Grain Supply Chain Management Optimization Using ArcGIS in Argentina

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Abstract:

This paper discusses the development and implementation of a GIS-based constrained linear programming model that minimizes transportation and storage costs for soybeans and its by-products in Argentina for 2006. Given the demand of Argentine soybeans at the crushing facilities and soybeans and its by-products at the exporting ports, this study identified the lowest-cost soybean producing and storage locations; grain transportation routes by truck, rail and barge; crushing facilities and exporting ports. The lowest-cost supply chains are optimized from the different rates charged and constrained by the capacities at each stage of the supply chain from up-stream to down-stream; this is, from the country elevator to the terminal elevator passing through crushing plants. General Algebraic Modeling System, GAMS, was used to optimize the linear programming cost-minimization model while ArcGIS Network Analyst was used to produce and map the Origin-Destination Cost Matrices for the supply chain analysis. ArcMap was used to map geographic data before and after the linear programming optimization in GAMS. ArcGIS ArcMap mapping possibilities and ArcGIS Network Analyst solving capabilities together with GAMS optimization capabilities can have a significant impact on agricultural supply chain management for trading firms as well as producers, elevators and crushers by providing detailed information and images of the lowest-cost producing regions, transportation modes, storage locations and exporting sites.

Key Words: Argentina, logistics, production, storage, supply chain, transportation

Introduction:

Agricultural supply chains are unique in the sense that they include several commodities (corn, soybeans, wheat, sunflower and cotton), that are produced in different regions of the world (United States' *Breadbasket*, Argentina's *Pampas* or Brazilian *Cerrados* for instance) and in different regions within countries (Corn-Belt, Cotton-Belt, Wheat-Belt in the United States), at different time-periods of the year (i.e. winter crops versus summer crops), and are transported through different modes of transportation (i.e. truck, railroads, barge and vessel). These agricultural commodities have different end-uses, food, feed, industrial and energy, and are relatively homogeneous. Agricultural commodities are transported and stored in bulk quantities which range from hundreds to several thousands metric tons.

Agricultural supply chains differ from manufacturing supply chains in that production and consumption are separated not only in time but also in distance, making storage and transportation a key challenge for these products. Transportation and storage of soybeans and its by-products along the supply chain is essential as production and consumption are separated in distance and time, respectively. The fact that agricultural commodities are biological products that can be produced only under certain spatial characteristics (i.e. soil characteristics, water availability, temperature range, frost-free areas, insects and diseases presence) and that consumption is separated in time and distance make a spatial economic analysis fundamental.

Agricultural supply chains include input vendors (seed, fertilizers, agro-chemicals, machinery, for instance), producers, country elevators, barge ports, crushing facilities, exporting ports and transportation (Figure 1). Marketing delivery channels for agricultural commodities, such as soybeans, are usually grouped according to the number of deliveries that have passed through from up-stream to down-stream. Soybean first delivery could be either from the producer to country elevators or from the producer to barge ports, exporting ports or crushing facilities, depending on trucking availability, trucking rates, and distances from the producing region to these outlets (Figure 1). Most frequently, soybeans that leave the farm are "short-hauled" to a country elevator. Soybeans are dried, cleaned and disinfected to meet grading standards at the country elevator.

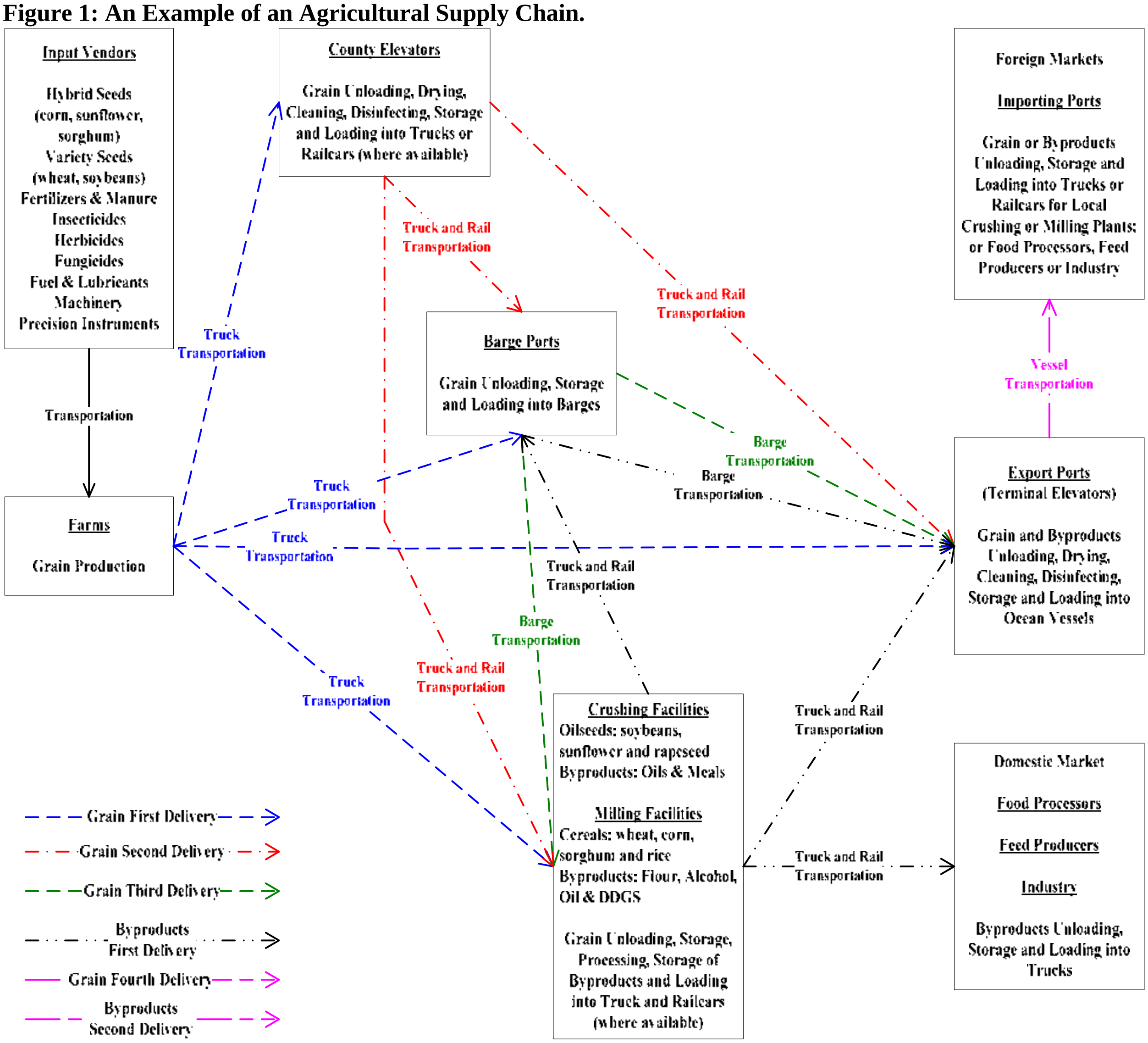
Soybean second-stage delivery originates at the country elevators with commodity flows towards crushing facilities, barge ports or exporting ports (Figure 1). Crushing facilities are usually located within the largest producing regions or next to the exporting ports (terminal elevators). This will depend on whether most of the crop will be used for the domestic market or the international market, respectively. For example, Brazil and the United States have most of their crushing capacity installed in the major soybean growing region areas to serve the domestic population while Argentina has almost all of the crushing capacity in the exporting ports to serve foreign markets. Soybean crushing produces soybean meal and soybean oil with a 78-80 percent and 18-20 percent yield, respectively. Soybean second-stage delivery can be either by truck or by rail depending on truck and railroad rates and shipping constraints. Rail-track availability at the country elevator, crushing plants and exporting ports is fundamental for shipping soybeans by railroads.

Soybean third-stage delivery includes the usage of inland waterway transportation through barges (Figure 1). Barge usage will depend on barge port proximity to major growing areas, barge rates and shipping capacity, loading capacity at the barge ports and unloading capacity at the exporting ports. Barge transportation is widely used in the United States and Paraguay while is not important in Argentina and Brazil. The United States transports 55 percent of its agricultural commodities by barge through the Mississippi-Missouri waterway to the exporting ports in the Gulf of Mexico (Nardi and Davis, 2006). In contrast, Brazil and Argentina transport only 5 percent and 1 percent, respectively of its agricultural products to the exporting ports due to lack of infrastructure in the first case and proximity of the producing region to river ports in the second case (Nardi and Davis, 2006).

Transportation of soybean meal and soybean oil occurs when crushing plants are located in the country side and not at the terminal elevators next to the exporting ports. Transportation of the soybean by-products is usually handled by railroad but could also be by truck or barge (Figure 1). Railroad transportation of agricultural commodities in the United States is highly developed and accounts for 38 percent of the export-bound movement (Nardi and Davis, 2006). In Brazil, railroad transportation represents 28 percent while in Argentina only 15 percent of the export bound movement of agricultural commodities due to lack of infrastructure (Nardi and Davis, 2006).

Finally, once soybeans, soybean meal and soybean oil are located at the terminal elevator, they are exported world-wide through vessel transportation (Figure 1). Soybeans and soybean meal are transported in bulk, dry vessels (Handymax, Panamax or Capesize size vessels) while soybean oil is transported in bulk, double-hooded, oil vessels. Major exporting ports in the United States are located in the Gulf of Mexico (New Orleans and Corpus Christi) and in the Pacific Northwest (Seattle) to a lesser degree (Nardi, 2006). In Brazil, major exporting ports are located in the Atlantic Seaboard in the Southeastern states of Sao Paulo (Santos), Parana (Paranagua), Santa Catarina (Sao Francisco de Sul) and Rio Grande do Sul (Rio Grande) (Nardi, 2006). In Argentina, major exporting ports are located in the Up-River Parana Ports (San Martin, San Lorenzo, Rosario, Villa Gobernador Galvez, Alvear) and in the Atlantic Seaboard of Buenos Aires province (Necochea and Bahia Blanca) (Nardi, 2006).

Figure 1: An Example of an Agricultural Supply Chain.



The objective of this paper is to describe and implement a linear programming model to optimize Argentina's soybeans and by-products supply chain for 2006, using ArcGIS and an optimizing software (General Algebraic Modeling System – GAMS). This model will minimize the transportation costs through the supply chain given resource constraints. The optimal supply chain will help agribusiness, producers and policymakers to understand the effect of infrastructure improvements, business growth and policies on supply chain costs and efficiencies.

Literature Review:

Previous research on spatial grain transportation and storage optimization in the United States has been conducted by Koo, Thompson and Larson (1985), Mckenzie, La Ferney, Wailes and Otwell (1993) and Wilson, Carlson and Dahl (2004). These studies, however, did not use Geographic Information Systems (GIS) to conduct their spatial analysis and focused on optimization or simulation. Furthermore, these types of research have not been conducted for other major grain exporting nations like Argentina, Brazil or Paraguay. These countries in South America have become major world exporters of agricultural commodities, but infrastructure has not been fully developed (Schnepf et al., 2001).

Koo, Thompson and Larson (1985) developed a spatial equilibrium linear programming model in order to evaluate the economic impacts of rail and barge transportation capacity constraints on the spatial flows of grain and the economic impacts of changes in transportation costs on the grain marketing system. They constrained the model with regional demand of grain, regional supply of grain, storage capacity in commercial storage locations, regional rail car supply and waterway capacities along inland water routes in the United States. They modeled three modes of transportation: rail, truck and barge; three time periods within the year; and three commodities: feed grains, soybeans and wheat. They allowed three transportation activities: 1) shipments from each producing region to each domestic crushing facility, 2) shipments from each producing regions to export ports directly, and 3) shipments from producing regions to export ports through commercial storage locations. They developed a cost model based on transportation costs and a rate model based on actual rate structures. They found that the average transportation cost difference between domestic markets and United States ports was largest for soybeans movement and lowest for feed grains movements. They argued that lower transportation cost to domestic markets for soybeans was due to the fact that soybean processors tend to be located near the production areas.

Mckenzie, La Ferney, Wailes and Otwell evaluated the optimal inter-modal soybean flow in Arkansas for the 1993 marketing year with projected effects of the North America Free Trade Agreement (NAFTA). They used both survey data and a linear programming to model grain flows. The authors induced that both approaches were consistent and that the linear programming model adequately captured real world behavior for Arkansas in that marketing year. They found that the optimal mode of transporting soybeans from elevators to in-state processors was by trucks; the optimal mode of transporting soybeans to Galveston exporting port was rail; and barge was the optimal mode for transporting soybeans to New Orleans exporting port. They concluded that the Arkansas soybean transportation infrastructure in 1993 was adequate to meet any increase in export demand resulting from NAFTA agribusiness.

Wilson, Carlson and Dahl (2004) developed a stochastic simulation model to evaluate trade-offs and effects of key variables on logistic costs in the grain supply chain in the United States. Demurrage costs were evaluated for each mode of transportation (railroad, barge and vessel) at each shipping facility. The stochastic variables in the simulation model included placement, transit times, export demand and vessel arrivals. In the base case scenario, average demurrage costs for the grain marketing system were $2.03 million per year. Barge demurrage costs were the highest (39 percent) in the supply chain, followed by vessel demurrage costs (37.1 percent) and rail demurrage costs (23.9 percent). The sensitivity analysis showed that changes in export demand caused the greatest disruptions to the supply chain and increased demurrage cost the most. For instance, if the quantity of grain exported increased by 10 percent, average demurrage costs increased three-fold to $6.17 million per year in their analysis.

Several studies have been performed in Argentina regarding the effect of transportation and storage on the growth of the agricultural sector and improved transmission of international prices to farm prices. Improved price transmission in the 1990's from government and market reforms allowed farmers in Argentina to capture a higher share from the international price. The adoption of technology coupled with low farm-level variable and fixed costs, boosted Argentina's agricultural output from 29 million metric tons in 1989 to 92 million metric tons in 2007 (SAGPyA, 2007). Investments in key logistic areas such as crushing capacity, port storage and loading capacities and dredging of the Parana River to 34 feet deep have been performed in Argentina (Nardi, 2006). However, investments in railroads, highways and country elevators storage capacity have not occurred, due macroeconomic instability resulting in fiscal and monetary uncertainty in Argentina (Nardi, 2006). Most of the studies performed have been descriptive and have not included a spatial analysis or optimization modeling techniques to estimate the transportation and storage costs. The research on the area range from studies that concentrate on price transmission and the effect on world competitiveness: Ciani (1993) and Nardi (2006); storage capacity constraints: Ciani (2001) and ONCCA (2004): transportation constraints: Nardi and Davis (2006); or have a broad view that covers all these issues: Oliverio and Lopez (2002, 2005 and 2007), Lopez (2003, 2004, 2005 and 2006), and CEEDS (2006).

Methodology and Data:

The least-cost spatial equilibrium mathematical programming model of the soybean, soybean meal and soybean oil transportation and storage system for Argentina in 2006 is modeled. The model incorporates transportation and storage activities in moving these commodities along the supply chain. The transportation activities are subject to constraints associated with regional availability for soybeans; country elevator, crusher and export port storage capacities; and constraints on truck, rail and barge shipping capacities in Argentina during 2006.

Soybean availability in Argentina for 2006 resulted from soybean beginning stocks (January 1st) plus soybean production during minus ending stocks (December 31st) at each county. Soybean production county level data was obtained from SAGPyA (2007) while soybean beginning and ending stocks county level data were obtained from ONCCA (2007). Soybean availability was assumed to be at the county-seat for each county, as most of the storage capacity is usually located in the county-seat. Through this assumption, we omitted soybeans short-haul from the farm into the country elevator as the long-haul represents the largest share of transportation cost (Nardi, 2006).

Crushing facilities, soybeans crushed, soybean oil and soybean meal production were obtained from SAGPyA (2007). Crushing capacity, soybeans, soybean meal and soybean oil storage capacity for each crushing facility were obtained from J.J. Hinrichsen Statistical Yearbook (2007). Since many crushing facilities are clustered in the same exporting ports both in the Parana Up-River ports as in the Southern Atlantic Ocean; they were pooled at city-level data in order to simplify the spatial analysis. Barge ports, storage and loading capacity data were obtained from J.J. Hinrichsen Statistical Yearbook (2006). Exporting port facilities, soybeans, soybean meal and soybean meal exported were obtained from SAGPyA (2007). Exporting capacity, soybeans, soybean meal and soybean oil storage capacity, and barge unloading capacity for each exporting port were obtained from J.J. Hinrichsen Statistical Yearbook (2007). Again, since many terminal elevators are clustered in the same exporting ports both in the Parana Up-River ports as in the Southern Atlantic Ocean; they were pooled at port-level data in order to simplify the spatial analysis.

Transportation constraints for barge and railroad in Argentina were taken from Nardi and Davis (2006). Country elevators storage capacity at the county level was obtained from ONCCA (2007). Transportation rates were obtained from SAGPyA (2007). Annual averages were used for truck, railcar and barge transportation. There are currently six railroad freight companies operating in Argentina: America Latina Logistica-Central (ALL-C), America Latina Logistica-Mesopotamica (ALL-M), Belgrano Cargas (BC), Ferro-Sur Roca (FSR), Ferro-Expreso Pampeano (FEP) and Nuevo Central Argentino (NCA). There are four companies with a wide gauge of 1.60 meters (ALL-C, FSR, FEP and NCA) while there is one company with a standard gauge of 1.4 meters (ALL-M) and one company with a narrow gauge of 1.0 meters (BC). Different gauges across the six companies therefore create logistics incompatibilities between the three different gauges. Furthermore, companies with the same gauge can only source in their respective track and cannot originate freight in non-owned track which also creates logistics barriers to develop freight market for agricultural commodities (Nardi, 2006).

Geographic data in shapefile format from Argentina regarding international borders, provincial limits, county limits, rivers, cities, highways and railroads were obtained from Aeroterra's website in the download section (http://www.aeroterra.com/eng/d-argentinagral.htm). Geographic data was also obtained from Argentina's Instituto Geográfico Militar (IGM) through ArcIMS server on their GIS site (http://www.sig.igm.gov.ar) on inter-provincial highways, provincial highways, dirt roads and railroads. Data from Aeroterra dates from 1996 while data from IGM it is up-to-date. However, some data did not change with time (e.g. political boundaries and cities) while other data did change with time (e.g. highways and railroad tracks). Selected geographical data were put in several Feature Datasets within a Personal Geodatabase with a common Spatial Reference System (GCS_WGS_1984). Databases from diverse agencies in Argentina were joined to Aeroterra's and IGM's databases to generate diverse maps in ArcMap.

Network Datasets were created for the different transportation modes: roads, railroad and waterways. Railroad included six Network Datasets, one for each company (BC, ALL-M, NCA, FSR, FEP and ALL-C). Railroad Network Datasets were the most difficult to generate since the geographic data available did not elicit the concession of the railroad tracks. Geographic data from Aeroterra included length for every shape but had mistakes in the concession of the tracks.

Geographic data from IGM did not include length and the concession of the tracks for each company has not been included in the attribute table. The privatization process in Argentina did not give each new company the same railroad tracks each state company used to own. Therefore, the selection of each new privatized freight railroad company was performed following railroad track maps from each company's website.

Figure 2: Soybean, Soybean Meal and Soybean Oil Supply Chain for Argentina in 2006 assumed in the Linear Programing Optimization Model.

The cost minimization model in GAMS determined the least-cost transportation and storage source of soybeans that satisfies the quantities demanded in Argentina's crushing facilities and exporting ports during 2006. Three commodities were considered in the model: soybeans, soybean meal and soybean oil. The model determined the optimal sourcing of soybeans from each county and soybean oil and soybean meal from each crushing facility. The model included three modes of transportation for Argentina in 2006: truck, rail, and barge along the inland water-ways. The water-ways include the Hidrovia Parana-Paraguay (HPP), the Uruguay River and the Rio de la Plata. However, not all of these water-ways had barge loading and unloading facilities. Transportation and storage activities, including origin and destination, commodities involved and transportation mode for Argentina were incorporated in the model (Figure 2).

The cost minimization model in GAMS determined the optimal flow of soybeans from country elevators to the exporting ports (Figure 2). Soybeans could be shipped to crushing facilities directly from the country elevators or to barge ports. Similarly, soybeans could be transported directly to the exporting ports from the country elevators. Once the soybeans were processed into soybean meal and soybean oil, these commodities were transported to terminal elevators next to the exporting ports. Finally, an important assumption is that a pull supply chain system exists in this model. This is, the crushing facilities and the exporting ports are the ultimate pulling forces in the different marketing channels for Argentina in 2006. The model developed in this study, and described in Equations 1-14, is based on a least-cost spatial equilibrium model developed by Koo, Thompson, and Larson (1985).

The mathematical-programming model was developed in the following steps. The indices of the model were defined first. Then the objective function and the constraints of the model were defined to minimize transportation and storage constraints along the supply chain. Third, the decision variables of the model were defined. Finally, the parameters of the model were defined with respect to quantity of commodity produced and required, distances among country elevators, crushing facilities, exporting ports and the barge ports, and transportation and storage rates.

Definition of the Indices of the Model:

The indices used in the base model are defined and listed in the following table.

Subscript	Name	Definition	Number
c	Commodities	Soybeans, soybean meal and soybean oil	3
s	Off-farm storage (country elevators)	Country elevators at county-seats in which soybeans were produced	217
e	Exporting ports (terminal elevators)	Exporting ports where soybeans, soybean meal and soybean oil were exported	13
j	Crushing facilities	Crushing facilities where soybeans were crushed	37
b	Barge ports	Barge ports where soybeans were transported	12
m	Transportation Modes	Truck, railcar (6) and barge.	8
f	Loading	Export of soybeans, soybean meal and soybean oil	13

Model Objective Function:

The objective function of the model was defined to minimize total transportation and storage costs associated with moving soybeans and by-products through the supply chain for Argentina in 2006. Each of the terms described in the equation of the objective function of the base model are explained through the following paragraphs. The objective function for the base model was as follows:

$$Min\ Total\ Cost = \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{e=1}^{13}\sum_{m=1}^{7} XSE_{csem}\cdot d_{se}\cdot r_{csem} + \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{j=1}^{37}\sum_{m=1}^{7} XSJ_{csjm}\cdot d_{sj}\cdot r_{sjm} +$$
$$+\sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{b=1}^{12}\sum_{m=1}^{1} XSB_{csbm}\cdot d_{sb}\cdot r_{sb} + \sum_{c=1}^{2}\sum_{j=1}^{37}\sum_{e=1}^{13}\sum_{m=1}^{7} XJE_{cjem}\cdot d_{je}\cdot r_{jem} +$$
$$+\sum_{c=1}^{1}\sum_{b=1}^{12}\sum_{j=1}^{37}\sum_{m=1}^{1} XBJ_{cbjm}\cdot d_{bj}\cdot r_{bj} + \sum_{c=1}^{1}\sum_{b=1}^{12}\sum_{e=1}^{13}\sum_{m=1}^{1} XBE_{cbem}\cdot d_{be}\cdot r_{be} + \sum_{c=1}^{3}\sum_{e=1}^{12}\sum_{f=1}^{12} XEF_{cef}\cdot r_{ef} \qquad (1)$$

The first term is the cost of transporting soybeans from the country elevators to the export ports. In greater detail, XSE_{csem} is the quantity (metric tons) of commodity *c* (soybeans) shipped from the country elevator *s* to export port (terminal elevator) *e* by mode of transportation *m* (truck and six railroad companies where available); d_{se} is the distance (in kilometers) between the *s* country elevator and the *e* exporting port (terminal elevator); and r_{csem} is transportation cost ($\$/mton\cdot km$) in shipping commodity *c* (soybeans) from country elevator *s* to export port (terminal elevator) *e* by mode of transportation *m* (truck and six railroad companies).

The second term is the transportation cost of transporting soybeans from country elevators to the crushing facilities. In greater detail, XSJ_{csjm} is the quantity (metric tons) of commodity *c* (soybeans) shipped from country elevator *s* to crushing facility *j* by mode of transportation *m* (truck and six railroad companies where available); d_{sj} is the distance (in kilometers) between the *s* country elevator and the *j* crushing facility; and r_{csjm} is transportation cost ($\$/mton\cdot km$) in shipping commodity *c* (soybeans) from country elevator *s* to crushing facility *j* by mode of transportation *m* (truck and six railroad companies).

The third term is the total cost in transporting soybeans from the country elevators into the barge ports. In greater detail, XSB_{csbm} is the quantity (metric tons) of commodity *c* (soybeans) shipped from country elevator *s* to barge port *b* by mode of transportation *m* (truck and six railroad companies where available); d_{sb} is the distance (in kilometers) between the *s* country elevator and the *b* barge port; and r_{csbm} is transportation cost ($\$/mton\cdot km$) in shipping commodity *c* (soybeans) from country elevator *s* to barge port *b* by mode of transportation *m* (truck and six railroad companies).

The fourth term is the total cost in transporting soybean meal and soybean oil from the crushing facilities into the terminal elevators next to the exporting ports. In greater detail, XJE_{cjem} is the quantity (metric tons) of commodity *c* (soybean meal and soybean oil) shipped from crushing facility *j* to export port *e* by mode of transportation *m* (truck and six railroad companies where available); d_{je} is the distance (in kilometers) between the *j* crushing facility and the *e* exporting port; and r_{cjem} is transportation cost ($\$/mton\cdot km$) in shipping commodity *c* (soybean meal and soybean oil) from crushing facility *j* to export port *e* by mode of transportation *m* (truck and six railroad companies).

The fifth term is the total cost in transporting soybeans from the barge ports into the crushing facilities. In greater detail, XBJ_{cbjm} is the quantity (metric tons) of commodity *c* (soybeans) shipped from barge port *b* to crushing facility *j* by mode of transportation *m* (barge); d_{bj} is the distance (in kilometers) between the *b* barge port and the *j* crushing facility; and r_{cbjm} is transportation cost ($\$/mton \cdot km$) in shipping commodity *c* (soybeans) from barge port *b* to crushing facility *j* by mode of transportation *m* (barge).

The sixth term is the total cost in transporting soybeans from the barge ports into the export ports. In greater detail, XBE_{cbem} is the quantity (metric tons) of commodity *c* (soybeans) shipped from barge port *b* to export port *e* by mode of transportation *m* (barge); d_{be} is the distance (in kilometers) between the *b* barge port and the *e* export port; and r_{cbem} is transportation cost ($\$/mton \cdot km$) in shipping commodity *c* (soybeans) from barge port *b* to export port *e* by mode of transportation *m* (barge).

The seventh term is the total cost in loading soybeans, soybean meal and soybean oil from the exporting ports into the ocean going vessels. In greater detail, XEF_{cef} is the quantity (metric tons) of commodity *c* (soybeans, soybean meal and soybean meal) loaded from export port *e* into vessels *f*; and r_{ef} is loading cost ($\$/mton$) in loading commodity *c* (soybeans, soybean meal and soybean meal) from export port *e* to vessel *f*.

Country elevator, crushing facility, barge port and export port storage costs ($\$/mton$) are estimated for the remaining stocks in each of them. Therefore the least-cost route takes into account not only transportation costs but also storage costs along the supply chain from the country elevators to the exporting ports in Argentina during 2006.

Model Constraints:

The objective function for the model was optimized subject to the following constraints. First, the model had to account for the inventory of commodities available in each region. Second, the model had to take into account for flows of commodities between the different marketing channels. Finally, the model had to consider transportation and storage capacity constraints along the supply chain.

The quantity of *c* commodity available at each country elevator *s*, OFFFARMINV*cs*, is defined in equation 2. It is the quantity of the *c* commodity available from the difference between beginning and ending stocks plus the total quantity of the *c* commodity produced in that county in 2006, minus the quantity of *c* commodity shipped to the *e* exporting port (terminal elevator), to the *j* crushing facility and to the *b* barge port.

$$OFFFARMINV_{cs} = STOCK_{cs} + PROD_{cs} - \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{e=1}^{13}\sum_{m=1}^{7} XSE_{csem} - \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{j=1}^{37}\sum_{m=1}^{7} XSJ_{csjm} - \sum_{c=1}^{2}\sum_{s=1}^{217}\sum_{b=1}^{12}\sum_{m=1}^{7} XSB_{csbm} \quad (2)$$

The quantity of commodities stored in each *j* crushing facility, CRUSHINV*cj*, is the quantity of the *c* commodity in inventory from the difference between beginning and ending stocks, plus the total quantity of *c* commodity shipped from the *s* country elevator and the *b* barge port, minus the quantity of *c* commodities transported to the *e* exporting port (terminal elevator). This equality is shown in equation 3.

$$CRUSHINV_{cj} = STOCK_{cj} + \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{j=1}^{37}\sum_{m=1}^{37} XSJ_{csjm} + \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{b=1}^{12}\sum_{m=1}^{7} XSB_{csjm} - \sum_{c=1}^{2}\sum_{j=1}^{37}\sum_{e=1}^{13}\sum_{m=1}^{2} XJE_{cjem} \quad (3)$$

The quantity of commodities stored in each *e* exporting port (terminal elevator), PORTINV*ce*, is the quantity of the *c* commodity stored from the beginning stocks, plus the quantity of commodity shipped from the *s* country elevator, from the *j* crushing facility and from the *b* barge port, minus the quantity of commodities loaded into the *f* vessels at the exporting port. This equality is represented in equation 4.

$$PORTINV_{ce} = STOCKS_{ce} + \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{e=1}^{13}\sum_{m=1}^{7} XSE_{csem} + \sum_{c=1}^{2}\sum_{j=1}^{37}\sum_{e=1}^{13}\sum_{m=1}^{7} XJE_{cjem} + \quad (4)$$

$$+ \sum_{c=1}^{1}\sum_{b=1}^{12}\sum_{e=1}^{13}\sum_{m=1}^{1} XBE_{cjem} - \sum_{c=1}^{3}\sum_{e=1}^{13}\sum_{f=1}^{13} XEF_{cef}$$

The quantity of commodities shipped from the *s* country elevators to the *e* exporting port (terminal elevator), to the *j* crushing facility and to the *b* barge port, plus the quantity stored does not exceed the quantity stored at each storage location. This inequality is shown through equation 5.

$$OFFFARMINV_{cs} \geq \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{e=1}^{13}\sum_{m=1}^{7} XSE_{csem} + \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{j=1}^{37}\sum_{m=1}^{7} XSJ_{csjm} + \sum_{c=1}^{2}\sum_{s=1}^{217}\sum_{b=1}^{12}\sum_{m=1}^{7} XSB_{csbm} \quad (5)$$

The quantity of commodities shipped from the *j* crushing facility to the *e* exporting port (terminal elevator) plus the quantity stored and received from the *s* country elevator and *b* barge port does not exceed the quantity crushed at each storage location. This inequality is described in equation 6.

$$CRUSHINV_{cj} \geq \sum_{c=1}^{2}\sum_{j=1}^{37}\sum_{e=1}^{13}\sum_{m=1}^{7} XJE_{cjem} \quad (6)$$

The quantity of *c* commodities loaded from the *e* exporting port (terminal elevator) to the *f* vessels plus the quantity stored and received from the *s* country elevator, the *j* crushing facility and the *b* barge port does not exceed the quantity received by each exporting port during 2006 in Argentina. This inequality is represented by equation 7.

$$PORTINV_{ce} \geq \sum_{c=1}^{3}\sum_{e=1}^{13}\sum_{f=1}^{13} XEF_{cef} \tag{7}$$

The quantity of *c* commodities stored on the country elevators must not exceed the *s* country elevator storage capacity during 2006 in Argentina. This inequality is described in equation 8.

$$CSS_{cs} \geq OFFFARMINV_{cs} \tag{8}$$

The quantity of *c* commodities stored in the crushing facility must not exceed the *j* crushing facility storage capacity during 2006 in Argentina. This inequality is shown in equation 9.

$$CJS_{cj} \geq CRUSHINV_{cj} \tag{9}$$

The quantity of *c* commodities stored in the *e* exporting port must not exceed the *e* exporting port storage capacity during 2006 in Argentina. This inequality is represented in equation 10.

$$CES_{ce} \geq PORTINV_{ce} \tag{10}$$

The quantity of *c* commodities loaded into the vessels in each exporting port *e* must not exceed the loading capacity during 2006 in Argentina. This inequality is shown in equation 11.

$$CLE_{ce} \geq LOAD_{cf} \tag{11}$$

The quantity of *c* commodities shipped by truck must not exceed the throughput capacity during 2006 in Argentina. This inequality is represented in equation 12.

$$CMT \geq \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{e=1}^{13}\sum_{m=1}^{1} XSE_{csem} + \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{j=1}^{37}\sum_{m=1}^{1} XSJ_{csjm} + \\ + \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{b=1}^{12}\sum_{m=1}^{1} XSJ_{csbm} + \sum_{c=1}^{2}\sum_{j=1}^{37}\sum_{e=1}^{13}\sum_{m=1}^{1} XJE_{cjem} \tag{12}$$

The quantity of *c* commodities shipped by railcar must not exceed the throughput capacity during 2006 in Argentina for the six railroad companies. This inequality is shown in equation 13.

$$CMR \geq \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{e=1}^{13}\sum_{m=1}^{6} XSE_{csem} + \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{j=1}^{37}\sum_{m=1}^{6} XSJ_{csjm} + \sum_{c=1}^{1}\sum_{s=1}^{217}\sum_{b=1}^{6}\sum_{m=1}^{1} XSJ_{csbm} + \sum_{c=1}^{2}\sum_{j=1}^{37}\sum_{e=1}^{13}\sum_{m=1}^{1} XJE_{cjem} \quad (13)$$

The quantity of *c* commodities shipped by barge must not exceed the inland waterway capacity during 2006 in Argentina. This inequality is described in equation 14.

$$CMB \geq \sum_{c=1}^{1}\sum_{b=1}^{12}\sum_{e=1}^{13}\sum_{m=1}^{1} XSE_{cbem} + \sum_{c=1}^{1}\sum_{b=1}^{12}\sum_{j=1}^{37}\sum_{m=1}^{1} XSJ_{cbjm} \quad (14)$$

Decision Variables of the Model:

The decision variables, those variables optimized by the model, are defined and listed according to their place in the objective function. There is a decision variable for each of the terms of the equation.

XSE_{csem} is the quantity of commodity *c* (soybeans) to ship (metric tons) from off-farm storage location (country elevator) *s* to export port (terminal elevator) *e* in 2006 by mode of transportation *m* (truck and rail) in Argentina; where $XSE_{csem} \geq 0$ for all *c*, *s*, *e*, *m*.

XSJ_{csjm} is the quantity of commodity *c* (soybeans) to ship (metric tons) from off-farm storage location (country elevator) *s* to crushing facility *j* in 2006 by mode of transportation *m* (truck and rail) in Argentina; where $XSJ_{csjm} \geq 0$ for all *c*, *s*, *j*, *m*.

XSB_{csbm} is the quantity of commodity *c* (soybeans) to ship (metric tons) from off-farm storage location (country elevator) *s* to barge port *b* in 2006 by mode of transportation *m* (truck and rail) in Argentina; where $XSB_{csbm} \geq 0$ for all *c*, s, *b*, *m*.

XJE_{cjem} is the quantity of commodity *c* (soybean meal and soybean oil) to ship (metric tons) from crushing facility *j* to export port (terminal elevator) *e* in 2006 by mode of transportation *m* (truck and rail) in Argentina; where $XJE_{cjem} \geq 0$ for all *c*, *j*, *e*, *m*.

XBJ_{cbjm} is the quantity of commodity *c* (soybeans) to ship (metric tons) from barge port *b* to crushing facility *j* in 2006 by mode of transportation *m* (barge) in Argentina; where $XBJ_{cbjm} \geq 0$ for all *c*, *b*, *j*, *m*.

XBE_{cbem} is the quantity of commodity *c* (soybeans) to ship (metric tons) from barge port *b* to exporting port *e* in 2006 by mode of transportation *m* (barge) in Argentina; where $XBE_{cbem} \geq 0$ for all *c*, *b*, *e*, *m*.

XEF_{cef} is the quantity of commodity *c* (soybeans, soybean meal and soybean oil) to transfer (metric tons) from the gate of the export port (terminal elevator) *e* into the vessel within the port at the origin *f* in 2006 in Argentina; where $XEF_{cef} \geq 0$ for all *c*, *e*, *f*.

Constraints of the Model:

In this section the parameters of the base model are defined and listed. They are grouped according to the quantity of commodity produced, stored and required within each stage of the supply chain; to the transportation and storage capacity constraints; to the distance among the different stages of the supply chain in each marketing channel; and to the transportation and storage rates.

Constraints Related to the Quantity of Commodity Produced and Required:

$STOCKS_{cb}$ is the quantity of commodity *c* (soybean) at barge port *b* in Argentina in 2006 (metric tons).

$STOCKS_{cj}$ is the quantity of commodity *c* (soybean, soybean meal and soybean oil) at crushing facility *j* in Argentina in 2006 (metric tons).

$STOCKS_{ce}$ is the quantity of commodity *c* (soybean, soybean meal and soybean oil) at exporting port *e* in Argentina in 2006 (metric tons).

$STOCKS_{cs}$ is the quantity of commodity *c* (soybean) at country elevator *s* in Argentina in 2006 (metric tons).

$CRUSHINV_{cj}$ is the quantity of commodity *c* (soybean) required at crushing facility *j* in Argentina in 2006 (metric tons).

$EXPORTINV_{ce}$ is the quantity of commodity *c* (soybean, soybean meal and soybean oil) required by export port *e* (terminal elevator) in Argentina in 2006 (metric tons).

$LOADED_{cf}$ is the quantity of commodity *c* (soybean, soybean meal and soybean oil) loaded into the vessels *f* by export port *e* in Argentina in 2006 (metric tons).

$OFFFARMINV_{cs}$ is the quantity of off-farm stored commodity *c* (soybean) at off-farm storage location (country elevator) *s* in Argentina in 2006 (metric tons).

Constraints Related to Transportation and Storage Capacity Constraints:

The following total transportation and storage capacities were for Argentina for 2006:

Note	Description	Unit	Total Values	Source
CMT	Truck hauling capacity (300 km)	$mton / year$	108,000,000	Personal estimation
CMR_1	BC railcar hauling capacity (1,069 km)	$mton / year$	703,928	Nardi and Davis, 2006
CMR_2	ALL-M railcar hauling capacity (576 km)	$mton / year$	592,012	Nardi and Davis, 2006
CMR_3	NCA railcar hauling capacity (479 km)	$mton / year$	6,450,545	Nardi and Davis, 2006
CMR_4	FEP railcar hauling capacity (473 km)	$mton / year$	3,701,408	Nardi and Davis, 2006
CMR_5	FSR railcar hauling capacity (388 km)	$mton / year$	446,554	Nardi and Davis, 2006
CMR_6	ALL-C railcar hauling capacity (771 km)	$mton / year$	1,664,696	Nardi and Davis, 2006
CMB	Barge hauling capacity (751 km)	$mton / year$	12,512,847	Nardi and Davis, 2006
CSS_{1s}	Storage capacity for country elevator *s*	$mton$	48,155,833	ONCCA, 2006
CES_{1e}	Grains storage capacity for exporting port *e*	$mton$	3,859,000	J.J. Hinrichsen, 2006
CES_{2e}	By-products storage capacity for exporting port *e*	$mton$	2,238,500	J.J. Hinrichsen, 2006
CES_{3e}	Oils storage capacity for exporting port *e*	$mton$	795,450	J.J. Hinrichsen, 2006
CJS_{1j}	Grains storage capacity for crushing facility *j*	$mton$	4,000,000	J.J. Hinrichsen, 2006
CJS_{2j}	By-products storage capacity for crushing facility *j*	$mton$	3,985,670	J.J. Hinrichsen, 2006
CJS_{3j}	Oils storage capacity for crushing facility *j*	$mton$	757,126	J.J. Hinrichsen, 2006
CLE_{1e}	Grains export loading capacity for exporting port *e*	$mton / hour$	46,150	J.J. Hinrichsen, 2006
CLE_{2e}	By-products export loading capacity for exporting port *e*	$mton / hour$	18,650	J.J. Hinrichsen, 2006
CLE_{3e}	Oils export loading capacity for exporting port *e*	$mton / hour$	11,780	J.J. Hinrichsen, 2006

Related to Transportation and Storage Rates:

The following transportation and storage average rates were for Argentina for 2006:

Notation	Description	Unit	Average Values	Source
RMT	Truck average rate (300 km)	$\$ / mton \cdot km$	0.070	SAGPyA
RMR_1	BC railcar average rate (1,069 km)	$\$ / mton \cdot km$	0.0205	SAGPyA
RMR_2	ALL-M railcar average rate (576 km)	$\$ / mton \cdot km$	0.0147	SAGPyA
RMR_3	NCA railcar average rate (479 km)	$\$ / mton \cdot km$	0.0164	SAGPyA
RMR_4	FEP railcar average rate (473 km)	$\$ / mton \cdot km$	0.0202	SAGPyA
RMR_5	FSR railcar average rate (388 km)	$\$ / mton \cdot km$	0.0204	SAGPyA
RMR_6	ALL-C railcar average rate (771 km)	$\$ / mton \cdot km$	0.0134	SAGPyA
RMB	Barge average rate (751 km)	$\$ / mton \cdot km$	0.0130	SAGPyA
RSS	Country elevator average storage rate	$\$ / mton$	11.00	Nardi, 2006
RSE	Export port average storage rate	$\$ / mton$	7.70	Nardi, 2006
RSJ	Crushing facility average storage rate	$\$ / mton$	7.70	Nardi, 2006
RSB	Barge port average storage rate	$\$ / mton$	7.70	Nardi, 2006
RLE	Average export loading rate	$\$ / mton$	4.00	Nardi, 2006

Constraints Related to the distance among the country elevators, the crushing facilities, the exporting port and the barge ports:

The following distances were calculated using the Origin-Destination Cost Matrix (ODCM) from Network Analyst in ArcMap. Besides giving distances matrixes, ODCM finds the country elevators, crushing facilities, barge ports and export ports automatically for each railroad company. This process is convenient as it permits to easily locate and evaluate the different component of the supply chain that can be connected through the available road, railroad and waterway infrastructure. The following distances were calculated for Argentina in 2006:

d_{se} is the distance between the *s* country elevator and the *e* exporting port (kilometers)

d_{se1} = distance for the road network dataset
d_{se2} = distance for the BC railroad network dataset
d_{se3} = distance for the ALL-M railroad network dataset
d_{se4} = distance for the NCA railroad network dataset
d_{se5} = distance for the FEP railroad network dataset
d_{se6} = distance for the FSR railroad network dataset
d_{se7} = distance for the ALL-C railroad network dataset

d_{sj} is the distance between the *s* country elevator and the *j* crushing facility (kilometers)

d_{sj1} = distance for the road network dataset
d_{sj2} = distance for the BC railroad network dataset
d_{sj3} = distance for the ALL-M railroad network dataset
d_{sj4} = distance for the NCA railroad network dataset
d_{sj5} = distance for the FEP railroad network dataset
d_{sj6} = distance for the FSR railroad network dataset
d_{sj7} = distance for the ALL-C railroad network dataset

d_{sb} is the distance between the *s* country elevator and the *b* barge port (kilometers)

d_{sb1} = distance for the road network dataset
d_{sb2} = distance for the BC railroad network dataset
d_{sb3} = distance for the ALL-M railroad network dataset
d_{sb4} = distance for the NCA railroad network dataset
d_{sb5} = distance for the FEP railroad network dataset
d_{sb6} = distance for the FSR railroad network dataset
d_{sb7} = distance for the ALL-C railroad network dataset

d_{je} is the distance between the *j* crushing facility and the *e* exporting port (kilometers)

d_{sj1} = distance for the road network dataset
d_{sj2} = distance for the BC railroad network dataset
d_{sj3} = distance for the ALL-M railroad network dataset
d_{sj4} = distance for the NCA railroad network dataset
d_{sj5} = distance for the FEP railroad network dataset
d_{sj6} = distance for the FSR railroad network dataset
d_{sj7} = distance for the ALL-C railroad network dataset

d_{bj} is the distance between the *b* barge port and the *j* crushing facility (kilometers)

d_{bj1} = distance for the waterway network dataset

d_{be} is the distance between the *b* barge port and the *e* exporting port (kilometers)

d_{bj1} = distance for the waterway network dataset

Results:

Several maps were generated to display the different geographic data used in the model as a part of the linear optimization cost minimization problem (Tables 1 through 4). The maps were catalogued into the following types: Stocks, Flows, Capacities and Infrastructure for each segment of the supply chain: Country Elevators, Crushing Facilities, Exporting Ports and Barge Ports (Tables 1 through 4).

Table 1: Maps Generated in ArcGIS before the Linear Programming Optimization in GAMS to display the geographic data used for the exporting ports.

Type	Title	Content	Source
Infra-structure	Soybean Exporting Ports	Map of Argentina displaying the ports that exported soybeans during 2006	SAGPyA
Flow	Soybeans Exports *(metric tons)*	Soybeans exported by ports (13) in 2006 out of total exporting ports (22).	SAGPyA
Stock	Soybeans Beginning Stocks at Exporting Ports *(metric tons)*	Soybeans stored at soybean exporting ports (13) in January 1st of 2006	SAGPyA
Stock	Soybeans Ending Stocks at Exporting Ports *(metric tons)*	Soybeans stored at soybean exporting ports (13) in December 31st of 2006	SAGPyA
Capacity	Storage Capacity at Exporting Ports *(metric tons)*	Storage capacity at the ports that exported soybeans in 2006.	J.J. Hinrichsen
Infra-structure	Soybean Meal Exporting Ports	Map of Argentina displaying the ports that exported soybeans during 2006	SAGPyA
Flow	Soybean Meal Exports *(metric tons)*	Soybean meal exported by ports (9) in 2006 out of total exporting ports (22).	SAGPyA
Stock	Soybean Meal Beginning Stocks at Exporting Ports *(metric tons)*	Soybean meal stored at soybean exporting ports (9) in January 1st of 2006	SAGPyA
Stock	Soybean Meal Ending Stocks at Exporting Ports *(metric tons)*	Soybean meal stored at soybean exporting ports (9) in December 31st of 2006	SAGPyA
Capacity	Storage Capacity at Exporting Ports *(metric tons)*	Storage capacity at the ports that exported soybean meal in 2006.	J.J. Hinrichsen
Infra-structure	Soybean Oil Exporting Ports	Map of Argentina displaying the ports that exported soybeans during 2006	SAGPyA
Flow	Soybean Oil Exports *(metric tons)*	Soybean oil exported by ports (8) in 2006 out of total exporting ports (22).	SAGPyA
Stock	Soybean Oil Beginning Stocks at Exporting Ports *(metric tons)*	Soybean oil stored at soybean exporting ports (8) in January 1st of 2006	SAGPyA
Stock	Soybean Oil Ending Stocks at Exporting Ports *(metric tons)*	Soybean oil stored at soybean exporting ports (8) in December 31st of 2006	SAGPyA
Capacity	Storage Capacity at Exporting Ports *(metric tons)*	Storage capacity for oils at the ports that exported soybean meal in 2006	J.J. Hinrichsen
Capacity	Loading Capacity at Exporting Ports *(metric tons)*	Soybean and soybean meal loading capacity at exporting ports in 2006 into vessels	J.J. Hinrichsen
Capacity	Loading Capacity at Exporting Ports *(metric tons)*	Soybean oil loading capacity at exporting ports in 2006 into vessels	J.J. Hinrichsen

Table 1: Maps Generated in ArcGIS before the Linear Programming Optimization in GAMS to display the geographic data used for the crushing facilities.

Type	Title	Content	Source
Infra-structure	Soybean Crushing Facilities	Map of Argentina displaying 37 crushing facilities that crushed soybeans out of a total of 48 crushing facilities that crushed oilseeds during 2006	SAGPyA
Flow	Soybeans Crushed at Crushing Facilities *(metric tons)*	Soybeans crushed at soybeans crushing facilities (37) in 2006 out of total crushing facilities (48)	SAGPyA
Stock	Soybeans Beginning Stocks at Crushing Facilities *(metric tons)*	Soybeans stored at soybean crushing facilities (37) in January 1st of 2006	SAGPyA
Stock	Soybeans Ending Stocks at Crushing Facilities *(metric tons)*	Soybeans stored at soybean crushing facilities (37) in December 31st of 2006	SAGPyA
Stock	Soybean Meal Produced at Crushing Facilities *(metric tons)*	Soybean meal produced at soybean crushing facilities (37) in 2006	SAGPyA
Stock	Soybean Meal Beginning Stocks at Crushing Facilities *(metric tons)*	Soybean meal stored at soybean crushing facilities (37) in January 1st of 2006	SAGPyA
Stock	Soybean Meal Ending Stocks at Crushing Facilities *(metric tons)*	Soybean meal stored at soybean crushing facilities (37) in December 31st of 2006	SAGPyA
Stock	Soybean Oil Produced at Crushing Facilities *(metric tons)*	Soybean oil produced at soybean crushing facilities (37) in 2006	SAGPyA
Stock	Soybean Oil Beginning Stocks at Crushing Facilities *(metric tons)*	Soybean oil stored at soybeans crushing facilities (37) in January 1st of 2006	SAGPyA
Stock	Soybean Oil Ending Stocks at Crushing Facilities *(metric tons)*	Soybean oil stored at soybeans crushing facilities (37) in December 2006	SAGPyA
Capacity	Storage Capacity at Crushing Facilities *(metric tons)*	Storage capacity for soybeans and soybean meal for each crushing facility during 2006	J.J. Hinrichsen
Capacity	Storage Capacity at Crushing Facilities *(metric tons)*	Storage capacity for soybean oil for each crushing facility during 2006	J.J. Hinrichsen

Table 3: Maps Generated in ArcGIS before the Linear Programming Optimization in GAMS to display the geographic data used for the country elevators.

Type	Title	Content	Source
Infra-structure	Counties with Soybean Available to be Shipped	Map of Argentina displaying 217 county-seats in which soybean was available to be shipped to crushing facilities, exporting ports or barge ports during 2006	SAGPyA ONCCA
Stock	Soybeans Beginning Stocks at Country Elevators *(metric tons)*	County-seats (150) where soybeans were stored in January 1st of 2006	ONCCA
Stock	Soybean Production *(metric tons)*	Counties (217) where soybeans were produced in 2006	SAGPyA
Stock	Soybeans Ending Stocks at Country Elevators *(metric tons)*	County-seats (175) where soybeans were stored in December 31st of 2006	ONCCA
Stock	Soybeans Available from Country Elevators *(metric tons)*	County-seats (217) where soybeans were available to be shipped to crushers, export ports and barge ports during 2006	SAGPyA
Capacity	Storage Capacity at Country Elevators *(metric tons)*	Storage capacity for each county-seat (217) in 2006	ONCCA

Table 2: Maps Generated in ArcGIS before the Linear Programming Optimization in GAMS to display the geographic data used for the barge ports.

Type	Title	Content	Source
Infrastructure	Soybean Barge Facilities	Map of Argentina showing 12 barge ports at the Parana and Uruguay Rivers.	SAGPyA
Capacity	Barge Loading and Unloading Capacities *(metric tons)*	Barge loading and unloading capacity for barge ports during 2006.	J.J. Hinrichsen

Maps were generated from each Origin Destination Cost Matrices for Country Elevators, Crushing Facilities, Exporting Ports and Barge Ports (Table 5). ArcGIS Network Analyst has the ability to display each of the links of the supply chain that can be connected through the eight different network datasets (road, BC railroad, ALL-M railroad, NCA railroad, FEP railroad, FSR railroad, ALL-C railroad and waterway). ArcGIS Network Analyst not only allows for a clear visualization of the network datasets but also permits to calculate the distances among all the stages of the supply chains. These calculations are fundamental for the GAMS model optimization.

Table 3: Origin-Destination Cost Matrices Generated in ArcGIS for the Linear Programming Optimization Model in GAMS.

#	Title	Origin	#	Destination	#	Network	Lines	Note
1	ODCM_1	Soybeans Available	227	Soybean Ports	13	Roads	2,951	d_{1se1}
2	ODCM_2	Soybeans Available	227	Soybean Crushing	37	Roads	8,399	d_{1sj1}
3	ODCM_3	Soybeans Available	227	Barge Ports	12	Roads	2,724	d_{1sb1}
4	ODCM_4a	Soybean Crushing	37	Soybean Meal Ports	9	Roads	333	d_{2je1}
5	ODCM_4b	Soybean Crushing	37	Soybean Oil Ports	8	Roads	296	d_{3je1}
6	ODCM_5	Soybeans Available	227	Soybean Ports	13	Gauge_N	340	d_{1se2}
7	ODCM_6	Soybeans Available	227	Soybean Crushing	37	Gauge_N	1,020	d_{1sj2}
8	ODCM_7	Soybeans Available	227	Barge Ports	12	Gauge_N	408	d_{1sb2}
9	ODCM_8a	Soybean Crushing	37	Soybean Meal Ports	9	Gauge_N	90	d_{2je2}
10	ODCM_8b	Soybean Crushing	37	Soybean Oil Ports	8	Gauge_N	90	d_{3je2}
11	ODCM_9	Soybeans Available	227	Soybean Ports	13	Gauge_S	23	d_{1se3}
12	ODCM_10	Soybeans Available	227	Soybean Crushing	37	Gauge_S	92	d_{1sj3}
13	ODCM_11	Soybeans Available	227	Barge Ports	12	Gauge_S	23	d_{1sb3}
14	ODCM_12a	Soybean Crushing	37	Soybean Meal Ports	9	Gauge_S	0	d_{2je3}
15	ODCM_12b	Soybean Crushing	37	Soybean Oil Ports	8	Gauge_S	0	d_{3je3}
16	ODCM_13	Soybeans Available	227	Soybean Ports	13	Gauge_W1	135	d_{1se4}
17	ODCM_14	Soybeans Available	227	Soybean Crushing	37	Gauge_W1	508	d_{1sj4}
18	ODCM_15	Soybeans Available	227	Barge Ports	12	Gauge_W1	101	d_{1sb4}
19	ODCM_16a	Soybean Crushing	37	Soybean Meal Ports	9	Gauge_W1	41	d_{2je4}
20	ODCM_16b	Soybean Crushing	37	Soybean Oil Ports	8	Gauge_W1	54	d_{3je4}
21	ODCM_17	Soybeans Available	227	Soybean Ports	13	Gauge_W2	120	d_{1se5}
22	ODCM_18	Soybeans Available	227	Soybean Crushing	37	Gauge_W2	328	d_{1sj5}
23	ODCM_19	Soybeans Available	227	Barge Ports	12	Gauge_W2	123	d_{1sb5}
24	ODCM_20a	Soybean Crushing	37	Soybean Meal Ports	9	Gauge_W2	40	d_{2je5}
25	ODCM_20b	Soybean Crushing	37	Soybean Oil Ports	8	Gauge_W2	40	d_{3je5}
26	ODCM_21	Soybeans Available	227	Soybean Ports	13	Gauge_W3	28	d_{1se6}
27	ODCM_22	Soybeans Available	227	Soybean Crushing	37	Gauge_W3	56	d_{1sj6}
28	ODCM_23	Soybeans Available	227	Barge Ports	12	Gauge_W3	56	d_{1sb6}
29	ODCM_24a	Soybean Crushing	37	Soybean Meal Ports	9	Gauge_W3	12	d_{2je6}
30	ODCM_24b	Soybean Crushing	37	Soybean Oil Ports	8	Gauge_W3	10	d_{3je6}
31	ODCM_21	Soybeans Available	227	Soybean Ports	13	Gauge_W4	28	d_{1se7}
32	ODCM_22	Soybeans Available	227	Soybean Crushing	37	Gauge_W4	56	d_{1sj7}
33	ODCM_23	Soybeans Available	227	Barge Ports	12	Gauge_W4	56	d_{1sb7}
34	ODCM_24a	Soybean Crushing	37	Soybean Meal Ports	9	Gauge_W4	12	d_{2je7}
35	ODCM_24b	Soybean Crushing	37	Soybean Oil Ports	8	Gauge_W4	16	d_{3je7}
36	ODCM_25	Barge Ports	12	Soybean Exports		Waterways	30	d_{1se8}
37	ODCM_26	Barge Ports	12	Soybean Crushing	37	Waterways	10	d_{1se8}

Finally, maps were generated in ArcMap to display soybeans, soybean meal and soybean oil remaining at country elevators, crushing facilities and exporting ports after the model was run in GAMS. The difference between the available values for each commodity at each stage before and after the linear programming optimization in GAMS gave estimates of how much each country elevator had participated in the different supply chains. Commodities from lower cost supply chains were moved to the crushing plants and exporting ports in larger quantities than those commodities in higher cost supply chains. Therefore, country elevators that did not have railroad availability or were distant from the crushing facilities and exporting ports had higher costs in moving soybeans and higher storage costs resulting from less soybeans being moved to these outlets.

Conclusions:

Supply chain analysis through a cost-minimization linear programming model of soybeans, soybean meal and soybean oil across 227 country elevators, 37 crushing plants, 13 exporting ports and 12 barge ports transported through eight different network datasets for Argentina in 2006 involved large amounts of geographic data. ArcMap was used to map geographic data before and after the optimization in GAMS. ArcMap allowed visualizing geographic data used in the model through creating maps grouped as infrastructure, stock, flows and capacity for the country elevators, crushing facilities, exporting ports and barge ports. ArcMap also permitted to visualize the possibilities of transporting soybeans, soybean meal and soybean oil through the eight network datasets by mapping all the possible combinations. Finally, ArcMap also provided images of the lower cost and higher cost supply chains as remaining commodities at the country elevators, crushing facilities and exporting ports after the optimization were mapped.

GAMS was used to optimize the linear programming cost-minimization model as constrained problems of this nature cannot be solved in ArcGIS at the present time. The model was constrained by both transportation constraints and storage constraints. Transportation constraints were used for the road network dataset, the waterway dataset and the six railroad network datasets, as there were six railroad companies operating in Argentina in 2006 (BC, ALL-M, NCA, FEP, FSR and ALL-C). Storage constraints were used on the country elevators, crushing facilities, exporting ports and barge ports. The network datasets used in the model were performed in ArcGIS Network Analyst. This extension from ArcGIS was used to produce and map Origin-Destination Cost Matrices for the supply chain analysis.

The fact that both ArcGIS and GAMS can read data from and generate results in Microsoft’s Excel makes ArcGIS a powerful tool not only for displaying geographic data but also for showing optimization results of the supply chain analysis. ArcGIS ArcMap mapping possibilities and ArcGIS Network Analyst solving capabilities together with GAMS optimization capabilities can have a significant impact on agricultural supply chain management for trading firms as well as producers, elevators and crushers by providing detailed information and images of the lowest-cost producing regions, transportation modes, storage locations and exporting sites.

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