

## **The Siting of Ethanol Plants in Quebec**

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There has been a renewed interest in the effect of transportation costs and economies of scale on the spatial distribution of economic activity (Krugman 1991a, 1991b). Interest in the production of fuel-grade ethanol for transportation has closely followed the oil market over the past fifteen years, with an increase in interest tracking an increase in the price of oil. This interest has generally manifested itself in the production of ethanol from corn and several large-scale production facilities have been constructed and brought on-line in the United States. Proponents of this industry argue that it provides an alternate market for excess corn that is particularly beneficial for farmers when corn prices are depressed. In fact this argument has been used to justify investment in this industrial sector in Quebec.

On the other hand, an argument can be made that an industry such as this is in a somewhat precarious situation, as any increase in the price of corn, although beneficial to farmers selling corn, will reduce profit margins for the industrial firms involved. What is perhaps needed is to find a way to support an ethanol industry using alternate biomass feedstocks. Such an alternate feedstock is Jerusalem Artichoke (*Helianthus tuberosus* L.). The potential for this feedstock has been investigated as an alternative, and more profitable crop for farmers to grow than hay by Baker et al (1993). This research indicates that this crop might indeed be a profitable choice for Quebec farmers, and there is an abundance of land in Quebec that can support this crop without reducing the land area allocated to grain corn.

The crop is a member of the sunflower family, which can be harvested in one of two ways. The tops can be harvested as a forage crop or the tubers can be lifted in a similar manner as potatoes. The tubers may look like a potato or more like a gingerroot depending upon the variety grown. As this is a perennial crop, it would be possible to harvest tops on an annual basis and then lift the tubers in the final year. The sugars within the plant move from the tops

into the tubers as the year progresses. Thus, if the tops are the desired production the harvest date will be earlier than in the case of tuber production.

This initial research (Baker et al 1993) focused on a single ethanol plant being located in the Montreal region with the feedstock being transported to the plant. Given that the economic impacts from such a plant were found to be positive (Thomassin et al 1992), it is interesting to investigate the optimal distribution of multiple plants throughout the region under study as the positive impacts could then be shared in Quebec regions outside of Montreal. This paper reports on this research and presents results of a mathematical modeling approach to such a problem.

### **The Location Problem**

The facility-location problem, as applied to agriculture, has typically been solved using mathematical programming techniques (Faminow and Sarhan 1983; Fuller et al 1976; Hilger et al 1977). However, these techniques are usually variants of mixed-integer programming and depend on the fact that the facility provides an essential good or service with no substitutes. As a result, the facility faces perfectly inelastic demand for its good or service. The problem, then, is one of locating the facility so as to minimise the travel cost for clients of the facility, given the fact that all clients will use the facility and have nowhere else to go.

Unlike most facility-location problems, the location decision in this paper is set in a competitive environment. Here, the optimal locations and capacities are determined for one or more ethanol plants that use an agricultural crop as a feedstock and which, in addition to ethanol, yield two by-products. The optimal location is that which minimises the cost, per litre, of ethanol, net of all transportation costs incurred by the producer and of proceeds from the sale of by-products. The market for ethanol is quite large and the share of production represented by the plants in this study is quite small. In other words, the ethanol producers described here face perfectly elastic demand for their product: above the market price, they sell nothing; at or slightly below the market price, they sell everything. As a result, minimising the unit cost and selling at the market price is the profit maximising strategy for our producers.

The markets for the feedstock and for the by-products are assumed to be competitive. More precisely, the supply of the feedstock to the ethanol plant depends on the price offered by the ethanol producer to the farmers for the crop, the farmers' costs in raising the crop, and the distance over which they transport the crop to the ethanol plant. Furthermore, both by-products are assumed to be sold in competitive markets.

The industrial plants produce ethanol from the tops of the Jerusalem Artichoke plants (identified as JA hereafter). Each of the ethanol plants can be located among 66 municipalities in the Province of Quebec, each municipality corresponds to one of the Province's census sub-divisions and all are connected by road. The two by-products of the distillation process are Distiller's Dried Grain (DDG), which can be used as a (close but imperfect) substitute for soymeal in the feeding of livestock, and carbon dioxide (CO<sub>2</sub>), used by bottlers for further industrial use. The capacities of the plants are determined by the amount of JA forthcoming from the farmers which, in turn, depends on the price they are offered, their JA production costs and on their transportation costs to the nearest ethanol plant. The demand for DDG and CO<sub>2</sub> are determined by their prices relative to local prices of soymeal and CO<sub>2</sub>, respectively, and by the amounts that can be supplied by the ethanol plant.

#### **The Economics of JA Production**

The tops of the JA are a low-cost source of sugar for ethanol production, and the plant itself can serve as a break crop, placed in a rotation with corn. It can also be grown on land more suitable for hay production. As hay land is generally lower quality land than corn land, this indicates that the JA crop is quite versatile in terms of the agricultural location decision. The economics of JA production have been examined elsewhere by Frappier et al (1990). Ethanol feedstock costs of production, for various yield and conversion factors (JA tops into ethanol), in Quebec are presented in Table 1.

The information presented in Table 1 illustrates how the ethanol feedstock cost changes, and thus becomes lower and more competitive, as the yield and or conversion factors increase. For comparison purposes, for a corn price of \$152.65 (which is the approximate average of the present market and stabilised prices) and a conversion factor of 386.9 l/tne (see Raphael Katzen Associates 1980) the feedstock cost is \$0.39/litre. This comparison would indicate that JA could compete favourably with corn as a feedstock for ethanol production.

Two components of production costs were found to vary with location: the yield of JA and the price of land. In this study, a relationship was established between both precipitation and growing-degree days and the JA yield for each census sub-division.<sup>1</sup> Similarly, land prices were obtained for each of the sub-divisions. Variations in JA yield owing to differences in soil fertility are poorly understood (Frappier et al 1990) and therefore could not be retained as a location-dependent variable in the calculation of production costs. The yield data were from a limited number of field trials, mostly in southwestern Ontario. In these experiments, the variability in climatological conditions and soil characteristics were just too limited to extrapolate to Quebec's different climate and variety of soil characteristics.

TABLE 1 Ethanol Feedstock Cost of Production Using JA Tops - Quebec

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Yield (tne/ha)	30.0	41.0	55.0	80.0	100.0
Conversion	(\$/litre of ethanol)				
90.0	0.55	0.40	0.30	0.21	0.17
100.0	0.50	0.36	0.27	0.19	0.15
110.0	0.45	0.33	0.25	0.17	0.14

Note: 1. Land Price: \$2,500/ha, cost of Production: \$1,492.14/ha.

Source: Thomassin et al 1990

#### The Economics of Ethanol Production

As described in Henning et al (1990), the ethanol is obtained first by hydrolysing and then fermenting the JA tops. In the course of fermentation, CO<sub>2</sub> and stillage are produced. The latter of these by-products is dried, to produce DDG. The ethanol is transported to a refinery in the city of Montreal where it is blended with gasoline, either as a gasoline extender (ethanol blended fuel) or as an octane enhancer.

Three aspects of production economics are of particular importance for this problem. First is the cost per litre of producing ethanol. This determines the overall profitability of ethanol production. Second are the location-dependent costs, in this case the local price of fuel oil and natural gas. Third, and perhaps most important, are the economies of scale to be had in ethanol production. The economies of scale have a centralising effect that counters the decentralising effect of minimising transportation costs for the CO<sub>2</sub>, DDG, ethanol and JA. The main sources of economies of scale are in fixed charges (including capital costs) and in labour. To a lesser extent, the cost of electricity also varies with plant size, as larger consumers enjoy lower rates from the provincial electric utility.

Ethanol production costs were calculated based on a modified and updated version of a study undertaken by Raphael Katzen Associates (1980) using corn as a feedstock. The updating of the Katzen study concerned a scaling of the plant size to be consistent with the size range assumed to be typical for the Canadian market versus the size assumed for the US. Also, the Katzen study related to plants using corn as the feedstock. In the case of this research, the plant costing had to be altered to accommodate JA tops as the feedstock.

For a 100-ML plant producing ethanol from JA tops, the estimated cost of production excluding feedstock cost and by-product credits was determined to be \$0.323 per litre (Thomassin et al 1990). This compares very favourably with estimated plant costs of approximately \$0.30 per

litre for a 100-ML plant using corn as the feedstock (Commercial Alcohols 1993). The corn plant for this comparison is assumed to be located in the Ontario/Quebec region. Comparisons with studies from the US (see Kane and Reilly 1989; Kane et al 1989; Economic Research Service 1988) should be used carefully as the US studies assume plant sizes much greater than assumed in Canada. Canadian studies, including this one, tend to assume plant sizes in the 100-ML per year range, whereas the US studies assume plant sizes in excess of 100 million gallons per year.

#### **The Facility Location Problem**

The standard facility-location problem is set on a network of points or nodes, where each node may contain either a facility, clients of the facility, or both. Arcs measure the distance between connected nodes. Typically, the services or goods provided by the facilities are essential so that the clients will want to use them, wherever the clients or facilities are located.

The standard problem can be solved in five stages:

- a specific configuration of the network is chosen by siting a number of facilities at different nodes;
- each client is allocated to the closest facility;
- all of the travel costs between clients and the nearest facility are summed for the configuration;
- the procedure is repeated for different configurations in which the locations of the facilities are made to vary; and
- all the configurations are compared and the optimal one is chosen, i.e., that configuration whose sum of transportation costs is least.

Under certain conditions, the optimal configuration will assign plants to nodes only, and not to intermediate points along the connecting arcs (Hurter and Martinich 1989). However, even if solutions cannot be restricted to nodes, there are other reasons for considering nodes only (Krarup and Pruzan 1990). In this case, it can be argued that the utilities required for ethanol production are less likely to be available at intermediate points along arcs.

The problem at hand departs from the standard facility-location in that there is more than one market for goods and that these markets are competitive. An iterative procedure is used instead of the traditional mixed-integer programming. First a number of plants and their configuration (i.e. locations) is chosen. For a given price for the feedstock (JA), and for a given configuration of plants, the supply forthcoming from the farmers is calculated, based on their production and transportation costs. This supply of feedstock then determines the plant

capacity. The corresponding ethanol production costs are calculated, including transportation costs and the cost of purchasing the feedstock, and net of revenues from the sale of by-products. Both the JA price and plant configuration is varied until a minimum cost per unit is reached for ethanol production.

#### **Solution Procedure**

In the following description of the solution procedure, each census sub-division is considered to be a potential source of JA tops. Furthermore, each sub-division is assumed to contain a population centre: the municipality. This centre serves two purposes: it is the potential site for an ethanol plant and it is the main centre to which the farmers in that census sub-division deliver their JA tops, bearing their own transportation costs.

Although the JA is indigenous to the Province of Quebec and the northeastern United States, it is not widely cultivated in this region.<sup>2</sup> It is therefore considered a new crop for our purposes and the amount of land under the JA is assumed to be proportional to the area under tame hay, provided that the JA can be grown and delivered at a profit. This assumption implies that corn will continue to be grown in Quebec for the grain market and will not be considered for the production of ethanol. As JA is not grown on a commercial scale in Quebec, some assumption must be made as to a reasonable area (total hectares) that might be grown if the economic conditions were attractive for farmers. For this study the maximum area that can be allocated to JA production is set as 20 per cent of the tame hay area in the region.<sup>3</sup> Tying this area to tame hay is justified as this crop can be profitably grown on marginal land, which is most suitable for tame hay production. This is particularly relevant if the crop is to be harvested as tops rather than in the tuber form. This was the assumption used in this study. Thus, there is no reason to convert land presently allocated to corn production. A detailed account of this and other production assumptions is provided in Frappier et al (1990). From a farmer's perspective it is worth noting that corn and JA are very imperfect substitutes for the following reason. JA is not a widely grown crop, meaning farmers are not well acquainted with its agronomic requirements. On the assumption that farmers are risk averse for the most part, hay would be considered the superior crop. However, since JA production is so limited in scope and data are lacking, there is no way of estimating elasticities empirically.

The locations of CO<sub>2</sub> bottlers in the Province of Quebec are taken as given beforehand and all are located at 'population centres'. Meanwhile, the DDG competes in each municipality with soybean meal (subject to the nutritional substitutability of these feed inputs) and is sold under a uniform pricing policy. For a price of DDG less than that for soybean meal, it is assumed that each census sub-division will demand the maximum amount possible of DDG, based on that

sub-division's livestock population. The ethanol producers behave as one, charging the same, uniform prices for DDG and CO<sub>2</sub>, and paying the same price for JA tops.<sup>4</sup> Consequently, the optimal location and plant sizes are those that minimise the net production cost of ethanol per unit over all plants.

The maximum plant capacity for each municipality, based on local utilities, was determined after corresponding with development officers for each municipality. One centre, namely Montreal, is also the site of a refinery to which all of the plants deliver their ethanol, at their own expense, for blending into gasoline. Lastly, transportation of each commodity is carried out at the going rates for the appropriate trucks.

The solution procedure can then be described as follows: in each sub-division, the cost of JA production is calculated based on, among other things, the local yield of the JA and land prices for the subdivision. For a given price of JA (Step 1 in Figure 1) and a given configuration of plants (Step 3), an amount of fresh JA, equal to the local yield multiplied by 20 per cent of the sub-division's land currently under tame hay, is supplied to the ethanol plant. This is subject to the condition that the farmers receive a price exceeding the sum of their production costs and the costs of transporting the JA from their sub-division's municipality to the plant, and the value of tame hay foregone. Otherwise, supply is zero. (It is assumed that the farmers bring the JA to their local municipality before it is transported further to the ethanol plant and that their transportation costs in doing so are zero.) Each municipality's supply is assigned to the nearest ethanol plant.<sup>5</sup>

The capacity of each ethanol plant is such that it can use all the feedstock supplied to it (as mentioned above) but not so much that it exceeds the capacity of the municipality's local services (Step 4). The production costs of ethanol are calculated based on the electricity rates for the plant's capacity, the local rates for fuel and other costs. The capital costs per unit of ethanol produced decline with the capacity of the plant; the corresponding economies of scale are determined by the power of the plant-capacity ratio, by labour and by electricity costs (Peters and Timmerhaus 1991). The amounts of CO<sub>2</sub> and DDG supplied are fixed proportions of ethanol production.

The bottlers are assumed to buy the nearest ethanol plant's entire output of CO<sub>2</sub>, provided that its delivered price, uniform for the whole Province, is less than that of locally available CO<sub>2</sub>. The price of CO<sub>2</sub> charged by the ethanol plant is varied until revenues, net of transportation costs, from the sales of the by-product are maximized (Step 5).

FIGURE 1 The Solution Procedure

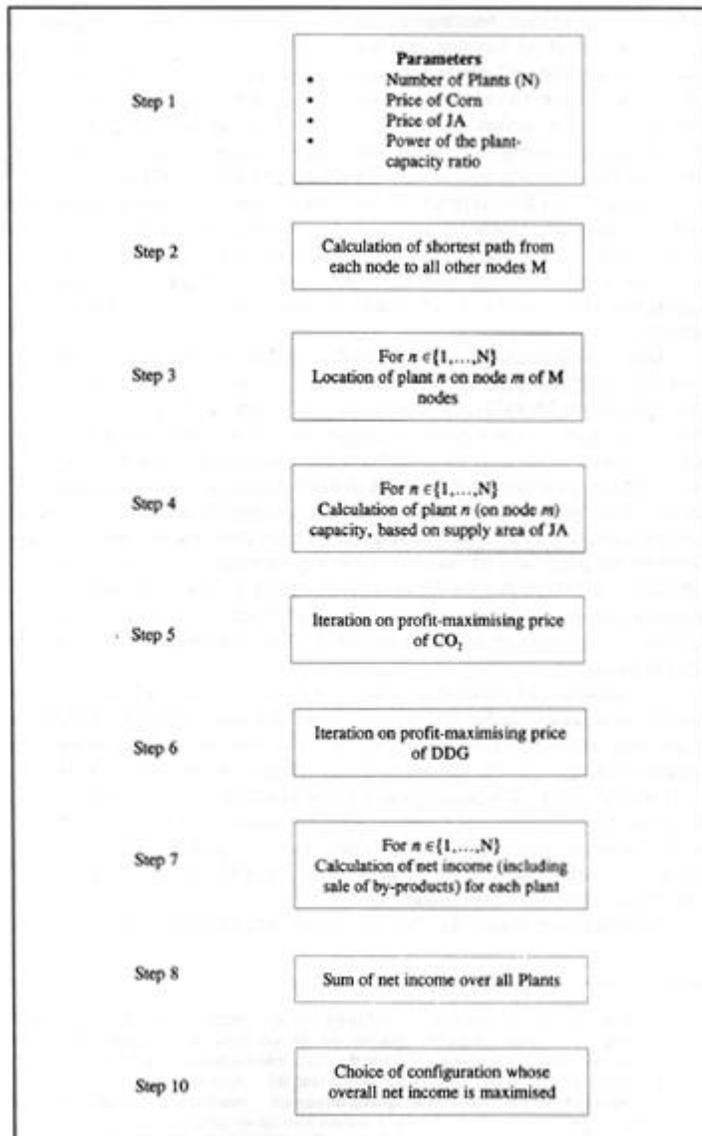


FIGURE 1 The Solution Procedure

The DDG is also sold to farmers at a uniform price. It is competitive with soymeal at 80 per cent of the latter's price, based on the superior nutritional content of soymeal. At a competitive price for DDG, the maximum shares possible of DDG in each livestock's feed rations were established after consultations with animal scientists. The total demand for DDG is equal to the populations of different livestock (hogs, cattle, etc.) in each sub-division, multiplied by the largest amount possible of DDG in the feed ration of each head of livestock. Of course, the amount bought by farmers is limited by the output of each plant. In the algorithm, the price of DDG is varied until maximum revenues, net of transportation costs, from DDG sales are obtained (Step 6).<sup>6</sup>

Finally, the ethanol is delivered to Montreal by tanker truck. The final cost per litre of ethanol is calculated based on the production cost of ethanol for all plants, plus the cost of transporting the ethanol to the refinery, less the revenues from sales of CO<sub>2</sub> and DDG (Steps 7 and 8). The locations of plants and the price paid the farmer for the JA are varied (Step 9), until a minimum production cost per litre is attained (Step 10).

### Results

The solution procedure described above was written in Fortran. Although more specialised software, such as GAMS, LINDO or GAUSS might have been used, it was felt that little would be gained from doing so. A reference scenario was established, in which two plants were located among 28 municipalities such that the net cost of ethanol, delivered to the city of Montreal, was minimised.<sup>7</sup> A number of different prices for the JA were tried; the results for four of those prices appear in Table 2.

The two plants for which costs are presented in Table 1 are Montreal and St-Damien. St-Damien is located north of Montreal and west of Trois Rivières. These are the optimal locations for a JA price of \$130 per tonne. The same sites were kept for alternative JA prices in order to isolate the effect of changes in the JA price on the supply area to the two plants. The two plants did not increase in capacity at the same rate, as there is a profit incentive for the lower cost plant to increase first and faster.

TABLE 2 Ethanol Cost, Two Plants, for Various JA Prices

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Net Cost (\$/l)	JA Price (\$/tne)	Total Capacity (MI)	Supply Area (ha)
0.3841	120	110.5	25,200
0.3793	130	147.3	37,200
0.3860	140	174.1	41,500
0.4282	150	188.8	47,100

TABLE 3 Ethanol Cost for Various Numbers of Plants

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Net Cost (\$/l)	Number of Plants	Plant Capacities (MI)						Total
		No. 1	No.2	No.3	No. 4	No. 5	No. 6	
0.4438	5	15.17	23.95	15.41	91.81	55.51	--	201.85
0.4257	4	--	23.95	15.41	91.81	55.51	--	186.68

0.4036	3	--	--	15.41	91.81	55.51	--	162.73
0.3793	2	--	--	--	91.81	55.51	--	147.32
0.3466	1	--	--	--	--	--	115.26	115.26

Note: 1. Plant No. 1 - Alma; plant No. 2 - Rimouski; plant No. 3 - Val D'Or; plant No. 4 - Montreal; plant No. 5 - St-Damien; plant No. 6 - Drummondville

A high price of JA has two effects: on the one hand, it increases the supply area to the ethanol plant, thus creating the potential for economies of scale and lower average costs of ethanol production; on the other, it increases the price paid out by the ethanol producers and raises the average cost of ethanol production. Of the four prices in Table 2, \$130 per tonne is the one that best balances these two effects. The last column shows the "catchment area", or the supply area of the JA under each price.

In addition, calculating the average cost of ethanol production for different numbers of plants can be seen in Table 3. The forces at play are the centralising effect of economies of scale and the decentralising effect of transportation costs. The first, economies of scale, provide an incentive for the ethanol producer to concentrate its production in one place. The second force, transportation costs, encourages decentralisation as ethanol plants are set up close to the supply areas of the JA so as to minimise transportation costs. (The transportation costs for ethanol, DDG and CO<sub>2</sub> were less important as they represented a smaller share of each product's value.) Table 3 shows that the effect of economies of scale dominated those of transportation-cost minimisation.

Plants tend to have the same capacity, regardless of the number of other plants as each has a relatively small catchment area around it from which it gets JA. Furthermore, it appears that these catchment areas have minimal overlap. As a result, if one plant closes down, its JA suppliers do not seem to find it profitable to grow JA and pay for transportation costs to the remaining plants. Also, the capacity of the one-plant solution is not necessarily larger than the capacity for the two-plant solution. Farmers who found it profitable to produce for one of the two plants may no longer find it profitable to produce for the single plant because it is further away (i.e. transportation costs are higher) than their choice of the two original plants.

The effects of economies of scale were examined further. This was accomplished by varying the power of the plant-capacity ratio, represented by  $a$  in the following equation:

$$C_S = C_R \left( \frac{K_S}{K_R} \right)^a \quad (1)$$

Where:

$C_s$	=	current	capital	cost
$C_r$	=	reference	capital	cost
$K_s$	=	current		capacity
$K_r$	=	reference		capacity

$a$  = power of the plant-capacity ratio.

This power determines the rate at which the capital costs increase as the size of the plant increases, capital costs being the main source of economies of scale in ethanol production. The results appear in Table 4, where the reference ratio was 0.70. The production cost of ethanol does not seem to be sensitive to this source of economies of scale.

Another change was made to the reference scenario to show how varying rates of adoption of the JA would affect the supply areas of the JA, and hence the economies of scale of ethanol production. The results appear in Table 5, with a reference rate of adoption of 20 per cent of the cropland currently under tame hay being switched over to the cultivation of the JA.

The net cost of ethanol production did not seem to be particularly sensitive to the rate of adoption of the JA by farmers. Increasing the area of land under tame hay from 20 per cent to 25 per cent, a 25 per cent increase, increased ethanol production capacity by 23 per cent. This resulted in a unit cost decrease from \$ 0.379 to 0.359 per litre - a decrease of 5.3 per cent. This does not seem to be a large decrease in the ethanol production cost, given the fact that the plant capacity increases from 147.3 MI to 181.8 MI (an increase of 23 per cent). After all, capital costs increase at a significantly slower rate than does the capacity - and capital costs per unit of ethanol actually fall fairly quickly as a result. As described earlier (see footnote 3), it makes little sense to consider greater adoption rates for a new crop such as JA than those described above.

TABLE 4 Ethanol Cost, Two Plants, for Various Powers of Plant-Capacity Ratio

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Net Cost (\$/l)	Power of Plant-Capacity Ratio	Total Capacity (MI)
0.3746	0.80	147.3
0.3793	0.70	147.3
0.3843	0.60	147.3

TABLE 5 Ethanol Cost, Two Plants, for Various Areas of Tame Hay Under JA

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Net Cost (\$/l)	Share of Tame Hay Under JA	Total Capacity (MI)
0.4081	15%	110.5
0.3793	20%	147.3
0.3588	25%	181.8

#### **Conclusion**

The model under study was able to incorporate these elements in an economically meaningful way by combining:

- a transportation model connecting 66 municipalities throughout the Province of Quebec;
- the economics of farming, transportation and ethanol production; and
- competitive markets for a number of commodities.

While the solution procedure discussed above is less elegant than the integer-programming procedure typically used to solve the facility-location problem, it allows for competitive markets for the facility's inputs and outputs. Two straightforward extensions can be made to improve the model's realism. First, facilities can be made to compete strategically with each other in both price and location. Second, all markets can be made to have less than perfect elasticity of substitution among goods, for example between DDG and soymeal.

Finally, the transportation component is general and the rest of the model is capable of handling other types of economic activity, agricultural and non-agricultural. As a result, the model is amenable not only to the analysis of the trade-off between transportation costs and economies of scale, but also to the impacts of a variety of economic activities on regional economies. In addition, the model could also incorporate a geographic information system, to visually represent location and scale, and the locational impacts of economies of scale.

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