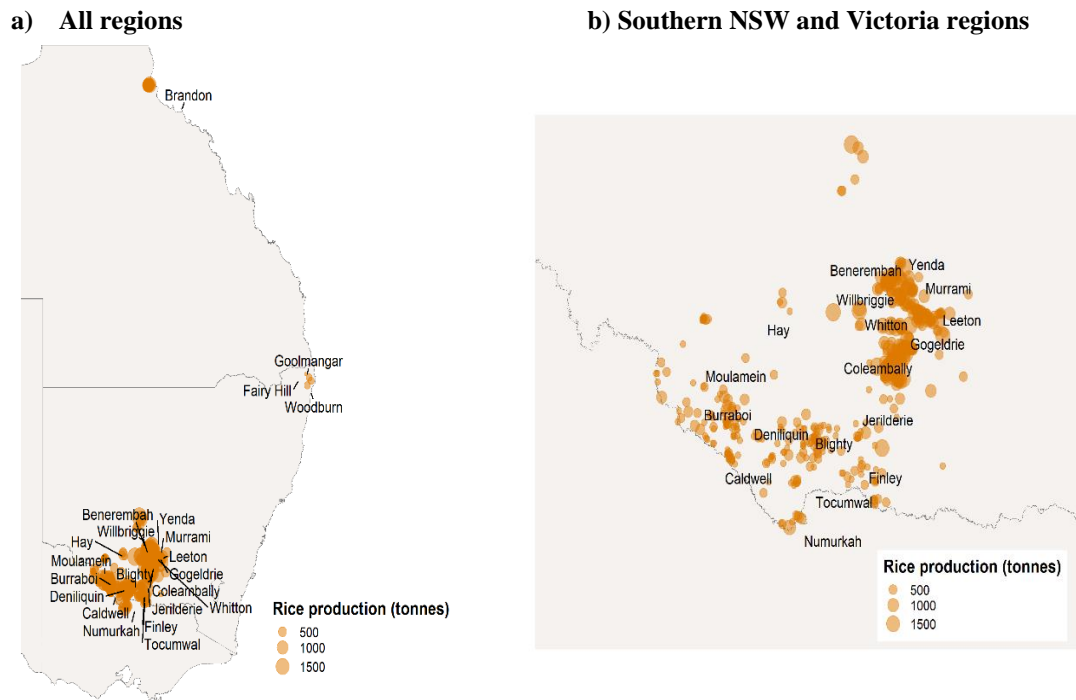
Figure 5a shows the rice growing regions of Australia. Figure 5b shows the rice growing in southern NSW and Victoria. Nearly all domestic rice production is located in the Murrumbidgee Irrigation Area of New South Wales and the Murray Valley in New South Wales and Victoria. Over 95 per cent of Australia's rice output is produced in New South Wales. Small amounts of rice are grown in northern New South Wales, around Lismore, and northern Queensland, around Ayr and Brandon (south of Townsville) and around Tully (between Townsville and Cairns).

Rice crops in Australia are mostly planted in October and harvested from March to May (RGA 2017a). Consequently, the majority of rice exports tend to occur in the financial year following the crop harvest. 85 per cent of rice is exported while the domestic market receives the remaining 15 per cent (ABARES 2017)

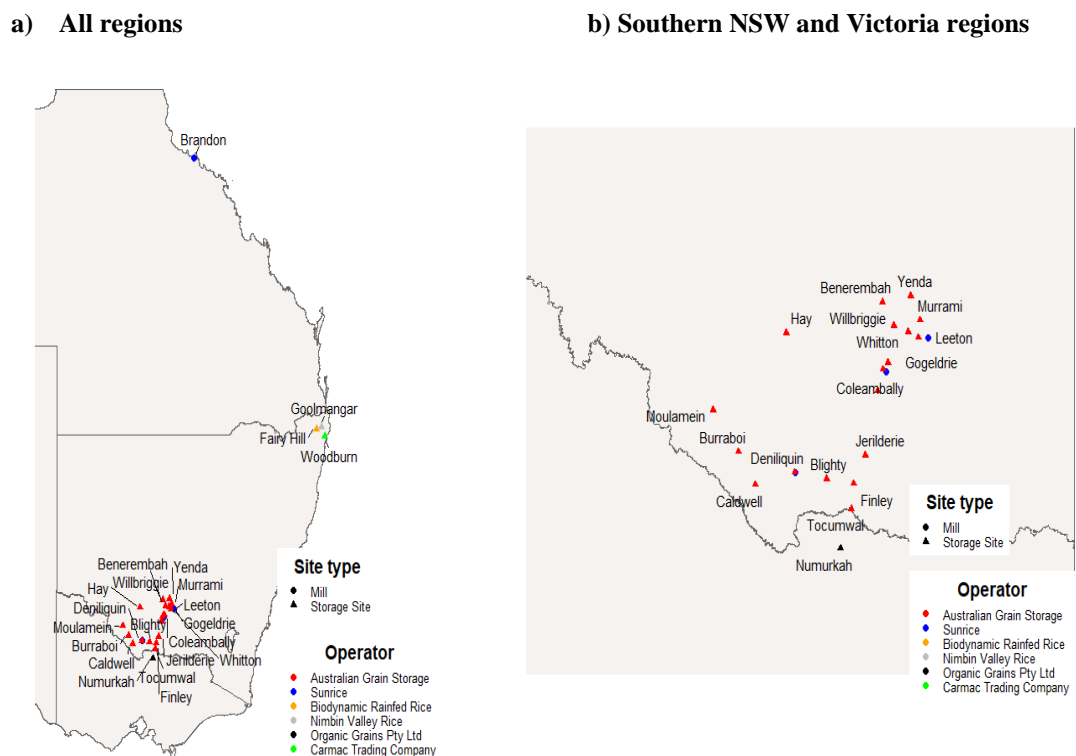
Once harvested, the unmilled rice—known as paddy rice—is transported to a paddy storage facility where the rice is sorted according to variety. It is then transported to industry mills for processing. The milling process involves the removal of the hard protective husk, and the germ and brown layers. These can be used to produce animal feed. The polished, white hard centre of the grain is what is known as white rice. The location of paddy storage facilities and industry mills are shown in Figure 6a. Figure 6b shows the mills and storage facilities in southern NSW and Victoria.

Where and how rice is moved depends on a number of factors, including prices, market volumes, transport costs and transport capacity. Transport of Australia's rice harvest is currently handled by a mix of road and rail transport modes. Movement of paddy rice from the farm to the paddy storage facility for sorting is handled almost exclusively by road transport.

**Figure 5: Rice growing areas in Australia**



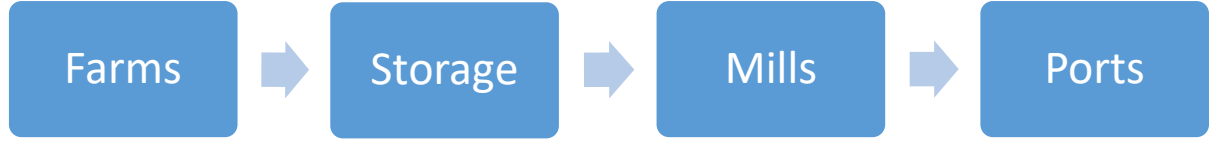
**Figure 6: Location of rice storage facilities and mills in Australia**



Source: Rice storage/milling companies.

Road transport is also used to transport unmilled rice to mills for processing. Finally, a mix of rail and road transport is used to transport the milled, white rice to authorised domestic buyers and to ports for export to overseas markets. Figure 7 provides a simple schematic diagram showing the key elements of the Australian rice supply chain.

**Figure 7: Stylised rice supply chain**



#### 4.2.2 Model formulation

Let :

- $F_i$ : ( $0 < i \leq q$ ): denote farms, where  $q$  is the total number of farms, which in our case is the total number of clusters that was implemented to reduce complexity, i.e. 500;
- $S_j$ : ( $0 < j \leq n$ ): denote storage, where  $n$  is the total number of storage facilities;
- $M_k$ : ( $0 < k \leq m$ ): denote mills, where  $m$  is the total number of mills;
- $P_x$ : ( $0 < x \leq p$ ): denote ports, where  $p$  is the total number of ports; and
- $F_i 2 S_j, S_j 2 M_k, M_k 2 P_x$ : denote the cost of travelling from  $F_i$  to  $S_j$ ,  $S_j$  to  $M_k$  and  $M_k$  to  $P_x$  respectively

Hence the problem is to minimize the cost function below for each farm,  $F_i$ : ( $0 < i \leq q$ ):

$$\boxed{[F_i 2 S_j]^N + [S_j 2 M_k]^N + [M_k 2 P_x]^N} \quad (2)$$

where  $N \in \{1,2\}$ , where 1 denotes road transport and 2 denotes rail transport.

#### 4.3 Model output

For both the commodities, cotton and rice, the task required was to minimise the cost function, Eq (1) and Eq (2) respectively.

Dijkstra's algorithm was used to find the solutions and as described in Section 2, the solution is arrived at by solving (minimizing) in stages, that is, for cotton,  $[F_i 2 G_j]^M$  is evaluated first and then  $[G_j 2 W_k]^M$  and finally  $[W_k 2 P_x]^M$  is minimised to obtain the minimum value of the total cost function and hence providing the cheapest path, either by road or rail or a combination of both, from the farms to the export ports.

##### 4.3.1 Cotton freight modelling results

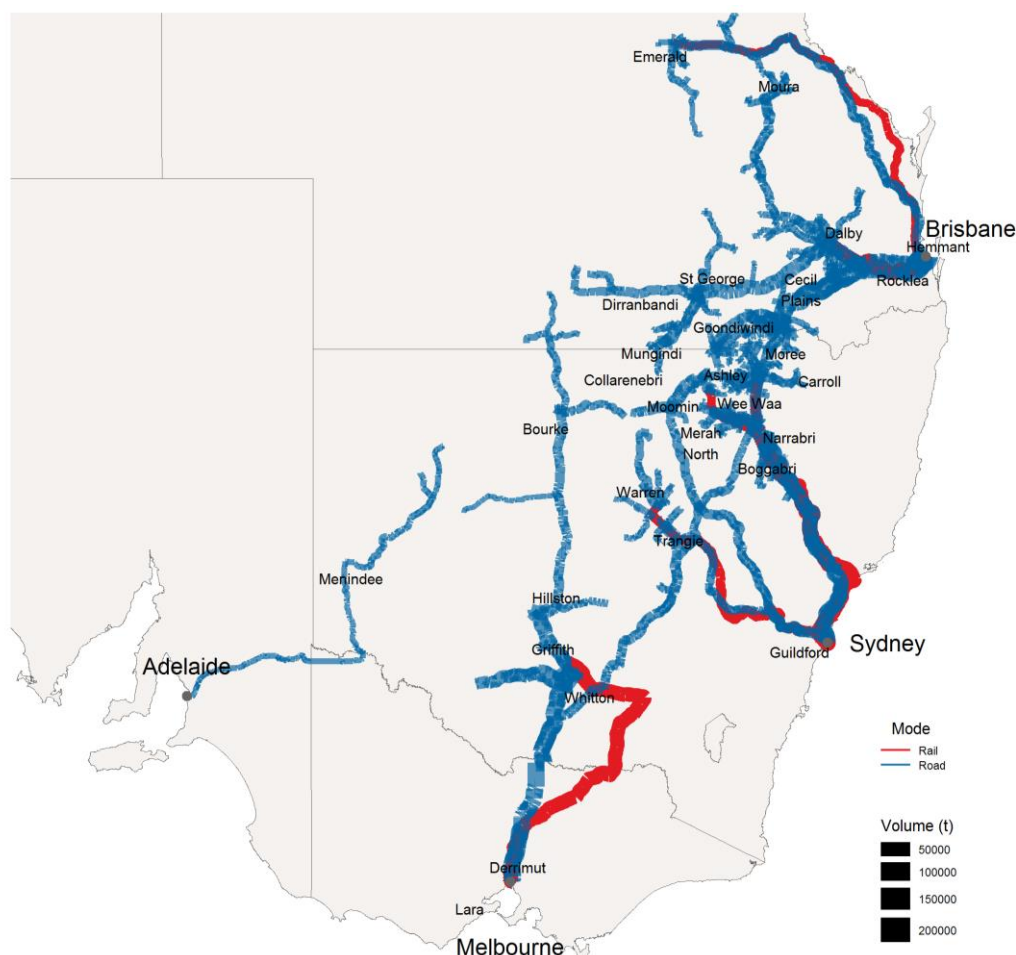
The supply chain of cotton in Australia is dominated by road. Figure 8 shows volumes for transportation from areas of production to ports via road and rail.

Transport of Australia's cotton harvest is currently handled by a mix of road and rail transport modes. Movement of cotton from farm to gins is almost entirely handled by road transport. Our model estimates that approximately 67 per cent of transportation of raw and processed cotton by weight is via road.

Overall, it is estimated that the total rail movements of cotton were approximately 99.6 million tonne kilometres<sup>4</sup> in 2015–16 with total road freight movements estimated to have been 289.5 million tonne kilometres (see Table 3).

The exports figures from each port generated from the modelling is shown in Table 4 and when compared to the data obtained from (ABS 2017c) is very similar. When the total percentage figures from Table 4 are rounded off to whole numbers, they exactly match the ones provided by (ABS 2017c), showing an acceptable result.

**Figure 8: Cotton transport volumes, by mode, 2015–16**



**Table 3: Estimated cotton transport flows, by jurisdiction and transport mode<sup>a</sup>**

Jurisdiction	Road	Rail	Total
	<i>(million tkm)</i>		
New South Wales	143.2	65.1	208.3
Queensland	126.3	18.9	145.2
Victoria	20.0	15.5	35.6
Total	289.5	99.6	389.0

a. Figures may not add to total due to rounding.

<sup>4</sup> One tonne kilometre is equivalent to one tonne moved one kilometre.

b. Total tonnage presented on uplift/discharge basis

**Table 4: Estimated Australian cotton lint exports, by delivery mode, 2015–16**

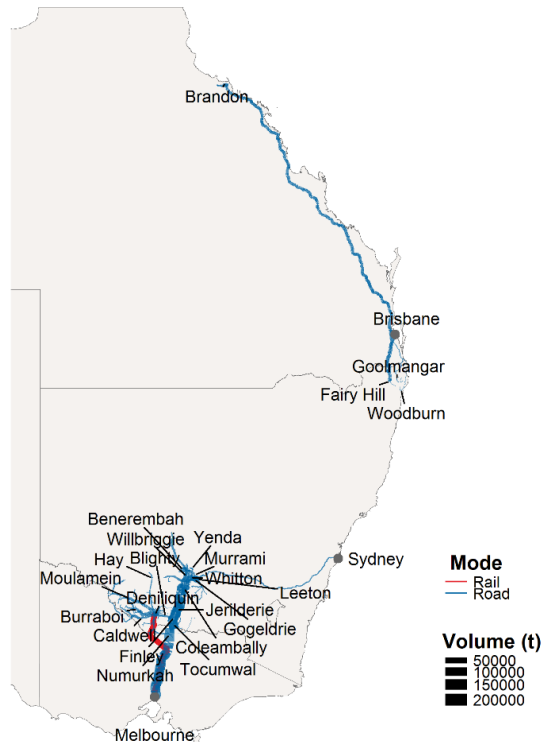
Port	Mode			Mode		
	Road	Rail	Total	Road	Rail	Total
	<i>(kilotonnes)</i>			<i>(per cent)</i>		
Brisbane	206.3	54.6	260.9	79.1	20.9	47.7
Sydney	81.7	75.4	157.1	52.0	48.0	28.7
Melbourne	77.7	50.5	128.2	60.6	39.4	23.4
Adelaide	1.2	0	1.2	100	0	0.2
Total	366.9	180.5	547.4	67.0	33.0	100

#### 4.3.2 Rice freight modelling results

Transportation by road currently dominates the supply chain of rice in Australia. Figure 9 shows significant road volumes for transportation from areas of production to ports. Overall, our modelled showed that total rail movements of rice were approximately 13 million tonne kilometres<sup>5</sup> in 2015–16 with total road freight movements estimated to have been 80.8 million tonne kilometres (see Table 5).

Our model estimates that approximately 76 per cent of transportation of rice by weight is via road. Estimated rice export volumes, for each port, generated from the model are shown in Table 6. (While there is little publicly-available data on port-level rice exports, anecdotal evidence that the modelled proportion of exports from individual ports are reasonable.)

**Figure 9: Rice transport movements, by mode, 2015–16**



<sup>5</sup> 1 tonne kilometre is equivalent to one tonne moved one kilometre

**Table 5 Estimated rice production and rice transport movement volumes, by mode and jurisdiction, 2015–16**

Jurisdiction	Road	Rail	Total
<i>(million tonne kilometres)</i>			
New South Wales	33.5	2.9	36.4
Queensland	14.6	0.0	14.6
Victoria	32.7	10.1	42.8
Total	80.8	13.0	93.8

a. Total tonnage presented on uplift/discharge basis, based on uplift state of origin.

Note: Figures may not add to total due to rounding.

**Table 6 Estimated Australian rice exports, by delivery mode, for 2015–16 production**

Port	Mode			Mode		
	Road	Rail	Total	Road	Rail	Total
<i>(kilotonnes)</i>				<i>(per cent)</i>		
Brisbane	6.9	0	6.9	100.0	0.0	3.9
Sydney	1.5	0	1.5	100.0	0.0	1.0
Melbourne	126.2	42.7	168.9	74.7	25.3	95.2
Total	134.7	42.7	177.4	75.5	24.5	100.0

## 5. Conclusion

This paper has formulated and modelled interregional commodity movements in Australia using Dijkstra's approach. The model was demonstrated using rice and cotton data and the freight movements presented. The results are quite encouraging and match the limited data that is available.

It is important to note that this model works with limited data, such as, only the initial production data, and produces likely paths that commodity moves to its possible destination. Due to confidentiality issues in Australia, this limited data availability issue is quite common and hence this approach is quite well suited.

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ABS—see Australian Bureau of Statistics

RGA – see Rice Growers' Association of Australia

RMB – see Rice Marketing Board for the State of New South Wales

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