A Modelling Framework for Optimising Investment for the Australian Livestock Industry

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Abstract. Despite the scale and importance of the beef industry in the north of Australia, recent political and environmental disruptions have highlighted the vulnerability of the supply chain. Ensuring that the supply chain remains resilient to climatic events as well as to unexpected decisions by the stakeholders will require careful planning and investment in logistics. In this paper, we outline an integrated methodology based on tactical and operational dynamic models, for assessing the effect of changes in the supply chain. Emphasis is on the development of an optimisation model that covers the flow of cattle from properties to agistment farms and feedlots to abattoirs/ports, and the selection of rest areas (spelling yards) along the path. The model selects the optimal location of spelling yards along the road network, subject to budget, site capacity, and service requirements. We show preliminary results for a case study comprising Western Australia and the Northern Territory.

Keywords: Beef supply chain, facility location, network flow optimisation, maximal covering

1 Introduction

The ever-increasing world population is putting pressure on the beef industry to become more efficient. As global demand continues to increase [1], thanks mostly to consumers in developing countries, so does the impact on the environment. Given that world resources are limited, the improvement must come from technology; it has been estimated that in the year 2050, world population will require 100% more food, and 70% of this must come from efficiency-improving technology [2]. Concrete problems to address include improving the efficiency of the transportation networks, exploiting possible synergies among economic

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actors and regions, and more strict and effective assessment of infrastructure investment.

Beef production in the north of Australia is currently at a crossroads due to recent environmental, political and economical changes. Economically, this is a very important activity: Australian farm exports earned the country \$32.5 billion in 2011, of which beef and veal production contributed 17%. The northern beef herd of 12.5 million head supplies nearly 90% of Australia's live export cattle, most of which is sent to Indonesia. However, live exports have been affected by the recent imposition of weight restrictions, as well as by Australia's decision to stop exports temporarily in June 2012 due to poor animal welfare. Investigation of alternative paths to market is a clear priority for the northern beef industry, paths which will certainly involve investment in new infrastructure.

Cattle production in the north is fundamentally different to the more intensive beef farming industry of the south because it takes place in an environment characterised by large-scale enterprises on pastoral lease, low herd density (10 head per km^2 or less), long distances to market, and significant annual interruptions of production and distribution processes due to heat, drought and tropical rainfall patterns. A significant increase in the costs of production has meant that many properties struggle to remain profitable [3]. Transport constitutes approximately one third of the total supply chain costs.

The analysis and ultimate selection of alternative capital investment and operational scenarios applicable to the northern Australian beef industry requires a much more multidisciplinary modelling methodology than anything attempted in the past. In this paper, we introduce the *Northern Australian Beef Industry Strategy* (NABIS[3]) as a framework to assess these scenarios, with special emphasis in the strategic optimisation component. Previous studies have focused on individual stages of the beef supply chain, as in [4], who use linear programming to assess the relative contribution that disease prevention could make to farm income and to its variability, or [5], who provide a review of optimisation and simulation models used for herd management. Logistic studies include [6], who optimised contracts between producers and abattoir given different market options, or [7], who select optimal locations for abattoirs. Other than the latter, models for simulating and optimising livestock logistics are limited, despite being more abundant in other supply chains (see [8,9] for reviews).

The remainder of this paper is organised as follows. Section 2 briefly describes the structure of the supply chain in question, introduces the structure of the NABIS framework, and sketches a concrete problem on infrastructure investment. Section 3 expands on the strategic optimisation model, whose aim is to select the optimal locations of spelling facilities. Section 4 presents and discusses preliminary results and Section 5 presents the conclusions and future work.

[3] www.regional.gov.au/regional/ona/nabis.aspx, retrieved on the 19 of September 2012.

2 A Framework for Capital Investment and Operations

Figure 2 shows a schematic of the northern Australian beef supply chain. Breeding properties typically produce weaner calves to the age of about 8 months, when their weight is approximately 330 kg. These cattle can then be sold to live export for finishing in other countries. Many breeding properties do not have enough forage to produce cattle to slaughter weight. Such cattle are transported by road trains to finishing properties where they are grass-fed, or to a more intensive confined feeding system (or feedlot) where they are grain-fed. Cattle spend a minimum of 100 days in feedlots until they reach suitable weight categories for sale. In sale yards, cattle of multiple classes are sold by auction to abattoirs, for breeding and for further finishing. Abattoirs transform the finished cattle into frozen or chilled meat products. Abattoirs vary significantly in terms of throughput (up to 2000 head per day) though Australia's largest 25 abattoirs account for 61% of production. Once processed, the meat is either transported in refrigerated containers to terminals or to domestic wholesale outlets.

The two most important cost components of this supply chain are transportation and construction of processing facilities. To better inform stakeholders on the most beneficial road and facility infrastructure investments and to release the supply chain's productive potential, the governments of the northern states of Australia are working with industry to provide a comprehensive analysis of the livestock industry value chain. An important outcome of this strategic partnership is the development of NABIS, an integrated set of models at different temporal and spatial scales. The aim of these models, introduced next, is to examine how changes in infrastructure could catalyse changes in logistics costs under different market scenarios.

2.1 The Northern Australian Beef Industry Strategy

NABIS consists of three components:

1. *Operational simulation model.* This model captures the real-time movements of individual transport vehicles (trucks and trains) between sites. It incorporates all the design features of the supply chain, such as individual ports and holding yards, vehicle and yard capacities, loading and unloading times and queuing times in order to quantify overall operational efficiency and assess "what-if" scenarios. Uncertainties related to road condition, queuing delays and disruptions can also be simulated and visualised with this model.
2. *Strategic simulation model.* This model simulates large-scale investment decisions of transport infrastructure. It aims to inform policy decisions that impact on the mass flow of cattle across the north of Australia by following the path of livestock between enterprises to ports or abattoirs. For each recorded movement of cattle, the model generates a "least cost" trip between origins and destinations. These are aggregated on a monthly basis to generate a cost estimate, so that changes due to network improvements such as road upgrades can be assessed.

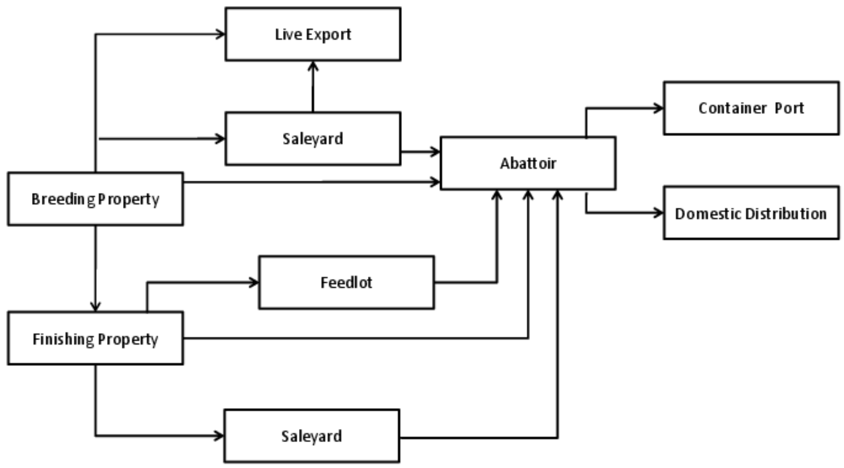

Fig. 1. Schematic of the northern Australian beef supply chain (reproduced from [10]).

3. *Strategic optimisation model.* This model is meant to highlight the best possible investment decisions. The stakeholders propose potential sites for the construction of facilities (spelling yards), but the selection of the best sites is difficult to assess. The problem becomes extremely complex as the number of proposals to be assessed increases. This model aims to select the optimal location of spelling yards along the road network subject to budget, site capacity, and service requirements. The model must also comply with the guidelines that determine maximum driving hours and maximum water deprivation times.

The rest of this paper explains in more detail the development of the strategic optimisation model.

3 Optimising Logistics and Spelling Yard Selection

The problem of selecting the best facility sites can be stated as follows: determine the locations of the spelling yards, paths and volumes of cattle transported, such that the profit of operating the supply chain is maximised, subject to network flow, inventory, capacity, operational and demand satisfaction constraints. Profit is expressed as the difference of the income from satisfying the demand from the terminal nodes, plus the income from the service provided by the spelling yards, minus transportation cost, minus agistment cost, minus the cost of opening the spelling yards.

Figure 2 illustrates the sites and transportation stages considered. Cattle of different breeds are transported in trucks from breeding properties S to fattening properties P, which can be either agistment farms F or feedlots L. The cattle pass through transhipment points R, some of which will be selected as spelling yards D, whereas the rest are simply road junctions H. When the truckloads arrive at the fattening properties, cattle spend a number of months gaining weight there, until they are ready to be sent to the terminal nodes A. Spelling yards and fattening properties are rest areas because the cattle stop there for prolongued periods. Terminal nodes can be ports, abattoirs or saleyards, and for the purpose of the model they are equivalent, except that the income they produce per truckload is different. The agistment period in agistment farms is six months, whereas for feedlots it is three months only.

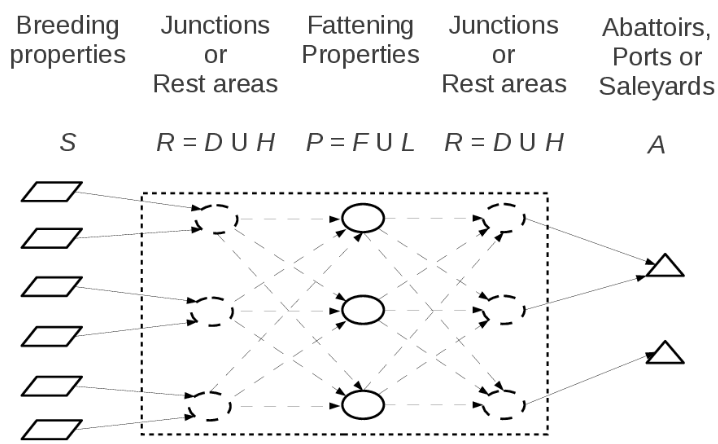

Fig. 2. Diagram of the northern Australian beef supply chain. Spelling yards must be chosen from a set of transit nodes R when transported from breeding properties S to fattening properties P, or from fattening properties to terminal nodes A (i.e., ports, saleyards or abattoirs).

The decision variables needed to model the system described above are as follows. Let y_{bgijt} be the flow in truckloads of breed b and age g (in months) from sites i to j in period t, q_{bgijt} the inventory of breed b and age g in property i at period t, z_i an indicator variable that takes the value 1 if the need for the service of a spelling yard at node $i \in \{S \cup A\}$ is covered for the whole time horizon, and zero otherwise, and x_j, which takes the value 1 if node $j \in D$ is selected as a rest area, and 0 otherwise. The model addresses the following questions:

1. Where should spelling yards be built so as to maximise the profit subject to infrastructure, budget and operational guidelines?
2. What is the optimal volume of cattle that each terminal node should process to ensure maximum benefit?
3. What are the flows to be transported and processed among facilities during the time horizon?

3.1 Objective Function

Maximise profit expressed as the income from satisfying the demand from the terminal nodes, plus the income from the service provided by the spelling yards, minus transportation costs, minus agistment costs, minus the cost of opening spelling yards:

$$\begin{aligned}\text{Maximise} &\sum_{t\in T}\sum_{b\in B}\sum_{g\in G}\sum_{(i,j)\in L:\ j\in A} AI_{bgjt}y_{bgijt} + \sum_{i\in\{S\cup A\}} h_i z_i \\ &-\sum_{t\in T}\sum_{b\in B}\sum_{g\in G}\sum_{(i,j)\in L^{SP}} TC_{ij}d_{ij}y_{bgijt} - \sum_{t\in T}\sum_{b\in B}\sum_{g\in G}\sum_{i\in P} AC_{it}q_{bgit} \\ &-\sum_{j\in R} OC_j x_j \ , \qquad (1)\end{aligned}$$

where AI_{bgjt} is the income per truckload of cattle of breed b of age g at site j at period t, h_i is the profit from satisfying truckload demand of site i, TC_{ij} is the transportation cost between i and j, AC_i is the agistment cost at farm i, and OC_j is the cost of opening a rest site at j.

3.2 Constraints

Constraints (2) to (4) are network flow constraints. Constraints (5) to (13) are derived from the maximal covering location problem (MCLP) [11] applied to the transportation from properties to farms, and from farms to terminal nodes (abattoirs, ports and saleyards).

1. *Flow constraints.* The balance of incoming and outgoing truckloads to each site is

$$\sum_j a_{ijt}y_{bgijt} - \sum_j a_{jit}y_{bgjit} = \begin{cases} p_{bgit} \ \forall b\in B,\ \forall g\in G,\ \forall i\in S,\ \forall t\in T \\ p_{bgit} - q_{bgit} + q_{b,g-1,i,t-1} \ \forall b\in B,\ \forall g\in G,\ \forall i\in P,\ \forall t\in T \\ 0 \ \forall b\in B,\ \forall g\in G,\ \forall i\in R,\ \forall t\in T\ . \end{cases} \qquad (2)$$

   where a_{ijt} is the availability of the link that joins i to j (for roads) at time t and p_{bgit} is the production of cattle of breed b and age g in node i at period t. Note that p_{bgit} can only be non-zero if $g = 1$ month, since calves of age $g > 1$ could not have been born at g.
2. *Agistment constraints.* The cattle truckloads received and produced in a breeding property are released only after that property's agistment period.

$$\sum_{j\in\{R\cup S\}} y_{bgjit} + p_{bgit} = \sum_{j\in\{R\cup A\}} y_{b,g+\tau_{ib},ij,t+\tau_{ib}}$$
$$\forall b\in B,\ \forall g\in G,\ \forall i\in P,\ \forall t\in T\ , \qquad (3)$$

   where $\tau_{ib}, i \in P = \{F \cup L\}$, is the agistment period of breed b in fattening at property i.

3. *Terminal capacity.* The terminals can process up to a specified number of truckloads,

$$\sum_{b\in B}\sum_{g\in G}\sum_{j\in\{P\cup R\}} y_{bgjit} \le AK_{it} \qquad \forall i\in A,\ \forall t\in T\ , \tag{4}$$

where AK_{it} is the total processing capacity of terminal i during period t.
4. *No-flow indicator constraints.* To make sure that rest areas are placed in sites through which there is flow, we introduce an indicator variable that shows whether or not there is no flow going out from a potential rest area,

$$\delta_i^O \ge 1-\sum_{t\in T}\sum_{b\in B}\sum_{g\in G}\sum_{j} y_{bgijt},\ \delta_i^O\ge 0,\quad \forall i\in N\ , \tag{5}$$

where N denotes the set of all nodes. Similarly and to ensure that nodes are serviced by at least one rest area only if there is flow into the nodes, we introduce

$$\delta_i^I \ge 1-\sum_{t\in T}\sum_{b\in B}\sum_{g\in G}\sum_{j} y_{bgjit},\ \delta_i^I\ge 0,\quad \forall i\in N\ . \tag{6}$$

5. *Demand satisfaction constraints.* Demand at a given site i is not satisfied until a site j that covers i is selected,

$$\sum_{j\in M_i^D} x_j \ge z_i \qquad \forall i\in S,\quad \forall t\in T\ , \tag{7}$$

where

$$M_i^D=\{j|d_{ij}\le \bar{v}\Theta^D,\ i\in\{S\cup A\},\ j\in\{R\cup P\}\} \tag{8}$$

is the set of all candidate locations that can cover demand point i within the maximum driving hours. Here, $\bar{v}$ is the average speed, Θ^D represents the maximum driving hours, and and d_{ij} is the distance between nodes i and j in the shortest path of network.
6. *Breeding-properties-as-yards constraints.* All the breeding properties are also spelling yards. Apart from the fact that cattle get rest during agistment, this constraint encourages direct transport from properties to farms that are within the distance that can be travelled within the maximum number of driving hours.

$$x_i = 1 \quad \forall i\in P\ . \tag{9}$$

7. *Combined rest site capacity.* Sites selected as rest areas can receive a limited number of truckloads,

$$\sum_{b\in B}\sum_{g\in G}\sum_{j} a_{jit}y_{bgjit}+\sum_{b\in B}\sum_{g\in G} p_{bgit}\le RK_i x_i \qquad \forall i\in\{R\cup P\},\ \forall t\in T\ , \tag{10}$$

where RK_i is the combined capacity of rest sites. In this constraint, the production term is different to zero only for agistment farms.

8. *Breeding property capacity.* The breeding properties can hold up to a limited number of truckloads,

$$\sum_{b \in B} \sum_{g \in G} q_{bgit} \leq PK_i x_i \qquad \forall i \in P,\ \forall t \in T\ , \tag{11}$$

where PK_i is the total storage capacity of breeding property i.
9. *Maximum number of spelling yards.* The number of spelling yards that can be built is limited,

$$\sum_{j \in R} OC_j x_j \leq BG\ , \tag{12}$$

where BG is the total available budget for construction of spelling yards. We assume that the cost of setting up fattening farms as rest areas is zero; see constraint (9).
10. *Service requirements.* We require every breeding farm and terminal node to be served by at least one rest site (that is, spelling yard or fattening farm), on the condition that there is flow through these sites. In other words, a site does not need to be served by a rest site if there is no flow through it (see constraint group 4 above).

$$\sum_{j \in M_i^Y} x_j \geq 1 - \delta_i^O \qquad \forall i \in S\ , \tag{13}$$

$$\sum_{j \in M_i^Y} x_j \geq 1 - \delta_i^I \qquad \forall i \in A\ , \tag{14}$$

where M_i^Y is analogous to M_i^D in Equation (8), but uses the cattle's maximum water deprivation time Θ^Y instead of the maximum driving time Θ^D.
11. *Conditional flow constraints.* Finally, we declare explicitly that spelling yards will not be built at sites through which there is no flow,

$$x_i \leq 1 - \delta_i^O \quad \forall i \in R\ . \tag{15}$$

3.3 Parameters and Input Data

The data sources which fed the model are the *National Livestock Identification System*, or NLIS, which is a historical record of cattle movements from 2007 to 2011, and operational codes such as the *Guidelines for managing Heavy Vehicle Driver Fatigue* [12] and the *Code of Practice for the Welfare of Animals* [13]. These provided the recommended maximum driving times and maximum water deprivation times, respectively, which are important parameters in our model.

4 Results and Discussion

Figure 3 is a map showing all the sites and the road network for the beef supply chain in Western Australia and the Northern Territory. The sites in Western

Australia are located along the coast, clustered in the Pilbara region in the southwest and the Kimberley in the northeast of the state, and connected through the Great Northern Highway. The sites in the Northern Territory are located along the Stuart Highway and cover the state from north to south, encompassing from the Top End to the regions of Katherine, Barkly and Central Australia. This network contains 486 sites, of which 84 are properties, 239 are fattening properties (226 agistment farms and 13 feedlots), 133 are candidate rest sites, eight are junctions, and 22 are terminal nodes (abattoirs, ports and saleyards). Figure 4 shows the location of the terminal nodes towards which all truckloads of cattle are sent.

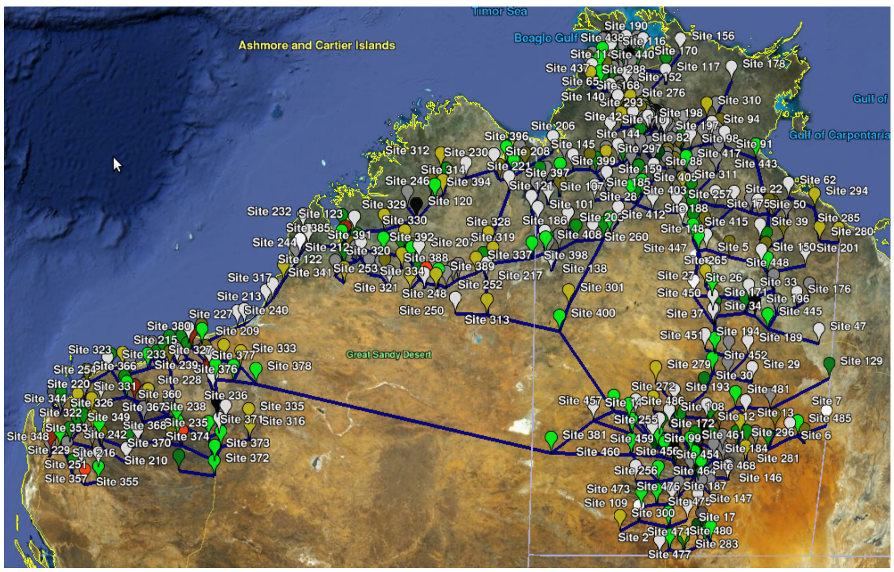

Fig. 3. A map showing all the participating sites in the supply chain.

All calculations were made using CPLEX 12.5[4] in a 64-bit Intel Xeon CPU with one processor of eight cores (2.27 GHz) each and 16 GB of RAM. The problem has 227746 variables and 102936 constraints, was coded in Java and a typical run is solved in approximately two hours. The locations of the 82 sites selected as spelling yards are indicated in Figure 5. These represent 61.6% of the candidate rest areas.

The cost of building a spelling yard is assumed to be \$0.34M. The number of spelling yards varies from 55 to 82, as the results in Table 1 show. On one hand, for budgets larger than the amount needed to build 82 spelling yards, the

[4] http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/, accessed on the 8 of April 2013.

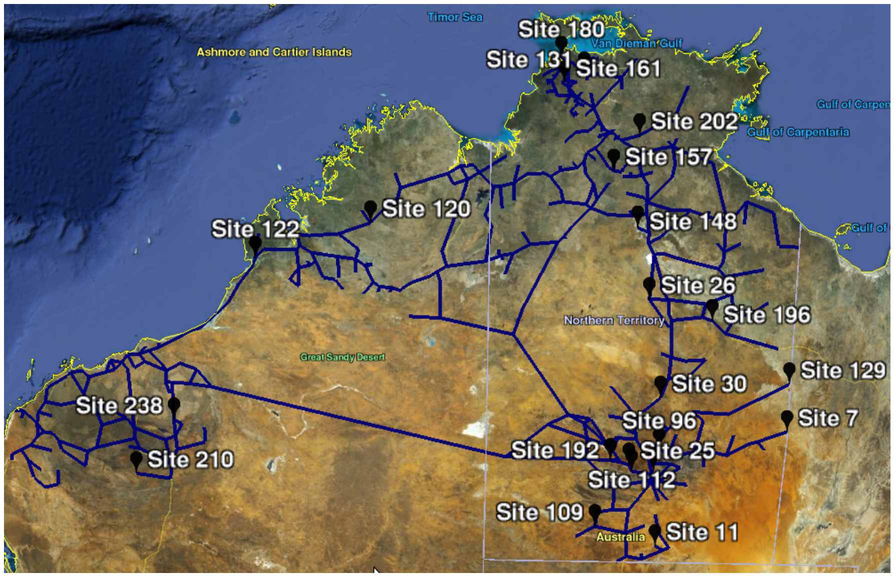

Fig. 4. A map showing all the terminal nodes in the Western Australian and Northern Territory beef supply chain.

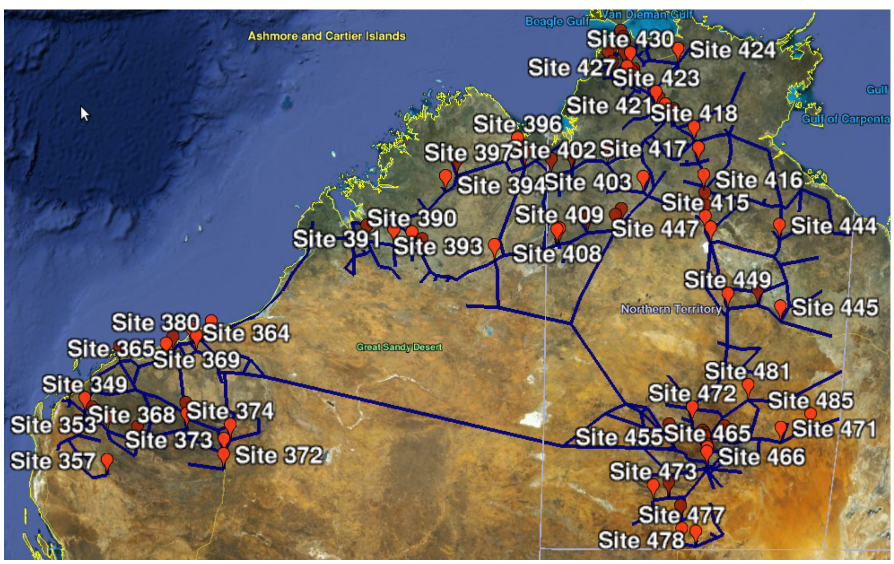

Fig. 5. Map showing the sites selected as spelling yards produced by the optimisation model.

model does not produce more than the 82 sites shown in Figure 5. If, on the other hand, the budget is lower than \$19M, the problem becomes infeasible. The general distribution of the sites selected when the budget is \$19M (not shown due to space limitations) is not too different from the distribution obtained with a budget of \$29M (Figure 5) in the sense that the same areas show a higher density of spelling yards, although with less sites. These areas are the Pilbara and Kimberley regions, and along the Stuart Highway. Overall, the percentage of selected sites among the candidate rest sites varies between %41.35 and %61.65.

Table 1. Number of spelling yards built as a function of budget.

Budget (M AUD)	$\sum_j x_j$
19.00	55
20.00	58
21.00	61
22.00	64
23.00	67
24.00	70
25.00	73
26.00	76
27.00	79
28.00	82
29.00	82

5 Conclusions and Directions for Research

Ensuring continuing operations of the beef supply chain in the northern states of Australia in the face of climatic events and changes in stakeholders' decisions requires careful planning and investment in logistics. We have introduced a three-pronged methodology for assessing the effect of environmental and policy changes in the operation of the supply chain, which consists of an operational simulation model, a strategic simulation model, and a strategic optimisation model.

The focus of this paper has been on describing the strategic optimisation model. This model adopts a systems view of the supply chain by using capital and operational costs as parameters. On the one hand, it incorporates infrastructure information, such as existing roads, location and type of properties that participate in the supply chain, and building costs and locations of new facilities. On the other hand, it also uses operational data regarding cattle flows along the network, transportation costs and the costs of operating facilities. With this information, the model determines the location of the spelling yards, the optimal volume of cattle that each terminal node should process, and the flows among facilities that respect maximum water deprivation times and maximum driving hours. Our results indicate that the regions where the spelling yards are located do not change as a function of budget, although, naturally, the number of sites does. Thus, the model can help prioritise spelling yard construction within regions on quantitative grounds.

Although the model already covers all the relevant aspects of the supply chain, the effort must centre now on verifying the accuracy of the data. Tuning is needed, for example, in the costing model, or in ironing out the inconsistencies found in the NLIS database. Another aspect of the problem that requires attention is the effect of seasonal conditions on road access: historical records are needed to model the availability of certain road segments as part of the transportation network at certain times of the year. Operational codes are also likely to change in the near future, and these need to be updated. To this end, a closer engagement with the stakeholders is necessary.

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