Managing biomass feedstocks: selection of satellite storage locations for different harvesting systems

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Abstract: Biomass feedstocks including switchgrass and corn stover are currently being considered for use in direct combustion systems, and for value-added products such as ethanol. A major roadblock associated with the utilization of biomass feedstocks is the high cost of handling and storage due to low bulk density of these feedstocks. A wide variety of existing harvest systems creates logistics difficulties for bioenergy industries. The utilization of herbaceous biomass materials requires low-cost handling systems to collect, store, and transport year round. This then requires selecting the most economical methods from various existing handling systems for loose and baled biomass materials. How these different harvesting systems can be integrated into a cost-effective supply system is a challenge. A method of selecting the lowest cost harvest and handling machine system was proposed; the model developed could calculate costs of different systems so as to assist field managers to select the best handling method for every point in a given location of a biorefinery plant. The results of the model calculation can provide users a map which shows the lowest-cost handling scenario for all handling systems analyzed by this program. This result will enable biorefinary industries and landowners to determine the most cost-effective way to harvest, store, and transport biomass materials according to the size of the biorefinery plant.

Keywords: herbaceous biomass, switchgrass, harvest, handling, storage location

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1 Introduction

The Department of Energy of United Sates found that the nation has over 1.2 billion Mg DM per year of biomass potential from urban, farm and forest sources, enough to produce biofuels to meet more than one-third of the current yearly demand for transportation fuels (Perlack et al., 2005). This estimate includes 405 million Mg DM of crop residues and 342 million Mg DM of perennial crops. These feedstocks have low bulk density and energy density as compared to traditional energy sources of coal and oil. Along with density these feedstocks differ in the time period in which harvest is practical; agricultural products are harvested over a short time period and stored until use. These two facts point to the need for research in densification, handling and storage of agricultural feedstock’s for bioenergy.

Generally, silage harvesting systems can be used to harvest biomass and harvested materials are in loose and chopped format; hay harvesting systems produce baled biomass materials. Handling of biomass feedstocks includes harvesting, grinding or chopping, loading and unloading trucks, various conveying operations, and transportation to the end-use points. Agricultural biomass has low bulk density, and it is normally densified in-field with balers, or chopped with a self-propelled forage harvester. Currently, there are four prominent harvesting technologies available for biomass harvesting. They are round baling, rectangular baling, chopping/trucking with a forage harvester, and self-loading/chopping wagon (Brownell et al., 2009).

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Large rectangular balers are more suitable for biomass harvesting since they have much higher efficiency compared to traditional small rectangular balers (Sokhansanj et al., 2009). Large rectangular bales have the advantages of taking less time for collecting bales from field, less truck loading/unloading time. In addition, large rectangular bales can be easily compressed for containerized long distance and ship transport. Bale compression machines normally produce small high density bales around 35 kg (Hierden, 1999). They are designed to slice and compress a large rectangular bale into smaller bales which are easy to handle by hand. These densified small bales have two or three times higher density than the field density of large rectangular bales (Steffen Systems, 2009). Studies have not yet been done to determine the costs associated with bale compression without slicing a bale into small sections. Full large bale compression may produce an easy-to-handle product with a low cost to reduce bale storage and handling costs.

Due to the large volume of materials to be handled, handling and storage of biomass crops will most likely occur at an intermediate location between the farm gate and the plant utilizing the biomass. These storage systems have been proposed under various names, such as Satellite Storage Locations (SSL) (Cundiff and Grisso, 2008), Satellite Depot Locations (Cundiff et al., 2009), and Regional Biomass Pre-Processing Centers (Carolan et al., 2007). These storage systems differ slightly, but all use multiple storage centers accepting materials from various farms. The storage centers process and store materials, and then delivers the materials to the biorefinary plant on demand or contract. The previous studies did not address the size, location or number of storage centers.

Handling, storage, and transport methods required to move large amounts of biomass feedstocks remain largely unproven. Stored biomass will be shipped to a biorefinary plant for final use. Thus, the plant size will be directly related to the amount of biomass needed. Multiple researchers have studied plant size as documented by Carolan (Carolan et al., 2007). These studies have found the optimal plant size ranging from 2,000 to 10,000 Mg DM based on developing technologies, crop yield, and biomass availability. Researchers found three optimal plant sizes based on a short, middle, and long term analysis of developing technologies (Hamelinck et al., 2005). They also found that 2,000, 5,000, and 10,000 Mg DM of biomass per day needed for plants created in 5, 10, to 15 years, and greater than 20 years, respectively. These three sizes of plants need to be further examined to determine the handling, transport, and storage methods needed for an efficient biomass supply chain.

Handling large amounts of biomass efficiently will include complex coordination between multiple parties. To increase the available amount of biomass and reduce landowners' investment costs, multiple farmers will deliver feedstocks in different formats including loose, chopped, and baled materials to satellite storage locations which will in turn feed the materials to the receiving facilities. A mathematical model is then expected to be the most efficient way to coordinate these complex movements of material. There are several models currently available to determine the time associated with various handling operations. The IBSAL (Integrated Biomass Supply Analysis and Logistics Model) is a simulation model, which runs over a time period and simulates operations in the field. This method allows users to identify potential bottlenecks that must be alleviated before a major investment can be made in a biorefinery (Sokhansanj et al., 2006). The IBSAL model is a time-based model which is limited to making conclusions about a sequential set of events. The IBSAL program will not show interactions between two handling systems and cannot show the size and storage locations.

Ravula et al. (2008) created a model by utilizing data from another low-density crop, cotton. This model examined different collection policies, and their impacts on total materials at the end use location. Bruglieri and Liberti (2008) have used "branch and bound" non-linear programming techniques; Leduc utilized mixed-integer techniques for biomass handling (Leduc et al., 2008); linear techniques were utilized by Berruto and Busato (2008). These models did not account for economic interactions between SSLs. Dunnett et al. (2007) proposed a program to optimize scheduling of a biomass supply system for direct combustion heating. The optimization suggests that costs of biomass handling can be improved 5% to 25% with a model as compared to manual scheduling.

The research presented here focused on the creation of a model to predict the feasible transport regions for biomass handling over an area with uniform biomass distribution. The research objectives were: (1) to collect data of four possible biomass harvesting systems, i.e. a self-loading wagon, a round baler, a large rectangular baler, and large rectangular baler plus bale compression; (2) to develop a model to predict the cost and economical area of a given biomass handling scenario; and (3) to create an algorithm to minimize the cost using this model for three different sizes of biorefinery plants.

2 Materials and methods

A model was created to calculate the most economical harvest and handling operations of a biomass receiving facility (the end user) utilizing SSL to store materials. The model input data are collected from published literature and through conducting field tests. The model output is a map showing the method and the most suitable biomass form (loose materials, round bales, large rectangular bales, or large rectangular bale plus bale compression) to be handled in each location for lowest cost.

2.1 Four scenarios of biomass handling

The model was based on four possible scenarios to move the biomass from the field to the end user. Data were collected for each of the four handling systems operating in dry switchgrass. The scenarios are as follows:

- Scenario 1 – Loose biomass harvest: a Pottinger Jumbo 8000 self-loading forage wagon
- Scenario 2 – Round bale harvest: a New Holland BR7070 round baler
- Scenario 3 – Large rectangular bale harvest: a Case-IH LB433
- Scenario 4 – Large rectangular bale compression: a Steffen Systems Model 3400

2.2 Input data

This model utilized field costs, costs at the SSL, and transport costs as shown in Table 1 to construct a scenario of the most economical handling procedures. Details about the cost data collection as shown in Table 1 can be found from previous publication (Brownell et al., 2009). The baled material transport and SSL costs are derived from previous studies (Sokhansanj et al., 2009). That research found that trucking costs for rectangular bales were comprised of a base cost of $5.70/Mg and a variable cost of $0.0854/Mg-km (Sokhansanj et al., 2009). The base cost provides the set-up and fixed costs for transport, while the variable cost accounts for the fuel and labor portion of transport. The SSL cost is comprised of the base trucking cost, while the transport cost is the variable cost. The compressed bales SSL cost is comprised of the fixed trucking costs included with the cost of compressing the large rectangular bales.

Table 1 Handling costs

Handling system	Field Costs (Dollars/Mg DM)	SSL Costs (Dollars/Mg DM)	Transport Costs (Dollars/Mg DM-km)
Loose material	5.23	-	0.3
Round bales	13.78	15.37	0.37
Large rectangular bales	14.12	7.68	0.18
Compressed bales	-	23.99	0.09

2.3 Model assumptions

Several assumptions were used to simplify the real world cases and to represent real biomass harvesting and handling scenarios with analytical equations. This model was then programmed to seek a suitable harvest and handling method, which has the lowest cost among all those four options. Following assumptions were made:

- Availability of biomass is one third of the surrounding area of the biorefinery plant; biomass yield is the same (6.0 Mg/ha DM in sample calculations);
- Only loose materials in a 5-km radius surrounding area of the biorefinery plant can be directly hauled to the plant on demand;
- Transport cost calculation is based on straight lines leading directly from field to SSL, and then

to biorefinery plant;

- All SSLs store bales under tarps, and the fixed cost of each SSL is the same.

Loose material is directly hauled to the plant on-demand, and is harvested as 15,708 Mg DM over the course of a harvesting season. This amount (15,708 Mg DM) of material is equivalent to the biomass available in an area of a 5 km radius surrounding the plant with a yield of 6.0 Mg/ha DM. This radius is selected based on a research on a self-loading forage wagon, and its efficiencies at varying hauling distances (Brownell et al., 2009). The yield was assumed to be a conservative amount of 6.0 Mg/ha DM according to the research of switchgrass harvesting in Pennsylvania, United States. SSL fixed costs are assumed to be $43,800 for storing bales on gravel pads, with tarps covering the bales. This figure assumes that a SSL stores 12,443 Mg DM of bales per year and the cost is $3.52/Mg DM. The storage costs are further explored in research conducted by Brummer et al. (2002).

2.4 Model description and algorithm

The model is comprised of two sections, a cost calculation sheet, and an actual Visual Basic (Microsoft Corp.) code section. The code section runs recursively, and gradually increments the location, size and overlap of each SSL. The biorefinery plant is located in the middle of all SSLs and only accepts loose material during the harvest season. During times of the year when this immediate hauling is impractical, biomass materials will be baled in round or large rectangular bales. Biomass materials will be transported from fields to the SSLs by landowners. SSLs will be owned or rented by the biorefinery plant receiving the biomass. Each SSL will store the biomass materials and will have the option to compress the large rectangular bales to save storage and handling costs. The farmer will deliver the material to the SSL during harvest season, and the biorefinery plant will pick up the biomass materials from SSLs when needed for production.

The number of SSLs, size, and overlap of SSLs will be increased through adjusting variables if the amount of biomass stored in SSLs is not enough to supply the production. Variables could be increased and/or decreased. After the program changes any size, location or the overlap of SSLs, the program compares the resulting area, and the cost of the updated handling scenario to the old scenario. By completing multiple cycles of the comparison, the storage locations are adjusted to find the lowest cost while covering a given area.

2.5 Method of calculations

The model to calculate costs associated with each scenario utilizes Equations (1) to (5). Equation (1) derives the overlap of two circles (Weisstein, 2010), while other equations were developed to calculate the cost and area of those SSLs. Three costs for four systems are shown in Table 1. These along with the variables (SSL Size, SSL ring size, number of SSLs per ring) are used to solve for the total cost and the area covered using those equations below. The objective of this calculation process is to minimize the cost calculated with Equation (5). SSL size is the measure of the area an SSL will accumulate material from; SSL ring size denotes the distance the SSL is from the plant. Variable *d* is the distance between two SSLs, *R* and *r* are the radii of the larger and smaller SSL respectively. Where *x* and *y* are position variables measured in km.

The overlap of two SSLs (Weisstein, 2010) (Figure 1) can be described with Equation (1).

$$Overlap = r^2\cos^{-1}\left(\frac{d^2+r^2-R^2}{2dr}\right)+R^2\cos^{-1}\left(\frac{d^2+R-r}{2dR}\right)-\frac{1}{2}\sqrt{(-d+r+R)(d+r-R)(d-r+R)(d+r+R)} \quad (1)$$

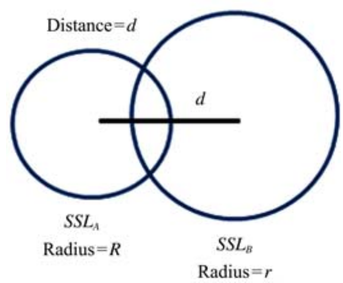

Figure 1 Overlap of two SSLs

Calculation of the area of SSL is given by Equation (2), where names of conventions can be found in Figure 1. The cost per ring can be calculated with Equation (3), and the total cost is given by Equation (4). The total area is defined by Equation (5).

$$Area_{SSL2A} = \pi r^2 - Overlap_{SSL2A,SSL2B} - Overlap_{SSL1A,SSL2A} \quad (2)$$

$$RingCost_{SSL2} + Yield \times (FieldCost + SSLCost + (DistToPlant \times TransportCost)) \times \sum_{y=A}^{m} Area_{SSL2y} \quad (3)$$

$$TotalCost = \sum_{x=1}^{n} RingCost_{SSLx} \quad (4)$$

$$TotalArea = \sum_{x=1}^{n}\sum_{y=A}^{m} Area_{SSLxy} \quad (5)$$

2.6 Procedures of cost calculation and decision making

The model initially starts with Figure 2, but may start at any arbitrary point and slowly changes variables until an optimal solution is reached. The variables to change are as follows: SSL size (radius), SSL Ring size (radius) and Number of SSL's per ring. A value of zero for SSL size corresponds to an inactive SSL. All SSLs located on the same ring are the same size. Material flows to the SSL where it is stored until the plant demands more material. The initial values of the model correspond to the cost and area covered, which are calculated in the cost calculation worksheet. The method proposed here is a decision-making assist. The user needs to input a size of the desired plant, which is the boundary of the model. The model increments in integer values starting with one and progressively increasing the increment. Costs and acreages are compared in a "double" numbering format with 15 significant digits of precision. Then the model follows the following algorithm to solve for the best (lowest cost) solution:

S1. Increase SSL size, until the area of the SSL ring equals the area the user inputted

S2. Record all variables and cost as "solution A"

S3. Increase one variable at a time (SSL Size, SSL ring size, Number of SSLs per ring)

– Record all variables and cost as "solution B"

– Compare A to B: If the cost is decreased, and area is increased or the same then go to S2

– If the cost is increased, disregard change then go to S4

S4. Decrease one variable at a time

– Record all variables and cost as "solution B"

– Compare A to B: If the cost is decreased, and area is increased or the same then go to S2

– If the cost is increased, disregard change then go to S5

S5. Increase one variable while decreasing another variable

– Record all variables and cost as "solution B"

– Compare A to B: If the cost is decreased, and area is increased or the same then go to S2

– If the cost is increased, disregard change then go to S6

S6. Repeat S3, S4, S5 for all combinations of variables

– If S6 changes any variables then repeat entire algorithm

– If S6 yielded no variable change then optimal solution found

The calculation processes provide and compare costs for all combinations of every variable, which would yield a lowest cost scenario to the mathematical equation. The program runs until the variables stop changing. This calculation process could take very long time. Actually, it can be manually stopped whenever the cost-effective decision becomes clear to the decision maker. This solution gives the best or lowest cost scenario of harvesting and handling biomass.

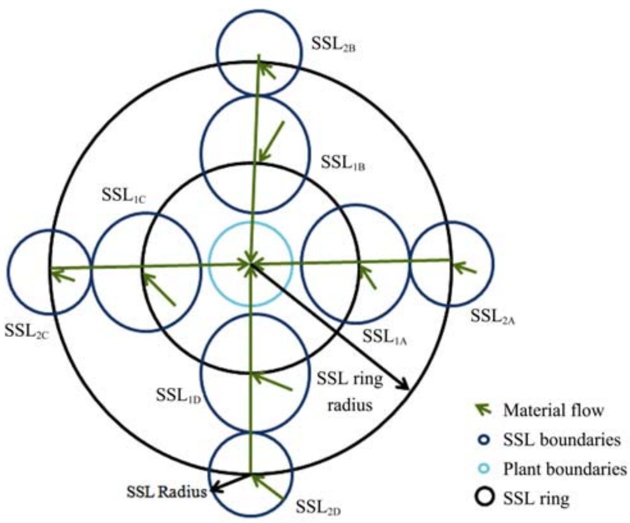

Figure 2 Satellite storage locations

3 Results and discussion

The model yielded three outputs for three different sized plants selected (Table 2). These areas represent three different sizes of plants based on research from Carolan et al. (2007). Each circle represents a feasible transport region in Figures 3 to 6. The center circle represents the biomass in the surrounding area of the plant, with the plant located at the origin. The outer circle represents SSLs that store biomass in harvest season allowing the plant to transport the biomass throughout the year on an as-needed basis. Figure 4 is a simplification of Figure 3, with only a single SSL shown for each ring, with the number of SSLs in that ring located in the legend, the medium and large scenarios are only shown in the simplified versions. As noted in the algorithm, one calculation iteration will run through all combinations of 30 variables (10 possible SSL rings with three variables each, radius, ring radius, and the number of SSLs per ring) or 435 calculations. This time limit resulted in approximately 100 iterations running in an hour depending on computer speed. The small plant algorithm ran for approximately 3,000 iterations and took 48 hrs to generate Figure 3. The medium plant algorithm ran for approximately 6,000 iterations and took 72 hrs to generate Figure 5. The large plant algorithm ran for approximately 10,000 iterations and took 96 hrs to generate Figure 6.

Table 2 Three plant sizes with biomass handling costs

SSL Size	Hectares Covered	Mg DM / Day	Dollars / Mg DM
Small	108,955	2,000	28.68
Medium	272,388	5,000	31.33
Large	544,776	10,000	33.98

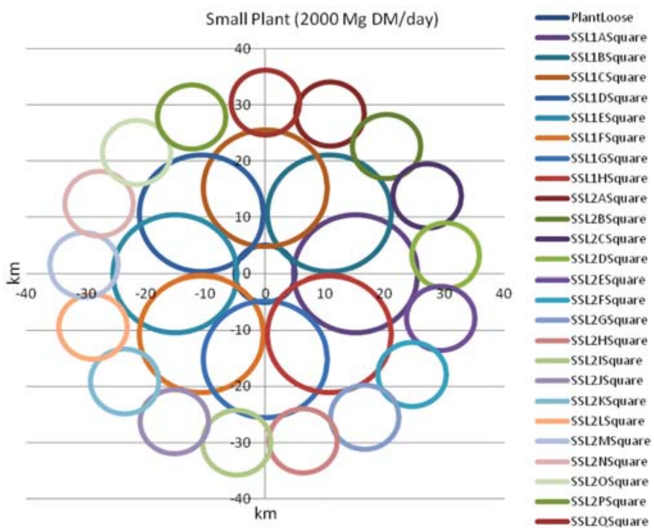

Figure 3 Small plant handling locations

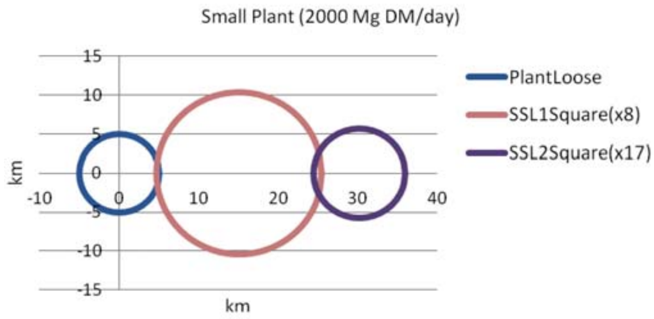

Figure 4 Simplified small plant handling locations

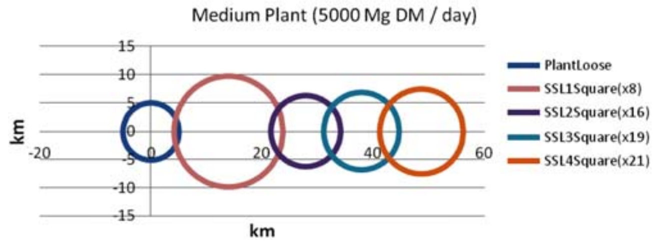

Figure 5 Medium plant handling location

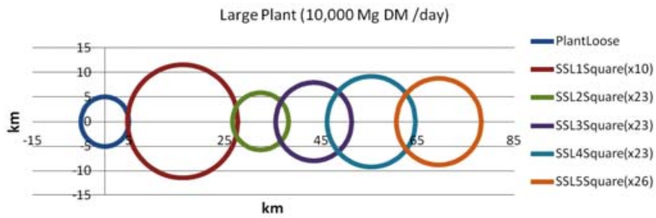

Figure 6 Large plant handling locations

At the size of the plant increased from small (2,000 Mg DM/day) to large (10,000 Mg DM/day), the computer program added more satellite storage locations. The program found 25, 64 and 105 SSLs for small, medium and large size plants, respectively. As the size increased, the program also increased the overlap of the SSLs to the front and sides. The SSL Ring 1 showed that the change from medium to large added two extra SSLs. These two extra SSLs did not capture a large amount of area; rather they captured small area closer to the plant. This captured area was very valuable, as the program chose to add SSLs in the inner circle rather than adding them to the outer edges. Although the model had several assumptions, it provided valuable information for machine design, mainly the interactions between handling systems. The model showed the need to harvest the area close to the plant as efficiently as possible, as the savings from close harvest allowed more area to be harvested farther away from the plant. This study also showed the need for efficient handling, as harvesting and transport largely affect the total cost. Large rectangular bales were the only form of biomass utilized by the program to store. Large rectangular bale compression was not utilized due to the high cost. The machinery cost was a main factor in the compression expenses. The analysis using this model also showed that the bale compression machine would be competitive with the rectangular baler at a transport distance of 181 km, while the largest transport distance in the model was around 80 km. This indicated the need to reduce the fixed cost of the compression machine mainly the initial cost of the machinery. The model analysis also showed that further investigation into interactions between densities and cost is needed as a low density product is less expensive to produce, but more expensive to handle. The compressed bale feasibility is very sensitive to legal loading limits, as loading a truck with bales twice as dense as field created large rectangular bales may overload the transport vehicle. The three handling scenarios are also very sensitive to fuel prices, as a large percentage of cost is derived from baling and transport.

4 Conclusions

Three typical sizes of biorefinery plant and accompanying SSLs were discussed, and results suggested that the size and location of satellite storage locations are sensitive to the amount of material needed by the plant. Mathematical models were developed to compare the costs of different optional handling methods. The simulated calculation processes also showed that the most economical handling system for each satellite storage location can be determined by increasing the area. The land closer to the plant became more valuable. The inner handling regions vary in size based on plant size, but always subsidized the outer locations. Economics of any size plant will depend upon securing a contract to the rights to harvest biomass in the area closest to the plant.

Field harvesting data showed that as the bulk density of the material to be handled increased, the costs of harvest increased, while the cost of transport decreased. This was due to the added high capital cost of densification equipment to compress that material. The denser the material was, the more efficient the transportation and storage were. The model and algorithm created showed the handling region for each system, and each satellite storage location. The areas covered were 108,955, 272,388 and 544,776 ha required to maintain a plant using 2,000, 5,000 and 10,000 Mg DM/day respectively. Although these maps did not show roads and actual travel distances, they might provide a base estimation of the economics of handling procedures.

Future work may include a model linked with a mapping program. This approach could allow the model to utilize actual road distances, along with actual areas of farmlands. Future models may also benefit from more flexibility by allowing the user of this model to change materials handled.

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