# Location Allocation of Sugar Beet Piling Centers Using GIS and Optimization †

**Nimish Dharmadhikari [1,\*] and Kambiz Farahmand [2]**

[1] Transportation Modeling Coordinator, 2 West Second Street, Suite 800, Tulsa, OK 74103, USA

[2] Industrial and Manufacturing Engineering, North Dakota State University, Department 2485, PO Box 6050, Fargo, North Dakota 58108-6050, USA; Kambiz.Farahmand@ndsu.edu

**\*** Correspondence: ndharmadhikari@incog.org Tel: +1-918-579-9423

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**Abstract:** The sugar beet is one of the most important crops for both social and economic reasons, even though the area under sugar beet cultivation in the Red River valley of North Dakota and Minnesota is comparatively smaller that of corn and other crop lands. It generates a large economic activity in local and regional level with a greater impact on jobs and stimulation of agriculture, transportation, and farm economy. Sugar beet transportation takes place in two stages in Red River Valley: the first step is from farms to piling centers (pilers) and the second step from pilers to processing facilities. This study focuses on the problem of optimizing piler locations based on supply variation. Sugar beet supply and harvest varies significantly due to numerous reasons such as weather, water availability, and different maturity dates for the crop. This provides for a variable optimal harvesting time based on the plant maturity and sugar content. Sub-optimized pilers location result in the high transportation and utilization costs. The objective of this study is to minimize the sum of transportation costs to and from pilers and the pilers utilization cost. A two-step algorithm based on the geographical information system (GIS) with global optimization method is used to solve this problem. This method will also be useful for infrastructure decision makers such as planners and engineers to predict the truck volume on rural roads.

**Keywords:** Optimization; GIS; location; sugar beet; infrastructure decision making

## 1. Introduction

The sugar beet is considered as one of the most important crops in Red River Valley of North Dakota and Minnesota in the United States. According to Farahmand et al. [1] this sugar beet co-op operation is the largest sugar beet producer in the United States. The co-op is owned by about 2,800 shareholders who raise nearly 40% of the nation's sugar beet acreage. They also mentioned that the last seeding usually takes place on June 20 while full stockpile harvest starts on October 1st. This explains the seasonal nature of sugar beet harvesting. American Crystal Sugar Company (ACSC) manages this co-op. ACSC has five processing facilities in the Red River Valley as shown in Figure 1.
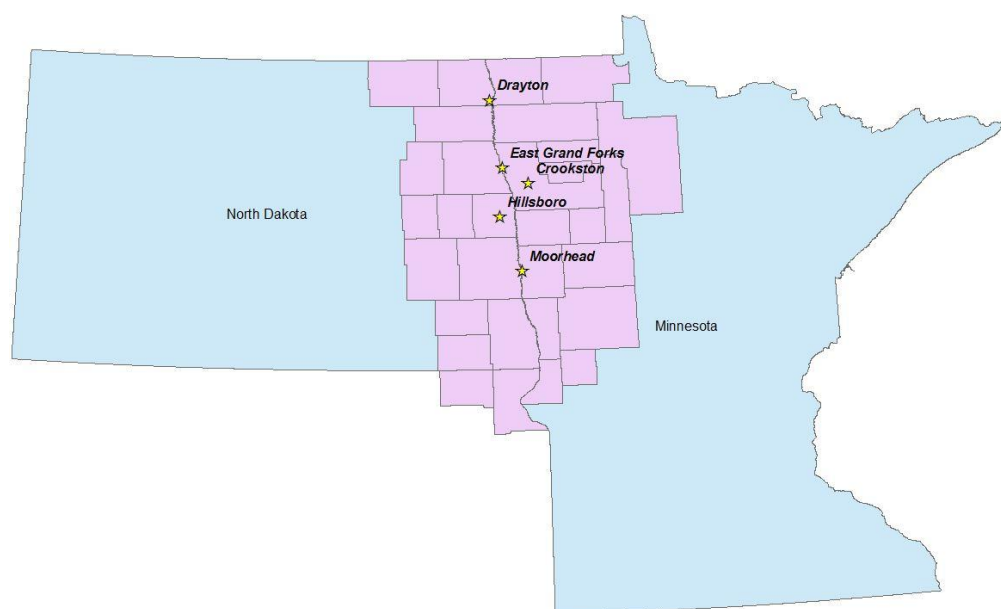
**Figure 1.** Sugar beet region and processing facilities in North Dakota and Minnesota.

Growers are responsible for delivering the crop to the piling centers. ACSC operates the piling centers for growers to deliver the load to five processing factories. Beets get unloaded at the piling center (piler) in piles and the responsibility shifts from grower to the ACSC. At the pilers, sugar beets are cleaned and are piled 30′ tall x 240′ long for long term storage through the winter. The beets need to stay cold and frozen for long term storage or otherwise they will rot. At processing time, these beets are loaded on the truck using conveyors. Once the truck is full, a new truck takes over loading the beets. The loaded trucks drive to the nearest sugar beet processing plant or receiving station. Figure 2 depicts this logistics system of sugar beet transportation from farms to processing plants.

Some beets are directly transported to the processing plants without storing them. This process is dependent on different factors. Farmers and ACSC decide whether to store beets or to take them to processing plant directly. This decision is mainly based on the maturity of the beets. The mature beet has the highest sugar content. The payment received by the farmer is based on sugar content thus farmers want to keep the beets in the ground to maximize sugar content. ACSC desires to start the harvest at an optimal time to ensure the processing plants are busy and remain at capacity throughout the season. This balance is important based on the planting time and harvesting time in order to minimize cost and maximize profit to the growers.
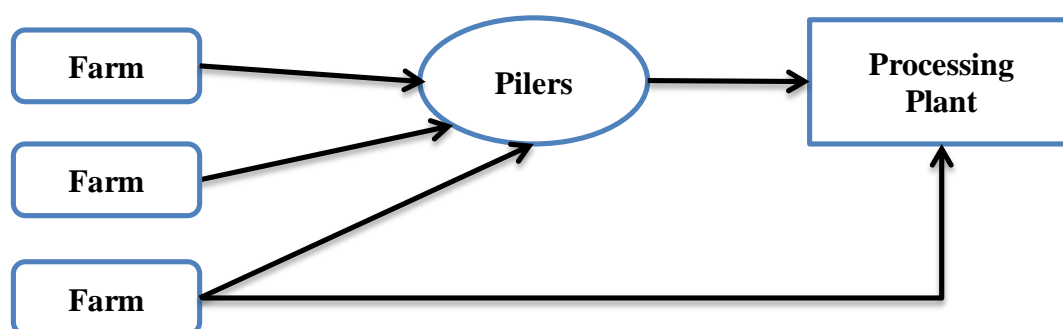


**Figure 2.** Sugar beet processing.

Pilers are considered as natural refrigerators to save beets from rotting. The colder temperatures in Red River Valley in winter helps the beets to stay at pilers for a longer time after harvest. Sugar

beet roots should be cleaned from excessive dirt, and properly defoliated and cleaned from weed or leaves to allow for proper ventilation while stored in piles. Sugar beets may be stored up to 4 months, and during this storage period the roots will decay and ferment. As a result, the sugar beet roots will heat up and the respiration leads to around 70% loss of sucrose. Decay and fermentation during storage could also cause sucrose loss of up to 10% and 20%. Some of the sucrose losses caused by the storage have been reduced through the utilization of forced-air ventilation, cooling in hotter areas and subsequent freezing of storage piles after mid-December in colder areas. Ensuring the root temperature never reaches 55° F will keep the roots from decay. During harvest, if air temperature is rising and the root temperature increases past 55° F, the harvest will stop, and no sugar beets will be accepted at the pilers. This will prevent storage rot. Cold weather and frost could also damage the roots. Foliage and leaves have proven to provide a natural barrier to frost conditions thus protecting the roots and the crown area. Exposed roots during a frost shutdown, experience a higher degree of frost damage.

This situation is ideal for a location allocation problem. The locations of the pilers are to be optimized to minimize the transportation and storage cost.

It is really hard for planners and engineers to predict the truck volume on the rural roads. For infrastructure decisions such as where to add lanes or which road needs widening needs data for the truck volume. This method will help to predict the truck volume thus it will be an important method for infrastructure decision makers.

This article is organized as follows. Section 2 studies the literature available for location allocation problems in agriculture and other settings. Section 3 describes the methodology and algorithm used for solution. Section 4 discusses a case study. Section 5 presents sensitivity analysis. Section 6 presents conclusions along with the path to future research.

## 2. Literature Review

Kondor [2] presented the initial problem of the sugar beet transportation. They tried to find the economic optimum results using the mathematical modeling of the problem. They established the relation between the processor starting date and the scheduling of the beet arrival. They provide the case study of Hungary. Scarpari and de Beauclair [3] developed a linear programing model for sugarcane farm planning. Their model delivered profit maximization and harvest time schedule optimization. They used GAMS® programing language to solve the problem. They solve this problem based on the case study of sugarcane farming in Brazil.

The location problem in a different setting is solved by Esnaf and Küçükdeniz [4]. They presented the multi-facility location problem (mflp) in logistical network. Their objective is to optimally serve set of customers by locating facilities. They studied the fuzzy clustering method and developed a hybrid method. Their method is a two-step method in which the first step uses fuzzy clustering for mflp and the second step further determines the optimum location using single facility location problem (sflp). The fuzzy clustering step uses MATLAB® for geographical clustering based on plant customer assignment. They compared their method with other clustering methods. Costs generated by the hybrid method are less than other methods. Zhang, Johnson, and Sutherland [5] presented a two-step method to find the optimum location for biofuel production. Step one uses Geographical Information System (GIS) to identify feasible facility locations and step two employs total transportation cost model to select the preferred location. They presented a sensitivity analysis of location study in the Upper Peninsula of Michigan.

Houck, Joines, and Kay [6] present the location allocation problem and its solution methodologies. They examine the applications of genetic algorithm to solve the problem. They propose that these problems are difficult to solve by traditional optimization techniques thus requiring the use of heuristic methods. Zhou and Liu [7] propose different stochastic models for the capacitated location allocation problem. They also propose a hybrid algorithm which integrates network simplex algorithm, stochastic simulation, and genetic algorithm. They test the effectiveness of this algorithm with numerical examples. In the further research Zhou and Liu [8] study the location

allocation problem with fuzzy demands. They model this problem in three different minimization models. They propose another hybrid algorithm to solve these models.

Lucas and Chhajed [9] provided a detailed review of literature in the field of location allocation involving agricultural problems. They express that there are a lot of location allocation problem solutions available but there is a lack of application-based research articles. They study six real world examples. Pathumnakul et al. [10] considered the different maturity times of sugarcane to find the optimal locations of the loading stations. They modify the fuzzy c-means method to consider cane maturity time as well as cane supply. Their objective is to minimize the total transportation and utilization cost. They compare the performance of their method with the traditional fuzzy c-means method to conclude their method provides a better solution for the problem. They test these methods with the help of a case study in sugarcane farming in Thailand.

Another location problem of sugarcane loading stations is studied by Khamjan, Khamjan, and Pathumnakul [11]. They compare the solution times of the mathematical model and the heuristic algorithm. Their objective function includes minimization of various costs such as investment cost, transportation cost, and cost of the sugarcane yield loss. They also applied their model to a case study to solve the industrial problem. In a recent study Kittilertpaisan and Pathumnakul [12] present a multiple year crop routing decision problem. Their model includes heuristic algorithm for a three-year period of sugarcane harvesting. They solve their problem to design the planting and routing such as sugarcane becomes mature in three years for harvesting.

Yeh and Chow [13] present an integrated location allocation approach for public facilities planning. They discuss integration of GIS and location allocation model. They use Hong Kong as an example. They provide an extensive review of earlier GIS and other location allocation studies. They also provide an alternating heuristic algorithm.

Church [14] discusses role of GIS in the location modeling. He presents the history of the use of GIS in location modeling. He states that GIS provide a richer dataset which can be used to find the optimal solution of location modeling.

Murray [15] enlists the contribution of GIS to location science in terms of input data, visualization, problem solution, and advances in theories. His focus is to showcase the contribution of GIS towards the advancements of the location allocation modeling theories. He reviews numerous studies showing the usefulness of GIS in the case of location allocation problem solutions.

Tolliver et al. [16] present a methodology to estimate the flows from crop zones to elevators and plants. They also forecast improvement and maintenance costs for roads. They provide a model with nodes, links, and paths. They provide a simplified grain distribution system. They provide an exhaustive GIS analysis. They describe the creation of the travel time matrix. They also discuss how the shortest path between origins and destinations is calculated in GIS using Dijkstra's algorithm.

This literature study shows that there are very few articles about sugar production and location problems and there are nearly zero articles about sugar beet harvesting and location problems involved in it. The use of GIS is well established for the solution of the location allocation problems as shown in the literature review. As the numbers of sugar beet fields are large, optimization algorithms suggested in some of the articles are not applicable in this situation. Also, there are very few articles studying the seasonal nature of the sugar beet harvest. Based on these problems this article tries to solve the location allocation problem for sugar beet harvesting using a two-stage GIS based Multi Facility Fuzzy Clustering (MFFC) algorithm.

## 3. Methodology

As stated earlier we use a two-stage method to solve a sugar beet piler location allocation problem. It involves stage one of GIS analysis with clustering and stage two of optimization. The solution algorithm is depicted in Figure 3.
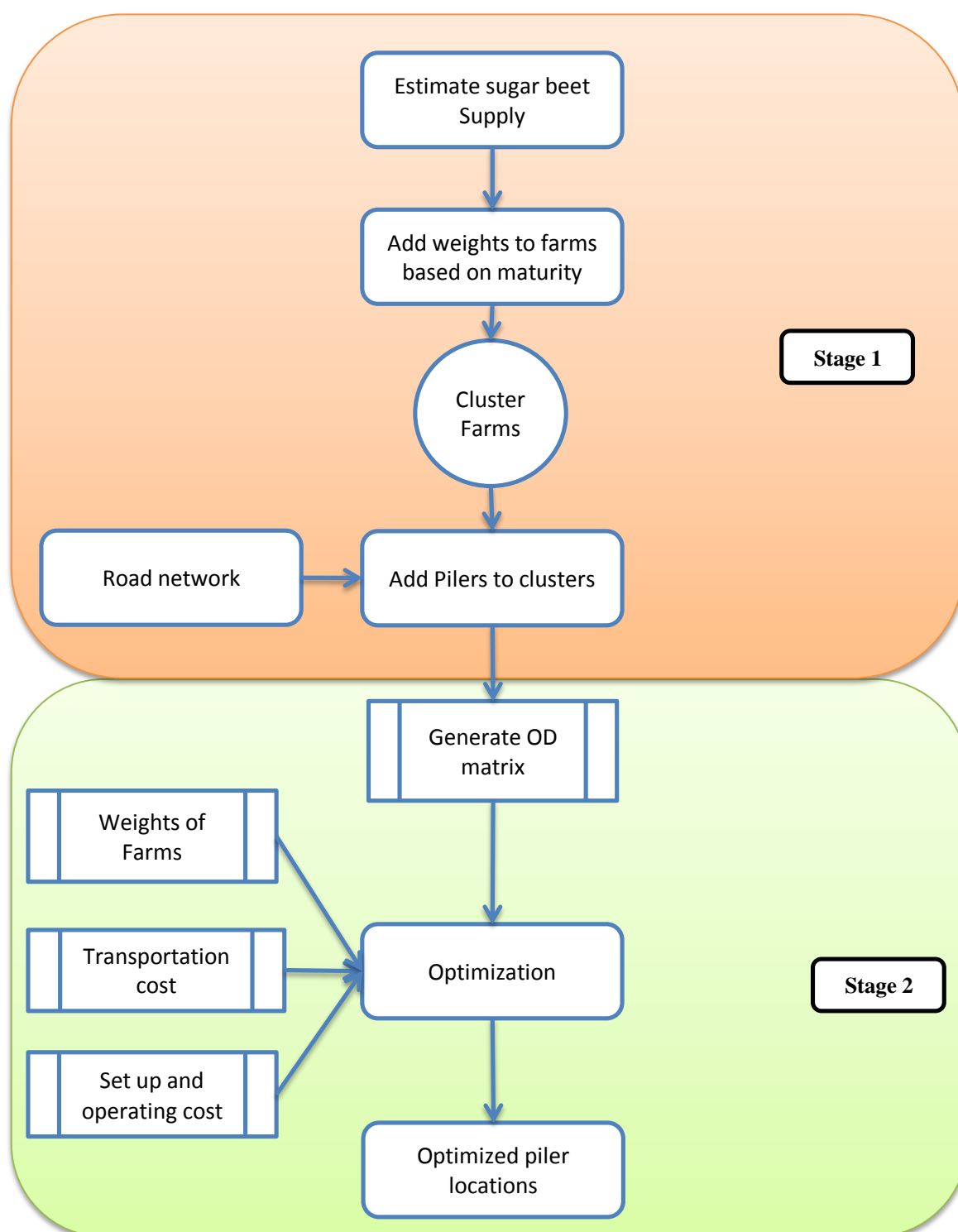
**Figure 3.** Solution algorithm. O–D: origin–destination.

### 3.1. Stage 1: GIS Analysis with Clustering

Stage 1 involves GIS analysis. As stated by Pathumnakul [10] clustering of farms is carried out in this stage. The goal of this stage is to generate an origin–destination (O–D) matrix. A GIS dataset is created with different shapefiles. The farm location shapefile is then added in the dataset. Along with the location of farms, this shapefile also has data about planting dates at each farm, weather

conditions, and yield. Weights are assigned to the locations of the farms based on the different harvest times due to different planting dates and weather conditions. In this study the weights are expressed in the preference of the harvest time. This method provides four harvest times: week group 1 is pre-harvest time which is earlier than peak harvest time, week group 2 and 3 are the peak harvest times, and week group 4 is post-peak harvest times. To form a complex model these weights in harvest times can be distributed in more than four groups. The farms are clustered in the groups of four based on these assigned weights in terms of harvest times. Farms which are planned to be harvested earlier because of earlier planting dates, weather conditions, or historical preference are clustered in the week group 1, farms late in the planting date or based on farmers and ACSC's preference, are clustered in week group 4. These clustered farms are origins. The locations of pilers are also added to this dataset which are designated as the destinations.

Finally, the road network is added in the dataset. The road network needs to have distances of each segment in miles, speed limits or observed speed over these segments, and time taken to travel the distance of each segment (travel time). The GIS software uses a shortest path algorithm to create the O–D matrix. This method is similar to the method in Dharmadhikari, Lee, and Kayabas [17]. The O–D matrix can be generated in two ways—1) distance in miles or 2) travel time between O–D pair. For this process we prefer to use shortest distance in miles which will be used as one of the inputs for optimization stage.

### 3.2. Stage 2: Optimization

The aim of the Stage two is to perform the optimization to find the pair of operating pilers and farms at the given harvest times. This will be a cost optimization process. The objective of the optimization function is to minimize the cost of logistics. Following are the important inputs for this process:

1. O–D matrix generated in Stage 1
2. Weights of farms from Stage 1
3. Transportation cost of sugar beets
4. Set up and operating cost of piler

The optimization is performed based on following assumptions:

1. Sum of all shipments should not exceed the total yield at farms
2. Piler is either open or closed at any given time
3. Quantity of sugar beets harvested should not be greater than piler capacity
4. Each sugar beet farm is assigned to one piler only
5. All pilers have the same capacity

The cost of logistics is expressed in terms of addition of different costs involved in the process such as the cost of transportation, the cost of yield loss if not harvested at the right time, and the cost of piler operation. These costs are further simplified in terms of the tangible variables which are easy to measure. These variables are piler set up cost, storage cost, distance, number of trucks, cost per mile for the truck, and yield loss cost. This gives us Equation (1) for the cost of logistics.

$$\text{Cost of logistics} = (\text{set up cost}) + (\text{storage cost}) + (\text{distance} \times \text{number of trucks} \times \text{cost per mile}) + (\text{yield loss cost}) \tag{1}$$

The objective function is represented in Equation (2). The objective function states the minimization of the cost of logistics. It is subject to the sum of all shipments being less than the total yield at farms (Equation (3)); A Piler can be open or closed (Equation 4); number of trucks should be greater than or equal to zero (Equation (5)); yield at the given farm should be greater than or equal to zero (Equation (6)); and quantity of sugar beets harvested should not be greater than total piler capacity (Equation (7)). The explanation of data sources is presented in the case study section.

$$\text{Minimize } C_l = \text{Minimize} \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{4} ((S_{uj} \times P_j) + (S_{tj} \times P_j) + S_{yi} + (X_{ijk} \times T_{ij} \times C_d)) \tag{2}$$

Subject to:

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\left(T_{ij} \times P_j \times t\right) \leq Y \tag{3}$$

$$P_j \in \{0,1\} \,\forall\, j \tag{4}$$

$$T_{ij} \geq 0 \,\forall\, i, j \tag{5}$$

$$y_i \geq 0 \,\forall\, i \tag{6}$$

$$\sum_{j=1}^{m} I_j \times P_j \geq Y \tag{7}$$

Where,

$X_{ijk}$ = distance (miles)
i = number of farms (1, 2, … n)
j = number of pilers (1, 2, … m)
k = number of distance (1, 2, 3, 4)
$y_i$ = yield at farm 'i' (tons)
Y = total yield from all farms = $\sum y_i$
t = sugar beet truck capacity (tons)
$T_{ij}$ = number of trucks from farm i to piler j = yi/t
$C_d$ = cost per mile
$I_j$ = capacity of the piler
$S_{uj}$ = set up cost of piler j
$S_{tj}$ = storage cost at piler j
$S_{yi}$ = yield loss cost at farm i
$P_j$ = 0 or 1 = Piler is used or not used
$C_l$ = cost of logistics

## 4. Case Study

Red River Valley of North Dakota and Minnesota is the study area. This area involves sugar beet production in nearly 30 counties as depicted in Figure 1. The sugar beet processing is handled by American Crystal Sugar Company (ACSC). They have five processing plants at locations Moorhead, Hillsboro, Crookston, East Grand Forks, and Drayton. As explained earlier, sugar beets are transported first to the piler locations by farmers for storage until ACSC transports them to one of the five processing plants. These piler locations are shown in the Figure 4 with the road network.

### 4.1. Data Sources

ACSC provided locations of the plants, pilers, and farms. These are the most important locations for the GIS analysis. ACSC also provided data related to the plant dates, costs, and yields at each farm. The road network was built upon using TIGER shapefiles from American Census Bureau [18]. Two shapefiles for road networks in North Dakota and Minnesota are downloaded. The road networks are then combined and cleaned. The boundary between these two states is defined by the Red River. There are numerous bridges on the river. The cleanup process involved finding locations of the bridges and connecting the road network where an existing bridge is present. This helps to provide a combined network to use in the GIS analysis. The process followed in this step is similar to the process in Dharmadhikari, Lee, and Kayabas [17]. Sugar beet truck fuel efficiency is assumed to be 10 miles per gallon and average fuel cost is assumed to be $3.00 per gallon for the study period.
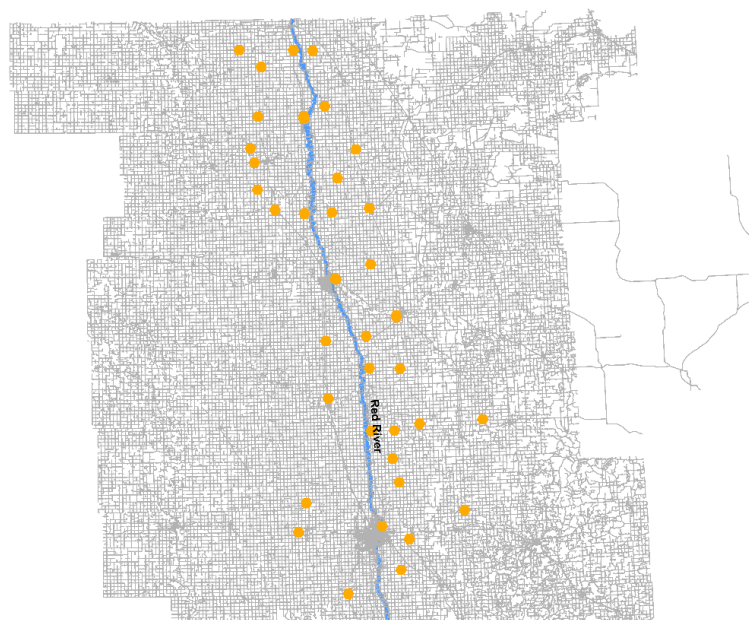
**Figure 4.** Red River Valley road network and piler locations.

*4.2. GIS Analysis*

Following the algorithm shown in Figure 3, GIS analysis is the first part of the study. This analysis involves combining all data sources and performing a clustering model with the goal of generating origin–destination (O–D) matrix. The road network of Red River Valley is added in the database. This road network is cleaned and combined as stated in data sources section. The road network contains attributes such as name, road type, and distance in miles which are important for the GIS analysis. Distance in miles is used in creation of the network dataset.

Clustering

The sugar beet harvest starts late in months of September and October. Thus, clustering of farms is carried out based on the harvest days. Harvest weeks are divided into four groups. These weeks are shown in Table 1. The farms are selected based on the harvest days falling within these four categories. Four separate clusters are formed for farms. The selection is carried out using select by attribute tool. These clusters are shown in Figure 5. By visual inspection, week group 2 and week group 3 have the largest number of farms in the cluster. The locations of the pilers are also added in this database. The small green pins in Figure 5 are the locations of the pilers.

**Table 1.** Week group division.

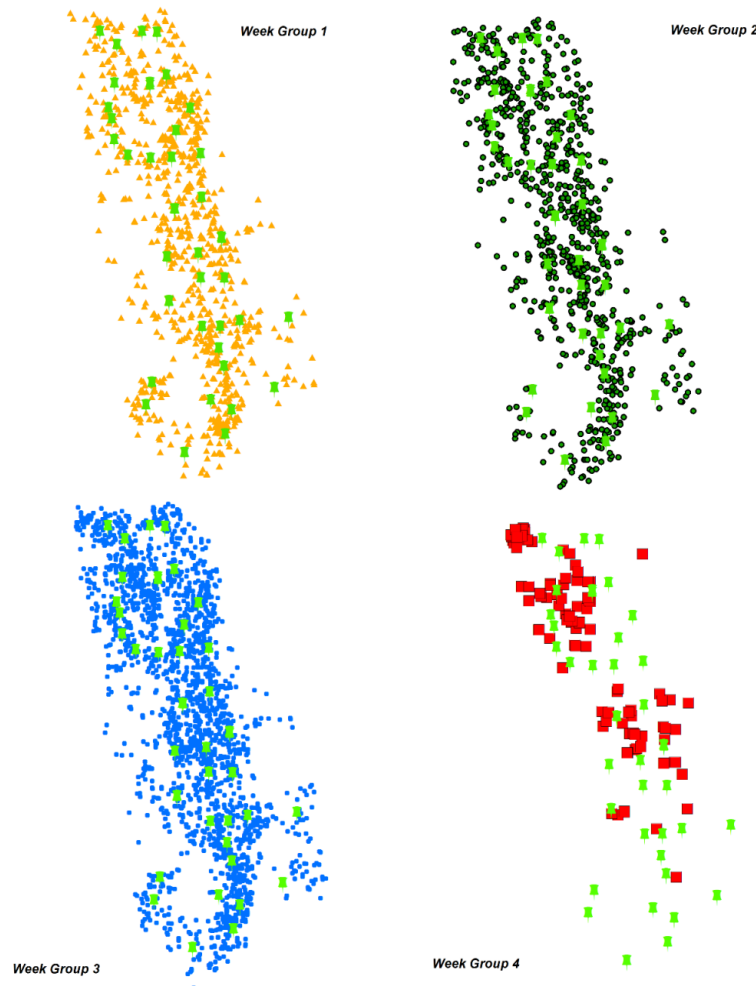| Harvest Weeks | Days of Year |
|---|---|
| Week Group 1 | Less than or equal to 280 |
| Week Group 2 | 281–287 |
| Week Group 3 | 288–294 |
| Week Group 4 | More than 294 |

**Figure 5.** Sugar beet farm clusters based on Week groups.

Closest facility

As stated in the methodology section, the clustered farms are connected to the pilers using closest facility method from ArcGIS®. This method uses the road network prepared in the data sources section. The cost of travelling for this analysis is based on the distance in miles between farm (incident) and piler (facility). This method finds the closest piler to any farm. A total of four closest pilers are found for each farm to generate origin–destination cost matrix. This gives us four distances in miles for each farm. The closest facility solution routes are shown in Figure 6. This cost matrix initially consists of distances in miles, which is later converted in the transportation cost matrix. The transportation cost is calculated using following method. This method states that the maintenance cost is assumed as seven miles per gallon. The total fuel plus maintenance cost is calculated by multiplying O–D distance matrix by two (for truck roundtrips) and then divided by seven to get gallons of fuel used. The resulting value is multiplied by average cost of diesel per gallon for the related year. These costs are added for all four-week groups.

**Figure 6.** Closest facility solution routes.

For further analysis, piler capacity is calculated from the ACSC data [19]. It states that Hillsboro factory has seven piler locations. Total beets produced in the catchment area of the Hillsboro factory are 1,402,421 tons per year. This is divided by seven to get the capacity of each piler. This comes to around 200,346 tons. We assume capacity of each piler as 200,000 tons.

Piler set up cost and storage cost are calculated from Farahmand et al. [1] The set-up cost is calculated with the help of overhead expenses. It is calculated with the addition of machinery lease cost, building lease cost, utilities per acre, and labor and management charges. The set-up cost comes to nearly $120 per acre. The Hillsboro pilers have an area of around 35 acres. Total Set up cost is calculated by multiplying area by the per acre cost, which comes to $4,200. This set up cost is assumed to be the same for all pilers. The storage cost is assumed to be $0.01 per ton of sugar beets. A piler capacity is 200,000 tons so storage cost of a piler is $2,000. Sensitivity analysis is performed based on set up cost and storage cost.

*4.3. Optimization Results*

After the GIS analysis, the following are the variables known:

1. Shortest distances from each farm to nearest 4 pilers. This gives a distance matrix for each farm location.
2. Plant date
3. Yield
4. Storage cost
5. Set up cost

Complete list of the variables used in the optimization model is given in equations 1 and 2. For performing the optimization, the distance matrix is converted into the cost matrix by multiplying the distances with the cost of fuel. In this case, we assume cost of the diesel fuel as $3.00 per gallon based on U.S. Energy Information Administration data. The optimization model is developed in the LINGO software from LINDO systems. The optimization results are presented in Table 2. It shows that the number of pilers required to be open in week group 1, 2, and 3 are 41. The number of pilers needed to be open in week group 4 are 16. This is depicted in Figure 7. It is also observed that for week group 1 to 3, the total cost is increasing but as week group 4 has less sugar beet to harvest, the total cost is then greatly reduced. The validation of the model is carried out by testing Week group 1. One or two pilers in Week group 1 are termed closed in the input data. It is expected that the model will not supply any volume to these pilers. Model performed as expected and it did not supply any volume to closed pilers while increasing the total cost.

Truck volume on the road network is predicted based on the optimization results. Based on the optimal farm-piler pairs trucks from each farm are assigned to the route between said farm-piler pair. Figure 8 shows a snippet of truck volumes on the road network. This figure shows the volume near Crookston Yard pilers for week group 4. It shows that the roads near pilers are experiencing higher truck volume. At the same time, it shows some other roads with higher truck volumes. This truck volume data can be plotted for the complete Red river valley road network for each week group. The total number of trucks for each week group is plotted in Figure 9. This follows similar pattern of the total cost. It can be seen that as the truck volume is higher for week group 3, total costs are higher for that week too.

**Table 2.** Optimization Results.

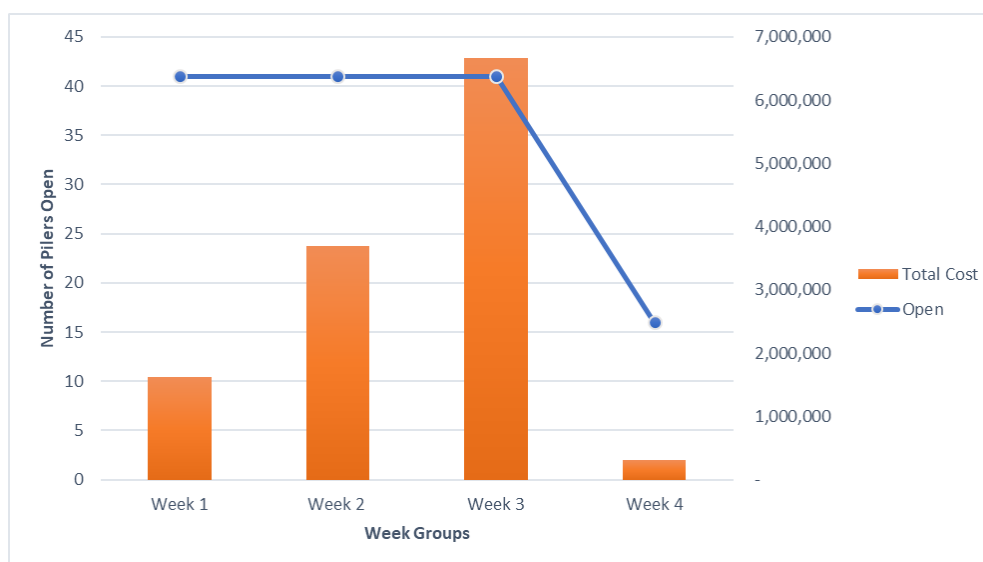| Week | Open Pilers | Total Cost |
|------|-------------|------------|
| Week Group 1 | 41 | 1,624,895 |
| Week Group 2 | 41 | 3,696,831 |
| Week Group 3 | 41 | 6,662,072 |
| Week Group 4 | 16 | 304,630 |



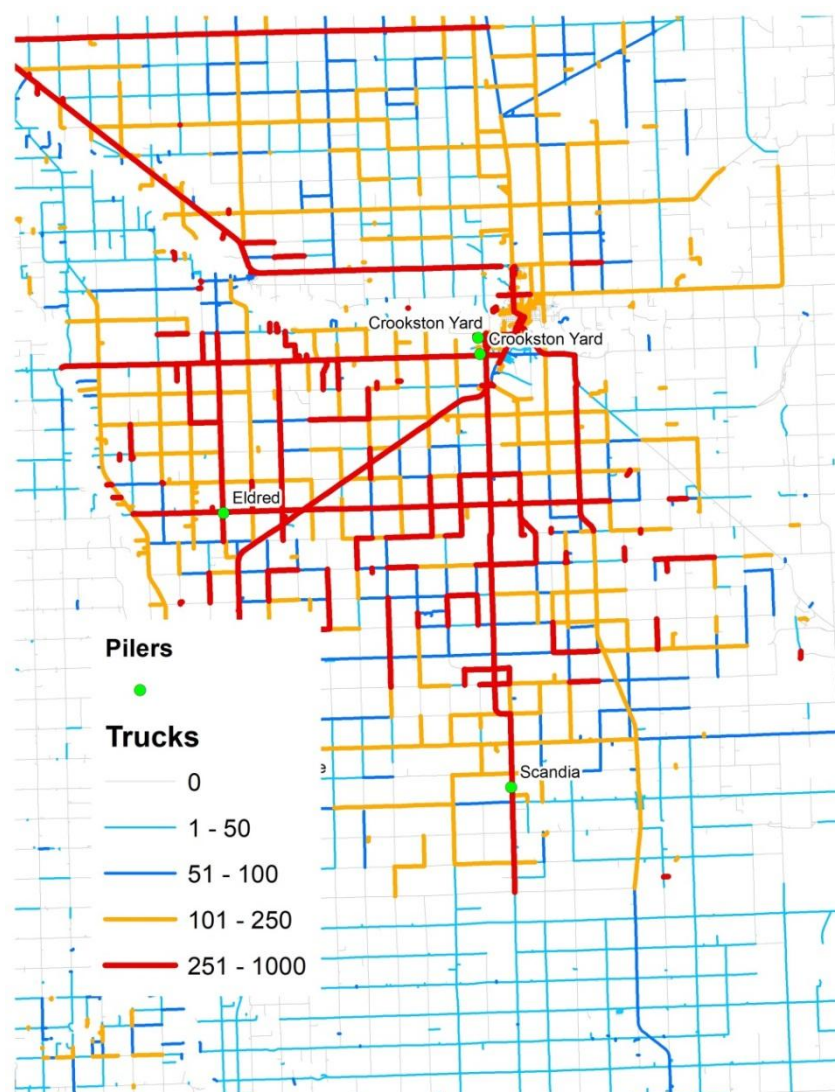**Figure 7.** Optimization Results.

**Figure 8.** Truck volume on the road network near Crookston Yard for Week group 4.



**Figure 9.** Truck volume during week groups 1–4 after optimization.

## 5. Sensitivity Analysis

The sensitivity analysis is carried out to check if the model is performing as expected. It is also important to examine the assumed values and how they perform. Week group 4 model is used to perform two types of sensitivity analyses. First analysis is carried out to test the changes in the yield whereas the second analysis is performed to check the effects of changing piler set up costs.

Different percentages of yield changes are assumed for performing the sensitivity analysis. The optimization model is run for these different yield values. The results of running these models are shown in Figure 10. The number of open pilers reduces as the yield at each farm is reduced by 50% and 75%. At the same time, the number of open pilers increases as the yield at each farm is increased from original yield to 300%. But this piler opening is not immediate and happens as a gradual increase. Number of open pilers are constant for original yield including a 10%–25% yield increase. As the yield increases from 25% to 50%, the number remains the same as it does for yield increases from 50% and 100%. A gradual increase in the total cost is also seen in the Figure 10.

Figure 11 shows the effects of changes in the piler set up costs on the number of open pilers and total cost. As the setup cost reduces, the number of open pilers increases. Even though the number of open pilers increases, the total cost decreases. As the setup cost increases the number of open pilers is reduced. There is a gradual pattern in this decrease. But it settles at eight for the number of open pilers finally. Eight is the minimum required number of open pilers to satisfy all supply at the farms in week 4. The total cost increases as the setup cost increases.
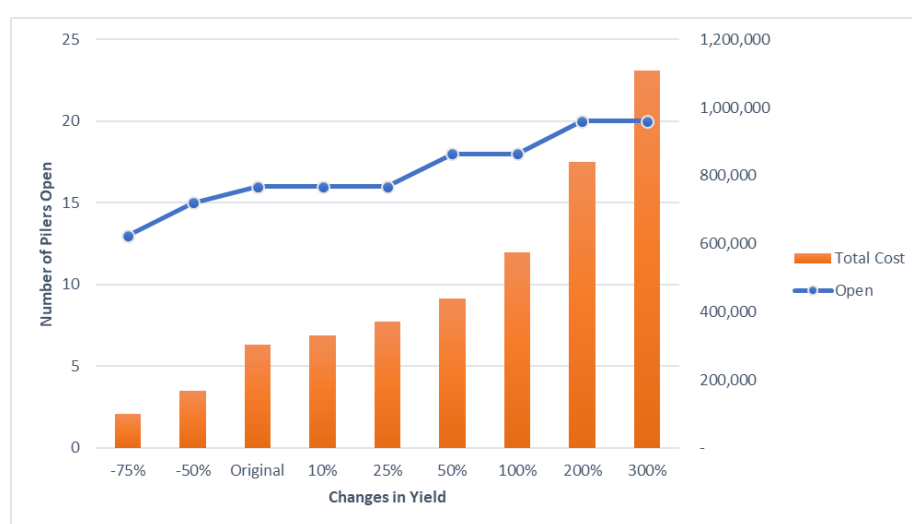


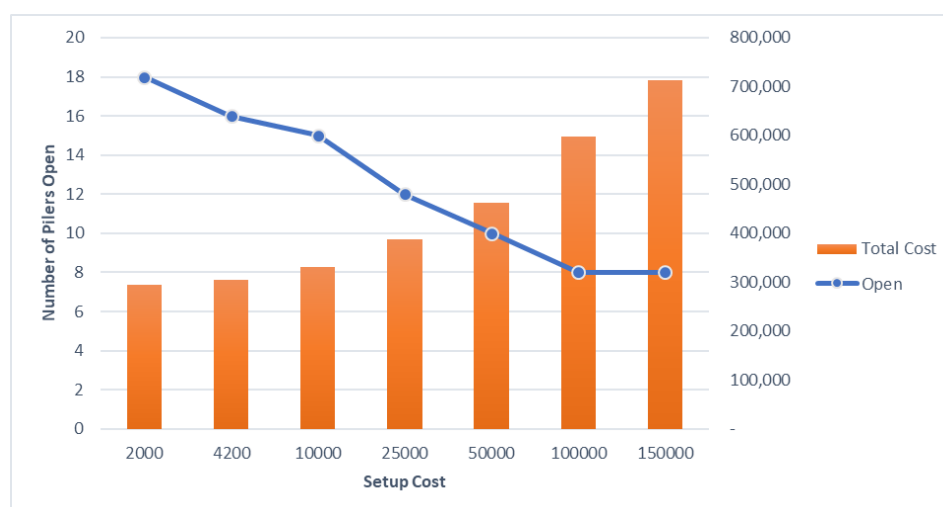**Figure 10.** Sensitivity analysis for yield change.



**Figure 11.** Sensitivity analysis for piler set up cost.

## 6. Conclusion

This study shows that a two-step method using GIS and optimization can be used to allocate the sugar beet piler locations. This method can be used to save the total transportation cost. This method is also useful for transportation planners and engineers to predict the truck volume on the rural roads.

It is hard to predict the truck volume so this will be one of the useful tools to make the infrastructure funding decisions.

As the farm to the piler cost is incurred by the farmers, this method can be helpful for farmers to save more money and reduce overall cost. At the same time this method considers the maturity period of sugar beets thus helping ACSC to transport beets at the peak of their maturity and receive highest sugar content. As seen in the sensitivity analysis as yield changes the number of pilers changes which can attribute to the supply variation. This method is also useful to find the optimal piler locations in this scenario. A reduced time interval such as half a week or less can be used for clustering to get better assessment of piler locations.

This study does not consider the computational time saving by comparing different studies, but it can be done in the future. While designing this type of study, additional consideration of the GIS component needs to be taken in to account. This study is a starting point which can be expanded into a complex model with additional steps of piler to processing plant, and processing plant to market. In the future, this method can be used with the results from Dharmadhikari et al. [20]. Their research performs yield forecasting which can be used as inputs for this study. Yield forecasting can become a very useful tool for predicting the harvest times and the yield at each farm, which can be used for weight assignment and clustering in GIS analysis. This study can also be a part of a comprehensive economic model of sugar beet production suggested in Farahmand et al. [1]. This model can be modified to be used as a base model for crops other than sugar beet.

**Author Contributions:**

Conceptualization, Nimish Dharmadhikari and Kambiz Farahmand; Data curation, Nimish Dharmadhikari; Funding acquisition, Kambiz Farahmand; Methodology, Nimish Dharmadhikari and Kambiz Farahmand; Software, Nimish Dharmadhikari; Supervision, Kambiz Farahmand; Validation, Nimish Dharmadhikari; Writing – original draft, Nimish Dharmadhikari; Writing – review & editing, Nimish Dharmadhikari.

**Conflicts of Interest**: The authors declare no conflict of interest.

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