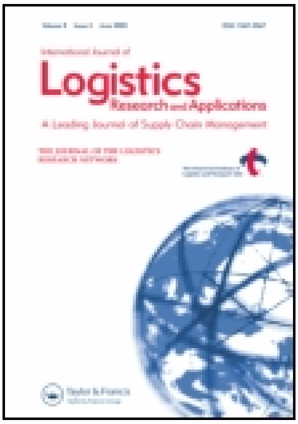

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Optimum location for export-oriented slaughterhouses in Mato Grosso, Brazil: a dynamic mathematical model

Juliana Domingues Zucchi [a], Amy Z. Zeng [b] & José Vicente Caixeta-Filho [a]

[a] ESALQ/USP, Economics, Administration and Sociology, Av. Pádua Dias, 11, Piracicaba, 13418-900, Brazil

[b] WPI, School of Business, Worcester, MA, 01609, USA

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Optimum location for export-oriented slaughterhouses in Mato Grosso, Brazil: a dynamic mathematical model

Juliana Domingues Zucchi[a]*, Amy Z. Zeng[b], and José Vicente Caixeta-Filho[a]

[a]*ESALQ/USP, Economics, Administration and Sociology, Av. Pádua Dias, 11, Piracicaba 13418-900, Brazil*
[b]*WPI, School of Business, Worcester, MA 01609, USA*

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This paper presents a dynamic mathematical model developed to determine the optimum location for new export-oriented slaughterhouses (EOSs) in the Brazilian state of Mato Grosso. The optimal locations are identified by minimising the costs of cattle transportation, EOS installation, and distribution from the EOS to export ports and from these ports to foreign destinations. The spatial arrangement is subject to a series of physical and behavioural constraints such as supply of raw materials, demand for beef, and EOS production capacity. Results show that the installation of three EOSs located in Mato Grosso regions closest to export ports would meet current foreign market demand for Mato Grosso beef and minimise logistical costs in the state's export beef supply chain.

Keywords: optimisation; dynamic mathematical model; slaughterhouse location; Brazilian beef

1. Introduction

The beef supply chain of Brazil's socio-economically important cut livestock market segment integrates input suppliers, farms, ranches, slaughterhouses (processors), and distributors (butchers and supermarkets) within an agro-industrial complex designed to satisfy final consumers.

Although not climatically restricted to a particular Brazilian region, cut livestock production has become concentrated in the country's centre-west due to this region's relatively low land prices and extensive natural pasture. As the herd moved to the centre-west, so did slaughterhouse construction, and over the last few decades, there has been a noticeable change in the concentration of these industrial units in Brazil. In the mid-1970s, approximately 70% of the country's large-scale slaughterhouses were to be found in the country's south and southeast regions (IEL *et al.* 2000). That percentage has been shrinking as beef-processing plants seek to minimise the distance between themselves and their inputs in Brazil's centre-west. In 1999, the country's large-scale units were located predominantly in both the southeast and centre-west regions (IEL *et al.* 2000).

*Corresponding author. Email: jdzucchi@esalq.usp.br

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Logistical decisions focused on operational issues are important to the Brazilian export beef supply chain's competitiveness. By choosing the right location for a new operational facility, chain-wide logistical costs will be optimised and chain integration strengthened; but to make the right choice, several factors must be strategically balanced. Locating an export-oriented slaughterhouse (EOS) in close proximity to its live inputs lowers cattle transportation costs and reduces animal stress, transportation damage, and weight loss. On the other hand, such locations also have disadvantages such as the need for costly refrigeration equipment and the use of containers, whether refrigerated or importer country specific, that are then less available for long distance travel. Our model presented in this article is designed to aid decision makers by helping to correctly balance factors that determine the best location for a new EOS.

1.1. *Brazilian beef supply chain: theoretical approaches*

Several theoretical approaches have been used to analyse coordination within the Brazilian beef supply chain: the structure–conduct–performance paradigm (Bliska *et al.* 1996), game theory (Bliska *et al.* 1998, Macedo 2002), theoretical–methodological apparatus of the agro-food system concept (Perosa 1999), dynamic systems (Wiazowski and Silva 1999, Wiazowski 2001), and the economic cost of transaction theoretical approach (Mathias 1999, Pitelli 2004).

Our paper uses Operations Research methodology to analyse coordination among supply chain members for various reasons. This approach has not yet been applied in a study of the chain; it permits modelling of the various chain links, and it allows for quantification of the product flow (cattle and beef) to determine minimum transportation costs and thereby optimal slaughterhouse deployment. In addition, the adopted model provides for the inclusion of time as a parameter, which is relevant given that this chain's raw material supply and the final product demand are affected by seasonality.

Because of the Brazilian beef sector's great importance in the country's economy and its foreign trade balance, the negative effects of poor coordination between this sector's main segments are significant. A model that can successfully determine the optimal location for slaughterhouses would positively affect the Brazilian economy by assisting agents active in the Brazilian beef sector as they attempt to maintain and solidify their competitive advantages in the international beef market.

This paper is divided into six sections after Section 1. Section 2 addresses both static and dynamic location models, with emphasis on the latter; Section 3 provides an overview of the main links in the Brazilian beef supply chain; Section 4 presents both the schematic and mathematical formulation of the model and its method for solution; Section 5 describes the real input data for the model; Section 6 reports product (cattle and beef) flows and optimal EOS locations; and Section 7 summarises the paper's main results.

2. Location models

Determining the best location for the installation of facilities along the logistics network provides format, structure, and form to the logistics system in question (Ballou 1999). In addition, selecting the right location for a high cost, long-term facilities investment improves the entire chain's competitive position (Current *et al.* 1997, Owen and Daskin 1998). The location candidates must address the system's current status and not negatively affect the system's viability during implementation (Owen and Daskin 1998). Operations Research has found a range of applications to solving transport problems, including problems encountered when determining an optimal facility location (Caixeta-Filho 2004). In this section, we review static and dynamic location models used to determine optimum facility locations.

A majority of the literatures analysing location optimisation is limited to simplified static and deterministic models (Owen and Daskin 1998), possibly because location decisions require a great deal of demand, transport, production, and market data. Studies of many different agro-industrial products have applied location optimisation techniques that are relevant at a specific point in time (Stollsteimer 1963, King and Logan 1964, Polopolus 1965, Cassidy *et al.* 1970, Chern and Polopolus 1970, Warrack and Fletcher 1970, Babcock *et al.* 1985, Canziani 1991, Zuo *et al.* 1991, Pooley 1994, Lopes 1997, Ramos 2001, Oliveira 2005). These static location models provide a long-run balance as a solution. However, this assumption may not be appropriate if the spatial pattern of supply and/or demand is changeable and if the costs of closing plants and/or opening new ones are significant (Kilmer *et al.* 1983).

By definition, dynamic models incorporate time (Current *et al.* 1997). These models capture the temporal aspects of location problems, making them more consistent with reality (Owen and Daskin 1998). According to Erlenkotter (1981), there are two essential characteristics that determine the need for a dynamic structure in a location model: there must be a change in demand or costs over time, and the costs for relocating or resizing the facilities should be significant. If the first characteristic is not found, then a static formulation is appropriate; if the second characteristic is missing, then a series of static discrete formulations would be sufficient. Both characteristics are present in the Brazilian beef export chain and affect the decision of where to locate EOSs, namely: international demand for Brazilian beef varies over the year, and there are high costs associated with slaughterhouse installation.

A number of papers have included the temporal aspect in their optimal-location models. Ballou (1968), in the first attempt to overcome the limitations of static and deterministic location modelling, used a series of static optimal solutions for solving the dynamic problem of determining the best location of a single warehouse in terms of profit maximisation. However, Sweeney and Tatham (1976) observed that Ballou's approach was limited because it only guaranteed sub-optimal solutions. They proposed an improved model using the results from a static location model in a dynamic programme and identified the long-term optimal configuration for multiple warehouses over the period considered.

Fuller *et al.* (1976) specified a dynamic model with the objective of minimising the total cost of assembly, storage, and processing in the cotton-ginning industry in a part of the Rio Grande Valley between Texas and New Mexico. Their study addressed the optimisation of processing capacity in several US southwestern irrigated valleys after production had suffered a multi-year decline. The authors analysed the results from three alternative scenarios that incorporated weekly spatial and temporal flows of raw product to active plants and found that the most cost savings could be realised by reorganising the study area to remove excess capacity.

Hilger *et al.* (1977) developed and applied a dynamic model to the location of grains sub-terminals (corn and soybeans) in northwestern Indiana. To minimise the fixed cost of opening each sub-terminal and the monthly costs of grain shipping and storage, the authors constructed two alternative scenarios, capturing either high or low export demand, and considered 19 possible sub-terminal locations.

Kilmer *et al.* (1983) analysed the dynamic adjustments required in terms of number, size, and location of fruit packing houses (grape and orange) in Florida to capture changes in the volume and location of primary production.

Monterosso *et al.* (1985) formulated a plant-size location model that incorporated spatial, temporal, and economic features to determine efficient storage size and location in three Brazilian grain-producing areas. The dynamic features of peak storage and transport demands were modelled by dividing the agricultural year into four periods. The authors reported that intermediate locations with very large storage capacities were seldom chosen by any modelled scenario. Large storage capacities were placed in the centres of intense grain production or along routes from the farms to the final destination.

Commer (1991) developed a spatiotemporal optimisation model to determine the optimum location, number, and size of slaughter facilities and the optimum location for feed-lots and grazing in Mississippi, Alabama, Georgia, and Florida. The study considered two scenarios: one with no regional price variation for animals of similar weights and one with regional price variation for animals of similar weights. Each scenario was further differentiated by grazing season, either summer or winter. All scenario results showed that the least-cost solution could be reached by winter grazing in Alabama and expanding feed-lot facilities.

Ferrari (2006) analysed the organisation of soybean storage units in the state of Mato Grosso, Brazil, to minimise storage, transport, and distribution costs. The study considered four scenarios. These scenarios incorporated changes in soybean demand, changes in the scale of warehouse construction, and changing the warehouses that supply the ports.

A recent study by Xavier (2008) developed a dynamic model for determining potential ethanol storage tank locations in Brazil with the objective of minimising transport, storage, and investment costs. The model identified Brazil's centre-south region as the optimal location for the construction of new tanks.

The objective function of the models referenced above was to minimise costs. However, when determining the best locations of some structures, none of the models dealt with export to overseas markets; our study aims to fill this gap. The model presented in this paper encompasses the impact of external market demand on the location decision process within Brazil, in particular, in the state of Mato Grosso.

3. Background

Favourable weather conditions permit environmentally sound, low-cost livestock production in Brazil, but unfortunately there is a lack of coordination within the Brazilian cut livestock market segment. This is the result of the great diversity of breeds, production systems, and trading forms in the country combined with a lack of collaboration stemming from unstable relationships among farmers, slaughterhouses, wholesalers, and retailers (Favaret Filho and Lima de Paula 1997, Siffert Filho and Favaret Filho 1998). Nevertheless, Brazil's livestock herds have grown since the 1990s largely due to the diffusion of advanced technologies in the fields of genetics, nutrition, and sanitary management (IEL *et al.* 2000; Carvalho 2007).

Brazil's slaughtering sector went through many changes in the twentieth century. At the beginning of that century, Brazilian industrial slaughterhouses only produced jerked beef. Today, the industry exports *in natura* and processed meat to several countries and is as technologically advanced as any in the world. Growing external demand for Brazilian beef has led the country's meat industry to invest aggressively in improving its production processes to meet the most rigorous international environmental and sanitary requirements.

According to the preliminary results of Brazil's 2006 Agricultural Census, the country contained approximately 170 million head of cattle. The herd was distributed as follows: centre-west, 31.6%; southeast, 20.6%; north, 18.4%; northeast, 15.3%; and south, 14.1%. Frozen boneless beef is the most important Brazilian beef export, making up 85% (1.1 billion tons) of Brazilian beef exports in 2006.

In 2006, the state of Mato Grosso, located in Brazil's centre-west region, contained the country's second largest cattle herd, about 19.6 million head, and was the third largest Brazilian exporter of frozen boneless beef, exporting about 165.9 thousand tons that year. The main Brazilian ports responsible for handling Mato Grosso's beef exports were Santos, in the state of São Paulo, which accounted for 58% of those exports, and Itajaí, in the state of Santa Catarina, which accounted for 34% of those exports. Frozen boneless beef was exported from Mato Grosso to 70 countries in 2006. In some cases, exports occurred only during specific months; however, a number of

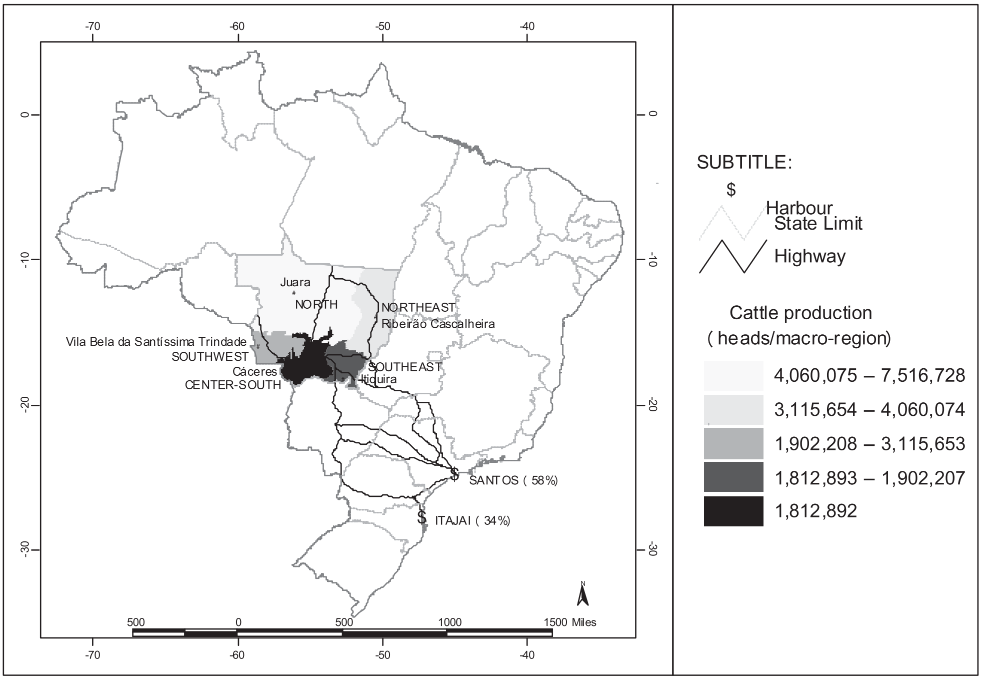

Figure 1. Map of Brazil highlighting the state of Mato Grosso and ports of Santos and Itajaí.

countries, such as Egypt, France, and Hong Kong, demanded Brazilian beef throughout the year. Figure 1 gives a breakdown of Mato Grosso's monthly beef exports in 2006 by port of departure.

Other Brazilian states could have been chosen to evaluate our model's ability to indicate the best capacities, number, and locations for new EOSs. Mato Grosso was chosen because it contains Brazil's second largest cattle herd, is the third largest exporter of Brazilian beef, and is far from any international port of embarkation, reflecting the current trend to locate slaughterhouses closer to the herd than to the port of embarkation. Additionally, states that are closer to the main ports than Mato Grosso either have no relevant cattle herds or are not important beef exporters.

4. The optimisation model

4.1. *Diagrammatic representation*

Figure 2 presents a schematic of the cattle and beef flows assumed in the model. There are n cut livestock production regions located in i with different effective herds ready for slaughter at a particular time. The monthly cattle flows from these regions go to f potential EOSs installed in j with c different slaughter capacities. The beef produced by these EOSs is then shipped monthly to p Brazilian export ports located in h to meet international demand m located in d continents. Any beef that remains after meeting international demand is shipped monthly from the EOSs to l main Brazilian internal markets located in o.

4.2. *Mathematical representation*

The model was designed to determine the best locations for installing EOSs in Mato Grosso. Its inputs included data on monthly cattle flows in Mato Grosso's production regions, the costs of

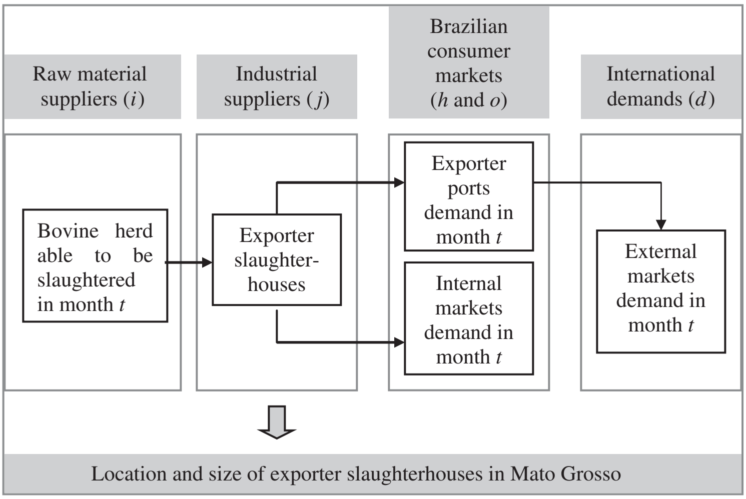

Figure 2. Diagrammatic representation of the dynamic location model applied to Mato Grosso's beef supply chain.

transportation from these cattle-producing regions to possible EOS locations in Mato Grosso, the costs of distribution from these locations to the main export ports and from these ports to the main importing continents, foreign demand, and the installation cost for new EOSs in Mato Grosso. Moreover, it is assumed that the external market should be satisfied first and that beef that is not exported is sent to the main domestic markets, primarily located in São Paulo, Sao Paulo (SP), and Belo Horizonte, Minas Gerais (BH).

We develop a three-stage modelling procedure to address the location decision. The first stage determines the monthly flow of cattle that would minimise transportation costs between producing regions and potential EOSs. The second stage examines EOS locations and capacities to ascertain minimum efficient installation costs in each studied region and the minimum transport cost between these slaughterhouses and the export ports of Santos and Itajaí or the internal market centres of Sao Paulo and Belo Horizonte. The last modelling stage addresses the distribution of Brazilian beef from port to foreign destination, seeking to minimise the cost of sea transportation, including refrigerated containers and Brazilian port costs.

The model is a mixed-integer programme involving continuous and integer variables that enable the determination of the optimum number of EOSs to be constructed, their optimal sizes, and their optimal locations. It was processed by a computer configured with a 2.26 GHz P8400 CPU and 4 GB of RAM. Processing time needed to reach the optimum solution was 2.2 s.

Using this model, one can ascertain locations that minimise transportation costs and test different slaughter capacities in each region to optimise slaughterhouse capacity. It should be pointed out that the EOS location problem is solved using a linear programming model. The mathematical structure of the model detailed below has been codified and processed by the General Algebraic Modeling System version 22.5 with CPLEX 10.1 as the solver. The detailed dynamic model is given below.

4.2.1. *The objective function*

Minimise

$$Z = \sum_{i=1}^{n}\sum_{j=1}^{f}\sum_{t=1}^{g} C_{ijt}X_{ijt} + \sum_{j=1}^{f}\sum_{c=1}^{e}\sum_{w=1}^{u} CI^{c}K^{c}_{jw}\mathrm{NFR}_{w} + \sum_{j=1}^{f}\sum_{o=1}^{l}\sum_{t=1}^{g} C_{jot}Q_{jot}$$

$$+\sum_{j=1}^{f}\sum_{h=1}^{p}\sum_{t=1}^{g} C_{jht}Q_{jht} + \sum_{h=1}^{p}\sum_{d=1}^{m}\sum_{t=1}^{g} Y_{hdt}(C_{hd} + \mathrm{cp}_h), \tag{1}$$

where Z is the objective function value to be minimised; C_{ijt} the cattle road transport cost in month t, in US\$ per ton, from producing regions to the EOS; X_{ijt} the cattle amount, in tons, transported in month t from the producing region to the EOS; CI^c the EOS installation cost with c capacity, in US\$; K^c_{jw} the binary variable associated with the decision of installing an EOS with c capacity; NFR_w the number of EOSs with c capacity to be installed; C_{jot} the beef road transport cost in month t, in US\$ per ton, from the EOSs to the Brazilian internal market; Q_{jot} the beef amount, in tons, transported in month t from EOSs to the Brazilian internal market; C_{jht} the beef road transport cost in month t, in US\$ per ton, from the EOSs to the exporter port; Q_{jht} the beef amount, in tons, transported in month t from the EOSs to the exporter port; Y_{hdt} the beef amount, in tons, exported in month t from the exporter port to the main importer country; C_{hd} the beef shipping cost, in US\$ per ton, from the exporter port to the main importer country; and cp_h the Brazilian port cost, in US\$ per ton.

4.2.2. *The constraints*

(i) *Cattle monthly supply*. The amount of cattle in metric tons transported monthly from region i to the EOSs located in j must not exceed the available monthly supply of cattle able to be slaughtered in the region itself, *id est*:

$$\sum_{j=1}^{f} X_{ijt} - R_{it} \leq 0 \quad \forall i, t, \tag{2}$$

where R_{it} is the available amount of cattle to be slaughtered in month t, in tons, in region i.

(ii) *EOS's monthly cattle demand*. The monthly amount of cattle transported within a region plus the amount that comes from other regions must not be less than the monthly demand for cattle by those EOSs with c capacity that will be installed in the region, i.e.:

$$\sum_{i=1}^{n} X_{ijt} - \sum_{c=1}^{e}\sum_{w=1}^{u} U^c_j K^c_{jw}\mathrm{NFR}_w = 0 \quad \forall j, t, \tag{3}$$

where U^c_j is the cattle demanded quantity in month t, in tons, by the EOSs with c installed capacity in region j.

(iii) *EOS's beef monthly amount supply*. The amount of beef supplied monthly by EOSs with c capacity to be installed in region j should not be less than the amount demanded by exporter ports located in region h, i.e.:

$$\sum_{c=1}^{e}\sum_{w=1}^{u} V^c_j K^c_{jw}\mathrm{NFR}_w - \sum_{h=1}^{p} Q_{jht} \geq 0 \quad \forall j, t, \tag{4}$$

where V^c_j is the quantity of beef supplied in month t, in metric tons, by the EOS with c capacity to be installed in region j.

(iv) *The balance between monthly supply and demand in the domestic market*. The balance between EOSs' monthly boneless beef supply and their respective cattle demands should be equal to the conversion rate of cattle into boneless beef, i.e.:

$$\sum_{n=1}^{s} Q_{jnt} - \left(\frac{200}{460}\right)\sum_{i=1}^{n} X_{ijt} = 0 \quad \forall j, t. \tag{5}$$

(v) *Brazilian ports monthly export beef demand*. The amount of beef transported monthly to the Brazilian exporter ports located in h should be equal to their respective demands:

$$\sum_{j=1}^{f} Q_{jht} - D_{ht} = 0 \quad \forall h, t, \tag{6}$$

where D_{ht} is the quantity of beef demanded in month t, in metric tons, by the Brazilian export port located in h.

(vi) *Brazilian internal market monthly beef demand*. The amount of beef transported to the Brazilian internal market monthly is the difference between the total amount of beef produced by the EOSs monthly and the amount of beef exported to foreign countries from the EOSs monthly, i.e.:

$$\sum_{j=1}^{f}\sum_{o=1}^{l} Q_{jot} = \sum_{j=1}^{f}\sum_{n=1}^{s} Q_{jnt} - \sum_{j=1}^{f}\sum_{h=1}^{p} Q_{jht} \quad \forall t. \tag{7}$$

(vii) *Brazilian internal market's residual beef demand*. The amount of beef transported monthly to the Brazilian internal market is a residual one, that is, after satisfying the external market, the remaining beef produced by the EOSs is transported to the main domestic consumer centres, i.e.:

$$\sum_{j=1}^{f} Q_{jot} \leq DM_o \quad \forall o, t, \tag{8}$$

where DM_o is the quantity of beef demanded, in metric tons, by Brazilian internal market located in o.

(viii) *Balance between monthly foreign market supply and demand*. The monthly amount of beef transported to the Brazilian exporter ports located in region h must be equal to the beef amount transported monthly to the importer continent d, i.e.:

$$\sum_{j=1}^{f} Q_{jht} - \sum_{d=1}^{m} Y_{hdt} = 0 \quad \forall h, t. \tag{9}$$

(ix) *Importer continent monthly beef demand*. The monthly amount of beef that reaches importers located in continent$d$ should not be less than their respective demands, i.e.:

$$\sum_{h=1}^{p} Y_{hdt} - M_{dt} \geq 0 \quad \forall d, t, \tag{10}$$

where M_{dt} is the demand quantity in month t, in metric tons, by importers located in continent d.

5. Data

Our EOS optimal-location model uses cattle supply data obtained from the 2006 Brazilian Agricultural Census and the 2006 Brazilian Quarterly Research for Slaughter of Animals to analyse monthly flows between the various links in the Mato Grosso beef supply chain. These data are displayed in Figure 3. One immediate finding from these data is that the highest level of bovine slaughter occurs in October and the lowest in February.

To facilitate modelling, we considered Mato Grosso into its several macro-regions. According to the classification system adopted by the Brazilian Institute of Geography and Statistics, Mato Grosso has 141 municipalities and is divided into five broad macro-regions: north, northeast, centre-south, southeast, and southwest (as shown in Figure 1). Each macro-region is represented by a centroid based on the municipality that has the largest effective cattle herd within the respective macro-region. As a result, the municipality of Juara represents the north macro-region, Ribeirão Cascalheira (Ribeirão C.) represents the northeast, Cáceres represents the centre-south, Itiquira represents the southeast, and Vila Bela da Santíssima Trindade (Vila Bela) represents the southwest. The centroid itself, as a proxy for a particular macro-region, need not be the actual site for future EOS installation in its region.

Monthly frozen boneless beef exportation data from January 2006 to December 2006 were recorded in the ALICE-Web system provided by the Brazilian Ministry of Development, Industry, and Foreign Trade. The 70 countries importing frozen boneless beef produced in Mato Grosso are grouped into the following continents: Asia (Asia); the Middle East (M.E.); Africa; North America (N. Am); Central America (C. Am.); South America (South Am.); and Europe. In the same way that a region of effective cattle supply is represented by a centroid, the importing continents are also represented by centroids, in this case, a country. The respective centroids considered are the United Arab Emirates, Egypt, the United States of America, Venezuela, and Russia, as shown in Figure 4. These external centroids are determined by which country in the designated continent has the greatest demand for Mato Grosso's frozen boneless beef.

Since Mato Grosso has 141 municipalities and has exported frozen boneless beef to 70 countries, the centroid approach is primarily adopted to reduce the scale of computational time required in the search for the best solution to the proposed model. Spatially, the model's flow would be from one of the five raw material macro-regions to one of the five potential EOS locations, continuing to either of the two Brazilian export ports or either of the two domestic market locations (SP and BH); then, the beef transported to the ports would be shipped to one of the five foreign markets for Brazilian beef. If one ignores the temporal aspect (12 months) and three EOS capacities, there are 500 ($5 \times 5 \times 4 \times 5$) possible flows. When the temporal aspect and different plant capacities are considered, there are 18,000 possible streams. The model also involves a possible 75 binary variables: three different EOS sizes times the five macro-regions times the maximum of five EOSs in each macro-region.

The greatest foreign demand for Brazilian frozen boneless beef occurs in September, as shown in Figure 4. September is also the month with the second highest number of beef slaughtered, as shown in Figure 3.

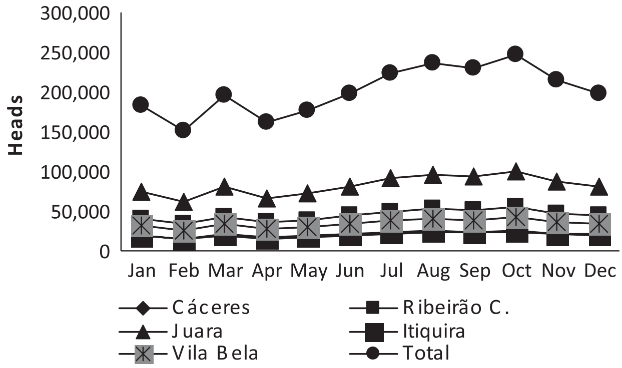

Figure 3. Monthly distribution of Mato Grosso cattle for slaughter, 2006.
Source: The Agricultural Census and the Quarterly Research for Slaughter of Animals.

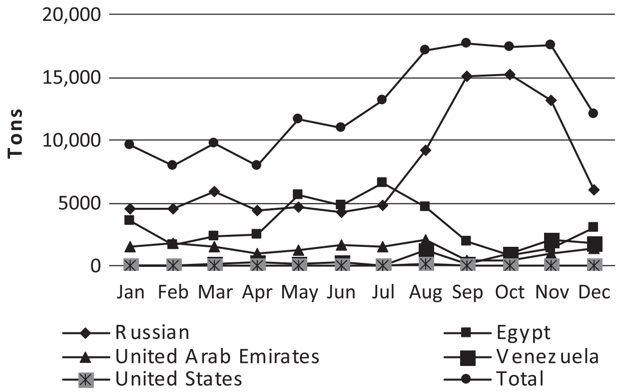

Figure 4. Monthly demand of foreign markets for Mato Grosso frozen boneless beef in 2006. Source: ALICE-Web system.

Although the model does take Brazilian port costs into consideration, it does not take the operational capacity of these ports into account. We assume that the ports of Santos and Itajaí have the ability and level of service required. Foreign port operational capacity and terminal costs are not considered.

The model considers the installation of EOSs with three different capacities: 1000, 1200, and 1500 head of cattle per day, or 22,000, 26,400, and 33,000 head of cattle per month if they are operating at peak efficiency 22 days per month. It is assumed that a head of cattle's average weight is 460 kg, that the dressed weight of the average head of cattle is 200 kg, and that the new EOSs have an output of 4400, 5280, or 6600 metric tons of boneless beef per month, depending on which of the three capacities the EOS has. We consider that all Mato Grosso's macro-regions can successfully accommodate the modelled EOS installations.

EOS installation costs are obtained directly from sector agents. Because most beef exported from Brazil is boneless, the figures are associated with industrial slaughterhouses that are able to perform slaughtering and de-boning. Furthermore, the figures are specific to slaughterhouses that employ the best available technology so as to meet stringent foreign trade and market requirements such as product standardisation, humanitarian slaughter, and sanitary standards. With the afore-mentioned caveats, installation costs of slaughterhouses with capacities of 1000, 1200, and 1500 head slaughtered per day are approximately US$ 50 million, US$ 60 million, and US$ 60 million, respectively. It should be pointed out that although the installation costs for the two larger capacity slaughterhouses are the same, the larger slaughterhouse has higher variable costs. These costs are not considered in the modelling. Although installation cost favours installation of the larger capacity EOS, the variable cost differential favours the slaughterhouse that has a capacity consistent with the availability of cattle for slaughter and foreign beef demand. There is no point choosing the biggest EOS if there are not enough cattle available for slaughter and/or if the external demand can be satisfied by a smaller capacity installation.

The Brazilian cattle and boned beef road freight transportation costs come from the Brazilian Freight Charges for Agriculture Information System. Port costs and ocean freight charges are based on a 40-foot container and were collected from sector agents.

6. Results and discussion

This section presents results from the mixed-integer programming model. These results include estimated monthly cattle flows to the regions indicated as the best locations for EOS installation, monthly flows from these regions to either the export ports of Santos and Itajaí or the main

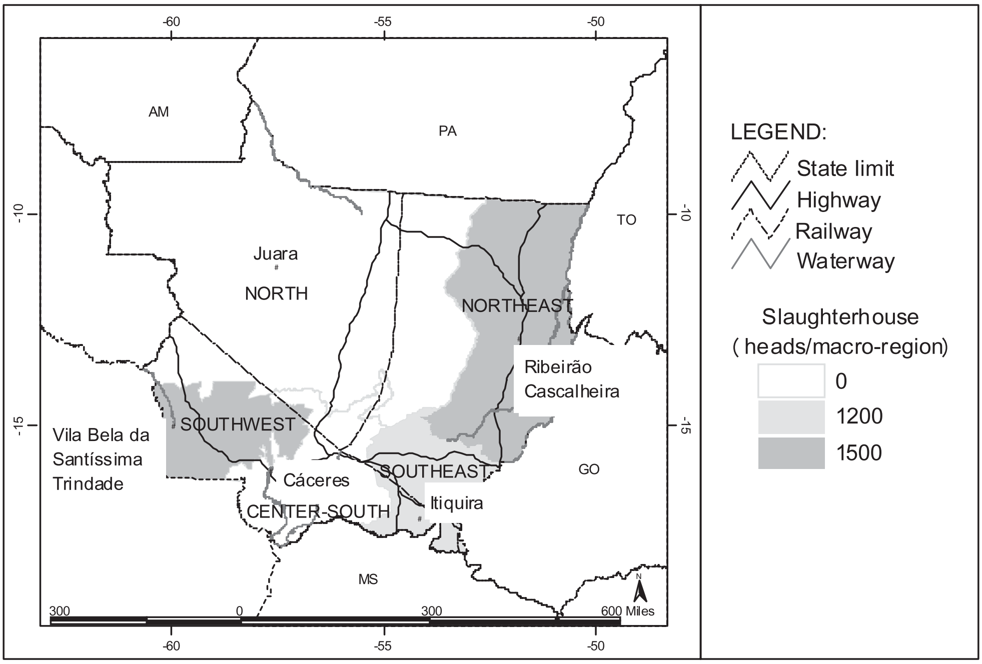

Figure 5. Proposed EOS locations in Mato Grosso, Brazil based on the newly developed dynamic model.

internal markets of SP and BH, and the monthly flows of beef from Mato Grosso to international markets.

The optimum solution that minimises all the costs in the Mato Grosso beef supply chain (road and sea logistics, slaughter industrial unit installation, and Brazilian ports) calls for the installation of three EOS (Figure 5): one 1500 head per day EOS in Ribeirão C. (in the northeast macro-region), one 1500 head per day EOS in Vila Bela (in southwest), and one 1200 head per day EOS in Itiquira (in southeast). These results do not correspond to the actual number of slaughterhouses in Mato Grosso, which contained 24 slaughterhouses in 2006 (Santos *et al.* 2007).

The model is at variance with reality for two very significant reasons. It was designed to indicate the optimal locations and capacities for slaughterhouses constructed to satisfy the external market primarily. In addition, since system-wide optimisation was our objective, the model does not consider plant idleness due to a lack of inputs: constraint (3) guarantees that the exporter slaughterhouses' monthly cattle demand is fully addressed. This stipulation is in variance with reality as excess capacity in the Brazilian slaughter segment is the main reason for the well-known financial instability of the country's slaughtering firms.

According to results from the model, most of the logistics costs stem from the installation of the three EOSs, accounting for 79% of the total minimum cost of US$ 228 million. Costs for transporting the beef from the EOSs to the Brazilian export ports are responsible for 9.4% of total costs. Port and international shipping costs represent 5.5% of total costs. Costs for transporting the processed beef to the main domestic markets are responsible for 4.7% of total costs. The transport of live cattle to the EOSs represents 1.4% of total minimum costs.

The model identifies the monthly flows of cattle to the regions where the proposed EOSs would be located. The EOS located in the Itiquira region would receive 26,400 head of cattle per month; the EOS located in the Vila Bela region would receive 33,000 head per month; and the EOS located in the Ribeirão C. region would receive 33,000 head per month. Table 1 reports these flows in a more detailed form. Due to the lower transportation cost, the greatest quantity of cattle supplied

Table 1. Monthly quantity of cattle (in heads) transported from the producing regions to the export slaughterhouses suggested by the newly developed dynamic model.

Producing region	Slaughter region	Jan	Feb	Mar	Apr	May	Jun
Cáceres	Itiquira	7420	10,235	6153	9757	8156	5849
Ribeirão C.			479				
Itiquira		18,980	15,686	20,247	16,643	18,244	20,551
Cáceres	Vila Bela	1912	4714		5740	3118	
Juara			2594				
Vila Bela		31,088	25,692	33,000	27,260	29,882	33,000
Ribeirão C.	Ribeirão C.	33,000	33,000	33,000	33,000	33,000	33,000
Producing region	Slaughter region	Jul	Aug	Sept	Oct	Nov	Dec
Cáceres	Itiquira	3230	1921	2675	965	4201	5911
Itiquira		23,170	24,479	23,725	25,435	22,199	20,489
Vila Bela	Vila Bela	33,000	33,000	33,000	33,000	33,000	33,000
Ribeirão C.	Ribeirão C.	33,000	33,000	33,000	33,000	33,000	33,000

Table 2. Quantities of boneless beef (in 1000 tons) transported from slaughter regions to Brazilian exporter ports and internal markets suggested by the newly developed dynamic model.

Beef meat origin	Port of destination	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Itiquira	Itajaí	2.8	1.5	1.7	1.4	4.2	2.4	2.9	2.3	1.4	3.0	4.6	5.2
Vila Bela	Itajaí							1.3	5.3	5.7	5.6	5.7	0.2
Total for Itajaí		2.8	1.5	1.7	1.4	4.2	2.4	4.2	7.5	7.1	8.6	10.3	5.5
Beef meat origin	Port of destination	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ribeirão C.	Santos	4.3	2.7	4.4	2.7	6.4	5.7	6.6	6.6	6.6	6.6	6.6	6.6
Itiquira	Santos	2.5	3.8	3.6	3.9	1.1	2.8	2.4	3.0	3.9	2.3	0.7	0.03
Total for Santos		6.8	6.5	8.1	6.6	7.5	8.5	9.0	9.6	10.5	8.9	7.3	6.6
Beef meat origin	Internal market	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ribeirão C.	SP	2.3	3.9	2.2	3.9	0.2	0.9						
Vila Bela	BH	6.6	6.6	6.6	6.6	6.6	6.6	5.3	1.3	0.9	1.0	0.9	6.4
Total internal market		8.9	10.5	8.8	10.5	6.8	7.5	5.3	1.3	0.9	1.0	0.9	6.4

to a particular slaughterhouse comes from its own region, although some supply does come from other regions.

Since the cattle demands would be fully addressed, there would be no idle capacity in the proposed EOSs. The Itiquira, Vila Bela, and Ribeirão C. slaughterhouses would produce 5280, 6600, and 6600 tons of boneless beef per month, respectively, which would exceed external market demands.

The estimated monthly flow of boneless beef from the proposed EOSs to Brazilian destinations outside Mato Grosso is summarised in Table 2. The port of Itajaí would receive boneless beef from the Itiquira beef-producing region over the entire year and from Vila Bela for the last half of the year. The port of Santos would be supplied by Ribeirão C. and Itiquira throughout the year. The SP internal market would only receive boneless beef from Ribeirão C. and only for the first 6 months of the year. The BH internal market would receive boneless beef from Vila Bela throughout the year.

Beef flows from the two ports to international destinations are summarised in Table 3. The results indicate that all boneless beef shipped to Asia and the M.E. should be loaded at the port of Santos, that boneless beef shipped to Africa should be loaded at the port of Santos during the first 7 months of the year and at the port of Itajaí throughout the year, and that boneless beef shipped to Europe should be loaded at the port of Santos throughout the year and at the port of Itajaí during the last 5 months of the year.

Table 3. Boneless beef (in 1000 tons) transported from the Brazilian exporter ports to demanding continents suggested by the newly developed dynamic model.

	Output by Itajaí											
Continent	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Europe								1.5	5.0	6.8	6.9	0.9
Africa	2.8	1.4	1.5	1.1	4.1	2.1	4.1	4.6	1.9	0.9	1.4	3.1
South Am.			0.1	0.2	0.08	0.3	0.06	1.3	0.2	0.9	2.0	1.7
N.&C. Am.	0.01	0.04			0.02	0.01	0.04	0.08	0.04		0.007	0.02
Total by Itajaí	2.8	1.5	1.6	1.3	4.2	2.4	4.2	7.5	7.1	8.6	10.3	5.5
	Output by Santos											
Continent	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Europe	4.5	4.5	5.9	4.4	4.7	4.3	4.9	7.6	10.1	8.5	6.3	5.3
Africa	0.8	0.2	0.8	1.3	1.5	2.6	2.6					
Asia and M.E.	1.5	1.8	1.5	1.0	1.3	1.6	1.6	2.0	0.4	0.4	0.9	1.3
Total by Santos	6.8	6.5	8.1	6.6	7.5	8.5	9.0	9.6	10.5	8.9	7.3	6.6

7. Conclusion

The recent expansion of Brazilian beef exportation, which has positioned Brazil as the world's leading beef exporter, made the timely development of our optimisation model imperative if Brazil is to maintain its competitive advantage in this market segment. The model relies on a mixed-integer programme and incorporates the dynamic factors, in that it considers time-based elements such as the seasonal nature of raw material production and demand for boneless beef.

Model results show that three properly sized new EOSs constructed in the Mato Grosso regions relatively close to export ports would be able to fully satisfy all importing countries' current requirements for Mato Grosso beef, efficiently utilise local cattle supply, and minimise logistical costs in the state's beef export supply chain. While the investments needed to construct these new slaughterhouses were found to represent a very substantial one-off expense, it is clearly important that new slaughterhouses are built in the best locations.

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